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FINAL REPORT FOR THE MINITRACK
TRACKING FUNCTION DESCRIPTION

Volume 1

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ABSTRACT

This report, in two volumes, describes the treatment of tracking data by the Minitrack system from the transmission of the nominal 136-MHz radio beacon energy from a satellite and the reception of this signal by the interferometer network through the ultimate derivation of the direction cosines (the angular coordinates of the vector from the tracking station to the spacecraft) as a function of time. Descriptions of some of the lesser-known functions operating on the system, such as the computer preprocessing program, are included. A large part of this report is devoted to the preprocessor, which provides for the data compression, smoothing, calibration correction, and ambiguity resolution of the raw interferometer phase tracking measurements teletyped from each of the worldwide Minitrack tracking stations to the central computer facility at Goddard Space Flight Center, Greenbelt, Md. An extensive bibliography of Minitrack hardware and theory is presented.

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Section 1

INTRODUCTION

The purpose of the Minitrack Tracking Function Description is to describe the operational functions of the Minitrack system in a manner that will allow the development of an accurate system-error model. Considerable emphasis has been placed on those features of the system that heretofore have escaped general understanding. Among these is an overall description of how the system operates, stated in simple, straightforward language. For this, a Minitrack primer is presented in section 2.

By its very nature, the preprocessing computer program, an additional element of the Minitrack system, has escaped general understanding. To those who customarily think in terms of antennas and racks of electronic gear, this preprocessor may appear to play a minor role. However, the preprocessing functions fulfilled by the general-purpose digital computers of the central computational facilities of Goddard Space Flight Center (GSFC) are as much a part of the Minitrack interferometer tracking system as are the phase meters of the pre-amplifier converters. Many reports have described the Minitrack electronic equipment now in use at the respective tracking facilities. Hardware instruction manuals (listed in the bibliography) clearly describe the functional characteristics of each electronic unit. Only one other document¹ besides this report provides insight into the preprocessing program. This technical note supplements our findings and will supply an adequate foundation for an understanding of the preprocessing functions.

It might have been desirable to duplicate or otherwise include in this report the many articles, technical papers, and manuals that have been produced as the Minitrack system has developed during the past decade. Such an effort would have extended this report into perhaps six or seven volumes rather than the present two volumes. It was considered to be in the best interest of all concerned to concentrate here on those elements of the system not yet adequately discussed and to relegate the information already published to a bibliography. It is recommended that the reader obtain copies of those documents that concern portions of the Minitrack system in which he is interested. A significant portion of the documents listed may be obtained through the Technical Reference Control Facility at GSFC, through the NASA Scientific and Technical Information Facility, College Park, Md., or through the Defense Documentation Center, Cameron Station, Alexandria, Va.

¹Edward R. Watkins, Jr.: *Preprocessing of Minitrack Data*. NASA TN D-5042, May 1969.

Two notable changes, one hardware and one software, were made in the Minitrack system during the writing of this report. The hardware at each tracking station was modified to double the radiofrequency tuning spectrum—the system now operates from 136 to 138 MHz. The software change involved the entire preprocessing program. For reference, the earlier *quadratic* preprocessing program listing and flow diagrams are listed in appendixes D and E, respectively, of volume 2. The major portion of the preprocessor description, however, deals with the *cubic* program, so called because of the mathematical order of the equation used in the data-smoothing routine. Considerable similarity exists between the cubic and quadratic programs, but the dissimilarities, although subtle, are sufficient to require the careful analysis of each program to understand its functional minutia.

The current cubic preprocessing program is listed in appendix A of volume 2. A step-by-step description of this program is developed in sections 4, 5, and 6 of volume 1. With this arrangement, the reader will be able to view both documents side by side for reference and correlation. The glossary of preprocessor variable names given in section 7 will be indispensable for comprehensive analysis.

The development of an antenna beam-switching calibration concept is a novel technological byproduct of this report. Though such a subsystem might not be unique enough to be called new technology, preliminary investigation indicates that such a scheme might substantially supplement, if not eliminate altogether, the use of aircraft in the calibration procedure. This technique should be investigated further for application in future improvements to the Minitrack system.

Section 2

A MINITRACK PRIMER

Although the reader may have worked with the Minitrack system in one capacity or another, we suggest that he review the basics of Minitrack in this section before proceeding further in the system functional description and the identification of probable error sources.

PURPOSE

The Minitrack network is a worldwide system of very-high-frequency (VHF) shortwave-radio receiving stations whose united function is to track Earth-orbiting spacecraft. In so doing, the Minitrack system provides information that is used to describe the motion of spacecraft around the Earth and to predict their positions in future orbits.

METHOD

To perform these tracking tasks, the designers of the Minitrack system selected the principle of the passive (receive only) radio interferometer. Thus, it was not necessary to employ large, highly directional antennas which must be aimed at a satellite as it moves across the celestial sphere. Rather, the Minitrack antennas at each tracking station are not movable.

Each Minitrack station has 13 antennas distributed across the facility field in a precise pattern. These receiving antennas are operated in pairs. Measurements are made with the associated receiving equipment to detect and record the difference in the electrical phase of the radio energy received at each of the two antennas of an interferometer pair. Through a comparison of the relationships of the electrical phase angles of the received spacecraft radio energy at several pairs of antennas, the system operators may pinpoint a satellite's location.¹

It should be noted that each Minitrack station provides information describing only the *direction* of a spacecraft passing overhead. The range, velocity, altitude, and other orbital elements of a satellite are known only after the directional data (appropriately time tagged) from several Minitrack stations are mathematically integrated at a central computing facility.

The coordinates describing the direction of a spacecraft in relation to a Minitrack interferometer station are known as *hyperboloidal coordinates*. These define the position of the satellite in terms of two-direction cosines, north-south and east-west. This, in effect, is the

¹John T. Mengel; and Paul Herget: "Tracking Satellites by Radio," *Sci. Amer.* 198(1): 23-29, Jan. 1958.

same as if the measurement were being made in azimuth and elevation angles by the land surveyor or in right-ascension and declination angles by the astronomer.

BACKGROUND

The Minitrack system was established initially for the International Geophysical Year (IGY) activities between 1955 and 1958. It was conceived by the engineers and scientists of the U.S. Naval Research Laboratory (NRL) to track the satellites launched by the Vanguard project, the first concerted effort by the United States to orbit spacecraft. The name of the system first appeared early in April 1955 on an NRL document entitled "Proposal for Minimum Trackable Satellite (Minitrack)."² It has remained with the system up to the present despite ever-increasing sophistication in space technology.

Throughout the intervening years, the Minitrack system has undergone several stages of change and improvement. Most notable among these was a complete redesign of the system around 1960, at which time the operating frequency was changed from 108 MHz to the band between 136 and 137 MHz. Some of the earlier Minitrack stations have been phased out of the system for various reasons; other, newer, stations have been added. Despite these changes, the Minitrack system today remains remarkably unchanged in principle. This, coupled with the fact that Minitrack continues to be a major workhorse in NASA's current space tracking effort, is a tribute to the insight and ingenuity of its initial planners. Although it was the first primitive system of the United States to track spacecraft, it has seen the birth and demise of numerous other, more elaborate tracking concepts within its lifetime.

Nonetheless, other tracking systems have been added to supplement the functions of Minitrack and have survived. Among these are the Goddard Range and Range Rate System and several generations of movable, high-gain, parabolic-reflector antennas. With the influx of these more recent tracking and data systems to the Minitrack facilities, the total network has come to be known as the Satellite Tracking and Data Acquisition Network (STADAN). The primary mission of STADAN is to track and receive data from Earth-orbiting, unmanned spacecraft. The Deep Space Network (DSN) and the Manned Space Flight Network (MSFN), though operated by NASA, are separate from STADAN, except that all are linked together by a worldwide communications network called NASCOM. A Minitrack station is now considered to be the 136-MHz interferometer equipment presently being used at 10 of NASA's STADAN facilities (fig. 2-1).

FUNDAMENTALS

The interferometer principle used in Minitrack essentially is the same as that used in optics, astronomy, underwater sonic direction finding, and terrestrial radio direction finding. Here, the position of a radiating object, whether the radiation be heat, light, sound, or radio spectra, is deduced by a measurement of the difference in phase of the energy received at

²William R. Corliss: *The Evolution of the Satellite Tracking and Data Acquisition Network STADAN*. NASA TM X-55658, Jan. 1967.

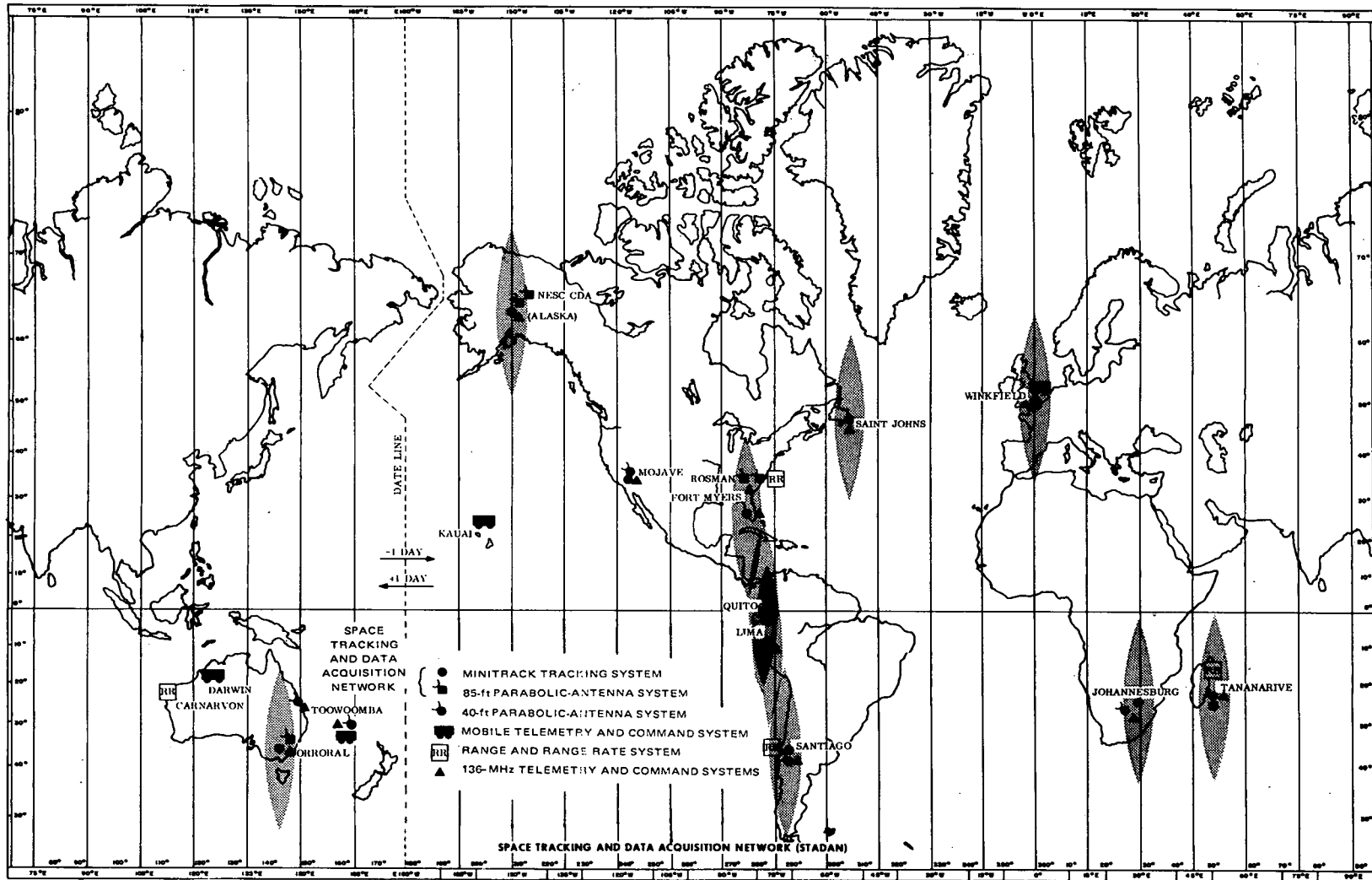


Figure 2-1.—Minitrack station locations (with equatorial fans shaded) in STADAN.

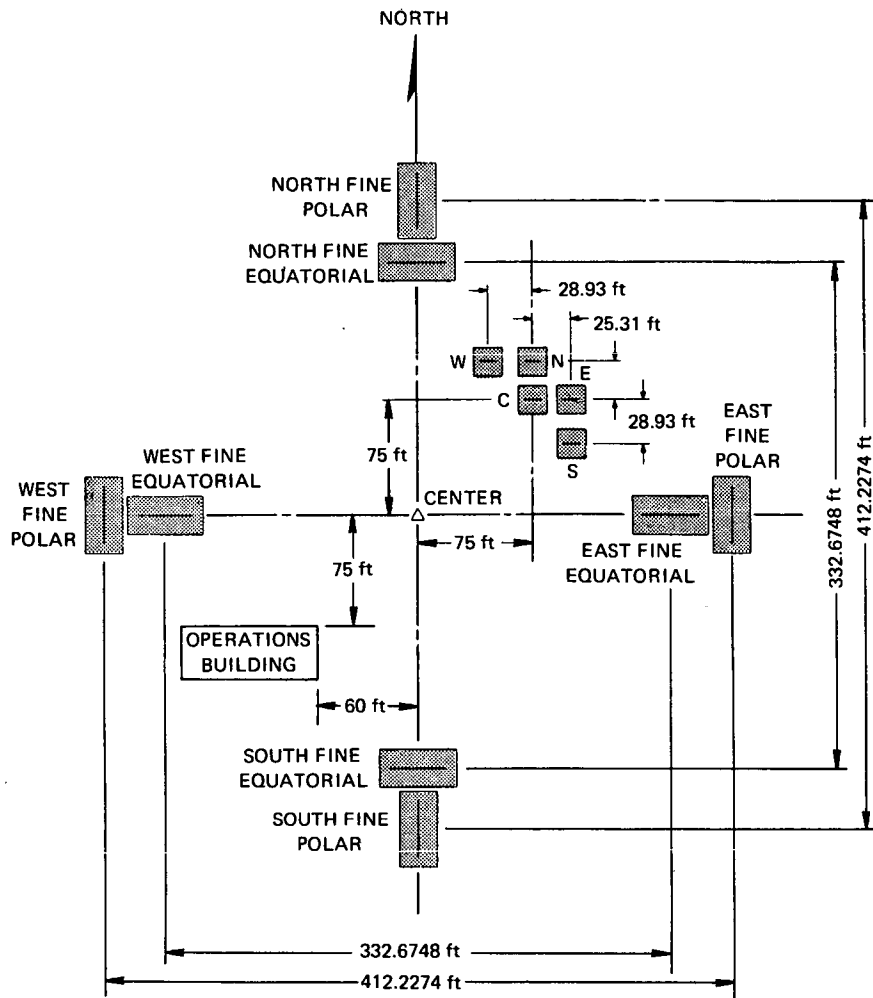


Figure 2-2.—Minitrack station layout showing antenna placement.

each of two detecting elements. It is not necessary, therefore, that the detecting array (in the case of Minitrack, the antennas) be pointed directly broadside toward the tracked object. Rather, the radiator may be anywhere within a relatively large sector range. A Minitrack station, for example, will track a spacecraft from horizon to horizon without losing contact or without presenting ambiguous readings, though lesser accuracy is experienced at lower elevation angles.

A Minitrack antenna field is arranged as in figure 2-2. The shaded rectangles represent the 13 antennas. At the four points of the compass are the larger antenna sets known as the *fine* antennas. The north fine polar array at the top of the figure, for instance, operates with the south fine polar array at the bottom of the figure as an interferometer pair. The fine antennas are arranged orthogonally on north-south and east-west baselines. A north-south pair and an east-west pair must operate simultaneously for a spacecraft to be tracked. The smaller

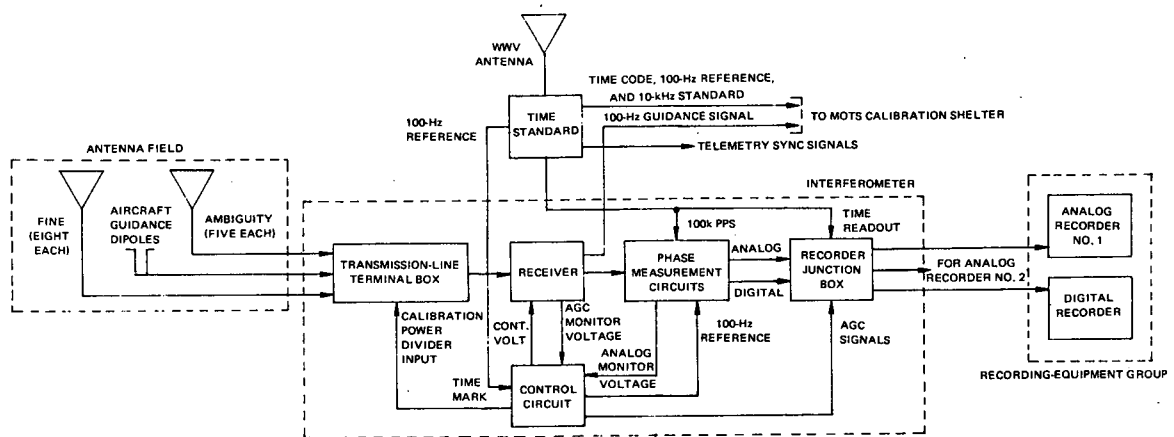


Figure 2-3.—Simplified station block diagram of the Minitrack interferometer system.

antennas clustered together in the figure are known as the ambiguity antennas. They are coupled to form *medium* and *coarse* interferometer pairs.

The limiting accuracy of a radio interferometer is fundamentally dependent on the distance in wavelengths of the received frequency between the outermost antennas. The outside antenna spacing is 412.2274 ft (fig. 2-2), which is equivalent to 57 wavelengths of 136-MHz radio energy when propagated in a vacuum. This distance was chosen partly because it causes the system to have a theoretical accuracy of the order of one-thousandth of a space degree at zenith and partly because it was a convenient dimension for inclusion within the older, 108-MHz Minitrack system antenna arrays, which were spaced at 500 ft.³ One-thousandth of a degree is approximately equivalent to one *fine Minitrack count*, a term used frequently in discussing the accuracy of the system.

A simplified block diagram of a Minitrack station is presented in figure 2-3. Here, the major functional elements of the station equipment are outlined: the antenna field, the interferometer, the recording-equipment group, and the timing system. This diagram is highly simplified; only two of the 13 antenna arrays are depicted. The box entitled receiver is, in fact, several independent channels, each a highly phase-stable, triple-conversion, superheterodyne receiver.⁴ At present, the Minitrack receivers are tunable from 136 to 137 MHz in 1-kHz steps.

Essential to the interferometer are the centrally located phase-measurement circuits where the critical comparisons of the phase of the radio energy being received from the

³Chesley H. Looney, Jr., Head, Time Measurement Branch, Code 4210: Memorandum No. 4210-1L: CHL:K to Edward J. Habib, Head, Systems Evaluation Branch, Code 4100, GSFC, Aug. 5, 1959.

⁴Bendix Corp.: *Instruction Manual for the 136 MC Minitrack Interferometer System*. Vols. I and II, Bendix Radio Division, 1965.

orbiting spacecraft by the respective antenna pairs are made. These include the circuits that perform the so-called Minitrack count function.

At the core of the recording-equipment group are two Sanborn-type paper-tape stylus recorders, each with eight channels. These strip-chart recorders provide a real-time, on-line indication of the performance of the Minitrack station for the convenience of the local operators. The analog recorder graphs the phase changes in a qualitative manner. It also records the fading and noise characteristics of two of the receiver channels. An extra binary stylus is added to provide a time-code pulse for correlation of the data with real time.

The digital recorder displays the same information as the analog recorder except that the data are quantized into discrete steps of the styli, thereby permitting the station operator to determine the precise state of the phase-measurement circuits. By decoding these digital steps, the station operator may resolve the raw direction cosines of the spacecraft within a few minutes after the spacecraft has passed.

The timing system contains the station frequency standard, a quartz-crystal oscillator. This standard is adjusted to synchronism with the international standard frequency from the shortwave-radio broadcasting station WWV in Boulder, Colo. Additionally, the timing system contains a digital clock that is slaved to the frequency standard and whose epoch is resolvable to the nearest microsecond of international time. A digital clock provides the time-code sequence to be used throughout the system, which is added to the recordings by the binary styli of the two Sanborn recorders. The timing system, through the use of counting and dividing circuits, provides reference signals and timing pulses that are employed in the digital phase meters of the Minitrack system.

Note that the recording-equipment group containing the analog and digital strip-chart recorders is primarily for the local use of the station operator to determine generally the quality of tracking at his Minitrack facility. These recordings seldom leave the field station except on special request. The greater bulk of Minitrack operational tracking data is transmitted in digital form to the central computing facilities at GSFC via the NASCOM teletypewriter circuits. Not shown in figure 2-3 is a punched-paper-tape, digital-recording subsystem that produces the Minitrack messages. In this equipment, the tracking data are multiplexed and formatted along with time codes, calibration codes, and satellite and station identification codes for retransmission to GSFC.⁵

Note also that the Minitrack teletypewriter message does *not* contain the resolved direction cosines of the spacecraft passing overhead. Rather, it contains the five-level-code (Baudot) encipherments of the phase conditions at each of six pairs of antennas—a north-south and an east-west pair for the fine, medium, and coarse systems, respectively.

It would be a severe omission not to mention in this section on fundamentals the Minitrack preprocessing program. Within this critical software iteration, which is performed at GSFC's central facility, the real direction cosines are generated: The station constants and

⁵T. P. Sifferlen and W. M. Hocking: *A Digital Recording System for Satellite Tracking Data*. NASA TN D-672, May 1961.

calibration factors are introduced into the data, lobe ambiguity is resolved, and corrections are made for the variations of different satellite transmitting frequencies.⁶

Minitrack direction-cosine data tagged with time, tracking location, and satellite identification are then passed from the preprocessing program to one of several existing orbital-determination (computer) programs (ODP) at the central facility. There, the tracking information from many observations at many sites is combined to generate the orbital elements of the respective spacecraft. It is from the ODP's that the predictive ephemerides map the positions each satellite will assume in future orbits. Thus, tabulations of the expected satellite track and time of appearance are formed for recirculation to the tracking sites or for distribution to the myriad scientific agencies about the globe that need such information.

INTERFEROMETRY

To understand how the Minitrack system functions, the reader may wish to review some of the principles of the interferometer. At the outset, the nature of radio propagation and the characteristics of broadbeam antennas should be noted.

Figure 2-4 depicts a spacecraft transmitting a continuous-wave (CW) radio signal from its transmitter beacon. The radio energy travels outward from the spacecraft in an ever-increasing spherical wave front moving at the speed of light. Figure 2-4 illustrates the

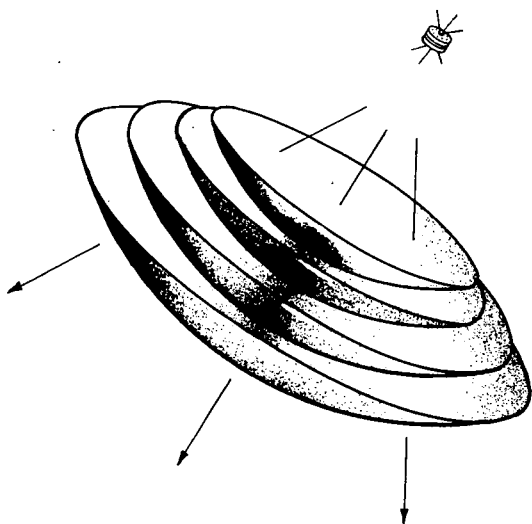


Figure 2-4.—Zero-phase wave fronts in the vicinity of the spacecraft.

progression of segments of successive wave fronts from the satellite transmitter. The shape and positions of the zero-phase cycles are shown at one instant in time. They are spaced one wavelength (1λ) apart.

Figure 2-5 shows these same zero-phase wave fronts as they arrive at the Minitrack interferometer station on Earth, which may be 200 to 400 miles or more away. The distance between consecutive zero-phase wave fronts is the same as in the vicinity of the spacecraft; this distance is inversely proportional to the operating frequency. The most notable difference between the wave fronts in the two figures is that in the former, the wave fronts are circularly curved, whereas in the latter, they appear to be flat sheets. This is not the case, however. The wave fronts in figure 2-5 are curved, but the curvature of this small increment of the total

⁶Edward R. Watkins, Jr.: *Preprocessing of Minitrack Data on the IBM-360*. NASA TM X-63266, May 1968.

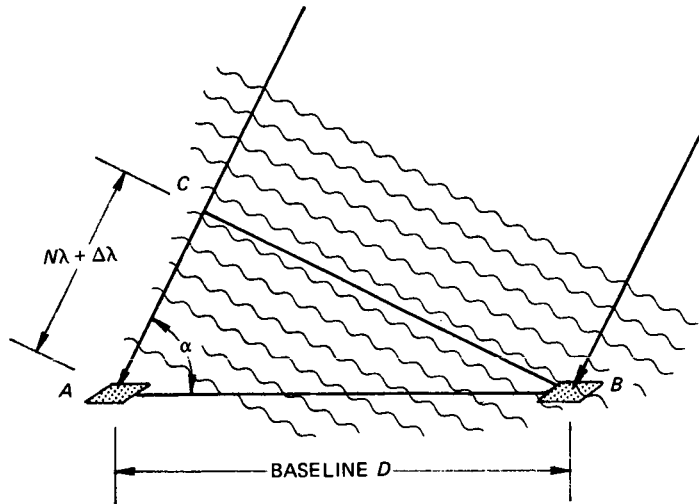


Figure 2-5.—Zero-phase wave fronts in the vicinity of the interferometer.

spherical wave front is so slight in the vicinity of the interferometer that it is considered to be a flat, linear sheet. The small amount of curvature at the interferometer is not resolvable by the Minitrack interferometer at a 100-mile or greater range.

An interferometer antenna pair is illustrated at positions *A* and *B* in figure 2-5. Each antenna is a flat, broadside array with reflecting screens parallel to the surface of the Earth. The beams of these antennas are broad and are directed toward the zenith, directly overhead.

In figure 2-5, the wave front from the satellite arriving at antenna array *B* has not yet reached antenna array *A*. Rather, the portion of this wave front which will arrive at *A* has, at this instant in time, only reached point *C*. At this instant, the distance between *C* and *A* may be defined in terms of an integral number of wavelengths $N\lambda$ plus a fractional part of a wavelength $\Delta\lambda$.

The fundamental task of each Minitrack station is to determine the length of the leg *AC* of the right triangle of figure 2-5. In so doing, the system may solve for the angle α indicated at *A*. The cosine of α is the length of the adjacent side of the triangle, $N\lambda + \Delta\lambda$, divided by the hypotenuse, the baseline *D*; i.e.,

$$\cos \alpha = \frac{N\lambda + \Delta\lambda}{D} \quad (1)$$

The direction angle α indicates the instantaneous direction of a spacecraft from the Minitrack station. The cosine of α is one of the two raw direction cosines required by the stations of the system to define satellite positions unambiguously.

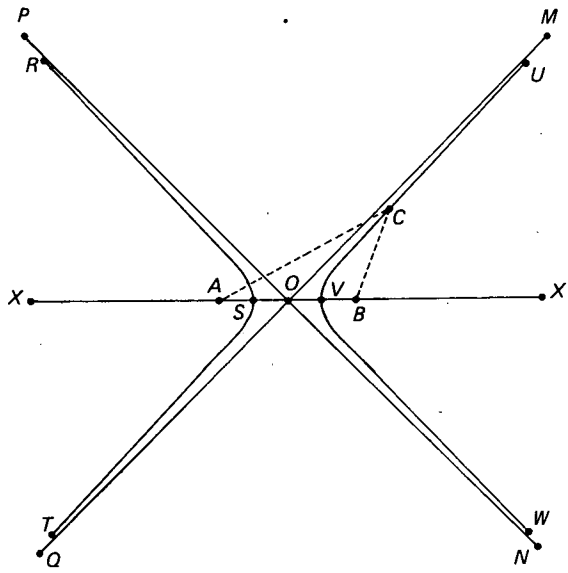


Figure 2-6.—Hyperbolic asymptotes of the locus of the constant-phase angle for an antenna pair.

Because the antenna positions are fixed, the baseline distance is known, both in feet and in wavelengths. Therefore, the task remains of determining the distance $N\lambda + \Delta\lambda$. The fractional part of a wavelength $\Delta\lambda$ is determined electronically by the interferometer phase meters. The whole integral number of wavelengths $N\lambda$ of the adjacent leg of the triangle is resolved by the use of the ambiguity interferometer antennas, whose medium- and coarse-baseline lengths are somewhat shorter than the fine-baseline lengths. This is discussed under "Ambiguity" in this section. First, some discussion is required regarding the nature of the hyperbolic system of coordinates.

Geometrically, the spacecraft must lie on a hyperbola whose foci are the two interferometer antennas; i.e., the

difference between the distances from any point on the hyperbola to the two foci is a constant length, in this case $N\lambda + \Delta\lambda$ (from eq. (1)). Figure 2-6 shows a pair of hyperbolic curves RST and UVW for the two fixed points A and B , which represent the centers of a pair of interferometer antennas. The direct-path lines from the satellite at point C to the antennas (shown by the dotted lines CA and CB) become virtually parallel as point C is moved out very far along the hyperbolic curve. As the curve is extended to infinity, it asymptotically approaches a straight line which passes through the origin O . Although the satellite is not an infinite distance from the antennas, it is sufficiently remote that it may be considered to lie on this straight line. With simple geometric calculations it may be demonstrated that at satellite altitudes the difference in position indicated by the straight line and the hyperbolic curve is negligible and that such errors are far beneath the theoretical resolution of the Minitrack system. The origin O in figure 2-6, then, is considered to be the same as the center of the Minitrack antenna field in figure 2-2; all fine direction cosines are referenced to this point.

In figures 2-5 and 2-6, we have considered only a two-dimensional situation in which the satellite is traveling in a plane perpendicular to the Earth, a plane that includes the single baseline. In a three-dimensional world, the locus of the spacecraft defined from a single pair of antenna arrays spaced along a baseline becomes a conical surface whose central axis is that same baseline (fig. 2-7). The conical surfaces are generated by the rotation of the straight-line asymptotes QM and PN (fig. 2-6) about the baseline XX' . Note that the angle α in figure 2-5 is the cone angle in figure 2-7. This angle is the elevation angle of the spacecraft only in the special two-dimensional case (figs. 2-5 and 2-6). In general, it should not be considered an elevation angle in the sense that a land surveyor or artillery gunner would use the term.

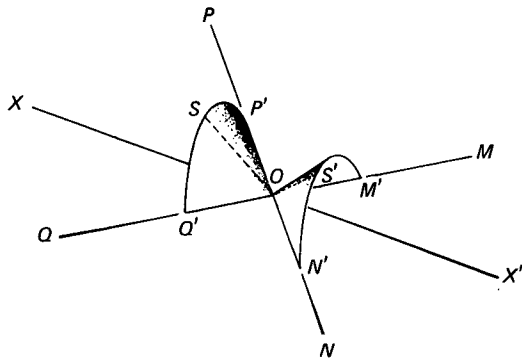


Figure 2-7.—Constant-phase cones: the locus of a tracked spacecraft for only one interferometer axis.

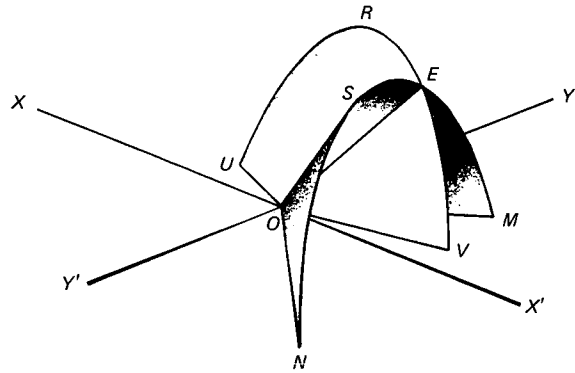


Figure 2-8.—Orthogonal cone intersection for the unambiguous location of a spacecraft.

Until now, the discussion has centered about the use of two fine-antenna arrays, one at each end of a single baseline. In order to define just which one of many radials in a single conical surface passes through the spacecraft, it is necessary to use a second interferometer antenna array pair whose baseline is at right angles to the first. These orthogonal baselines define the east-west and north-south positions of the fine-antenna arrays (fig. 2-2).

Thus, a second conical surface is generated as another general locus of the spacecraft. This cone intersects the first, as shown in figure 2-8, and thereby defines the unique radial *OE* from the origin, which is common to both cones and which points directly to the spacecraft. The cosines of the angles of these two cones are the direction cosines of the spacecraft at any one instant in time. These direction cosines are referred to as *l* and *m* for the east-west axis cone and the north-south axis cone, respectively.

ANTENNAS

Each of the Minitrack antennas is a dipole array suspended over a flat, reflecting back screen parallel to the Earth. Each of the fine arrays is made of eight linear skeleton slot elements spaced one-half wavelength on centers and elevated approximately one-half wavelength above the back screen. Each element is fed by an English-type, split-tube balun which, in turn, is joined to a single coaxial transmission line by a combining network. The smaller ambiguity antennas each have only one dipole element positioned above their respective back screens.

A narrow, fan-shaped antenna-beam pattern is produced by the fine-antenna arrays (fig. 2-9). The flat side of the fan is perpendicular to the length of the array. The thickness of the antenna fan beam is approximately 11° , whereas the width is of the order of 76° . Each of these is measured at the half-power points. These fan-shaped antenna patterns of the fine interferometers were chosen to produce a higher signal-to-noise ratio and to create a wider aspect angle across the baselines. In so doing, the system has a high probability of recording acceptable data from a wide range of orbital inclinations.

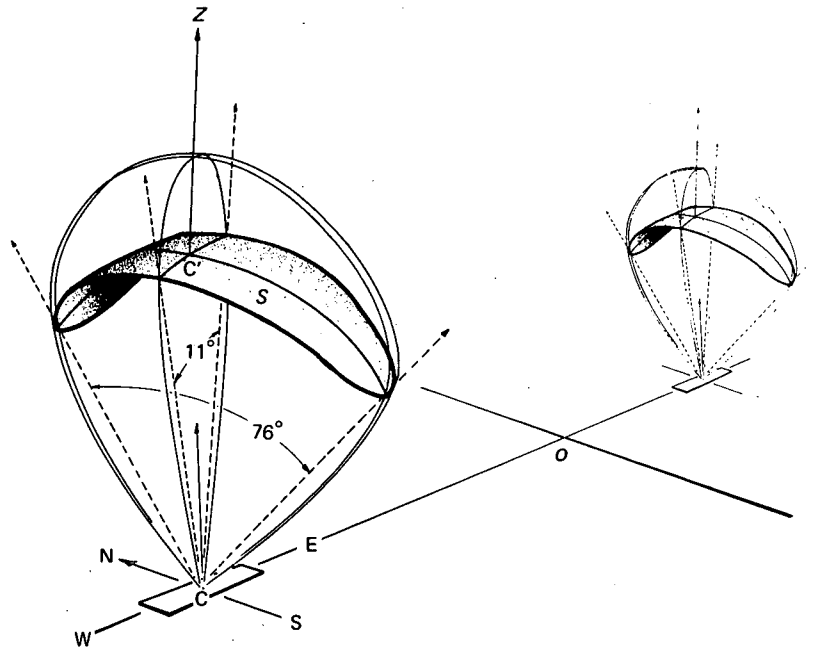


Figure 2-9.—Antenna patterns for the fine-interferometer antenna pair, equatorial set, east-west baseline.

The antenna-field layout (fig. 2-2) contains two sets of fine-antenna pairs. Two array pairs are designated *equatorial*, and two pairs are labeled *polar*. One or the other of these sets is used during a satellite pass, the choice depending on whether the spacecraft was launched generally in an equatorial or a polar orbit. The operator has the option from his console to switch the system electronics to the equatorial fine antennas or to the polar fine antennas by the use of relays.

The cross-sectional ellipticity of the antenna beam patterns of each of the ambiguity arrays is low because their respective *E*-plane and *H*-plane half-power aspect angles are 106° (north-south) and 78° (east-west). Although the ambiguity antenna beams are optimized for neither equatorial nor polar orbits, they have sufficient gain to receive spacecraft radio energy and to perform the ambiguity resolution function for any orbital inclination.

In figure 2-9, the antenna patterns appear to center around the physical center of the antenna array. Great care has been taken in the precise antenna design, fabrication, and maintenance to insure that the electrical centers (phase centers) of the antennas coincide with the mechanical centers. It has been observed that a displacement of these centers by as little as one-twelfth of an inch will produce a system error of one Minitrack fine count.⁷

The phase center is that point in an antenna array from which the far-field energy from that antenna, if it were transmitting, appears to originate. As in the case of the satellite shown

⁷Edward P. Greene: *Study and Simulation of Calibration for Minitrack Stations*. (NAS5-9705, Task IX), ADCOM, Inc., Cambridge, Mass., 1967, p. 20.

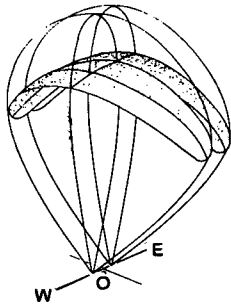


Figure 2-10.—Partial convergence of antenna patterns at 5000 ft.

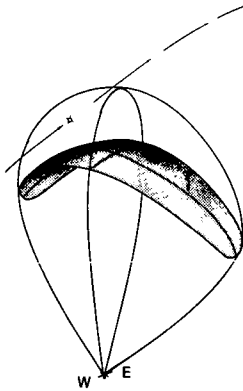


Figure 2-11.—Antenna pattern showing complete convergence at 200 miles.

in figure 2-4, radio energy moves out from an antenna array in a spherical wave front. The phase center is that point in space where all lines perpendicular to the wave front surface converge, in the vicinity of the radiating antenna array.

Of course, the Minitrack antennas do not radiate because the system is passive (receive only). The rule of reciprocity remains valid, nonetheless, and the receiving antenna patterns and phase centers will be the same as those determined in the transmitting case. The surface S in figure 2-9 is an elliptical section of the spherical wave front emanating from the array phase center at C . It should be remembered that the surface S continues beyond the borders of the depicted antenna pattern and that the receiving system is sensitive from horizon to horizon.

The solid antenna pattern shown in figure 2-9 is a surface containing the E - and H -plane obovate-shaped antenna patterns. It is the locus of all points in space from which a constant-power isotropic radiator will be received with a constant signal strength. Spacecraft radio signals are received in the interferometer antenna main lobes at angles much lower than the half-power, E - and H -plane angles of 11° and 76° shown. In fact, the spacecraft actually may be picked up on the interferometer smaller secondary lobes at extremely low angles, though tracking data obtained through these lower lobes (not shown) are not used because of the uncertainties in the positions of the phase centers of these lobes and also because of rapid fading at these angles.

The antenna patterns in figure 2-9 may suggest that the spacecraft passes through the main lobe of first one antenna and then the other. This is not the case, however, because these two patterns overlap each other at orbital altitudes (figs. 2-10 and 2-11).

AMBIGUITY

A review of equation (1) reveals that the term $N\lambda$ of the expression

$$\cos \alpha = \frac{N\lambda + \Delta\lambda}{D} \quad (1)$$

cannot be resolved with a single interferometer antenna pair whose baseline distance D is several wavelengths long. Only the $\Delta\lambda$ term is resolvable (i.e., the fractional part of a wavelength). The value of N may be any integer (0, 1, 2, 3, . . .) up to the whole number of wavelengths contained in the baseline.

A short baseline of one-half wavelength between antenna centers would give an unambiguous indication of the position of a spacecraft in the celestial hemisphere. This would be

Table 2-1.—Antenna Pair Combinations

Measured parameter	Antenna pairs employed	
	Equatorial orbit	Polar orbit
North-south fine	North and south fine equatorial	North and south fine polar
East-west fine	East and west fine equatorial	East and west fine polar
North-south medium	East and south ambiguity	East and south ambiguity
East-West medium	North and west ambiguity	North and west ambiguity
North-south coarse	North and common ambiguity	North and common ambiguity
East-west coarse	East and common ambiguity	East and common ambiguity

ideal except that the angular resolution of such a system is inadequate and that it is virtually impossible to build two antenna arrays that are one-half wavelength apart without having interaction by mutual coupling. Therefore, baselines of several wavelengths are employed.

For the fine interferometer arrays, polar and equatorial, the spacing is 57λ and 46λ between centers, respectively. The foreshortening of the equatorial array baseline was done purely for mechanical reasons; it was impossible to place the equatorial arrays directly on top of the polar arrays while maintaining the same baseline centers at each station.

In the case of the ambiguity antenna arrays (the small cluster of five rectangles slightly off the center of the field in fig. 2-2), the baseline lengths of the medium and coarse interferometer pairs are 4λ and 3.5λ , respectively. These arrays, for the sake of identification, are called the north, south, east, west, and common ambiguity antennas. Ordinarily, eight separate arrays would be necessary in the ambiguity group—two pairs with a 4λ baseline and two pairs with a 3.5λ baseline. The designers of the system, however, were able to double up on the use of the ambiguity antennas; therefore, only five arrays are required.

Each time a satellite pass is recorded through a Minitrack station, six basic interferometer signal parameters are measured: An east-west and a north-south phase measurement is obtained for each fine, medium, and coarse baseline system. Table 2-1 summarizes the antenna combination permutations. As each phase measurement is made, the fractional part of the received radio energy wavelength difference between the arrays of an antenna pair is recorded. The integer N is yet to be resolved. Without this N term, the locus of the spacecraft measured from a single baseline pair is rightfully represented by a family of several concentric conical manifolds, as illustrated in figure 2-12. The task of ambiguity resolution, then, becomes that of selecting from a family of manifolds the single conical surface on which the spacecraft truly lies.

An additional short-baseline interferometer whose antennas are spaced at one-half wavelength would be helpful in roughly indicating the correct fine manifold to be selected. As stated above, it is impractical for mechanical reasons to build two antenna arrays whose centers are displaced only one-half wavelength. The system designers have elected, therefore, to create mathematically a half-wavelength baseline, or, more specifically, to create

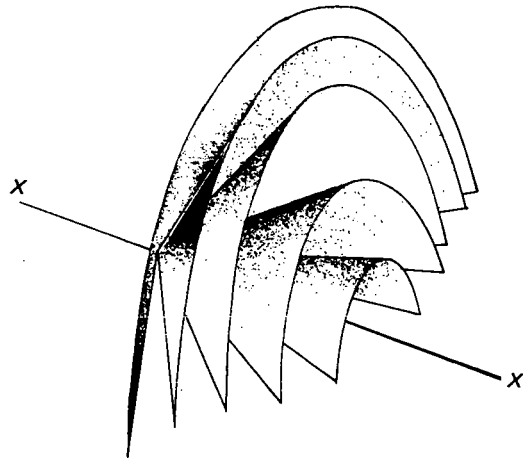


Figure 2-12.—A set of zero-phase cones for one interferometer axis.

mathematically the incremental phase difference which a half-wavelength-spaced antenna array pair would exhibit if it existed and were receiving radio energy from the spacecraft. This mathematical operation is done quite simply by subtracting the phase-condition reading of the coarse interferometer (3.5λ spacing) from the phase-condition reading of the medium interferometer (4λ spacing).

It should be remembered that this mathematical operation and those described in the following paragraphs are performed in the preprocessing program in the central computer facility at GSFC. The fine, medium, and coarse phase counts are the only interferometer magnitudes transmitted back to the central facility.

Figure 2-13 shows the absolute angles of zero-phase cones for a set of Minitrack baselines, both real and artificial (mathematically derived). For the fine polar (57λ) interferometer, there are 113 conical surfaces whose phase angles are zero. (Only one of two quadrants is shown because they are mirror images.) A fine digital phase meter can resolve each of the fine-antenna zero-phase increments to the nearest thousandth of a wavelength. The ambiguity system determines which fine increment contains the cone through which the tracked satellite is passing.

Rather than merely explain the ambiguity resolution process, a numerical example of the operation is given:

Suppose that the three interferometer phase measurements of the north-south polar systems are recorded as follows (where the numerical subscripts denote baseline lengths):

$$\begin{aligned} \text{Fine count } a_f &= .997\lambda \\ \text{Medium count } a_4 &= .67\lambda \\ \text{Coarse count } a_{3.5} &= .34\lambda \end{aligned}$$

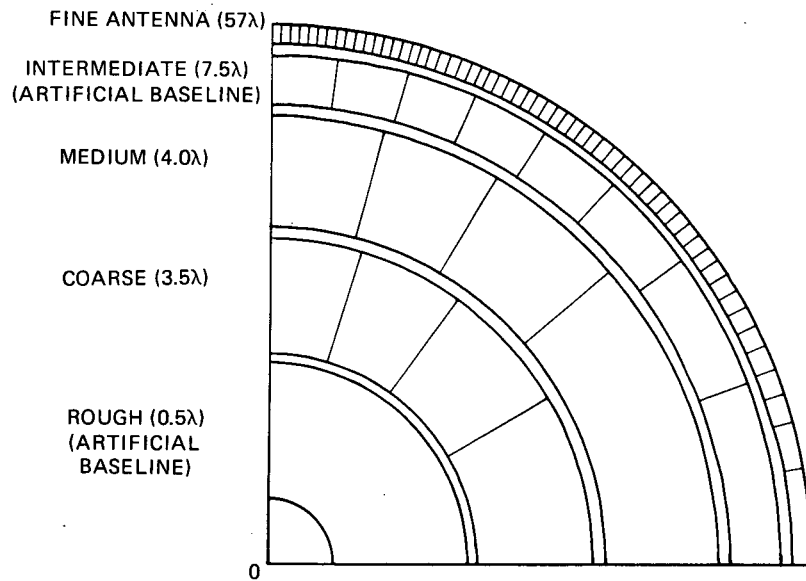


Figure 2-13.—Zero-phase cone angles for the 136-MHz Minitrack interferometer.

The medium and coarse counts are recorded only to the nearest hundredth of a wavelength. For each interferometer, we do not know the whole number that belongs to the left of the decimal. This number is determined as follows: The coarse count $a_{3.5}$ is subtracted from the medium count a_4 to obtain the rough count $\bar{a}_{0.5}$, namely, the count that the artificial half-wavelength interferometer would have if it existed and were operating simultaneously with the other (real) interferometers. The bar indicates absolute phase. Thus, the rough count is found by

$$\begin{aligned}\bar{a}_{0.5} &= a_4 - a_{3.5} \\ &= .67 - .34 \\ &= .33\end{aligned}$$

The value of $\bar{a}_{0.5}$ may lie between -0.500 and $+0.500$.

The absolute phase of the coarse interferometer $\bar{a}'_{3.5}$ is determined by multiplying the rough absolute phase by the integer 7. Thus,

$$\begin{aligned}\bar{a}'_{3.5} &= 7\bar{a}_{0.5} \\ &= 2.31\end{aligned}$$

Similarly, the absolute phase of the medium interferometer \bar{a}'_4 is determined by multiplying the rough absolute phase by the integer 8:

$$\begin{aligned}\bar{a}'_4 &= 8\bar{a}_{0.5} \\ &= 2.64\end{aligned}$$

Thus, for both a 3.5λ and 4λ baseline, the value of the unknown N in the length of the adjacent leg of the triangle in figure 2-5 is 2. Because the decimal fraction actually measured by the interferometer is more accurate than that determined mathematically, the measured values are substituted and the absolute phase values are held to be

$$\begin{aligned}\bar{a}_{3.5} &= 2.34 \\ \bar{a}_4 &= 2.67\end{aligned}$$

These two numbers are then added to derive the absolute phase value of a second, or intermediate, artificial baseline having a length of 7.5λ :

$$\begin{aligned}\bar{a}_{7.5} &= \bar{a}_{3.5} + \bar{a}_4 \\ &= 5.01\end{aligned}$$

The calculated absolute value of the fine interferometer \bar{a}_f is the product of the intermediate absolute phase value and the ratio of the number of wavelengths in the fine baseline to the number of wavelengths in the intermediate (artificial) baseline:

$$\begin{aligned}\bar{a}_f &= \bar{a}_{7.5} \times \frac{57}{7.5} \\ &= 38.076\end{aligned}$$

The computed whole number of wavelengths is 38, and the computed additional fraction is $.076\lambda$. The fine interferometer measurement, however, was $.997\lambda$; therefore, the computer substitutes the number 37.997 for the absolute value of the unknown leg of the triangle in figure 2-5 to represent the fine interferometer. (The computer preprocessing program substituted 37 as the value of N instead of 38 because the value 38.076 is closer to 37.997 than it is to 38.997.)

The direction cosine for the spacecraft is calculated from equation (1):

$$\begin{aligned}\cos \alpha &= \frac{37.997}{57} \\ &= 0.66661\end{aligned}$$

SLIDE RULE

Each Minitrack station is equipped with a rough means of determining the position of the spacecraft. This is done by using a special circular slide rule whose outer diameter is about 12 in. By scaling the traces of the strip-chart (Sanborn) recorders after a satellite has completed its pass and by applying these scale values in the slide-rule operation, it is possible to derive the instantaneous north-south and east-west elevation angles of the spacecraft.

The slide rule is not normally used operationally because its function is adequately covered in the preprocessing program. The slide rule is useful, nonetheless, in enabling the local tracking station operator to resolve direction vectors of spacecraft in order to make

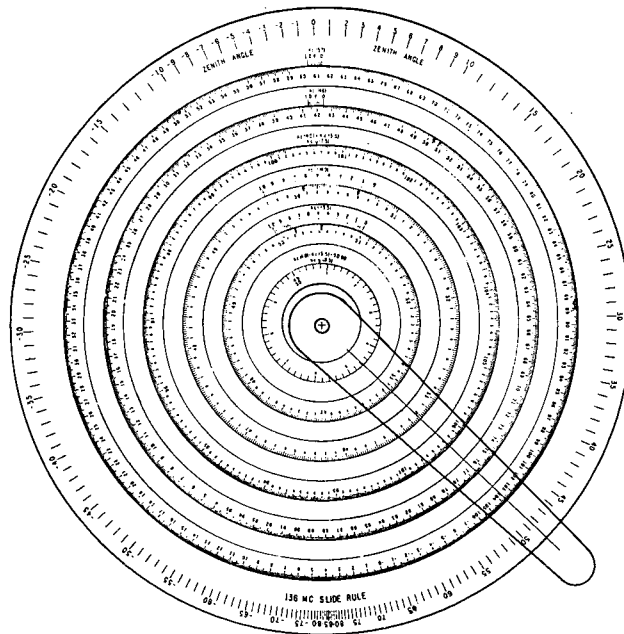


Figure 2-14.—Minitrack ambiguity resolver: 136-MHz circular slide rule.

RESETTING INSTRUCTIONS

NORTH—SOUTH

- Lay cursor arm hairline along 0.5 on the drift scales.
- Rotate 57 λ equatorial scale until NSF(E) K_e from new calibration lies under hairline. Mark an NS arrow on equatorial scale pointing to new NSF(E) K_e on equatorial drift scale.
- Repeat Step B for the 46 λ polar scale using new NSF(P) K_e and K_{11} , the 4.0 λ ambiguity scale using new NSM K_e and K_{11} , and the 3.5 λ ambiguity scale using new NSC K_e and K_{11} .

EAST—WEST

Repeat Steps A, B, and C, using EWF(E), EWF(P), EWM, and EWC K_e and K_{11} .

AMBIGUITY RESOLUTION

NORTH—SOUTH

SETUP:

- Rotate the 57 λ , 46 λ , 4.0 λ , and 3.5 λ annular rings until the NS arrow on each ring points to our current K_e value on corresponding drift scale.
- Read $K_e(4.0)$ value below arrow on 4.0 λ ring. Add 50.00 to this value. Read $K_e(3.5)$ value below arrow on 3.5 λ ring. Subtract $K_e(3.5)$ from $K_e(4.0) + 50.00$ to compute $K_e(0.5) = K_e(4.0) - K_e(3.5) + 50.00$. Rotate 0.5 λ ring so computed $K_e(0.5)$ lies under $K_e(0.5)$ arrow.
- Use above values of $K_e(4.0)$ and $K_e(3.5)$ to compute $K_e(7.5) = K_e(4.0) + K_e(3.5)$. Rotate 7.5 λ ring until computed $K_e(7.5)$ lies under $K_e(7.5)$ arrow.

OPERATION:

- Using outermost scale, rotate cursor arm to zenith angle given in prediction. Hairline on cursor arm should now be near proper 3.5 λ baseline and 4.0 λ baseline Minitrack NS readings on the 3.5 λ and 4.0 λ rings.

If no prediction is given, take the 4.0 λ baseline Minitrack NS reading as 00.XXX and add 50.000 to this. Then subtract from this sum the 3.5 λ baseline Minitrack NS reading as 00.YYY to obtain the hypothetical 0.5 λ baseline Minitrack NS reading as 49.ZZZ or 50.ZZZ = (50.XXX - 00.YYY). When the hairline is rotated to this computed value on the 0.5 λ ring, it should then be near the proper 3.5 λ baseline and 4.0 λ baseline Minitrack NS readings on the 3.5 λ and 4.0 λ rings.

- Adjust hairline to fall halfway between proper 3.5 λ and 4.0 λ ring readings. This step is the mechanical analog of mathematically adding the 3.5 λ baseline Minitrack reading to the 4.0 λ baseline Minitrack reading to obtain the proper reading for the hypothetical 7.5 λ baseline. Both techniques should give the same 7.5 λ baseline reading to which the hairline should be adjusted.
- The hairline should now be adjusted to the nearest 46 λ or 57 λ ring reading having the same value as the corresponding Minitrack 46 λ or 57 λ baseline NS reading. The correct lobe number for this reading may now be read directly off the proper ring scale.

EAST—WEST

Repeat above using EW readings and arrows.

Figure 2-15.—Ambiguity resolver instructions printed on rear of slide rule.

on-the-spot correlations with satellite prediction data that may be at hand. A reduced illustration of the slide rule and a reproduction of the instructions printed on its reverse side are shown in figures 2-14 and 2-15, respectively.

SUMMARY

The Minitrack network, though it was the earliest operational spacecraft tracking system in the free world, still remains an important source of orbital observations. Its strength lies in the relative simplicity, minimum cost, and ease of installation of its tracking facility equipment. Its effectiveness in the determination of orbits is dependent on the successive observation of satellites from several tracking stations and on the expertise exhibited in the preprocessing and orbital data processing programs at the central facility. At present, the effects judged most crippling to the accuracy of the system are the relative difficulty of calibrating the interferometers and the progressive loss of calibration confidence extant between calibration intervals.

Section 3

TYPICAL MINITRACK STATION OPERATING PROCEDURES

As much as possible, the operating procedures at each Minitrack facility are the same. Slight variations in the equipment arrangement and layout from site to site may cause minor differences in the applications of the standard operational procedures (SOP). From time to time, an operator or technician will make a change in his mode of approach to save time or tend to reduce error. In this section what is considered to be a typical Minitrack station operating procedure is listed. All stations follow this sequence quite closely.

1.0 SCHEDULES

- 1.1 Inspect satellite files at the start of each shift to insure that all scheduled tracks are posted on the prediction board and that the figures so posted are realistic.
- 1.2 A check of the authenticity of the meridian crossing time may be performed by matching the Equator crossing time with the meridian crossing time to obtain a realistic differential of N number of minutes.
- 1.3 The number of minutes N may be found through the use of the Miller cylindrical projection map and the satellite plot as follows: In order to ascertain the approximate local meridian crossing coordinate and time—
 - (1) Place the satellite plot on the Equator at the longitude of the Equator crossing on hand (left-hand edge of the plot on the Equator crossing).
 - (2) Locate the area of plot where the plot and station meridians meet (east, west, north, south).
 - (3) Take the Equator crossing time and add the correction factor from the plot to give the time.

Note: When using this type of local prediction, start tracking 10 min before the calculated time.
- 1.4 Check all satellite SOP's and special orders pertaining to the tracking parameters.
- 1.5 With information found in the above, set up the Minitrack checkoff board.

2.0 EQUIPMENT PREPARATION

- 2.1 Insure that Sanborn recorder number 1 and the digital recording system (DRS) high-speed perforator have sufficient paper to record the pass.
Note: DRS tape to be oil-perforated tape *only*.
- 2.2 Tune in the WWV time signal and ascertain that all clocks and the serial decimal coded time (SDCT) are correct.
- 2.3 Set the system to the correct frequency as found on the prediction board under each satellite column (tracking frequency).
- 2.4 Set the Minitrack-console switches to the following positions.
- | | | |
|---------|--------------------------|------------------------------|
| 2.4.1 | All POWER switches | ON |
| 2.4.2 | TRACK/CALIBRATE switches | CALIBRATE |
| 2.4.3 | TRACK/RF/CALIBRATE | CALIBRATE |
| 2.4.4 | TRACK/PHASE/CALIBRATE | TRACK FULL SCALE |
| 2.4.5 | ATTENUATOR | dBm 80 |
| 2.4.6 | CALIBRATE ADJUST | 60 (on meter) |
| 2.4.7 | RECEIVER GAIN | AUTOMATIC GAIN CONTROL (AGC) |
| 2.4.8 | DATA TIME/PHASE LOCK | PHASE LOCK |
| 2.4.9 | WAVEFORM GENERATOR— | |
| 2.4.9.1 | OPERATE MODE | TRIGGER |
| 2.4.9.2 | VERNIER | CALIBRATE |
| 2.4.9.3 | WAVEFORM DURATION | 2.5 |
| 2.4.9.4 | MULTIPLIER | 10 |
| 2.4.9.5 | GATE OUT/PULSE OUT | GATE OUT |
- 2.4.10 Set the PHASE LOCK ADJUST control so that the display on the DATA TIME/ PHASE LOCK indicator shows a line from top left to lower right.
- 2.5 Insure that all crossovers are sharp. Slight adjustment of preamplifiers may be necessary. (See table 3-1 for adjustment locations.)
- 2.6 Insure that the correct filters are installed in the fine buffer channels.
- 2.7 Insure that the Sanborn junction box is properly connected.
- 2.8 Sanborn recorder number.
- 2.8.1 Switch positions.

Table 3-1.—Locations of Potentiometers in the Preamplifiers for Various Crossover Adjustments

Channel	Preamplifier	Potentiometer
NSF	North fine	R11
	South fine	R11
EWF	East fine	R11
	West fine	R11
EWM	West	R11
	North	R09
NSC	North	R11
	Center	R09
EWC	Center	R11
	East	R09
NSM	East	R11
	South	R11

- 2.8.1.1 RANGE switches (amplifiers 1 and 2) 1
- 2.8.1.2 RANGE switches (amplifiers 3 through 8) 10
- 2.8.1.3 POWER switches ON
- 2.8.1.4 TIMER/OFF/MARKER OFF
- 2.8.1.5 SPEED 2.5 mm/s
- 2.8.2 Set the MOTOR switch to ON and adjust the temperature controls for the correct writing temperature. Ascertain that all pens and charts are operating correctly.
- 2.8.3 Set the MOTOR switch to OFF.
- 2.9 Digital recording system.
 - 2.9.1 Switch positions.
 - 2.9.1.1 RECORDING RATE to desired rate
 - 2.9.1.2 POWER switches ON
 - 2.9.1.3 RECORDER ON/OFF ON
 - 2.9.1.4 TEST/FEED/OPERATE OPERATE
 - 2.9.1.5 CLOCK switch 1 PPS
 - 2.9.2 Insure that the 28-, 15-, and 10-V power supplies are supplying the correct voltage. Adjust if required. (A constant temperature must be maintained in the operations room, otherwise these voltages will vary.)

C

- 2.9.3 Set the TEST/FEED/OPERATE switch to the FEED and OPERATE positions to ascertain the status of the high-speed perforator.
- 2.9.4 Return the TEST/FEED/OPERATE switch to the OPERATE position.
- 2.9.5 Return RECORDER ON/OFF switch to the OFF position.

3.0 SYSTEM CALIBRATION

- 3.1 MAX and MIN calibration.
 - 3.1.1 Place the Sanborn recorder MOTOR switch to the ON position.
 - 3.1.2 Adjust the GAIN controls of Sanborn recorder amplifiers 3 through 8 so that the pens are reading full scale (MAX) on the 1000 count of the chart (left-hand side).
 - 3.1.3 Place the Minitrack TRACK/PHASE/CALIBRATE switch to ZERO position.
 - 3.1.4 Adjust the position controls of Sanborn recorder amplifiers 3 through 8 so that the pens are reading zero (MIN) on the 0000 count of the chart (right-hand side).
 - 3.1.5 Repeat steps 3.1.2, 3.1.3, and 3.1.4 until there is no interaction.
- 3.2 AGC calibration.
 - 3.2.1 Adjust the GAIN controls of Sanborn recorder amplifiers 1 and 2 to full CW.
 - 3.2.2 Set the Minitrack attenuator switch to -125 dBm.
 - 3.2.3 Adjust the position controls of Sanborn recorder amplifiers 1 and 2 so that each pen aligns on the 900 line of the chart.
 - 3.2.4 DRS AGC should read 1. (Adjust the pot on H114, slot 02 for a position of 1.)
 - 3.2.5 Set the Minitrack attenuator switch to -80 dBm, AGC pens 1 and 2 on the Sanborn recorder should read approximately 100 or a swing of 800 counts. (Adjust the gain for 100.)
 - 3.2.6 DRS AGC should read 9. (Adjust the pot on card M113 in slot 01 for a position of 9.)
 - 3.2.7 Run the Minitrack attenuator from -80 to -125 dBm in 10 steps, and ascertain the linearity of the AGC indication on Sanborn recorder channels 1 and 2 and the DRS AGC indicator, -80 to -120 dBm in 10-dBm steps, -125 to -85 dBm in 10-dBm steps.
 - 3.2.8 Set the Sanborn recorder MOTOR switch to OFF.
- 3.3 Time clocks and data time.
 - 3.3.1 Recheck all clocks and data time. Enter results in the time correction log.
 - 3.3.2 Setting data time.

- 3.3.2.1 Set the DATA TIME/PHASE LOCK ADJUST switch to the DATA TIME position.
- 3.3.2.2 Set the TRACK/PHASE/CALIBRATE switch to the FULL TRACK position.
- 3.3.2.3 Set all TRACK/CALIBRATE switches to the TRACK position.
- 3.3.2.4 Set the indicator scope VOLT/DIV switch to position 5, and adjust the horizontal position control so that the trace starts at left side of scope.
- 3.3.2.5 Through the use of the waveform generator MULTIPLIER switch and TIME RESOLVER control, position the negative pulse leading edge at the start of the trace. At this time, the DATA TIME light should flash in sync with the standard (STD) time light. (Lock the TIME RESOLVER control.)
- 3.3.2.6 Place DATA TIME/PHASE LOCK switch to PHASE LOCK position, waveform generator multiplier switch to position 10, and indicator scope VOLT/DIV switch to position 0.5 V. Adjust horizontal position control so that positioned trace is in center of scope. DATA TIME light should still be in sync.

4.0 PRECALIBRATION

- 4.1 Set Sanborn recorder 1 MOTOR switch to the ON position.
- 4.2 With Sanborn recorder running at 2.5 mm/s, adjust the Minitrack attenuator from -80 to -120 dBm in 10-dBm steps and from -125 to -85 dBm in 10-dBm steps, while placing an AGC calibration sequence on the Sanborn chart and observing the linear progression of the DRS AGC indicator as well.
- 4.3 With the Sanborn recorder still running, the six channels (3 through 8) are recording the K_{s2} error.
- 4.4 Run off several lines of DRS K_{s2} in 1-s bursts.
- 4.5 Switch the Sanborn recorder motor to OFF.
- 4.6 Change the Sanborn recorder speed to 10 mm/s. (Note: It may be advantageous to set the speed to a higher or lower value depending on the type of satellite passage.)

5.0 TAKING THE PASS

- 5.1 Set the TRACK/RF/CALIBRATE switch to the correct mode (EQUATORIAL/POLAR).
- 5.2 Insure that all antenna relays are switched correctly and that the DATA TIME light is still synchronized.
- 5.3 Watch the indicator scopes for a pattern.
- 5.4 When a pattern is present in the coarse and medium channels, set the Sanborn recorder MOTOR switch to ON.

- 5.5 When a pattern is present in the fine channels, switch DRS to OPERATE.
- 5.6 When the satellite reaches the predicted local meridian time, place an identifying mark on the Sanborn recording.
- 5.7 When the pattern on the fine channels fades out, switch DRS off.
- 5.8 When sufficient analog data are obtained, perform postcalibration.

6.0 POSTCALIBRATION

- 6.1 With the Sanborn recorder running, place the TRACK/RF/CALIBRATE switch to CALIBRATE; this will place K_{s2} on the Sanborn record.
- 6.2 Adjust the attenuator from -80 to -120 dBm in 10-dBm steps and from -125 to -85 dBm in 10-dBm steps. This will place the AGC calibration on the Sanborn record.
- 6.3 Set all TRACK/CALIBRATE switches to the CALIBRATE positions.
- 6.4 Set the TRACK/PHASE/CALIBRATE switch to the ZERO position. This will place both MAX and MIN on the Sanborn chart.
- 6.5 Set the MOTOR switch on the Sanborn recorder to the OFF position after sufficient paper is run off for removal.
- 6.6 Remove the paper.
- 6.7 Repeat step 3.3.1, and enter the results in the log.

7.0 REDUCTION

- 7.1 Place the Sanborn recorder paper on the reduction table with the time code on the bottom.
- 7.2 Run off a hard copy of the DRS data on Teletype (TTY).
- 7.3 Post the K_{s2} and calibration figures on the Sanborn chart and reduction board.
- 7.4 Smooth the data by the use of a straight edge and parallel rule if necessary.
- 7.5 By the use of the 136-MHz slide rule, determine the true meridian crossing point and post it on the reduction board. (For the use of 136-MHz slide rule, see step 8.0 or the $K_c - K_{s1}$ figures.)
- 7.6 Through the use of figures from the reduction board (as determined by the 136-MHz slide rule), draw the vertical meridian crossing line to the nearest second marker by locating the position obtained for equatorial east-west angles and for polar north-south angles.

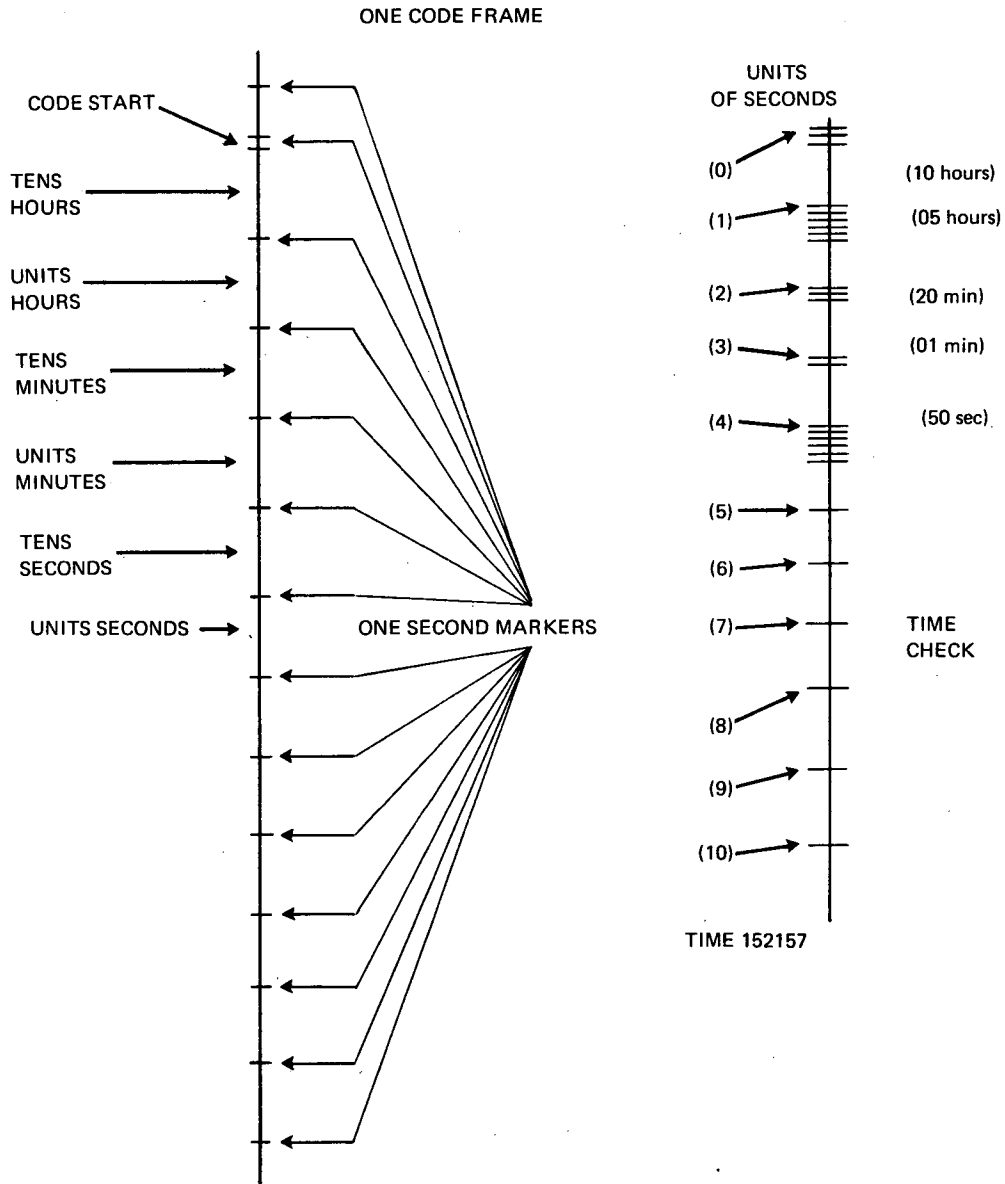


Figure 3-1.—Serial decimal coded time.

- 7.7 Determine the local meridian crossing time from the SDCT on the bottom of the chart where the vertical line intersects the time code. (See fig. 3-1 for the SDCT breakdown.) Post the time on the chart and reduction board.
- 7.8 Determine the zenith angle (as explained in step 8.0) and ascertain that it agrees with that predicted.
- 7.9 Draw a horizontal line from the fine AGC plot to indicate the maximum AGC. Use the AGC line found in step 7.9 as a reference; match it against the AGC calibration on the chart of the pass to determine the maximum AGC.

7.10 Stamp the Sanborn record with the satellite stamp:

- (1) SATELLITE
- (2) DATE
- (3) TIME
- (4) QUALITY
- (5) LOBE
- (6) TYPE DIG ANA

Fill in the following information:

- (1) Satellite number.
- (2) Date pass was taken.
- (3) Local meridian crossing time.
- (4) Maximum AGC in decibels.
- (5) Zenith angle
- (6) Type of recording; check DIG if digital is recorded on chart and ANA if analog. (Note the type of message sent.)

7.11 On passes that are 120 dBm or less and contain good DRS data, proceed as follows.

7.11.1 Using the transparent scale, check the DRS hard copy of the precalibration line and pass data.

Note: For the DRS breakdown, see figure 3-2.

7.11.1.1 Precalibration line. Check the following:

- (1) That the five AGC readings read 9.
- (2) That the five east-west and north-south fine K_{s2} readings are repetitive.
- (3) That all the K_{s2} readings agree with those found on the Sanborn record.
- (4) That the hour, minute, and second are correct.
- (5) That the antenna number is 2.
- (6) That the station number is correct.

7.11.1.2 Pass data. Check the following:

- (1) That the hour, minute, and second are correct.
- (2) That the AGC's are progressive.
- (3) That the station number is correct.

5886.5929484.4587.5939484.2362.5929484.25201.5929484.212.5929484.

SECONDS	---
EAST-WEST MEDIUM	---
EAST-WEST FINE	---
AGC	---
NORTH-SOUTH FINE	---
MINUTES	---
EAST-WEST COARSE	---
EAST-WEST FINE	---
AGC	---
NORTH-SOUTH FINE	---
HOURS	---
NORTH-SOUTH MEDIUM	---
EAST-WEST FINE	---
AGC	---
NORTH-SOUTH FINE	---
DAY	---
NORTH-SOUTH COARSE	---
EAST-WEST FINE	---
AGC	---
NORTH-SOUTH FINE	---
ANTENNA NUMBER	---
STATION NUMBER	---
EAST-WEST FINE	---
AGC	---
NORTH-SOUTH FINE	---

Figure 3-2.—DRS format breakdown for 1 s of data.

(4) That the antenna number is correct:

1-136 equatorial.

2-136 polar.

0-2-Hz filters.

(5) That all phase readings correspond with that recorded on the Sanborn record.

7.11.2 DRS tape.

Select the portion of the tape to be transmitted; mark and cut so that the transmission starts with a carriage return, linefeed, and the first digit in the first line. End with the last digit of the last line. Repeat the above procedure on the calibration line.

7.11.3 The message must contain a minimum of five lines after the calibration line is given.

7.11.4 Send the data to COMPUTE via TTY as in the following examples.

7.11.4.1 FLD ...

RR COMPUTE

DE STATION NAME

R.

BT

&62681 (Prefix ampersand and satellite number, no space between. No carriage returns or linefeeds required after the satellite number.)

7.11.4.2 Transmit headings, calibration line, and data, in that order, and end with—

BT

DATA TIME GROUP

8 linefeeds

NNNN

7.11.5 Enter pertinent information in the tracking status report file. Note: Consult the latest STADAN Network Control Center (NETCON) SOP No. 3 on the correct procedure for entry into the tracking status report.

7.11.6 Attach a hard copy of the data message to the Sanborn record, and place the message tape on the peg provided, to be held for 1 week in case of a rerun request from COMPUTE.

The following steps are presented as a guide to the use of the 136-MHz slide rule.

8.0 136-MHz SLIDE RULE

8.1 Equatorial reduction.

8.1.1 Using figures posted on the reduction board, proceed as follows for the reduction of the meridian crossing.

8.1.1.1 Make the following K_{s2} corrections using the red K_{a1} error correction marks.

8.1.1.1.1 The 46λ ring red mark to EWF K_{s2} on the drift scale (fine).

8.1.1.1.2 The 4λ ring red mark to EWM K_{s2} on the drift scale (medium).

8.1.1.1.3 The 3.5λ ring red mark to EWC K_{s2} on the drift scale (coarse).

8.1.1.2 Place the cursor on zero zenith angle and read off EWF readings from the 46λ EWM from the 4λ ring, and EWC from the 3.5λ ring. Post these readings on the reduction board.

8.1.2 Through the use of figures posted on the prediction board, proceed as follows for reduction of the zenith angle.

8.1.2.1 Make the following K_{s2} corrections with the blue K_{a1} error correction marks.

8.1.2.1.1 The 46λ ring blue mark to NSF K_{s2} on the drift scale (fine).

8.1.2.1.2 The 4λ ring blue mark to NSM K_{s2} on the drift scale (medium).

- 8.1.2.1.3 The 3.5λ ring blue mark to NSC K_{s2} on the drift scale (coarse).
- 8.1.2.1.4 Referring to the Sanborn analog chart, ascertain NSF, NSM, and NSC phase angles by measuring from the bottom of the scale to the intersection of the phase slope and meridian crossing.
- 8.1.2.1.5 By using the angles found in step 8.1.2.1.4 and starting with NSC, position the cursor on the rule where NSF, NSM, and NSC angles align in a straight line. The zenith angle may be read on the outer scale. Note: negative (-) = S; positive (+) = N.
- 8.2 Polar reduction.
- 8.2.1 Through the use of figures posted on the prediction board, proceed as follows for the reduction of the meridian crossing.
- 8.2.1.1 Make the following K_{s2} corrections with the blue K_{a1} error correction marks.
- 8.2.1.1.1 The 57λ ring blue mark to NSF K_{s2} on the drift scale (fine).
- 8.2.1.1.2 The 4λ ring blue mark to NSM K_{s2} on the drift scale (medium).
- 8.2.1.1.3 The 3.5λ ring blue mark to NSC K_{s2} on the drift scale (coarse).
- 8.2.1.2 Place the cursor on zero zenith angle and read NSF from the 57λ ring, NSM from the 4λ ring, and NSC from the 3.5λ ring. Post these readings on the reduction board.
- 8.2.2 Through the use of figures posted on the prediction board, proceed as follows for the reduction of the zenith angle.
- 8.2.2.1 Make the following K_{s2} corrections with the red K_{s1} error correction marks.
- 8.2.2.1.1 The 57λ ring red mark to EWF K_{s2} on the drift scale (fine).
- 8.2.2.1.2 The 4λ ring red mark to EWM K_{s2} on the drift scale (medium).
- 8.2.2.1.3 The 3.5λ ring red mark to EWC K_{s2} on the drift scale (coarse).
- 8.2.2.2 Ascertain EWF, EWM, and EWC phase angles by measuring from the bottom of the scale to the intersection of the phase slope and meridian crossing line.
- 8.2.2.3 By using the angles found in step 8.2.2.2 and starting with EWC, position the cursor on the rule where EWF, EWM, and EWC angles align in a straight line. The zenith angle may be read on the outer side. Note: negative (-) = W; positive (+) = E.

Section 4

FUNCTIONAL DESCRIPTION OF THE MINITRACK PREPROCESSING PROGRAM

INTRODUCTION

The preprocessing computer program is central to the Minitrack system. The daily tracking messages are transmitted in Baudot code, Teletype form, through the NASCOM worldwide communications network to the network central processor at GSFC. Instead of printing these messages in paged format, the central communications processor, the Univac 494, converts the Teletype code to hexadecimal machine language and briefly buffers these messages onto 494 magnetic tapes before passing them on to a magnetic tape storage unit of the IBM 360/95 at GSFC. The entire procedure of transmitting tracking data from the worldwide STADAN facilities by Teletype to the preprocessing computer is done without human intervention.

Early each morning at GSFC, a computer operator initiates the Minitrack preprocessing program on the IBM 360/95 and processes the tracking data of the previous day. The tracking messages from other tracking systems, such as range and range rate and optical, are intermixed, cued, and stored on the 360/95 along with the Minitrack data. The computer sorts these messages and "bins" them in disc storage according to the kind of tracking observation made (i.e., Minitrack, range and range rate, and so forth). A preprocessing program for each bin of data is brought into action serially throughout the morning by the computer according to the commands of the master control program presented in the form of a job control language (JCL) deck of Hollerith automatic data processing (ADP) cards.

The Minitrack preprocessing program is a FORTRAN program for an OS/360 system with a level H compiler. Functionally, the preprocessor program consists of two discrete programs: (1) program MIN-B and (2) program OBS-B. The sequence of the application of these two programs is fixed; the output of program MIN-B serves as the basic input for program OBS-B.

OBJECTIVES OF PROGRAM MIN-B

Program MIN-B, by far the longer of the two programs, transforms the raw Minitrack data, phase differences as a function of time for the six active baselines during a satellite pass (east-west coarse, medium, and fine baselines and north-south coarse, medium, and fine baselines), into unbiased direction cosines with respect to two orthogonal baselines as a function

of time. When such discrete observations of direction cosines for specific times are integrated with the data from other Minitrack stations, an accurate orbit determination of the particular satellite can be made. The preprocessor does not perform the orbit determinations but only supplies the input for the ODP's.

A preliminary procedure for the preprocessor is to verify the data format for each satellite pass. Several steps are devoted to the comprehensive tagging of the appropriate station, satellite, and baseline codes. Previously, this task was done manually. |

OBJECTIVES OF PROGRAM OBS-B

The output of MIN-B contains satellite, station, antenna, frequency, and bias information for each satellite pass. However, the basic output of MIN-B is simply a pair of direction cosines (with respect to the east-west and north-south baselines) at the time of the midframe for each satellite pass and the coefficients of a Taylor series expansion of the phase difference as a function of time in the neighborhood of the midframe (actually a function of frame number, but the frame rate is preselected by the operator and therefore a conversion to time is straightforward).

Using these output data of MIN-B as input, the first basic function of OBS-B is to calculate the direction cosines at any point in time in the vicinity of the midframe. The second basic function of OBS-B is to correct the direction cosines for the antenna-field pattern of the particular Minitrack station. A third basic function of this program is to calculate the direction cosine at the crossover of the baseline, that is, the east-west baseline for polar orbits or the north-south baseline for equatorial orbits. This point is a convenient reference because one of the two direction cosines must be identically zero and also because for most actual satellite orbits, especially the high-altitude ones, the refraction correction will be a minimum at crossover. The latter point is due to the relatively short slant path through the troposphere and especially the ionosphere, which can be the larger component at low elevation angles for the Minitrack frequency range of 136 to 138 MHz. These three functions of program OBS-B will be described briefly.

CALCULATION OF ADDITIONAL DIRECTION COSINES

From the previously mentioned output of MIN-B, the phase difference for either baseline in the neighborhood of the midframe may be calculated from the truncated Taylor series:

$$R_i = R_M + \frac{\partial R_M}{\partial N} N + \frac{\partial^2 R_M}{\partial N^2} N^2 + \frac{\partial^3 R_M}{\partial N^3} N^3$$

where

R_M = phase difference of either the east-west or north-south baseline at the midframe

N = number of frames from the midframe (. . . , -2, -1, 0, 1, 2, . . .)

and the partial derivatives evaluated at the midframe (that is, the coefficients of the Taylor series) are known from MIN-B. It should be mentioned that this implies that higher order terms are insignificant. However, in the particular configuration of the Minitrack preprocessor, a cubic polynomial is used to approximate the phase difference R as a function of time. Because the highest term is a cubic term in time T (or equivalently in frame number N), the fourth partial derivative of the phase difference as a function of time and all higher partials are identically equal to zero, i.e.,

$$\frac{\partial^P R_M}{\partial N^P} \equiv 0 \quad \text{for } P \geq 4$$

The ratio of this calculated phase difference R_i and the baseline length in wavelengths yields the desired direction cosine at an additional point.

Program OBS-B is set up to generate values for a direction cosine pair at a number of additional points given by the variable IPTS. If IPTS = 1, only the midframe direction cosine pair is given. If IPTS is odd, the pair at the midframe plus (IPTS - 1)/2 pairs are calculated on each side of the midframe with uniform spacing up to and including the end points of the interval which are equivalently the first and 31st frames. If IPTS = 2, the direction cosine pair at the midframe and the direction cosine pair one frame after the midframe (usually 1 s because the predominant frame rate is 1 frame/s) are calculated. If IPTS is even and greater than 2, the same pairs are calculated as for the odd number (IPTS - 1).

In this manner, the output of MIN-B becomes the direction cosines in OBS-B. It should be pointed out that even if the data for one of the two orthogonal baselines, that is the east-west or the north-south, are unusable, the data of the other baseline can still be utilized to determine an orbit for the satellite. This is achieved by combining the data for any given satellite from many of the Minitrack stations. In fact, even when the data from both baselines are acceptable, the emphasis is on the correlation of data from multiple stations on each satellite. Only in cases such as a preliminary orbit does one rely solely upon multiple passes at a single station. Such an orbit determination is highly inefficient because it samples only once per orbit. An orbit determination has an intrinsically low accuracy because the angular segment of the satellite orbit is small when observed from only a single station. Furthermore, any systemic errors for the particular station cannot be discovered from the data.

At this point it should be apparent that the Taylor polynomial expansion of phase difference as a function of time in the neighborhood of the midframe exists to provide more than one data point (that is, one pair of directions) for each satellite pass at any given satellite. Throughout the history of Minitrack, a controversy concerning the use of such calculated points besides the smoothed midframe point has continued. The two extremes are represented by the following attitudes: either preference should be given to the data at the midframe in any data smoothing process, or one Minitrack data point is as good as any other.

The details of the optimum sampling of data for the fitting functions used to smooth the data in the actual Minitrack preprocessor are discussed in section 6 under "Least-Squares Fitting Errors." In this section, the concept that the fitting error of a polynomial of degree n

can be expected to be smallest in the vicinity of the roots of the Legendre polynomial of degree $n + 1$ is considered. Also, in general, the fit will be worst at the end points. The reader is referred to this section for the actual development. The actual application of the fitting procedure is described in the following step-by-step description of program OBS-B.

ANTENNA-FIELD PATTERN CORRECTION

The prepass Minitrack system calibration (see vol. II, app. C) presents its results by two different components. The first component is the average calibration constant K_c for each of the six active baselines used during the satellite pass under consideration. (See p. 55 for an explanation and definition.) These average values are obtained by sampling over the half-power rectangular grid of approximately 10° by 80° centered at the zenith. Because a Minitrack data point occurs at one discrete position in the antenna-field pattern, the application of the average calibration constant is just a preliminary correction.

The second component of the Minitrack system calibration is a set of polynomial antenna-field equations. That is, for each of the two orthogonal baselines a higher order polynomial is determined to account for the residual fluctuations about the average values mentioned above. The general antenna-field polynomials can be written as

$$R'_{EW} = C_0 + C_1 R_{EW} + C_2 R_{NS} + C_3 R_{EW} R_{NS} + C_4 R_{EW}^2 + C_5 R_{NS}^2 + C_6 R_X^3 + C_7 \sin 2\pi R_{EW} + C_8 \cos 2\pi R_{EW}$$

$$R'_{NS} = C_0 + C_1 R_{EW} + C_2 R_{NS} + C_3 R_{EW} R_{NS} + C_4 R_{EW}^2 + C_5 R_{NS}^2 + C_6 R_Y^3 + C_7 \sin 2\pi R_{NS} + C_8 \cos 2\pi R_{NS}$$

where

R_{EW} = smoothed, absolute phase difference for the east-west baseline

R_{NS} = smoothed, absolute phase difference for the north-south baseline

R'_{EW} = east-west absolute phase difference corrected for antenna-field pattern

R'_{NS} = north-south absolute phase difference corrected for antenna-field pattern

$R_X = R_{EW}$ for a polar array or R_{NS} for an equatorial array

$R_Y = R_{EW}$ for a polar array or R_{NS} for an equatorial array

C_0, C_1, \dots, C_8 are the polynomial coefficients determined from the calibration procedure correlating the optical and radio positions of the calibration aircraft, one set for the east-west baseline and another set for the north-south baseline.

The basic description of the determination of the polynomial coefficients is given by Berbert, Oosterhout, Engels, and Habib.¹ The general forms given above apply when the

¹J. H. Berbert, J. D. Oosterhout, P. D. Engels, and E. S. Habib: "Minitrack Calibration System." *Photogr. Sci. Eng.* 7(2): 78-83, 1963.

satellite is within the half-power rectangle. When the satellite is outside this rectangle, the cubic and the pure and mixed quadratic terms are not considered reliable and are not used in the fitting procedures. (For a complete explanation, see the variables C and E in the OBS-B glossary of sec. 7, vol. 1.)

DIRECTION COSINE AT CROSSOVER

The third basic function of program OBS-B is to calculate the direction cosine with respect to the baseline in the direction of the extended length of the Minitrack fan beam pattern at the instant of the satellite's crossover of the baseline, or more correctly, at the instant of the satellite's passage through the vertical plane containing the baseline. The Minitrack antenna pattern at satellite heights is basically a 10° by 80° fan beam centered at the zenith. However, each Minitrack station has the option of activating a polar or equatorial set of two fine orthogonal baselines. These are the outer (57.0λ) and inner (46.0λ) baseline sets, respectively (fig. 2-2). A switch from one set to the other is equivalent to a rotation of 90° about the zenith axis. For satellites that exhibit predominantly polar orbits, the polar set is chosen for which the extended portion (80°) of the fan beam is in the east-west direction. Alternatively, for predominantly equatorial orbits, the equatorial set is chosen for which the extended portion of the fan beam is in the north-south direction.

Figure 4-1 portrays the geometry of a polar pass. Point O is the origin, the center of the Minitrack station; plane $NESW$ is the horizon plane for the station, with north, east, south, and west points; plane $ZEOWC_{PO}$ is the vertical plane containing the east-west baseline (i.e., the direction of the extended (80°) portion of the Minitrack fan beam for the polar set); point C_{PO} is the crossover point; point U is the point where the satellite rises above the horizon; point D is the point where the satellite sets below the horizon; and point P is the projection of the North Pole onto the celestial sphere. The general definitions for the direction cosines, regardless of which antenna set is employed, are—

$\cos \alpha$ = direction cosine with respect to the east-west baseline (positive from the east point)

$\cos \beta$ = direction cosine with respect to the north-south baseline (positive from the north point)

Let us consider the crossover direction cosine angles $\alpha_{C_{PO}}$ and $\beta_{C_{PO}}$ for the polar pass shown in figure 4-2. Because the crossover point C_{PO} is in the vertical plane of the east-west baseline, it is equidistant from the north and south arrays. Therefore, the corresponding absolute phase difference (including the integral number of cycles) is zero for the north-south baseline. Further, the direction cosine with respect to a given baseline is the phase difference for that baseline divided by the baseline length in wavelengths at the transmitting frequency; thus,

$$\cos \beta_{C_{PO}} = 0$$

or

$$\beta_{C_{PO}} = 90^\circ$$

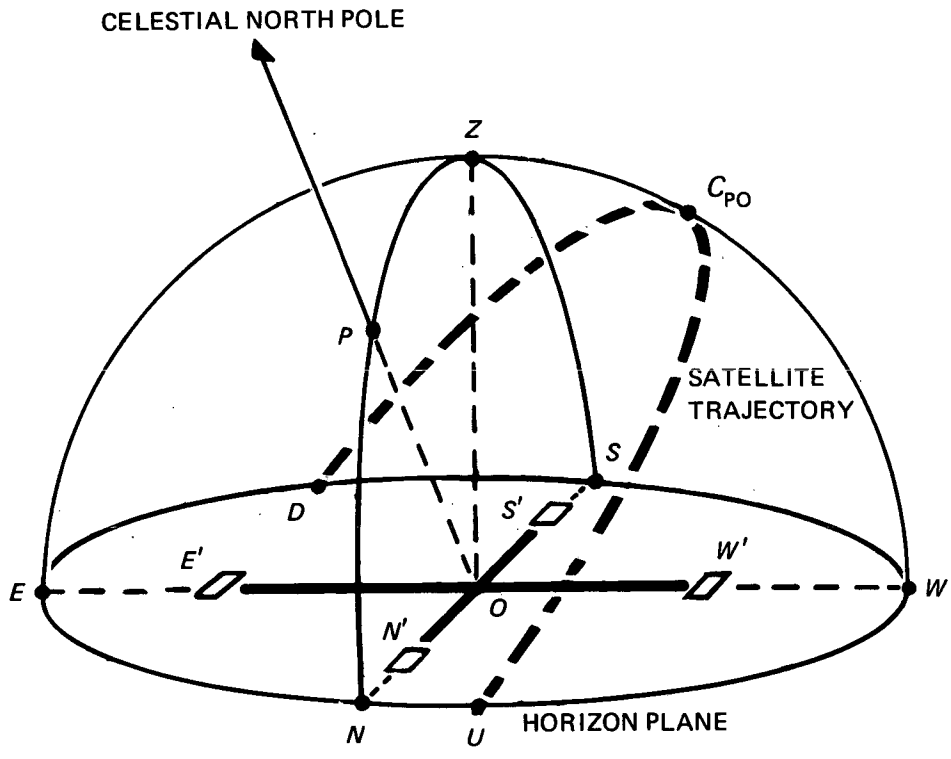


Figure 4-1.—Polar pass configuration.

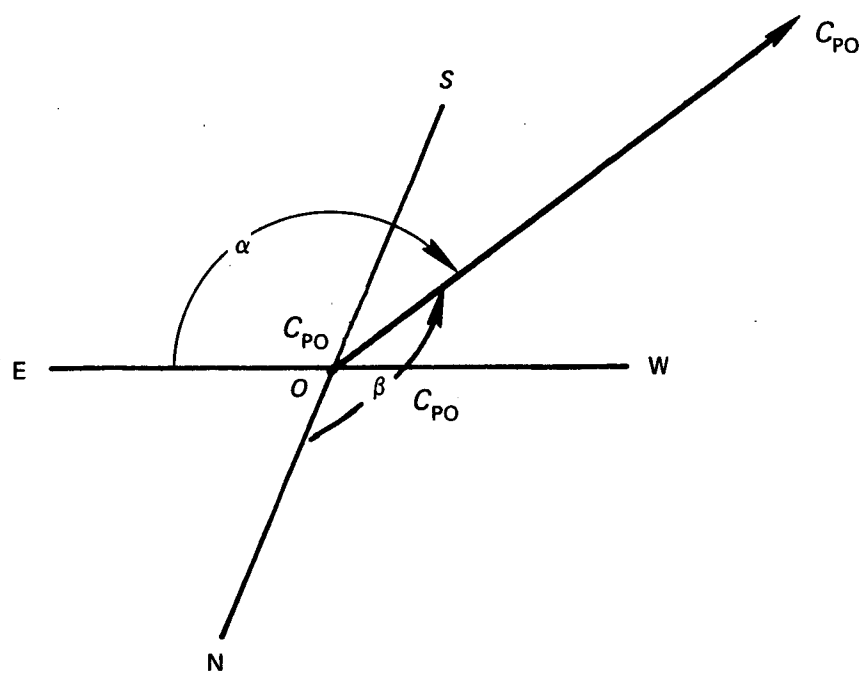


Figure 4-2.—Polar pass.



On the other hand, the crossover point is not, in general, equidistant from the east and west arrays (unless the satellite passes through the zenith); therefore, the absolute, east-west phase difference at crossover $(PD_{EW})_C$ produces the direction cosine

$$\cos \alpha_{CPO} = \frac{(PD_{EW})_C}{B}$$

where B is the baseline length.

Employing similar arguments for a predominantly equatorial pass will produce similar but interved direction cosines. The combined results are--

Polar pass:

$$\cos \alpha_{CPO} = \frac{(PD_{EW})_C}{B}$$

$$\cos \beta_{CPO} = 0$$

Equatorial pass:

$$\cos \alpha_{CEQ} = 0$$

$$\cos \beta_{CEQ} = \frac{(PD_{NS})_C}{B}$$

The preprocessor must determine the appropriate crossover direction cosine (for the associated one is identical to zero at crossover) and its instant of occurrence given only the output of program MIN-B (that is, the phase differences and direction cosines at the midframe time). To accomplish this, the technique of differential corrections is invoked, where

$$PD_C = PD_M + \Delta PD$$

$$T_C = T_M + \Delta T$$

in which PD is the phase difference, the subscript C refers to crossover, the subscript M refers to midframe, ΔPD is the differential phase difference correction, T is the time, and ΔT is the differential time correction.

The justification of the use of small differential corrections is based upon the Minitrack data-handling procedures. For a particular satellite pass at any Minitrack station, the data frame rate is preselected by the operator to cover a considerable arc of the apparent trajectory across the line of sight. However, before the message is transmitted to the central processor at GSFC, the data for a satellite pass are manually edited so that up to a maximum of 31 data frames are selected, with the midframe of these being determined from the crossover estimated from the analog data records. This selective alignment insures that the midframe is within the neighborhood of the crossover point.

The actual calculation of these differential corrections makes use of the coefficients of the terms of the Taylor series expansion of the phase difference as a function of time in the vicinity of the midframe. The first-derivative terms are used as estimates of the phase difference rate; i.e.,

$$\Delta PD = \left(\frac{\partial PD}{\partial T} \right)_C \Delta T$$

where $\partial PD/\partial T$ is the first-derivative term of the Taylor series expansion for the crossover direction cosine (nonzero direction cosine, except for case of zenith pass).

At this point, because the time of crossover T_C is not known, $\Delta T = T_C - T_M$ appears indeterminate. However, because the information for the orthogonal baseline refers to the same times T_C and T_M , an estimate of the crossover time can be made from the known midframe time and the phase difference rate for the baseline with the zero direction cosine at crossover $PD_C = 0$; i.e.,

$$\begin{aligned} \Delta T &= T_C - T_M \\ &= \frac{PD_C - PD_M}{(\partial PD/\partial T)_Z} \\ &= \frac{-PD_M}{(\partial PD/\partial T)_Z} \end{aligned}$$

The application of these last two equations in the reverse order will produce the crossover direction cosine and its time of occurrence.

At this point, the Minitrack preprocessor has prepared two corrected direction cosines as a function of time; the third dependent direction cosine follows immediately. Because the origin of the system was chosen to be the intersection of the Minitrack fine baselines, the three direction cosines for a given time uniquely specify the angular position of the satellite in a topocentric coordinate system. Later, in the ODP's, atmospheric corrections and coordinate systems are applied to the fundamental satellite tracking data supplied by the Minitrack system.

PROGRAM MIN-B

Step 1

Read data discriminators. The first active step of the preprocessor is to read three input data items from a single punched card supplied by the program user. These data are IDT, IGRADE, and IFIX.

IDT is a two-digit year number for the date of the tracking data being analyzed.

IGRADE is a single-digit integer whose value selects one of two alternatives concerning the grading of the quality of the data for all the satellite passes to be processed in this program run. If IGRADE = 1, the data are graded qualitatively based upon the quantitative values of the standard deviations of the least-squares solutions of the phase difference as a function of time for the coarse, medium, and fine baselines. The east-west and north-south data are considered separately. For the quantitative basis of this grading, refer to AST(4) and AST(6) in the MIN-B glossary. However, if IGRADE \neq 1, a high-quality grade is automatically assigned to the data without any consideration of the internal consistency of the data.

IFIX is a single-digit integer to identify whether the so-called standard frequency has been transmitted from the satellite. The program allows each satellite four frequencies, which are contained within a frequency table (see step 4). Actually, the Minitrack system is capable of handling 2000 discrete frequencies from 136.000 MHz to 137.999 MHz in 1-kHz steps. The standard frequency is defined for each satellite, so it may vary from satellite to satellite. If IFIX = 2, the program considers the standard frequency for each satellite, which has been preselected and is contained in the frequency table generated within the preprocessor under the variable name FRQ1. If IFIX \neq 2, the program examines the value of an auxiliary variable ILINK to decide which of the four frequencies has been used. (For further explanation, see FREQ in the MIN-B glossary.)

Step 2

Station biases are determined. It is well known that the electrical and mechanical alignments of the Minitrack system at the various stations are rarely perfect and rarely the same. Therefore, biases in both phase difference and time—the two fundamental quantities of Minitrack—are introduced at each station which must be known and included in the reduction of the Minitrack data. The program MIN-B reads from punched cards and prints out for display various station biases for the 10 active Minitrack stations.

Time delays due to the narrow-passband electronic filter in each of the lines from the east-west and north-south fine baselines are one type of bias. The explicit function of these filters is to provide the narrow postdetection bandwidth for the received signal. The filter bandwidth between half-power or 3-dB points is 10 Hz, which corresponds to an effective postdetection rectangular bandwidth² of 8 Hz. However, the phase difference changes with time because of the motion of the satellite with respect to the baseline; therefore, the measured phase difference must be incremented or decremented because of the variation of phase difference during the filter delay time. Alternatively, because the frequency is simply the time rate of change of phase, the satellite motion during the filter delay represents a frequency shift with respect to the received frequency which when multiplied by the filter delay time gives the appropriate first-order phase correction in number of cycles. That is,

$$\Delta R \approx \Delta f \Delta t \frac{\Delta R}{\Delta t} \Delta t$$

²C. A. Schroeder, C. H. Looney, Jr., and H. E. Carpenter, Jr.: *Phase Measurement*. Minitrack Rept. No. 1, NRL Rept. 4995, July 26, 1957.

where ΔR is the phase difference correction due to the filter, Δf is the frequency shift, and Δt is the filter delay time. In MIN-B, a Taylor expansion of phase difference as a function of time including second- and third-degree terms instead of the oversimplification above is applied to the filter delay correction. (See step 53.)

At the other end of the signal path, there is an additional time delay. In effect, the phase differences measured at the Minitrack station refer to the instant of transmission at the satellite and not the time of reception at the station. However, it is the latter of these times that is recorded. This is simply the classical light time correction, which for a satellite above most of the ionosphere (approximately 300 to 350 km) amounts to approximately a 1-ms time delay, compared to the typical 30- to 40-ms filter time delays. Neither this correction nor the second-order effect of the increased time delay due to passage through the dispersive ionosphere is treated in the Minitrack preprocessor. These corrections can be included, if desired, in the orbit determination programs or other analyses by the individual researchers.

A second form of bias results from propagation delays of the timing signal. The epoch of the timing system at each Minitrack station is synchronized with the standard time signals from WWV (Fort Collins, Colo.) or WWVH (Hawaii). However, the transit times from these transmission stations to the Minitrack stations represent time biases in the range of 10 to 58 ms that must be included in the time corrections.

Cable length inequalities for the ambiguity baselines cause a third type of bias. The cable lengths from the arrays at either end of each of the ambiguity baselines to the receiver junction box are not necessarily of equal physical length. Because the phase changes continuously along these coaxial transmission lines, the inequality in length is equivalent to a phase difference for that particular ambiguity baseline even though the frequency is constant. These phase difference biases are represented by the calibration constants $K_c - K_{s1} + K_{s2}$, which are discussed later within this step. In this point, we are concerned with the phase difference bias due to the cable length inequality at the satellite frequency $FREQ$, which is not in general the calibration frequency.

In terms of the cable length inequality in feet ΔL , the frequency difference between calibration and satellite frequency in hertz Δf , and the velocity of transmission through the cable in feet per second V , the phase difference correction in cycles (or wavelengths) ΔR is given by

$$\Delta R = \frac{\Delta L}{V} \Delta f$$

It is assumed that the calibration frequency is constant at 136.5 MHz; thus, $\Delta f = (136.5 - FREQ) * 10^6$, with $FREQ$ in megahertz. It is also assumed that the transmission velocity V is constant for all cables at all Minitrack stations under all observing conditions of temperature, pressure, and relative humidity. The value of the velocity of transmission used by the preprocessor is $V = 8.46 \times 10^9$ ft/s. This corresponds to a value of the transmission factor (TF) for the cable of $V/C = 0.860$, where C is the velocity of light in vacuum (9.835712×10^8 ft/s). This velocity factor of 86.0 percent is the nominal value for the typical type of

jacketed coaxial transmission cable used at the Minitrack stations (RG 254/U). The cable length inequalities are quoted to the nearest foot and are always less than 100 ft; therefore, the calculations for the correction in cycles should be sufficient for three significant figures, which are compatible with the two significant places representing the ambiguity phase differences. It is conventional to assign a positive sign if the excess cable length is in the north or east arm. Also, because the input format for the cable length inequalities contains a scaling factor of 10^{-3} , the FORTRAN statement form is $(\Delta L/0.846)$ (136.5 - FREQ). The physical lengths of the pair of cables for either of the four fine baselines are tested and cut for equality. Thus, the equivalent cable length inequality correction for the fine baselines is precluded.

In the input to the preprocessor, the filter delay and propagation delay appear in an algebraic composite form. The two biases KFA and KFB (in milliseconds) are read from punched cards for each station:

$$KFA = 400 + T_{\text{WWV}} - T_{\text{EW filter}}$$

$$KFB = 400 + T_{\text{WWV}} - T_{\text{NS filter}}$$

The factor of 400 ms is the time offset between the arbitrarily chosen time origin, the beginning time of the east-west fine midframe, and the actual time within the midframe, 0.4 s later, which is the time representing the smoothed phase differences used in the final calculations for the direction cosines. Because the Greenwich mean time (GMT) code at the instant of transmission from the broadcast station is earlier in proper time than when that same code is received at the Minitrack station, the associated transit time must be added to the frame time for any calculations to obtain the proper GMT. Further, it is obvious that this propagation delay for a given station is the same for the calculation of both KFA and KFB. On the other hand, because the observed phase difference for a baseline refers to the time of reception at that baseline (neglecting the light time correction), whereas the time recorded by the Minitrack system refers to the internal detection time including the filter delay, the filter delay time must be subtracted from the frame time to obtain the proper GMT.

The filter and propagation delays are not separable by the preprocessor; these individual delays are represented for convenience in table 4-1 along with their composite values and the cable length inequalities for the ambiguity baselines, CLEWM (east-west medium), CLEWC (east-west coarse), CLNSM (north-south medium), and CLNSC (north-south coarse). The filter delays represent recent measurements taken from Watkins,³ and the cable length inequalities are values taken from Minitrack input data provided by GSFC. The six-character station name STATIO and the two-digit station number KSTA are included for identification. The obvious discontinuities in the station numbers are due to the replacement, relocation, phasing out, or converting of Minitrack stations within the integrated STADAN system. Originally, the Minitrack stations were predominantly along the 75th meridian to accommodate the early satellite orbits with low equatorial inclinations; however, this trend has been modified since its inception during IGY to track satellites in polar orbits.

³Edward R. Watkins, Jr.: *Preprocessing of Minitrack Data*. NASA TN D-5042, May 1969.

Table 4-1.—Minitrack Time Delays and Cable Length Inequalities

Station location	STATIO	KSTA	T_{filter} (east-west), ^a ms	T_{filter} (north-south), ms	T_{WWV} , ms	KFA, ms	KFB, ms	Cable length inequalities ^a			
								CLEWM, ft	CLEWC, ft	CLNSM, ft	CLNSC, ft
Fort Myers, Fla.	FTMYRS	03	36	36	9.65	374	374	+28	+25	0	+26
Quito, Ecuador	QUITOE	05	36	37	19.07	383	382	0	0	0	0
Lima, Peru	LIMAPU	06	38	38	23.00	385	385	+28	+52	0	0
Santiago, Chile	SNTAGO	08	37	37	31.64	395	395	0	0	0	0
St. Johns, Canada Winkfield,	NEWFLD	12	36	36	15.29	379	379	+29	+25	0	+28
United Kingdom	WNKFLD	15	36	37	26.12	390	389	-29	+25	0	+28
Johannesburg, South Africa	JOBURG	16	32	33	53.67	422	421	-29	0	-29	0
Fairbanks, Alaska	ALASKA	19	38	37	13.49	375	376	0	0	0	0
Orronal Valley, Canberra, Australia	ORORAL	21	36	36	^b 30.10	394	394	0	0	0	0
Tananarive, Malagasy Republic	MADGAR	23	37	38	57.72	421	420	0	0	0	0

^aExcess cable in north or east arm is positive.

^bBroadcast station is WWVH in Hawaii.

The final types of biases to be discussed are station calibration biases $K_c - K_{s1}$. Besides the obvious bias in the ambiguity phase differences, numerous phase difference biases may exist that would be extremely difficult or at least impractical to disentangle. Some of the possible biases are baselines not exactly orthogonal, baselines not exactly horizontal, small errors in the baseline lengths, small errors in measuring antenna centers, variations in antenna centers as a function of arrival angle of the radio wave differentially between antennas, unknown actual radio lengths of the radiofrequency feed lines, and drifts in any of the above biases with time. The cumulative effect of these biases would be to produce a nonzero phase difference for a given baseline when a transmitting satellite is in the plane formed by the perpendicular bisectors to that baseline (that is, when the path difference for the two arrays forming that baseline should be zero). A standardized radio-optical calibration technique has been set up so that each station can determine this zero offset.⁴ Such calibrations are scheduled to occur once or twice annually at each station. Briefly, during such a procedure, an aircraft with a synchronized, photographable flashing light and radio transmitter flies through the antenna-field pattern in a prescribed and monitored pattern sometime between sunset and sunrise. Because a high accuracy (1 to 2 arcsec) can be obtained from well-established optical reductions for the flashing light, the radiofrequency phase difference biases for each baseline can be determined by comparing the observed radio phase difference and the derived, accurate optical phase differences. Effectively, this bias K_c is the *average* system phase difference bias at the time of calibration:

$$K_c = \frac{1}{n} \sum_{i=1}^N (a_r - a_{opt})_i$$

where N is the number of data points used in various positions in the antenna-field pattern, a_r is the observed radio phase difference, and a_{opt} is the derived optical phase difference for the same time. Because the interval between calibrations is long, it is desirable to try to check for time-variant differential phase differences. The bias K_c includes differential shifts in the antennas, cables, and receivers. A partial check for time variations is accomplished by considering the variations in this bias that result from the receivers only. An integral part of each calibration procedure is to inject a common signal into the receiver preamplifiers with the antennas and cables switched out of the system. This common signal should produce zero phase differences for all baselines in a perfectly aligned system. These nonzero values or biases due to just the receivers at the time of calibration are the K_{s1} biases. By performing the same test just before each satellite pass, there would be a prepass calibration value K_{s2} due to just the receiver. Therefore, the difference $K_{s2} - K_{s1}$ represents the drift in K_c that results from the receivers, whereas $K_c - K_{s1} + K_{s2}$ represents the average phase difference bias including the receiver drift. Two tacit assumptions are made in the above analysis: (1) that differential phase shifts during the interval between calibration and prepass calibration that result from deterioration in the antennas and coaxial cables are negligible and

⁴J. H. Berbert, J. D. Oosterhout, P. D. Engels, and E. S. Habib: "Minitrack Calibration System." *Photogr. Sci. Eng.* 7(2): 78-83, 1963.

Table 4-2.—Typical Station Biases $K_c - K_{s1}$ (February 1968)

STATIO	EWM	EWC	EWFP0	EWFEQ	NSM	NSC	NSFPO	NSFEQ
FTMYRS	0.058	0.372	0.958	0.140	0.902	0.113	0.011	0.430
QUITOE	.952	.871	.821	.753	.078	.727	.030	.002
LIMAPU	.443	.696	.950	.019	.962	.981	.257	.882
SNTAGO	.983	.112	.076	.945	.003	.971	.059	.965
NEWFLD	.457	.052	.933	.168	.887	.503	.942	.921
WNKFLD	.540	.222	.067	.870	.107	.779	.976	.011
JOBURG	.410	.201	.051	.092	.586	.850	.937	.866
ALASKA	.654	.960	.937	.438	.059	.497	.076	.921
ORORAL	.015	.780	.787	.031	.770	.298	.117	.929
MADGAR	.666	.037	.041	.019	.033	.831	.889	.157

Note: Units are in fractions of a cycle or wavelength.

(2) that the frequencies of the input signal for K_c and K_{s1} at calibration and also K_{s2} at pre-pass calibration are equal (standard procedure employs 136.5 MHz) or have negligible variations with frequency in this range.

In this step, the preprocessor reads from punched cards only the eight biases $K_c - K_{s1}$ determined from the most recent calibration. (See DATE in the MIN-B glossary, sec. 7.) These eight biases include east-west and north-south medium, coarse, fine polar, and fine equatorial readings: EWM, EWC, EWFP0, EWFEQ, NSM, NSC, NSFPO, and NSFEQ. Sample values for these biases applicable in February 1968 are contained in table 4-2 in fractions of a cycle or wavelength for that particular baseline.

Step 3

Station coefficients are determined. Each calibration constant in step 2, namely, each of the eight values $K_c - K_{s1}$, is actually an average over the antenna-field pattern investigated during the calibration procedure. Effectively, this field is 10° by 100° centered at the zenith. To account for the residual fluctuations about this average or mean, a higher order polynomial is applied to the data. It should be emphasized that the average corrections are applied to the individual ambiguity and fine baselines; however, the polynomial correction is applied later when the ambiguity and fine data have been correlated and smoothed to a single value for the absolute north-south phase difference.

At this point in the preprocessor, nine polynomial coefficients determined from the calibration procedure for each of the four fine baselines (including polar and equatorial sets) are read from punched cards and printed. However, the actual correction is not applied in this program but rather in program OBS-B in which they are again read from punched cards and printed. Because of this redundancy, further explanation of this correction will be deferred to program OBS-B where the correction is actually made.

Step 4

Read satellite parameters. Through the use of punched-card input, the preprocessor generates the frequency table discussed previously under IFIX. The five-digit satellite identification number KSAID and the up to four possible transmitting frequencies in megahertz for each satellite, FRQ1, FRQ2, FRQ3, and FRQ4, are assimilated. In its present form, the program can accommodate a maximum of 50 satellites—a number established by the dimension of the five above variables. KSATCT is the number of satellites actually in the table.

Whereas in the previous steps a working background for the satellite tracking reductions was accumulated from input cards, control is now transferred to the Minitrack data tape (a magnetic tape labeled Unit 9). The format for each satellite pass on the data tape is a satellite identification line, a prepass calibration line (essentially the $K_{s,2}$'s), and up to a maximum of 31 data lines or frames. A concise explanation of this data format has been presented by Watkins.⁵ Figure 4-3 and table 4-3 contain a copy of this sample Minitrack data

```
GPU083C
RR GPUR
DE LWNK 061
03/13 12Z

46406401 1 690103
4350.2639114.3580.2639114.1230.2639114.00380.2639114.215.2639114.
1456.3071750.4503.3231736.1217.3121830.00354.3251831.215.3391904.
1662.3591152.4505.3531199.1222.3761243.00355.3771280.215.3751324.
1861.4081559.4504.4241597.1217.4221636.00339.4252685.215.4321729.
2061.4741972.4505.4672022.1220.4761060.00342.4812083.215.4881142.
2263.5342388.4506.5391436.1222.5301463.00347.5411519.215.5472546.
2463.5911798.4507.5912840.1227.6082885.00348.6062920.215.6102969.
2664.6502208.4507.6491255.1228.6522305.00350.6721342.215.6792385.
2863.7162633.4505.7212679.1232.7312717.00351.7372762.215.7452802.
3064.7882057.4508.7992104.1236.8062143.00354.8202186.215.8192239.
3265.8572483.4507.8672528.1238.8342574.00358.8842604.215.8961652.
3467.9482918.4507.9481950.1238.9612006.00359.9592031.215.9802078.
3668.0162345.4508.0281380.1241.0372431.00366.0482459.215.0582517.
3867.1022771.4509.1162812.1247.1242870.00365.1312904.215.1412946.
4068.1892200.4507.2011247.1249.2102297.00366.2152342.215.2252384.
4269.2831634.4510.2992684.1251.2932731.00371.3131768.215.3051830.
4469.3721086.4511.3871115.1256.3921171.00370.4031207.215.4121258.
4670.4741514.4511.4821560.1259.4921607.00376.4941661.215.5021704.
4870.5701966.4511.5801993.1261.5871055.00376.5981087.215.6031146.
5071.6691395.4513.6841450.1265.6931033.00379.6941544.215.7081598.
5271.7781848.4512.7841909.1268.7951947.00383.8001990.215.8281045.
5472.8891289.4514.8961351.1271.9131397.00385.9151439.215.9310481.
5672.9841751.4515.0030801.1273.0231826.00387.0161901.215.0611942.
5874.1140218.4516.1190238.1278.1370292.00390.1691338.215.1500394.
0074.2341658.4615.2440702.1281.2700759.00393.2860777.215.2850835.
0274.3590109.4616.3740175.1283.3990211.00397.3930246.215.4070299.
0475.4750568.4619.5000615.1287.5170665.00300.4830695.215.5330745.
0676.6200008.4619.6460072.1290.6330121.00302.6540176.215.6470231.
0879.7680522.4620.7230527.1294.7930567.00305.7900650.215.8420678.
1078.8250954.4620.8280014.1298.9310035.00308.9620126.215.9690143.
1280.1020389.4621.0980426.1200.0230478.00309.0300507.215.0990595.

6406401
03/13 12Z JAN LWNK
```

Figure 4-3.—Sample Minitrack data message. (See table 4-3 for explanation of the entries).

⁵Edward R. Watkins, Jr.: *Preprocessing of Minitrack Data*. NASA TN D-5042, May 1969.

Table 4-3.—Digital Recording System Frame Format

Character	Content
1, 2	Second (time) of frame start
3, 4	Hundreds and tens digits of east-west medium phase
5	Period “.” separator
6 to 8	First east-west fine phase
9	Signal strength indicator (AGC)
10 to 12	First north-south fine phase
13	Period “.” separator
14, 15	Minute of frame start
16, 17	Hundreds and tens digits of east-west coarse phase
18	Period “.” separator
19 to 21	Second east-west fine phase
22	Signal strength indicator (AGC)
23 to 25	Second north-south fine phase
26	Period “.” separator
27, 28	Hour of frame start
29, 30	Hundreds and tens digits of north-south medium phase
31	Period “.” separator
32 to 34	Third east-west fine phase
35	Signal strength indicator (AGC)
36 to 38	Third north-south fine phase
39	Period “.” separator
40 to 42	Day of year for frame start
43, 44	Hundreds and tens digits of north-south coarse phase
45	Period “.” separator
46 to 48	Fourth east-west fine phase
49	Signal strength indicator (AGC)
50 to 52	Fourth north-south fine phase
53	Period “.” separator
54 ^a	Equatorial/polar antenna indicator 1 = equatorial 2 = polar
55, 56	Station number 03 = FTMYS 15 = WNKFLD 05 = QUITOE 16 = JOBURG 06 = LIMAPU 19 = ALASKA 08 = SNTAGO 21 = ORORAL 12 = NEWFLD 23 = MADGAR
57	Period “.” separator
58 to 60	Fifth east-west fine phase
61	Signal strength indicator (AGC)
62 to 64	Fifth north-south fine phase
65	Period “.” separator

^aThis position of the internal calibration frame is used to manually insert a filter indicator whenever it is used in a standard data message: 0 = 2-Hz filter in fine channels, 2 = 10-Hz filter in fine channels, and 3 = narrowband tracking filter system.

message and an explanation of the entries, respectively. To simplify the verification of the data, which are a composite of literal and numerical characters, each of the possible 33 lines per satellite pass are read in under a one-dimensional alphameric array of 65 characters, namely, DATA (I), where $I = 1, \dots, 65$. However, this extremely useful process does necessitate an additional consideration in verifying legal numeric characters between 0 and 9. For each numeric character read under the alphameric format, the zone bits represent the hexadecimal F so that the numeric quantity 1 is F1, the numeric quantity 2 is F2, and so forth. To operate with these numerical quantities, the zone bits are masked out; this is accomplished by subtraction of the hexadecimal zero, which is F0. An example of this type of masking arithmetic would be $F9 - F0 = 9$. In the preprocessor this quantity is identified with the recurrent variable BIN.

Step 5

Read, verify, and prepare satellite identification line. The program performs the following commands:

- (1) Read a line with the DATA array format. An ampersand, which characterizes a satellite identification line, must be in column 1 unless another line is read in.
- (2) Form the five-digit satellite identification number SAT in one of three prescribed ways and check the table formed in step 4 for the legitimacy of the satellite identification. If this number is not an element of the table, the error message SAID NOT IN TABLE is printed.
- (3) If $IFIX \neq 2$ (see step 1), examine columns 9 through 65, one column at a time, until a nonblank column is encountered, which is construed to represent the secondary frequency discriminator ILINK. Search the remaining columns of the array DATA, one at a time, until a nonblank column is encountered. This digit and the next five columns represent the common six-digit calendar date (YEAR/MONTH/DAY).

If $ILINK = 1, 2, 3,$ or 4 , examine the frequency in megahertz to insure that it is within the Minitrack operating range, 136 to 138 MHz. Next, form the seven-digit Department of Defense satellite number SATT from columns 2 through 8. This number contains a two-digit year number, a three-digit launch number, and a two-digit part number; e.g., 6902702 represents the second orbiting part of the 27th satellite launched in 1969.

If $ILINK \neq 1, 2, 3,$ and 4 , an error message $FREQ. LINK NOT IN TABLE$ is printed. This activates the reading of a new data line.

If $IFIX = 2$, the standard frequency $FREQ = FRQ1$ is established; and a five- or six-digit satellite number SATT is formed in one of two ways depending upon the format of the identification line.

Step 6

Read, verify, and prepare the internal calibration line. As indicated in the sample Mini-track message in figure 4-3, the line immediately following the satellite identification line is the internal calibration. Essentially, it contains the prepass calibration constants K_{s2} for each of the six baselines. The format is the same as the data lines that follow so that there are five east-west fine, five north-south fine, and one of each of the four ambiguity baseline phase difference readings, or 14 all together. Treatment of this line proceeds as follows:

- (1) Read from the array DATA(I), $I = 1, \dots, 65$.
- (2) Reject line if an ampersand occurs in column 1.
- (3) Provide format check for the required occurrence of the 10 period separators in the line; if any period is missing, print the error message CAL. LINE ERROR.
- (4) Check each of the remaining 55 columns for legal numerical values (0 through 9) by masking the zone bits as described earlier in step 4.
- (5) Because the calibration line data are obtained by inputting a standard signal to the preamplifiers, the AGC or signal strength indicators should all have a constant value. The maximum value of 9 for each of the five readings per line is checked by recognizing that their sum must be 45 unless the line is rejected.
- (6) A two-digit station number CSTA is formed from the calibration line (columns 55 and 56) and checked against all the station numbers whose station parameters have been provided KSTA(L), $L = 1, \dots, 12$. If no match is found the error message WRONG STATION IN CAL. LINE is printed.
- (7) Convert the 14 phase differences from alphameric to digital form for computations. The final units are decimal fractions of a phase cycle, .XXX for the fines and .XX for the ambiguities.
- (8) Form the filter indicator CANT = DATA(54), where the value of CANT is 0 if a 2-Hz filter is in the fine lines, 2 if a 10-Hz filter is in the fine lines, or 3 if a narrowband tracking filter is used. The value of CANT not only indicates the fine filter but also keys a correction to the total time delays KFA and KFB given in table 4-1; as mentioned earlier, these values are for the 10-Hz filters. If the special 2-Hz or narrowband filter system is used, the time delay must be corrected. This quantity is represented by IDIF. (See XKFA in the MIN-B glossary, sec. 7.) If the 2-Hz filter is employed (CANT = 0), then IDIF = 0.120 s is added to the appropriate KFA and KFB. When the narrowband filter system (CANT = 3) occurs, the pre-processor assigns a zero correction, IDIF = 0; however, IDIF should be 0.100 s for this case. The actual addition occurs later in step 51.
- (9) Form the complete station biases for the four ambiguity baselines for the Lth station; namely, $K_c - K_{s1} + K_{s2}$:

$$CEWM = EWM(L) + CEWM$$

$$CEWC = EWC(L) + CEWC$$

$$CNSM = NSM(L) + CNSM$$

$$CNSC = NSC(L) + CNSC$$

- (10) The complete station biases for the fine baselines are not computed until the five east-west and five north-south values of K_{s2} are condensed into one smoothed midpoint value each by the application of a standard compression formula. Because each subsequent data line experiences the same compression, a full explanation is given under the compression of the fine data lines. For reference, the formulas are

$$CEWF1 = CEWF3 + [9. * (IDIF3 - IDIF2) - 3. * (IDIF4 - IDIF1)]/35.$$

$$CNSF1 = CNSF1 + [9. * (IDIF3 - IDIF2) - 3. * (IDIF4 - IDIF1)]/35.$$

where IDIF1, IDIF2, IDIF3, and IDIF4 are the four differences formed from pairing the five successive readings for each fine baseline.

- (11) Apply the cable length inequality correction as given in step 2 and table 4-1 to the calibration line; e.g., for the east-west medium baseline,

$$CEWM = [(CLEWM(L)/.846) * (136.5 - \text{FREQ})] + CEWM$$

- (12) Print out all pertinent calibration quantities on FORTRAN Unit 11.

Step 7

Read, verify, and prepare the data lines. After a check to guarantee that only a maximum of 31 data frames will be allowed and that the last data line has been read as indicated by blanks in columns 10, 30, and 50, the sequence of steps is as follows:

- (1) See (1) of step 6.
- (2) See (2) of step 6.
- (3) See (3) of step 6.
- (4) See (4) of step 6.
- (5) The time in GMT, which is the proper time system for all the Minitrack stations, is read in hours, minutes, and seconds from the Minitrack data clock and converted to the total number of seconds GMT for the date of observation:

$$\text{TIM}(K) = \text{HORD}(K) * 3600. + 60. * \text{MIND}(K) + \text{SECD}(K)$$

that is, the second of the day at the beginning of the Kth frame.

- (6) Form the antenna set indicator $\text{ANTD} = \text{DATA}(54)$ where

$$\text{ANTD} = \begin{cases} 1 & \text{for equatorial set} \\ 2 & \text{for polar set} \end{cases}$$

(7) The length of the fine baselines ANT in wavelengths is established,

$$\text{ANT} = \begin{cases} 57. & \text{for polar set} \\ 46. & \text{for equatorial set} \end{cases}$$

as is the two-digit station number STAD.

- (8) Convert the 14 phase differences from alphameric to digital form for computations. The final units are decimal fractions of a phase cycle, .XXX for the fine baselines and .XX for the ambiguity baselines.
- (9) Because the ratio of the fine phase differences and the ambiguity phase differences per frame is 5:1, a five-point smoothing or compression formula is used to condense the five fine readings to one in each frame. A complete derivation of this methodology and the similar process for the calibration line referred to in step 6 is contained in "Compression of Fine Data" in section 6. Two steps are necessary for the preparation of the fine data. First, the four differences formed by subtracting the phase differences of successive values are calculated; for example, for the east-west fine data,

$$\text{IDIF1} = \text{EWF2} - \text{EWF1}$$

$$\text{IDIF2} = \text{EWF3} - \text{EWF2}$$

$$\text{IDIF3} = \text{EWF4} - \text{EWF3}$$

$$\text{IDIF4} = \text{EWF5} - \text{EWF4}$$

Second, these four differences are sent through subroutine NORMAL so that the differences will represent the original numerical sequencing. The details are included in subroutine description NORMAL in section 5.

- (10) A counter correction is applied to the fine data. The fine phase differences can have values from .000 to .999, or equivalently, 1000 Minitrack fine counts of .001. A finite time is required for the registers to accumulate a fine phase reading. The counter frequency that is employed is 100 kHz, or equivalently, 10^{-5} s per fine count. Therefore, the counting time Δt in seconds is

$$\begin{aligned} \Delta t &= \text{phase} \times 10^{-2} \\ &= \text{phase count} \times 10^{-5} \end{aligned}$$

where

$$0.0 \leq \text{phase} < 1.0$$

$$0 \leq \text{phase count} < 1000$$

This yields a maximum counting delay of 0.01 s, or 10 ms. During this "count-down" time, the phase difference for that baseline is changing. The fine phase differences must be adjusted because of this variation.

The digitizer format for the fine readings spaces the five readings a_i , where $i = 1, \dots, 5$, at 0.2-s intervals occurring essentially at 0.0, 0.2, 0.4, 0.6, and 0.8 s from the frame start (that is, the frame time recorded by the data clock). The smoothed or compressed value of the previous step is \bar{a}_3 and occurs at frame time 0.4 s. An estimate of the phase-difference rate with respect to time is obtained from the approximation that the average rate of change in phase cycles per 0.2 s can be given by the expression

$$\frac{(a_2 - a_1) + (a_3 - a_2) + (a_4 - a_3) + (a_5 - a_4)}{4}$$

or equivalently,

$$\frac{\text{IDIF1} + \text{IDIF2} + \text{IDIF3} + \text{IDIF4}}{4}$$

Thus, the average phase rate $\Delta R/\Delta t$ (in phase cycles per second) is

$$\frac{\Delta R}{\Delta t} = \frac{5}{4} (\text{IDIF1} + \text{IDIF2} + \text{IDIF3} + \text{IDIF4})$$

The estimated change in phase difference ΔR (in phase cycles) for the middle point a_3 during the counting time Δt can be calculated from

$$\begin{aligned} \Delta R &= \frac{\Delta R}{\Delta t} * \Delta t \\ &= \frac{5}{4} (\text{IDIF1} + \text{IDIF2} + \text{IDIF3} + \text{IDIF4}) * 10^{-2} a_3 \\ &= 0.05 * \text{IDIF5} * a_3 \end{aligned}$$

where

$$\text{IDIF5} = \frac{\text{IDIF1} + \text{IDIF2} + \text{IDIF3} + \text{IDIF4}}{4}$$

Notice that the raw reading a_3 is used because we are interested in the actual delay time. Because the consecutive differences are less than 0.500, the rate per second must be less than 2.500. Because the reading is less than 1.000, the delay must be less than 0.01 s. This means that the adjustment must be less than 0.025.

Clearly, the error remaining after this adjustment is applied is of second order. It appears, therefore, that this adjustment procedure is accurate to less than one fine count, 0.001. This is borne out by numerical results in the single case we have examined.

There is a small possibility of error when the reading is large and increasing. Subroutine NORMAL will guarantee that the preliminary computation of \bar{a}_3 is correct. However, the correction will be done on the basis of the raw data a_3 . It is conceivable that, e.g., $a_3 = .005$ could represent 1005 fine counts.

This can occur if the reading passes through a phase zero while the counter is in operation. For instance, the phase difference may be 0.995 wavelength when the counter starts and becomes 0.005 while the counter is counting. Presumably, the counter will then give a reading of 0.005.

Subroutine NORMAL will guarantee that the preliminary calculation of a_3 is correct. However, the counter correction will be done on the basis of the raw datum a_3 . If the smoothed value is used, the preprocessing program actually uses the raw datum.⁶ This could mean the elimination of the counter correction almost completely.

The probability of such an occurrence is about 0.01 for a 400-km circular orbit. This probability decreases for higher orbits and increases to about 0.025 for 120-km orbits. (This probability is estimated by the fact that the correction will be wrong for any reading a_3 greater than

$$\left(1 - 0.01 \frac{\Delta R}{\Delta t}\right) \frac{1}{5}$$

Step 8

The total calibration constants $K_c - K_{s1} + K_{s2}$ for the two fine baselines used during the satellite pass under consideration are computed using the previously compressed K_{s2} values, namely CEWF1 and CNSF1. The use of the two polar fine baselines and the two equatorial fine baselines are mutually exclusive cases, so the baseline length indicator ANT is called upon to select either the equatorial or polar calibration corrections:

Polar:

$$CEWF1 = CEWF1 + EWFPO(L)$$

$$CNSF1 = CNSF1 + NSFPO(L)$$

Equatorial:

$$CEWF1 = CEWF1 + EWFEQ(L)$$

$$CNSF1 = CNSF1 + NSFEQ(L)$$

Step 9

The applicable fine calibration constants are printed on unit 11.

⁶Edward R. Watkins, Jr.: *Preprocessing of Minitrack Data*. NASA TN D-5042, May 1969.

Step 10

Check the time sequencing of the data frames:

- (1) If the difference between the time for any frame and the previous frame is negative, a new day has been entered. The preprocessor adds the number of seconds in a day, 86400, to the later frame to linearize the time sequence. It should be pointed out that this adding is done until the later time is greater; no check is made to insure that it is done only once.
- (2) The time interval of each pair of successive values is examined for equality with the seven frame rates: 1, 2, 10, 20, 60, 120, and 600 s/frame. Internal counters accumulate the number of frames for which each of the above rates is used and then select the rate that has occurred the maximum number of times. The variable TILI is set equal to this rate. At the same time, the frame-rate indicator AST(3) is assigned a value. (See MIN-B glossary, sec. 7.)

Step 11

A superfluous check is made to see that the frame times are linearized with the adjusted values unless an error message is printed. This step also checks to see if the time interval between any two accepted frames exceeds five times the frame rate TILI. A positive test implies that more than five consecutive frames were unacceptable, so the data for the entire satellite pass are questionable, necessitating their being skipped.

Steps 12 through 30 treat the processing of the east-west ambiguity and fine baselines data.

Step 12

The east-west medium and coarse data for each acceptable frame are submitted to subroutine LOBASN, in which the proper relative phase differences are determined. Direct reference should be made at this time to the complete explanation of this process in the separate subroutine descriptions immediately following the delineation of the preprocessor steps.

Step 13

The east-west medium data from the previous step are submitted to subroutine LSQQUA, in which a least-squares quadratic equation is fitted to the raw phase differences as a function of the frame time:

$$R = \alpha + \beta T + \gamma T^2$$

In this routine, the data are screened by a sigma-rejection process in an attempt to reduce the inclusion of random errors. The reader is referred to the complete description of this subroutine's function in section 5.

Step 14

Determine the absolute phase difference for the midframe of the east-west medium baseline. Because of the double translation of the origin in the phase-time plane performed in subroutine LSQQUA, the fitted value of the absolute phase difference at the midframe, that is, at $T = 0$, must be calculated from the following equation:

$$\text{fitted phase difference} = \text{raw phase difference} + \alpha$$

The corresponding program statement is

$$\text{EWMA} = \text{EWMD}(\text{MID}) + \text{ALPHA}$$

Step 15

Correct for the absolute time for the east-west medium midframe time. It should be emphasized that the midframe time refers to the beginning of the frame that is midway between the total number of data frames, up to a maximum of 31. Ultimately, the matching coarse, medium, and fine phase differences are registered at separate times in a preselected sequence controlled by the multiplexer of the digital recording system. In addition, the ambiguity times include a delay time due to a 2-Hz bandwidth filter in each of the ambiguity channels.

At this time a functional description of the timing system would be helpful:

T'_F = GMT or frame time when the radio signal is received at the ambiguity baseline

T_F = GMT or frame time at the beginning of the midframe as registered by the Mini-track data clock

T_D = 2-Hz filter delay between signal arrival at baseline and at the register

T = GMT or absolute time for the appropriate position within the midframe at which the particular baseline is sampled, as directed by the digital recording system format

T_B = time interval due to the sampling sequence within the midframe

Therefore,

$$T'_F = T_F - T_D$$

where $T_D = 0.150$ s.

$$T_B = \begin{cases} 0.0 \text{ s, east-west medium} \\ 0.2 \text{ s, east-west coarse} \\ 0.4 \text{ s, north-south medium} \\ 0.6 \text{ s, north-south coarse} \end{cases}$$

the equation

$$\begin{aligned} T &= T'_F + T_B \\ &= T_F - T_D + T_B \end{aligned}$$

reduces to

$$T = \begin{cases} T_F - 0.15, & \text{east-west medium} \\ T_F + 0.05, & \text{east-west coarse} \\ T_F + 0.25, & \text{north-south medium} \\ T_F + 0.45, & \text{north-south coarse} \end{cases}$$

In this particular step, the correction for only the east-west medium baseline is made:

$$\text{EWMT} = \text{TIM}(\text{MID}) - 0.15$$

Step 16

The standard deviation for the least-squares quadratic fit to the east-west medium data is assigned a name; i.e.,

$$\text{SA} = \text{SIA}$$

Step 17

Print the pertinent output (Unit 11) for the east-west medium baseline, namely, σ , α , β , γ , the midframe number, and the first-order phase rate.

Steps 18 through 22

These steps are analogous to steps 13 through 17 for the east-west medium baseline but refer to the east-west coarse baseline. These produce—

$$\text{Phase difference: } \text{EWCA} = \text{EWCD}(\text{MID}) + \text{ALPHA}$$

$$\text{Time: } \text{EWCT} = \text{TIM}(\text{MID}) + 0.05$$

$$\text{Standard deviation: } \text{SB} = \text{SIA}$$

Step 23

Estimate the rate of change of the east-west fine phase differences with time. Because the phase difference for the fine baselines from frame to frame can change by more than 0.5 cycle, some estimate of the fine phase-difference rate must be available to assign the proper lobe integers or relative phase-cycle numbers to the progression of the fine data frames. This estimate for the phase-difference rate is made from the approximate values of the medium

and coarse rates and the direct proportionality between the phase-difference rate and the baseline length ANT.

$$\text{RATE}_{\text{fine}} = \frac{\text{ANT}}{2} \left(\frac{\text{RATE}_{\text{coarse}}}{3.5} + \frac{\text{RATE}_{\text{medium}}}{4.0} \right)$$

This procedure is fully outlined in the description of subroutine LOBASN in section 5.

Step 24

The standard deviations of the east-west medium and coarse fits are checked for an excess. If σ is greater than 0.1 phase cycle, a corresponding warning message is printed:

EAST MEDIUM CHANNEL EXCEEDS 100 COUNTS

or

EAST COARSE CHANNEL EXCEEDS 100 COUNTS

and the data-grading indicator AST(6) is set. (See MIN-B glossary, sec. 7.)

Step 25

East-west fine lobe assignment is made. Through the use of the estimated phase-difference rate calculated in step 23, the east-west fine data enter subroutine LOBASN to establish the proper relative phase cycles, or, equivalently, the proper relative lobe integers. The treatment of the fine data in contrast to the treatment of the ambiguity data is presented in the description of subroutine LOBASN in section 5.

Step 26

Calculate the least-squares cubic fit to the east-west fine phase readings. In performing a least-squares solution for the fine phase differences as a function of time, a cubic polynomial was found to be more suitable than the quadratic polynomial applied to the ambiguity data. A complete derivation for the least-squares cubic solution is contained in the description of subroutine LSCUB in section 5. Further, a detailed comparison has been made between the previously used quadratic form and the presently used cubic form by generating ideal Minitrack data from a Minitrack simulator. This analysis can be found under "Least-Squares Fitting Errors" in section 6.

Step 27

The absolute time for the east-west fine midframe is computed. The compressed and smoothed fine readings at this point do not refer to the beginning of the midframe but rather to a point 0.4 s from it. This does not include the filter delay time and the propagation delay. These three corrections have been included in KFA, as discussed in step 2. However, the Minitrack time system has been set up so that the frame time at the beginning of

the midframe for the east-west fine data, that is, TIM(MID), is the zero-reference time. Therefore,

$$EWFT = TIM(MID)$$

In general, the compressed and smoothed north-south fine phase differences refer to the same time so that SNFT = TIM(MID). As indicated above, the fine phase differences do not refer to the beginning of the midframe. Step 53 recognizes this by "interpolating" the final phase differences from the real time to the zero-reference time at the beginning of the midframe.

The date for this zero-reference time is also defined at this point by IDAYD(1) = IDAYD(MID).

Step 28

Determine the absolute phase difference for the east-west fine midframe. Analogous to the east-west medium phase difference in step 14, the fitted value of the absolute phase difference at the midframe is the sum of the compressed value for that frame plus the value of the cubic polynomial at $T = 0$, namely, α :

$$EWFA = EEFW(MID) + ALPHA$$

Step 29

The label SC = SIA is assigned to the east-west fine standard deviation of fit and converted to a convenient hexadecimal form in subroutine ZERO for transfer and further usage in later programs.

Step 30

Print output (Unit 11) of absolute phase differences and times for the east-west coarse, medium, and fine baselines.

Steps 31 through 49

These steps parallel steps 12 through 30 but handle the north-south data rather than the east-west data. The principal results are the fitted phase differences for the midframe:

$$SNMA = NSMD(MID) + ALPHA$$

$$SNCA = NSCD(MID) + ALPHA$$

$$SNFA = ENSF(MID) + ALPHA$$

where the ALPHA's refer to their respective fitted polynomials, and the times for midframe:

$$\text{SNMT} = \text{TIM}(\text{MID}) + 0.25$$

$$\text{SNCT} = \text{TIM}(\text{MID}) + 0.45$$

$$\text{SNFT} = \text{TIM}(\text{MID})$$

as described in steps 15 and 27.

Step 50

Calculate the phase-difference residuals for all six baselines for each frame. To assist in the interpretation of the goodness of fit by the least-squares solutions for the phase differences, the residual or difference between raw or input values and the fitted values for the same time for each of the frames is calculated and printed out. The procedure follows:

- (1) Reference the frame time for the desired frame (Ith frame) to the midframe:

$$T = \text{TIM}(\text{I}) - \text{TIM}(\text{MID})$$

In the program, because of the changes of step 15 in typical expressions such as for the east-west medium time, this is equivalently

$$T = \text{TIM}(\text{I}) - \text{EWMT} - .15$$

- (2) Using the derived polynomial parameters α , β , γ (and δ for the fine data), determine the fitted value at the time calculated above from the appropriate quadratic or cubic polynomial.
- (3) Subtract the raw (or compressed values for the fine baselines) readings and the fitted values to yield the residual.

Step 51

Time adjustments are made for the fine baselines. The time corrections KFA and KFB in milliseconds which represent the combined 10-Hz filter delay, WWV propagation delay, and the 400-ms data-formatting shift are converted to seconds and combined with the differential filter correction IDIF, which allows for the usage of other filters in the fine lines. IDIF is already in seconds. For the east-west data,

$$\text{XFA} = \frac{\text{KFA}(\text{L})}{1000.} + \text{IDIF}$$

For the north-south data,

$$\text{XFB} = \frac{\text{KFB}(\text{L})}{1000.} + \text{IDIF}$$

Step 52

Calculate the correct frame time for north-south data. The statement

$$\text{TCOR} = \text{EWFT} - \text{SNFT} - \text{XKFB}$$

is included in the eventuality that the east-west and north-south fine times for the midframe are not the same. In step 27, it was indicated EWFT = SNFT = TIM(MID). A close inspection of subroutine LSCUB in which the value of MID is calculated shows that MID must be the same for the east-west and the north-south fine data. Therefore, in the present form of the program,

$$\text{EWFT} = \text{SNFT}$$

Step 53

Correct the fitting parameters α , β , γ , and δ for the fine data. In step 27, the zero-reference time was established as the beginning of the midframe for the east-west fine data, that is, TIM(MID); however, the fine phase differences did not refer to this time but to this time adjusted by XFA or XFB. (See step 51.) If the polynomial fitting parameters α , β , γ , and δ are to be used to calculate the phase difference at other desired times, these four parameters must also be adjusted for XFA or XFB. This differential correction can be accomplished by a Taylor series expansion of the phase difference R as a function of time in the neighborhood of the midframe. In functional notation,

$$R(T) = \alpha + \beta T + \gamma T^2 + \delta T^3$$

where T equals midframe time. For a point $T + T_0$ in the neighborhood of T , the phase difference can be given by the Taylor series

$$R(T + T_0) = R(T_0) + TR'(T_0) + \frac{T^2}{2} R''(T_0) + \frac{T^3}{6} R'''(T_0)$$

where the primed notation is used for derivatives. Differentiating the basic cubic polynomial above and evaluating at T_0 yields

$$R'(T_0) = \beta + 2\gamma T_0 + 3\delta T_0^2$$

$$R''(T_0) = 2\gamma + 6\delta T_0$$

$$R'''(T_0) = 6\delta$$

Therefore,

$$R(T + T_0) = \alpha + \beta T_0 + \gamma T_0^2 + \delta T_0^3 + T(\beta + 2\gamma T_0 + 3\delta T_0^2) + T^2(\gamma + 3\delta T_0) + T^3(\delta)$$

or, by replacing the terms in parentheses by primed parameters,

$$R(T + T_0) = \alpha' + \beta' T + \gamma' T^2 + \delta' T^3$$

In the preprocessor, the primed parameters are calculated with $T_0 = -XFA$ for the east-west baseline and $T_0 = \text{TCOR}$ for the north-south baseline in the expressions in parentheses in the previous equation. These new parameters are the ones printed and transferred to subsequent programs.

Step 54

Interpolate the ambiguity phase differences. The phase differences for the four ambiguity baselines are properly adjusted values for their particular sampling times; however, to derive a unique set of direction cosines, the ambiguities must refer to the same time as the fine baselines. Because the east-west fine time is the reference, the ambiguity phase differences must be interpolated from their observed times to the common time EWFT:

$$R_{EWFT} = R_{AMB} + \alpha + \beta(T_{EWFT} - T_{AMB}) + \gamma(T_{EWFT} - T_{AMB})^2$$

where R_{AMB} and T_{AMB} are the ambiguity phase difference and time, respectively; R_{EWFT} and T_{EWFT} are the east-west fine phase difference and time, respectively; and the parameters α , β , and γ are the fitted values for the least-squares solution of the ambiguity baseline AMB.

Step 55

Include the total calibration constants. The calibration constants $K_c - K_{s1} + K_{s2}$ are finally subtracted from their corresponding phase differences:

$$EWCBB = EWCA - CEWC$$

$$EWMBB = EWMA - CEWM$$

$$EWFBB = EWFA - CEWF1$$

$$SNCBB = SNCA - CNSC$$

$$SNMBB = SNMA - CNSM$$

$$SNFBB = SNFA - CNSF1$$

Steps 56 through 70 perform the correlation of the coarse, medium, and fine phase differences calculated in the above step to construct the artificial baselines necessary to eliminate the ambiguities, reduce random errors, and produce direction cosines. These steps parallel those given in the Minitrack primer. A concrete example can be carried through if desired.

Step 56

Remove lobe integers from the six phase differences of step 55, leaving only the decimal fractions to construct the necessary artificial baselines.

Step 57

Calculate the phase difference for the artificial one-half wavelength baseline. The phase difference for a one-half wavelength baseline can be constructed from the difference of the medium and coarse baseline phase differences (4.0λ and 3.5λ , respectively). These are the rough counts in the Minitrack primer. For east-west,

$$AB = EWMBB - EWCBB$$

for north-south,

$$BC = SNMBB - SNCBB$$

These values are submitted to subroutine NORMAL to restore the proper monotonic sequencing.

Step 58

Calculate the absolute phase differences for the coarse and medium baselines as the seventh and eighth multiples of the one-half wavelength baseline. For the east-west baselines—

$$\text{Coarse: } AB3 = AB * 7.$$

$$\text{Medium: } AB4 = AB * 8.$$

For the north-south baseline—

$$\text{Coarse: } BC3 = BC * 7.$$

$$\text{Medium: } BC4 = BC * 8.$$

Step 59

Calculate the “error” between the constructed (step 58) and final phase difference (step 55); e.g., for the east-west medium case,

$$EAB4 = AB4 - EWMBB$$

then, EAB4 is submitted to subroutine NORMAL.

Step 60

Calculate the absolute phase difference for the medium baselines; e.g., for the east-west medium baseline,

$$DE = AB4 - EAB4$$

An examination of the absolute value of these medium phase differences is made to check that the values are within the allowed range of ± 4.0 cycles. If the phase difference is outside this range, the value of the phase difference is complemented by the extent of one complete range of 8.0 cycles to bring the value in bounds.

Steps 61 and 62

These steps are similar to the two previous steps; however, these refer to the calculation and checking of the absolute phase difference for the coarse baselines.

Step 63

The program performs the following:

$$EWFB = EWFB + 2. * EWFC * (-XKFA) + 3. * EWFE * (-XKFA) ** 2.$$

This is a definite error in the preprocessor because this correction has already been applied once in step 53 when the fitting parameters were adjusted by a Taylor series expansion. This duplication has been corrected in the current operational program. This statement duplicates the correction for β' pertaining to the east-west fine baseline. Because these adjusted parameters are used to calculate the phase differences and thus direction cosines at other times, the east-west direction cosines calculated in program OBS-B will reflect this error. The removal of this statement will easily rectify this situation.

Step 64

Construct the artificial 7.5λ baseline. In an attempt to smooth any random errors in the medium or coarse baselines, the two are added algebraically to simulate a 7.5λ baseline. For the east-west case,

$$CORE = DE + DE3$$

For the north-south case,

$$CORN = FG + FG3$$

Step 65

Compute the absolute phase differences of the fine baselines. Using the artificial 7.5λ baselines and the direct proportion of phase difference and baseline length, the preprocessor calculates phase differences for the fine baselines. For the east-west baselines,

$$COREF = \frac{ANT}{7.5} * CORE$$

For the north-south baselines,

$$CORNF = \frac{ANT}{7.5} * CORN$$

Step 66

Compute the absolute phase differences for the fine baselines. Similar to steps 58 through 60 for the medium baselines and steps 61 through 63 for the coarse baselines, this step calculates the absolute phase differences for the fine baselines, EWLOBE and SNLOBE.

Step 67

Residuals for the ambiguity baselines are computed. For each of the four ambiguity baselines, the phase difference calculated from the absolute phase difference for the appropriate fine baseline (step 66) and the calculated values for the absolute phase differences for the ambiguities (step 60 for the medium baselines and step 62 for the coarse baselines) are

compared by subtraction. The difference represents an internal residual or error. For example, with the east-west medium baseline,

$$EWMER = \frac{4.}{ANT} * EWLOBE - DE$$

Step 68

Calculate the phase difference per unit wavelength for all five baselines. For an ideal system, the phase difference per unit wavelength should be a constant. The values of this ratio for the five baselines, 0.5, 3.5, 4.0, 7.5, and ANT wavelengths are calculated and printed out for both the east-west and the north-south baselines.

Step 69

A label is written on output Unit 11 to designate whether the data refer to an equatorial or polar pass. At the same time, the codes to distinguish an east-west direction cosine, IAO = 2, and a north-south direction cosine, IBO = 3, are set up.

Step 70

Direction cosines are calculated as follows:

- (1) The baseline length in vacuum wavelengths is adjusted for the frequency of observation:

$$\text{baseline length at } \text{FREQ}(\text{MHz}) = \frac{\text{FREQ}}{136.} * \text{ANT}$$

where

$$\text{ANT} = \begin{cases} 57 \text{ vacuum wavelengths at } 136 \text{ MHz (polar set)} \\ 46 \text{ vacuum wavelengths at } 136 \text{ MHz (equatorial set)} \end{cases}$$

- (2) The direction cosines are given by the simple ratio

$$\frac{\text{absolute phase difference (in wavelengths or cycles) at } \text{FREQ}}{\text{baseline length (in wavelengths) at } \text{FREQ}}$$

that is, for the east-west direction,

$$\text{ACOS} = \text{EWLOBE} / [(\text{FREQ}/136.) * \text{ANT}]$$

and for the north-south direction,

$$\text{BCOS} = \text{SNLOBE} / [(\text{FREQ}/136.) * \text{ANT}]$$

In essence, the program MIN-B calculations are over. The remainder of the program performs conversions and prints the output.

Step 71

Direction cosines are rounded off, converted to integers, and then converted to hexadecimal form by subroutine ZERO for convenient storage and transfer.

Step 72

- (1) Fine phase differences are converted to integers (step 66).
- (2) Ambiguity residuals are converted to integers (step 67).

Step 73

Modified fitting parameters α' , β' , γ' , and δ' are converted twice: first, to integers, and then, the independent variable, frame time, is converted to frames by the multiplication of the appropriate power of TILI, one of the seven frame rates available (1, 2, 10, 20, 60, 120, or 600 s/frame). This is necessary because in subsequent programs such as OBS-B, the mid-frame value and values for the desired number of frames surrounding this midframe on either side are called for rather than the values at specific times. The east-west results are—

$$\alpha' = \text{IERATE} = \text{EWFB} * 10^5 * \text{TILI}$$

$$\beta' = \text{IEACC} = \text{EWFC} * 10^7 * (\text{TILI})^2$$

$$\gamma' = \text{IEWFE} = \text{EWFE} * 10^8 * (\text{TILI})^3$$

Step 74

The program performs the conversion of midframe time, date, station, final phase differences, ambiguity residuals, modified fitting parameters, and number of original frames of data to hexadecimal form for transfer and later usage in other programs.

Step 75

Data are graded. A qualitative grading system is invoked to specify the quality of the standard deviations of the fine and ambiguity residuals. (See AST(4) and AST(6) in MIN-B glossary, sec. 7.)

Step 76

Final printing of output for the east-west and north-south data sets (Unit 11) and the recording of output for the east-west and north-south data sets (Unit 15) on magnetic tape are performed.

Step 77

Recycle the preprocessor to begin reducing the next satellite pass.

PROGRAM OBS-B

Step 1

Read Data Discriminators. Similar to program MIN-B, program OBS-B's first executable statement is to read from a punched card the user-supplied data discriminators IGRADE and IYEAR. In the present form of the program, the variable IYEAR, a two-digit year number referring to the reduction of observations, is required as input but has no explicit function. However, the value of the variable IGRADE decides which quality of derived, direction cosine data should be accepted from MIN-B and processed in OBS-B. If IGRADE = 2, any quality data are accepted and processed. If IGRADE \neq 2, the direction cosines for both the east-west and the associated north-south data must be of high quality to be processed. The actual criteria are presented in the OBS-B glossary (sec. 7) under IGRADE, AST(7), and AST(6).

Step 2

Read IPTS. From a second punched card, the preprocessor reads the variable IPTS, which is the number of points for which final direction cosines are to be calculated for each satellite pass during this particular run of OBS-B. These final direction cosines, corrected by the antenna-field pattern equation, are to be calculated from the midframe direction cosine for each satellite pass transferred from MIN-B (that is, uncorrected for antenna-field pattern) and from the corrected coefficients of the Taylor expansion of the phase difference as a function of the frame in the neighborhood of the midframe, also transferred from MIN-B. Steps 6 and 7 actually input these required parameters.

Steps 3 through 5

The next three steps of OBS-B read in (punched cards) and print out for display the station biases, the station coefficients (for the antenna-field pattern equation), and the satellite parameters, respectively. The FORTRAN statements and associated formats to accomplish this are essentially exact duplicates of those contained in steps 2 through 4 of MIN-B; therefore, the reader is referred to these steps for the complete descriptions of these input parameters (except the polynomial coefficients of the antenna-field pattern). It was mentioned previously that the zero-offset phase-difference bias for each baseline, $K_c - K_{s1} + K_{s2}$, is actually an *average* over the entire antenna-field pattern. In OBS-B, a polynomial antenna-field pattern equation that accounts for the residual fluctuations about these averages or means is incorporated as a standard correction procedure. This is the polynomial fit obtained from the calibration data in which the derived optical phase difference a_{opt} is a function of the simultaneously observed radio phase differences $(a_{EW})_r$ and $(a_{NS})_r$ for the east-west and north-south phase differences discussed in the introduction. Again, it is to be pointed out that unlike the average station biases, the $K_c - K_{s1} + K_{s2}$, which refer to each of the six active baselines during the particular satellite pass (i.e., east-west and north-south coarse, medium, and fine), the polynomial antenna-field equation is applied to the single east-west

Table 4-4.—Data Output of Program MIN-B

Parameter	East-west data set	North-south data set
Satellite number code	IA, IB, . . . , IF	IA, IB, . . . , IF
Frequency discriminator	ILINK	ILINK
Filter code	AST(1)	AST(1)
Station number	CSTA	JSTA
Antenna-set code (P or E)	CANT	JANT
East-west and north-south data set code	IAO	IBO
Data-quality code	AST(7)	AST(6)
Frame-rate code	AST(4)	AST(3)
Number of data frames	IFIT	JFIT
Date for data set	BDATE	JDATE
Hour for data set	HOR	JHOR
Minute for data set	MIN	JMN
Second for data set	SEC	JSC
Taylor series coefficients:		
Absolute phase difference	EWLOBE	SNLOBE
First derivative	EWRATE	SNRATE
Second derivative	EWACC	SNACC
Third derivative	EWD	SND
Standard deviation of cubic fit	IENO	INNO
Medium "error"	EWMER	SNMER
Coarse "error"	EW CER	SNCER
Direction cosine	ACOS	BCOS

value obtained by correlating the east-west coarse, medium, and fine data; similarly, the polynomial is applied to the single north-south value obtained by correlating the north-south coarse, medium, and fine data as outlined in the Minitrack primer. Because it is not known at this point of inputting whether the satellite pass under consideration refers to a polar or equatorial pass, the preprocessor reads in nine polynomial coefficients (C0, C1, C2, . . . , C8) for each of the four fine baselines in the sequence (1) east-west equatorial, (2) north-south equatorial, (3) east-west polar, and (4) north-south polar for each of the Minitrack stations. To verify later the proper association of a polar or equatorial baseline with its appropriate polynomial coefficients, a single-letter code, P or E, is read in under the variable name IANT in addition to the two-digit station number ISTA so that comparison with the two-digit station number KSTA, associated with the average calibration constants in step 2, can be made.

The entire output from MIN-B is read into OBS-B from the Minitrack output tape. The data are broken up into east-west and north-south data sets. The data information contained in each data set is given in table 4-4.

Step 6

Read and verify east-west data set. After the data set is read in, the data discriminator IGRADE is inspected. If the grading is not automatic, the grading code AST(7) is tested. If

the data set is of high quality, the east-west data set identifier IAO is checked for the value of 2. A positive test transfers control to step 7 for the north-south data set. If the data set is not of high quality or $IAO \neq 2$, a new data set is read in. This set should be a north-south set in the normal sequence; the IAO test will reject this as a set and read the next set which should be a legitimate east-west data set.

Step 7

Read and verify north-south data set. This step is an exact parallel of step 6 for the east-west set except here the grading indicator is $AST(6)$ and $IBO = 3$ for a legitimate north-south data set.

Step 8

Check the simultaneity of data sets. For the preprocessor to utilize the accepted associated pair of east-west and north-south data sets, the two must refer to the same epoch of time. That is, the hour, minute, and second of the east-west data set must equal the corresponding hour, minute, and second of the north-south data set unless a new data set is read in under step 6.

Step 9

Form satellite number. A five-digit satellite number is formed from the satellite number codes in one of two ways. The synthesis of this composite number from the individual codes resembles the progenitor, SATT, of MIN-B.

Step 10

Perform data identifications. Several identifications of the accepted data sets are performed:

- (1) Which Minitrack station, $KSTA(L)$, is being considered.
- (2) Which baseline set is being used, equatorial or polar.
- (3) Baseline length in vacuum wavelengths at 136. MHz is established:

$$ANT = \begin{cases} 57.0, & \text{polar set} \\ 46.0, & \text{equatorial set} \end{cases}$$

- (4) Which of the 50 satellites in the generated satellite table is being considered. Transfer to step 6 occurs if the satellite number is unmatched.
- (5) Which of seven frame rates was selected by the operator—1, 2, 10, 20, 60, 120, or 600 s/frame.
- (6) Change of variables for the fine phase differences generated in MIN-B:

A = EWLOBE

B = SNLOBE

- (7) Transmitting frequency FREQ selected from table if possible unless error message FREQ. LINK NOT IN TABLE occurs and control is transferred to step 6.
- (8) Transmitting frequency checked to insure that it is within the Minitrack operating range of 136 to 138 MHz.
- (9) Which of the four baselines in the data set refers to east-west or north-south, polar or equatorial.

If the satellite pass is a polar arc, the index IM is incremented by $IM = IM + 2$ because of the sequential filing of the polynomial coefficients to be applied, namely east-west equatorial, north-south equatorial, east-west polar, and north-south polar.

Step 11

Perform midframe time conversion. The midframe time in Greenwich mean time is converted from hours, minutes, and seconds to the total number of seconds by

$$TIM = (HOUR * 3600) + (60 * MIN) + SEC$$

Step 12

Calculate baseline length in wavelengths. The number of vacuum wavelengths in the baseline under consideration is calculated for the actual transmitting frequency in megahertz, FREQ, on the basis that at 136.0 MHz the polar and equatorial baselines are exactly 57λ and 46λ , respectively. Because the higher the transmitting frequency, the larger the number of these wavelengths in a given baseline, we have

$$B_{FREQ} = \frac{FREQ}{136.} * B_{136.}$$

Step 13

Compute auxiliary quantities for the desired output points. This step computes several auxiliary quantities for the determination of both the phase difference and time for each of the desired output points IPTS.

- (1) The number of points IY on either side of the midframe, that is, the midpoint:

$$IY = \frac{IPTS - 1}{2}$$

where FORTRAN integer arithmetic is applied to accomplish truncation. Therefore, if IPTS is odd, IY is the number of output points on either side of the

midpoint or midframe. If IPTS is even, IY is the number of output points on the earlier side (in time sequence) of the midpoint.

- (2) The number of frames per output point on either side of the midframe IZ, where

$$IZ = \begin{cases} 1 & \text{if } IY = 0 \text{ (that is, IPTS = 1 or 2)} \\ \frac{IFIT}{2 * IY} & \text{if } IY \neq 0 \text{ (that is, IPTS > 2)} \end{cases}$$

- (3) The number of frames spanned by the output points on the earlier side of the midframe JT, where

$$JT = \begin{cases} 0 & \text{if } IY = 0 \text{ (that is, IPTS = 1 or 2)} \\ -IZ * IY & \text{if } IY \neq 0 \text{ (that is, IPTS > 2)} \end{cases}$$

- (4) The interval of time in seconds from the earliest output point to the midframe:

$$TT = \begin{cases} 0 & \text{if } IY = 0 \text{ (that is, IPTS = 1 or 2)} \\ T * JT & \text{if } IY \neq 0 \text{ (that is, IPTS > 2)} \end{cases}$$

- (5) The starting time (in seconds of GMT) for the earliest output point $TIMA = TIM + TT$.

- (6) The time interval (seconds) per output point, that is,

$$\frac{\text{seconds}}{\text{output point}} = \frac{\text{seconds}}{\text{frame}} * \frac{\text{frames}}{\text{output point}}$$

or

$$TT = T * IZ$$

Step 14

Determine absolute phase differences of east-west and north-south baselines for each output point. From program MIN-B, the absolute phase differences of the east-west and north-south baselines at the time of the midframe are available. If it is assumed that the desired output points are in the vicinity of the midframe, the absolute phase difference for each desired output point may be calculated from a Taylor series expansion of the phase difference as a function of the frame number in the neighborhood of the midframe. Let

R_M = phase difference of either the east-west or north-south baseline at the midframe

N = number of frames from the midframe (. . . , -2, -1, 0, 1, 2, . . .)

Then, for the i th desired output point of the IPTS,

$$R_i = R_M + \frac{\partial R_M}{\partial N} N + \frac{\partial^2 R_M}{\partial N^2} N^2 + \frac{\partial^3 R_M}{\partial N^3} N^3$$

where all higher order terms are considered negligible. The partials or coefficients have already been read in during the execution of steps 6 and 7. In the preprocessor, the phase-difference expressions are

$$AA = A + EWRATE * JT + EWACC * JT^2 + EWD * JT^3$$

$$BB = B + SNRATE * JT + SNACC * JT^2 + SND * JT^3$$

for the east-west set and north-south set, respectively.

Step 15

Compute preliminary direction cosines for output points. With the absolute phase differences of step 14 and the appropriate baseline length in wavelengths from step 12, the direction cosines are easily computed. For the east-west set,

$$\cos \alpha = CC = AA/FQ,$$

and, for the north-south set,

$$\cos \beta = DD = BB/FQ$$

where each direction cosine is the cosine of the angle between the radius vector to the satellite from the Minitrack center and the baseline vector. However, these are preliminary values.

Step 16

Produce the polynomial antenna field equations. The combined optical-radio calibration procedure produces a high-order calibration polynomial with nine coefficients (C0, C1, . . . , C8) for each of the four baselines, east-west and north-south polar and east-west and north-south equatorial. However, the calibration experiment essentially covers only the half-power rectangular grid of 10° by 80° centered at the zenith, with a few degrees to spare on all sides. In the preprocessor, the boundaries of this half-power rectangle are considered absolute. If the satellite is within the half-power rectangle at the point under consideration, all nine terms for each of the two active baselines of either the polar or equatorial set are employed in the calibration polynomial. If the satellite is outside this half-power rectangle, the higher order terms, that is, the two quadratic and the single cubic terms, are considered untrustworthy so that the C4, C5, and C6 terms, respectively, are not considered in the polynomial correction equation.

The reader will recall that the extended dimension (80°) of the half-power rectangle is in the east-west direction for the polar set, or equivalently, for a predominantly polar satellite pass. For the equatorial set, this half-power rectangle is simply rotated 90° about the zenith, with the extended dimension then in the north-south direction.

All the possible combinations of antenna sets, baselines, and inside or outside boundaries of the half-power rectangle are given in the OBS-B glossary (sec. 7) under the variable names C and E. The reader is referred to these sections of the glossary for the actual algebraic configurations for the final absolute phase differences.

The final operation of this step is a simple change of variables for the final, corrected absolute phase differences at the desired output points:

$$AA = C$$

$$BB = E$$

Step 17

Form day number. The six-digit calendar date (YEAR/MONTH/DAY) is converted to a three-digit running day number for the year of observation by subroutine DCOUNT.

Step 18

If necessary, make possible correction to time and day number. If the frame time TIMA in seconds for the desired output point occurs on the day before the midframe value TIM, the value of TIMA may be negative from the basic relation $TIMA = TIM + TT$. Example: TIM = 00001 second of April 16 and TT = -2 seconds before the midframe imply that $TIMA = -00001$. To correct this, the number of mean seconds in a day are added to the output point time:

$$TIMA = TIMA + 86400 = 86399$$

Similarly, the date for the output point is the day before the midframe value; thus,

$$BDATE = BDATE - 1$$

Step 19

Calculate the final, corrected direction cosines for the desired output points. Given the antenna-field-corrected, absolute phase differences with the change of variables indicated at the end of step 16, the final, corrected direction cosines for the Minitrack preprocessor at each of the desired output points are, for east-west orientation,

$$\cos \alpha = ACOS = C/FQ$$

and, for north-south orientation,

$$\cos \beta = BCOS = E/FQ$$

Step 20

Perform the direction cosines' form change. In this step the final direction cosines of the previous step are converted to integers, rounded to six significant figures, and converted to hexadecimal form by subroutine ZERO for later transfer to the ODP's.

Step 21

Perform the time conversion. The Greenwich mean time in seconds for the final direction cosines is reconverted to hours, minutes, and seconds; condensed in form for easy transfer; and converted to hexadecimal form by subroutine ZERO.

Step 22

Write output. The east-west and north-south final direction cosines with their appropriate station and satellite identification and time tags are printed on Units 6 and 15 with separate statements.

Step 23

Reinitialize the loop for the calculation of the next output point:

- (1) Time is incremented for the next output point:

$$TIMA = TIMA + TT$$

- (2) The index for the proper calibration coefficients is reset to start with the east-west equatorial set by

$$IM = IM - 1$$

In the next five steps, program OBS-B calculates the crossover direction cosine and its associated proper time of occurrence. An outline of the general definitions and procedure is presented in the general introduction to the preprocessor program. It is recommended that that description be used as a supplemental aid to the following abbreviated step descriptions.

Step 24

Assign variables based on the type of satellite pass:

- (1) Set up single-digit code to indicate crossover direction cosine data; namely,

$$IAO = 9.$$

- (2) Ascertain which antenna set was employed for the satellite pass under consideration from the discriminator variable CANT:

$$CANT \begin{cases} = PO, \text{ polar set was used} \\ \neq PO, \text{ equatorial set was used} \end{cases}$$

- (3) As discussed in the introduction, the choice of two possible antenna sets yields for the crossover two mutually exclusive possibilities:

Polar pass:

$$\cos \alpha_C = \frac{(PD_{EW})_C}{B}$$

$$\cos \beta_C = 0$$

Equatorial pass:

$$\cos \alpha_C = 0$$

$$\cos \beta_C = \frac{(PD_{NS})_C}{B}$$

where $(PD_{EW})_C$ and $(PD_{NS})_C$ are the absolute phase differences at crossover for the east-west and north-south baselines, respectively.

Through the use of the discriminator CANT, the variable ZLOB is set up for the absolute phase difference for the midframe, which is needed to calculate the absolute

$$ZLOB = \begin{cases} EWLOBE & \text{if polar set used} \\ SNLOBE & \text{if equatorial set used} \end{cases}$$

- (4) To apply a differential correction to the phase differences to go from the known midframe value to the desired crossover value, the phase-difference rate is needed. This value is estimated by applying the value of the first-derivative term of the Taylor series expansion for the phase difference as a function of the frame in the neighborhood of the midframe. (These were calculated in and transferred from program MIN-B.) It should be noted that in the general description of the preprocessor, it was implied that these rates had time as the independent variable rather than the frame count. Actually, OBS-B is presented with the frame rate of change, but conversions are made internally, so that nothing essential is added to the previous description. The variable ZRAT is assigned for the phase-difference rate, in phase difference per frame, in the neighborhood of the midframe, which is needed to calculate the phase difference at crossover:

$$ZRAT = \begin{cases} EWRATE & \text{if polar set used} \\ SNRATE & \text{if equatorial set used} \end{cases}$$

- (5) Use information from the zero direction cosine baseline. The information from the automatic zero direction cosine baseline at crossover, although apparently useless, does fulfill the function of providing important time information as previously implied in the preprocessor introduction. That is, the differential time correction for the crossover time with respect to the midframe time was shown to be

$$\Delta T = - \frac{PD_M}{(\partial PD / \partial T)_Z}$$

The phase-difference rate for the zero direction cosine baseline given in the denominator above is represented simply by the variable

$$RATE = \begin{cases} SNRATE & \text{if polar set used} \\ EWRATE & \text{if equatorial set used} \end{cases}$$

The corresponding phase differences for the zero direction cosine baseline at the time of the midframe are given by

$$\text{ZOBE} = \begin{cases} \text{SNLOBE} & \text{if polar set used} \\ \text{EWLOBE} & \text{if equatorial set used} \end{cases}$$

Step 25

Use the information from step 24, item (5). The preprocessor calculates the differential time correction ΔT in the form

$$\text{ZB} = - \frac{\text{ZOBE}}{\text{RATE}} * \text{T}$$

that is,

$$\Delta T = T_C - T_M = \frac{\text{PD}_C - \text{PD}_M}{\text{PD/frame}} \times \frac{\text{time}}{\text{frame}}$$

where

$\Delta T = \text{ZB} =$ number of seconds between crossover and midframe

$T =$ number of seconds per frame (see OBS-B glossary, sec. 7)

$\text{PD}_C = 0$ for this baseline

After the differential time correction ZB , in seconds, is truncated to an integer by the statement $\text{IB} = \text{ZB}$, this correction is added to the midframe time TIM to produce the time of crossover TIMA .

Step 26

Determine the direction cosine at crossover. The differential phase-difference correction ΔPD given in the preprocessor introduction for phase difference at crossover is calculated using the differential time correction computed in step 25 from the zero direction cosine baseline and the estimated phase-difference rate computed in step 24, item (4); that is,

$$\Delta\text{PD} = \text{ZRAT} * \text{ZB} * \frac{1}{\text{T}}$$

where the last factor is for units conversion as given in the previous step. When this phase-difference correction is added to the phase difference at the midframe, the crossover phase difference, represented by ZA , can be used directly for the calculation of the direction cosine at crossover. Simple division of this phase difference by the actual number of wavelengths FQ in the fine baseline at the satellite frequency is the only remaining step.

Immediately afterwards, the crossover direction is transformed to an integer, rounded off to six significant digits, and finally converted to hexadecimal form for subsequent transfer.

Step 27

Compute the time of crossover:

- (1) A three-digit running day number (1 through 365 in a nonleap year) is formed by subroutine DCOUNT from the known six-digit calendar date (YEAR/MONTH/DAY) for the observations.
- (2) The time of day (GMT) in seconds TIMA is checked to see if a different day is involved for crossover than for the midframe. A positive test applies the algebraic subtraction of 86,400 s, the number of mean seconds per day, and appropriately changes the date of observation. These time data are then condensed into a shorter form and converted into hexadecimal form for subsequent transfer and usage.

Step 28

Print out label and all pertinent crossover direction cosine and time information for the satellite under consideration at a specific Minitrack station.

Section 5

SUBROUTINES

Such functions as the cubic preprocessing of Minitrack data (described in sec. 4) are accomplished by the MIN-B and OBS-B computer programs. Each of these main programs calls up certain subroutines during its processing sequence—subroutines that perform special critical mathematical tasks. The subroutines were written especially for the preprocessing programs and are thus considered part of the preprocessor package.

Listings of the subroutines may be found among the cubic preprocessor computer listings in volume II, appendix A. The present section describes how the subroutines work and includes several flow diagrams that graphically illustrate the subroutine functions. Certain of the subroutines are peculiar to the usage of only one or the other of the two main preprocessor programs; two are used by both. The subroutines, listed under the appropriate program, are—

<i>MIN-B</i>	<i>OBS-B</i>
LSCUB	PYRD
LSQUA	DCOUNT
LOBASN	ZERO
NORMAL	
PYRD	
ZERO	

SUBROUTINE LSCUB

The object of subroutine LSCUB (fig. 5-1) is to fit a *least-squares cubic* equation to the modified fine phase differences as a function of the frame time for up to 31 frames of data per satellite pass. The subroutine list is

LSCUB (T, SALPHA, XY, ITO, L, SIGMA, SBETA, SGAMMA,
SDELTA, SM, INN, IOT)

The subroutine is called twice in the main routine of MIN-B, once for the east-west fine baseline data and once for the north-south fine baseline data; that is,

CALL LSCUB (TIM, ALPHA, EEWF, K, MID, SIA, EWFB; EWFC,
EWFE, SM, ENC, EOC)

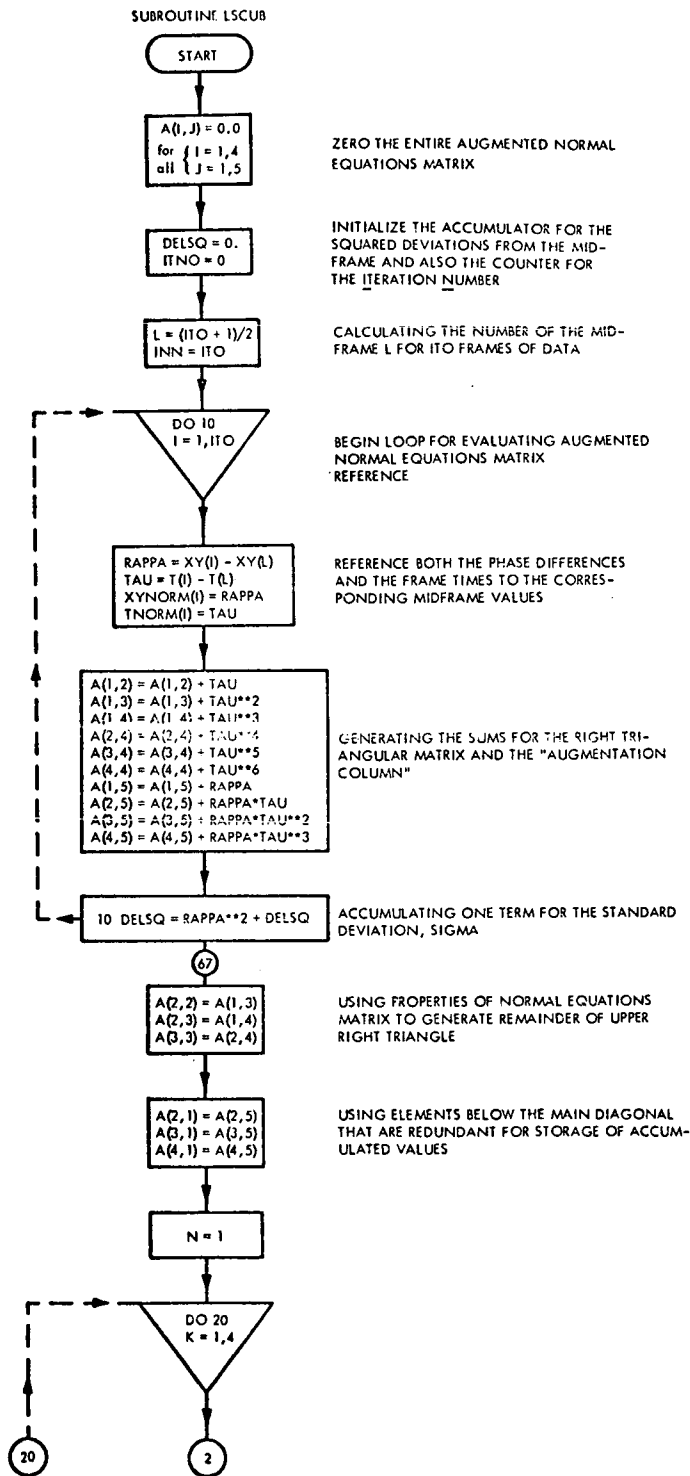


Figure 5-1.—Subroutine LSCUB.

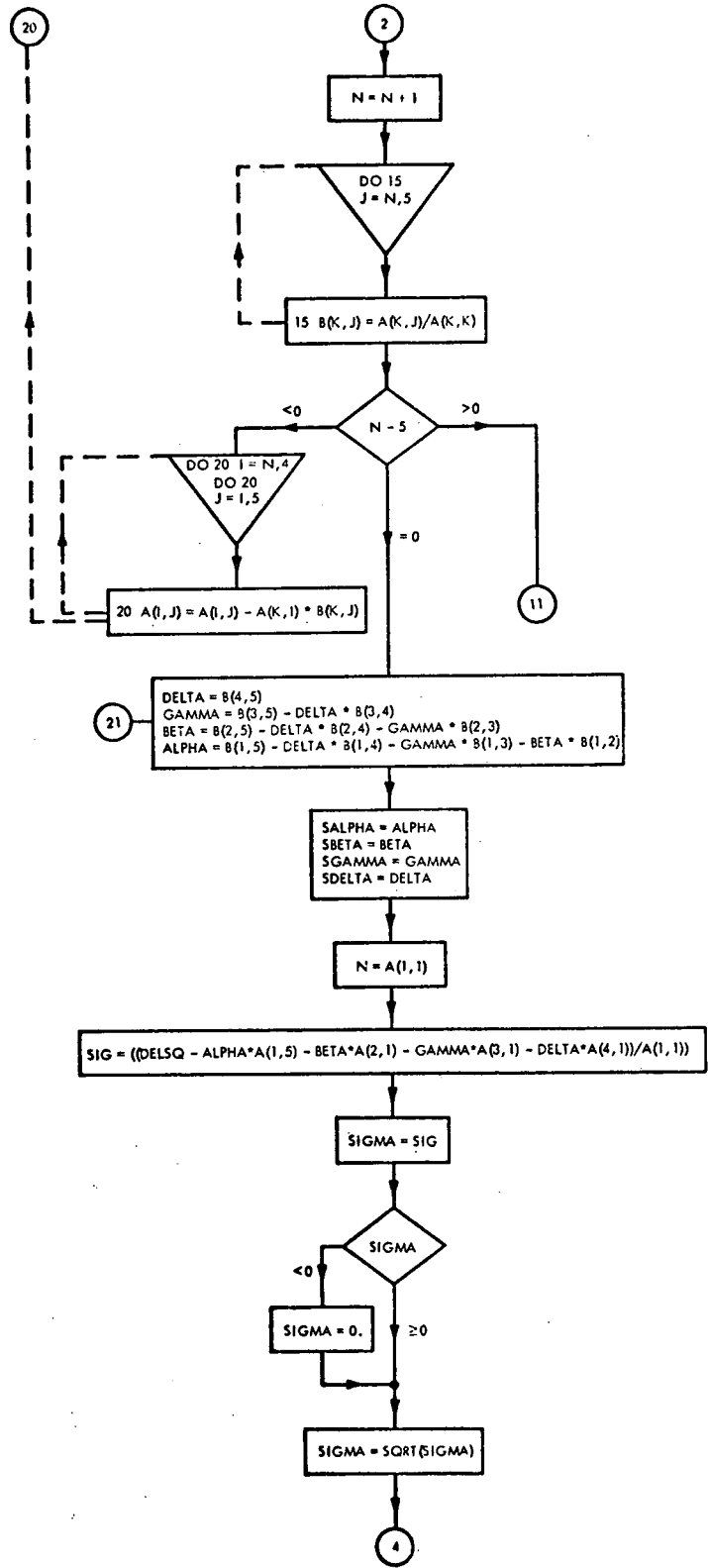


Figure 5-1 (continued).—Subroutine LSCUB.



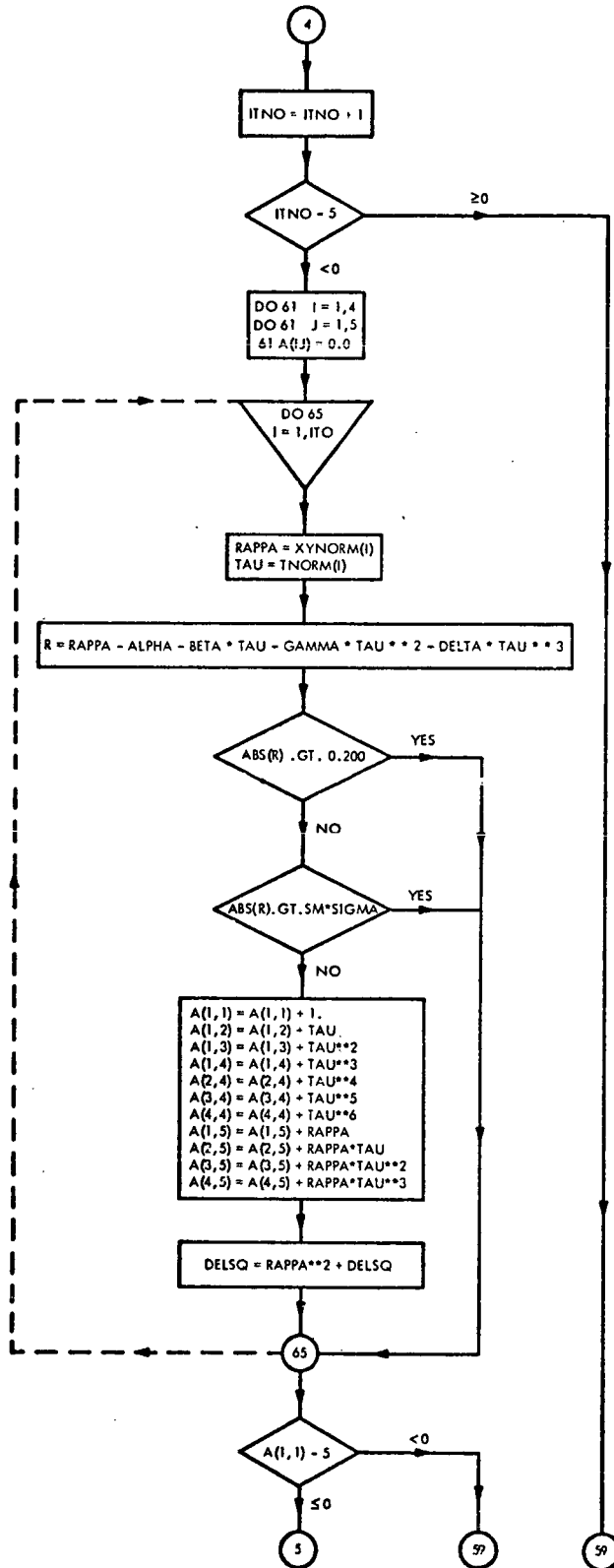


Figure 5-1 (continued).—Subroutine LSCUB.

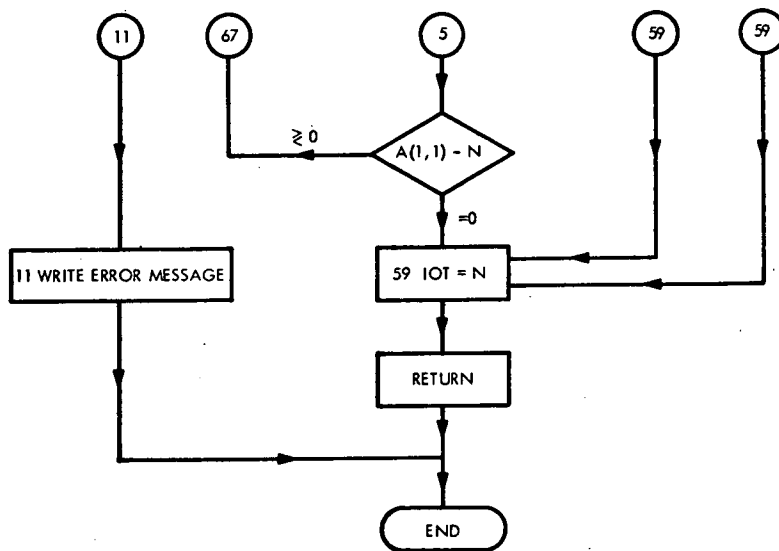


Figure 5-1 (concluded).—Subroutine LSCUB.

CALL LSCUB (TIM, ALPHA, ENSF, K, MID, SIA, SNFB, SNFC,
SNFE, SM, ENF, EOF)

Fine data for the east-west and north-south baselines are treated separately. In each case the form of the equation to be fitted, that is, the *equation of condition*, is

$$R = \alpha + \beta T + \gamma T^2 + \delta T^3$$

For each baseline, the data are first arranged to pivot about the middle of the actual frame for which the desired direction cosines will be calculated in program MIN-B. This is accomplished by a double translation of the coordinate origin of the system; that is, first, the frame time T is referenced to the midframe time. Therefore, the frame time for the i th frame is given by

$$T = \text{Time}_i - \text{Time}_{\text{midframe}}$$

Similarly, the phase differences are referenced to the phase difference for the midframe; that is, for the i th frame,

$$R = \text{phase difference}_i - \text{phase difference}_{\text{midframe}}$$

With this equation of condition, up to 31 observational equations are generated to correspond to the data frames for one of the fine baselines. Collectively, these equations represent an $N \times 4$ array (N is the number of data frames). This then must be condensed into the standard *normal equations* to form a 4×4 array equivalent to four simultaneous equations in four unknowns α , β , γ , and δ . The condensation is achieved by using accumulators whose functions are fulfilled by the elements of the array $A(I, J)$ in the subroutine. This yields the *normal equation matrix*:

$$\begin{bmatrix} N & \sum T & \sum T^2 & \sum T^3 \\ \sum T & \sum T^2 & \sum T^3 & \sum T^4 \\ \sum T^2 & \sum T^3 & \sum T^4 & \sum T^5 \\ \sum T^3 & \sum T^4 & \sum T^5 & \sum T^6 \end{bmatrix}$$

where the summations occur over the N data frames.

Because the normal equations matrix is symmetric, it is sufficient to generate just the upper right triangular matrix and use the symmetry property for the remaining elements below the principal diagonal (dashed line in the matrix). For any element of the i th row and j th column a_{ij} , $a_{ji} = a_{ij}$. Some of the positions below the diagonal are used for storage of other products in order to retain their original values (see first column of following array). With these considerations in mind, the reader may observe that the subroutine sets up the 4×5 standard *augmented normal equations matrix*:

$$\begin{bmatrix} N & \sum T & \sum T^2 & \sum T^3 & \sum R \\ \text{storage} \rightarrow \sum RT & \sum T^2 & \sum T^3 & \sum T^4 & \sum RT \\ \text{storage} \rightarrow \sum RT^2 & \dots & \sum T^4 & \sum T^5 & \sum RT^2 \\ \text{storage} \rightarrow \sum RT^3 & \dots & \dots & \sum T^6 & \sum RT^3 \end{bmatrix}$$

Again, the summations occur over the N data frames.

To derive values for the four unknown parameters α , β , γ , and δ , the subroutine employs the well-known technique of Gaussian reduction. This is the successive elimination of the unknowns by sequentially reducing the system from four equations in four unknowns to three equations in three unknowns, then to two equations in two unknowns, and finally to one equation in one unknown. The equations are solved in the reverse order for the values of δ , γ , β , and finally α .

A matrix of the same dimensions in general notation is developed in the subroutine:

$$\begin{bmatrix} A_{11} & A_{12} & A_{13} & A_{14} & A_{15} \\ A_{21} & A_{22} & A_{23} & A_{24} & A_{25} \\ A_{31} & A_{32} & A_{33} & A_{34} & A_{35} \\ A_{41} & A_{42} & A_{43} & A_{44} & A_{45} \end{bmatrix}$$

Then, the following iteration scheme leads to the required solution for the desired constants:

- (1) Evaluation of the auxiliary variables

$$B_{1j} = \frac{A_{1j}}{A_{11}}$$

where $j = 2, 3, 4, 5$

- (2) The new coefficients of a reduced system of three equations in three unknowns are given by the array values

$$(A_{ij})_1 = A_{ij} - A_{i1}B_{1j}$$

where $i \geq 2, j \leq 5$.

- (3) Evaluation of the auxiliary variables

$$B_{2j} = \frac{(A_{2j})_1}{(A_{22})_1}$$

where $j = 3, 4, 5$.

- (4) The new coefficients of a reduced system of two equations in two unknowns are given by the values

$$(A_{ij})_2 = (A_{ij})_1 - (A_{i1})_1 B_{2j}$$

where $i \geq 3, j \leq 5$.

- (5) Evaluation of the auxiliary variables is given by

$$B_{3j} = \frac{(A_{3j})_2}{(A_{33})_2}$$

where $j = 4, 5$.

- (6) The new coefficients of a reduced system of one equation in one unknown are given by the values

$$(A_{ij})_3 = (A_{ij})_2 - (A_{i1})_2 B_{3j}$$

where $i \geq 4, j \leq 5$.

(7) Evaluation of

$$B_{4j} = \frac{(A_{4j})_3}{(A_{44})_3}$$

where $j = 5$.

The desired unknowns now can be quickly calculated from the relations

$$\delta = B_{45}$$

$$\gamma = B_{35} - \delta B_{34}$$

$$\beta = B_{25} - \delta B_{24} - \gamma B_{23}$$

$$\alpha = B_{15} - \delta B_{14} - \gamma B_{13} - \beta B_{12}$$

The B_{ij} 's form the well-known lower left triangular solution matrix.

These values of α , β , γ , and δ represent a preliminary solution for the cubic fit that includes all of the data points. This is represented as K in the main program but as ITO in this subroutine.

To eliminate any data points with inordinately large deviations from their corresponding fitted or calculated values, the process of sigma rejection is employed. In essence, the process calculates the absolute value of the deviation of each data point. All points whose deviations in absolute magnitude exceed either some previously established multiple of the standard deviation of the cubic fit or the value 0.200 in phase difference are eliminated from consideration. From the surviving data points, a new cubic fit is generated that yields new values for the parameters α , β , γ , and δ . Again, the residual of each remaining data point is examined with respect to its new calculated value for sigma rejection. This scheme is repeated until all the remaining data points in any one iteration are accepted or until less than five data points remain, whichever occurs first.

Within the subroutine, the above quantities can be found as follows:

- (1) The deviation of i th data point (frame) for the phase differences referenced to the midframe phase and time is given by R in subroutine, where

$$R = \text{observed} - \text{calculated from fit} = R_i - (\alpha + \beta T_i + \gamma T_i^2 + \delta T_i^3)$$

- (2) The sigma rejection tests are operated wherein

$$|R| > \begin{cases} 0.200 \\ \text{or} \\ SM * \sigma \end{cases}$$

and then the data point is thus rejected, where SM is the sigma multiplier (2.0 for ambiguity baselines and 2.5 for fine baselines) and σ is the standard error of estimate, that is, the standard deviation of the cubic fit.

- (3) The standard deviation of the cubic fit σ is generated as follows:

$$\sigma = \sqrt{\frac{\sum_{i=1}^N (R_i - R_{ci})^2}{N}}$$

where R_i is the observed value of phase difference for the i th frame and R_{ci} is the calculated value of phase difference for the i th frame (from the cubic fit). The actual form used for σ in the subroutine is a less common form than that above but is much more amenable to calculation inasmuch as all the necessary summations have already been calculated for the normal equations matrix. The derivation then is

$$\begin{aligned} \sum_{i=1}^N (R_i - R_{ci})^2 &= \sum [R_i - (\alpha + \beta T_i + \gamma T_i^2 + \delta T_i^3)]^2 \\ &= \sum R_i [R_i - (\alpha + \beta T_i + \gamma T_i^2 + \delta T_i^3)] \\ &\quad - \alpha \sum [R_i - (\alpha + \beta T_i + \gamma T_i^2 + \delta T_i^3)] \\ &\quad - \beta \sum T_i [R_i - (\alpha + \beta T_i + \gamma T_i^2 + \delta T_i^3)] \\ &\quad - \gamma \sum T_i^2 [R_i - (\alpha + \beta T_i + \gamma T_i^2 + \delta T_i^3)] \\ &\quad - \delta \sum T_i^3 [R_i - (\alpha + \beta T_i + \gamma T_i^2 + \delta T_i^3)] \end{aligned}$$

The last four of the five terms shown above are all equal to zero. They are actually the transposed forms of the normal equations. Therefore, the σ value may be written as

$$\sigma = \sqrt{\frac{\sum_{i=1}^N R_i [R_i - (\alpha + \beta T_i + \gamma T_i^2 + \delta T_i^3)]}{N}}$$

- (4) The SM is obtained for the ambiguity baseline data points with a deviation within $\pm 2\sigma$. This corresponds to a confidence level of 95.45 percent. The tolerance for

the fine baselines is $\pm 2.5\sigma$, which corresponds to a confidence level of 98.76 percent.

Two comments should be made concerning the procedure of this subroutine. First, if the normal equations are ill conditioned or if any of the leading elements A_{11} , $(A_{22})_1$, $(A_{33})_2$, or $(A_{44})_3$ in the denominators of the auxiliary variables B_{ij} are zero or close to zero, spurious results will ensue. When less than five data points remain from the sigma rejection process, the parameters of the last fit are accepted. No warning message is printed even though the fitted parameters might be of marginal value. Also, to minimize the effects of roundoff common in this type of solution, customary practice dictates using the largest coefficient in each iteration as the leading element for the denominator of the auxiliary variable B_{ij} . In effect, this choice reduces the roundoff error accumulation. This practice has not been followed in either this subroutine or the least-squares quadratic fit for the ambiguity data.

The second comment is pertinent for those cases in which the equations are so ill conditioned that calculation of the square of the standard deviation of the cubic fit results in a negative value. Of course, in the usual form, σ^2 is positive because we are dealing simply with the sum of the squares of the deviations. However, in the expression for σ^2 that is presently being employed, negative values can arise. Hence,

$$\sigma = \sqrt{\sigma^2}$$

where only $\sigma^2 \geq 0$ is allowed. However, the program sets $\sigma = 0$ when $\sigma^2 < 0$. Further, because each data point is examined for sigma rejection based on

$$|R| > SM * \sigma = 0$$

essentially all data points will be rejected for the absolute value of all deviations which are greater than or equal to zero (by definition of the absolute value). In the DO loop for the accumulators (see DO 65 I = 1, ITO), no accumulation can take place if all points are sigma rejected. Therefore, $A(1, 1) = 0$. In the statement number EFN 65 plus 1, namely,

IF [A(1, 1) - 5] 59, 66, 66

the routine must branch to statement number 59. This will provide a normal exit from the routine, but no alarm or message is provided for the data analyzer. If number 11 is substituted for 59 in the above statement and the statement IOT = N is inserted between statements EFN 11 and EFN 7, an error message will be printed to alert the analyzer. These comments apply equally to the least-squares quadratic subroutine for the ambiguity baselines, that is, subroutine LSQQUA.

SUBROUTINE LSQQUA

Subroutine LSQQUA fits a *least-squares quadratic* equation to the raw phase differences as a function of the frame time for up to 31 frames of data per satellite. Each of the four ambiguity baselines is treated separately. The subroutine list is

LSQQUA (T, ALPHA, SY, ITO, L, SIGMA, F, BETA, GAMMA, SM, INN, IOT)

The subroutine is called four times in the main routine of MIN-B, once for each of the four ambiguity baselines, east-west medium and coarse and north-south medium and coarse; that is,

CALL LSQQUA (TIM, ALPHA, EWMD, K, MID, SIA, SL, EWMB, EWMC, SM, ENA, EOA)

CALL LSQQUA (TIM, ALPHA, EWCD, K, MID, SIA, SL, EWCB, EWCC, SM, ENB, EOB)

CALL LSQQUA (TIM, ALPHA, NSMD, K, MID, SIA, SL, SNMB, SNMC, SM, ENX, EOD)

CALL LSQQUA (TIM, ALPHA, NSCD, K, MID, SIA, SL, SNCB, SNCC, SM, ENE, EOE)

Subroutine LSQQUA for the ambiguity baselines is essentially the same as subroutine LSCUB for the fine data except that the fitting equation is one degree lower. The resulting system of equations is appropriately reduced.

Analogously, the equation of condition is

$$R = \alpha + \beta T + \gamma T^2$$

where R and T are the phase difference and time, respectively, referenced to the corresponding values of the midframe. In this case, the normal equations matrix is a 3×3 array, whereas the augmented normal equations matrix is given by a 3×4 array, with some of the spaces below the principal diagonal for the normal equations again being used for storage.

The matrix is

$$\left[\begin{array}{cccc} N & \sum T & \sum T^2 & \sum R \\ \text{storage} \rightarrow \sum RT & \sum T^2 & \sum T^3 & \sum RT \\ \text{storage} \rightarrow \sum RT^2 & \dots & \sum T^4 & \sum RT^2 \end{array} \right]$$

where the summations are over the N data frames. With the notation and Gaussian reduction scheme for subroutine LSCUB and the stipulation that the maxima of the indices i and j are reduced from 5 to 4, the left triangular solution matrix can be written out as follows:

$$\gamma = B_{34}$$

$$\beta = B_{24} - \gamma B_{23}$$

$$\alpha = B_{14} - \gamma B_{13} - \beta B_{12}$$

Once a solution is obtained, the process of sigma rejection is used to eliminate any data points having inordinately large deviations from their corresponding fitted values.

As in LSCUB, all points whose deviations (in absolute magnitude) exceed some previously established multiple of the standard deviation of the quadratic fit are eliminated. A new quadratic fit is performed with the remaining data points. The multiple in this case, SM, is set equal to 2.0 for the four ambiguity baselines. (It was equal to 2.5 for the two fine baselines.) Thus, the confidence level that the fitted value of the phase difference will lie within $\pm 2\sigma$ of the actual value is 95.45 percent for the ambiguity baselines.

In LSQUA, the standard deviation of the quadratic fit occurs in the computationally economical but somewhat uncommon form

$$\sigma = \sqrt{\frac{\sum_{i=1}^N R_i [R_i - (\alpha + \beta T_i + \gamma T_i^2)]}{N}}$$

This can be derived as easily as the corresponding expression presented in LSCUB. Finally, the last two comments concerning ill-conditioned equations for the LSCUB procedure also apply to the LSQUA subroutine.¹

SUBROUTINE LOBASN

Subroutine LOBASN provides the proper relative phase cycle numbers for each baseline during the preprocessing of each satellite pass. More specifically, it supplies the proper relative lobe assignments for the phase differences of all the data frames. The need for such a routine arises because the Minitrack system can only register the fraction of a phase cycle for the phase difference for each baseline. That is, the fine and ambiguity data are represented by the decimal fractions .XXX and .XX, respectively. Thus, after 1000 phase counts (0 through 999) for the fine baselines and 100 phase counts (0 through 99) for the ambiguity baselines, a new cycle is entered. The system, however, does not accumulate each successive integer. Therefore, in order to reclaim the proper relative sequence for the phase differences, the integer position must be incremented or decremented by 1 whenever a new phase cycle (or lobe) is entered. An increase or decrease in the value of this integer depends upon whether the phase differences are increasing or decreasing as a function of the frame time. Of course, the proper absolute sequence for the phase differences, that is, the actual integers plus decimals, can only be reconstructed later when the ambiguity and fine data are correlated.

Subroutine LOBASN contains the criterion for determining when a new lobe (or phase cycle) has been entered for a given baseline. Essentially, the absolute value of the difference

¹The inclusion of a flow diagram for LSQUA would be redundant, so the reader is referred to the diagram for LSCUB (fig. 5-1). An economy of computer time could be achieved if the two subroutines were merged into one routine. In so doing, the order of the polynomial desired for the fitting may be used as a control for the discriminator of the parallel solutions.

Table 5-1.—Phase Differences

Actual (absolute)	On Minitrack data tape	Output of LOBASN (relative)
2.97	0.97	0.97
2.98	.98	.98
2.99	.99	.99
3.00	.00	1.00
3.01	.01	1.01
3.02	.02	1.02

of each pair of successive phase measurements for a baseline is examined. Since the maximum number of frames allowed is 31, there is a maximum of 30 differences. If the absolute value of any of these differences exceeds one-half lobe, that is, one-half phase cycle (or one-half wavelength in path difference), this condition is taken to indicate that a new cycle has been entered. Therefore, the integer of the phase difference of the later of the pair (in time) is incremented or decremented appropriately. Of course, this criterion is based upon the assumption that the phase difference between two successive frames cannot exceed one-half phase cycle. A difference in absolute value greater than one-half phase cycle can only indicate an integer has been dropped. For the ambiguity baselines only, this assumption is valid for essentially all of the satellite orbits of interest. For example, the medium baseline (4.0λ) has a maximum change of eight phase cycles as the satellite goes from horizon to horizon.

Table 5-1 portrays how LOBASN establishes the relative rather than the absolute sequence for the phase differences with selected data from one of the medium baselines.

The reader will recall that the maximum ranges of phase difference are ±3.5 phase cycles (or lobes) for the coarse baseline, ±4.0 phase cycles (or lobes) for the medium baselines, and ±46.0 or ±57.0 phase cycles (or lobes) for the equatorial or polar fine baselines, respectively. These extrema are achieved for the simple case of a satellite orbit confined entirely to the vertical plane of the baseline under consideration.

Because the data for each of the baselines are treated separately, it is necessary to make six calls to this subroutine from the main program of the preprocessor. Further, because the ambiguity and fine baselines are treated somewhat differently within the subroutine, their description has been segregated below.

The subroutine list is

SUBROUTINE LOBASN (TEM, I, A, RATE, L)

The calling statements follow:

- (1) For the ambiguity baselines, LOBASN operates directly on the raw phase differences, namely, EWMD, EWCD, NSMD, and NSCD:

CALL LOBASN (TIM, K, EWMD, RATE, ITD)

CALL LOBASN (TIM, K, EWCD, RATE, ITD)

CALL LOBASN (TIM, K, NSMD, RATE, ITD)

CALL LOBASN (TIM, K, NSCD, RATE, ITD)

- (2) LOBASN operates on the fine phase differences only after the five fine readings per frame have been condensed to one smoothed value by the compression formula. It operates after these compressed values have been modified by the counter correction imposed as a result of the finite time required for the system to accumulate the number of phase counts (1000 phase counts equal one phase cycle or lobe):

CALL LOBASN (TIM, K, EEFW, RATE, ITD)

CALL LOBASN (TIM, K, ENSF, RATE, ITD)

where I is the frame number, TEM(I) is the time in seconds for the *i*th frame, and L is the internal counter used to insure that an interminable loop is not formed while trying to assign the proper relative lobe.

To assist the explanation which follows, the reader should make reference to the accompanying flow diagram for LOBASN (fig. 5-2).

Ambiguity Baselines

In general, the variable RATE represents the time derivative of the phase difference. Because we are considering a series of discrete values of the phase difference, the program uses an approximation of the derivative incorporating the quotient of the finite differences:

$$\text{RATE} = \frac{\Delta \text{ phase difference}}{\Delta \text{ time}}$$

For the ambiguity baselines, LOBASN is entered with RATE = 0. Therefore, only the relative sequence of the phase differences can be established at this point. After the ambiguity data exit from LOBASN in the proper relative sequence, they enter subroutine LSQQUA in which a least-squares quadratic function is fit to the phase differences versus time; i.e.,

$$R = \alpha + \beta T + \gamma T^2$$

Normally, *R* and *T* would be the absolute phase difference and time, respectively; but, as indicated, the absolute phase differences for the ambiguities are not available at this point. However, the subroutine is able to make the fit by referencing both the phase differences and the corresponding times of measurement in the relative sequence to the corresponding phase difference and time for the midframe:

$$R = \text{phase difference}_i - \text{phase difference}_{\text{midframe}}$$

$$T = \text{time}_i - \text{time}_{\text{midframe}}$$

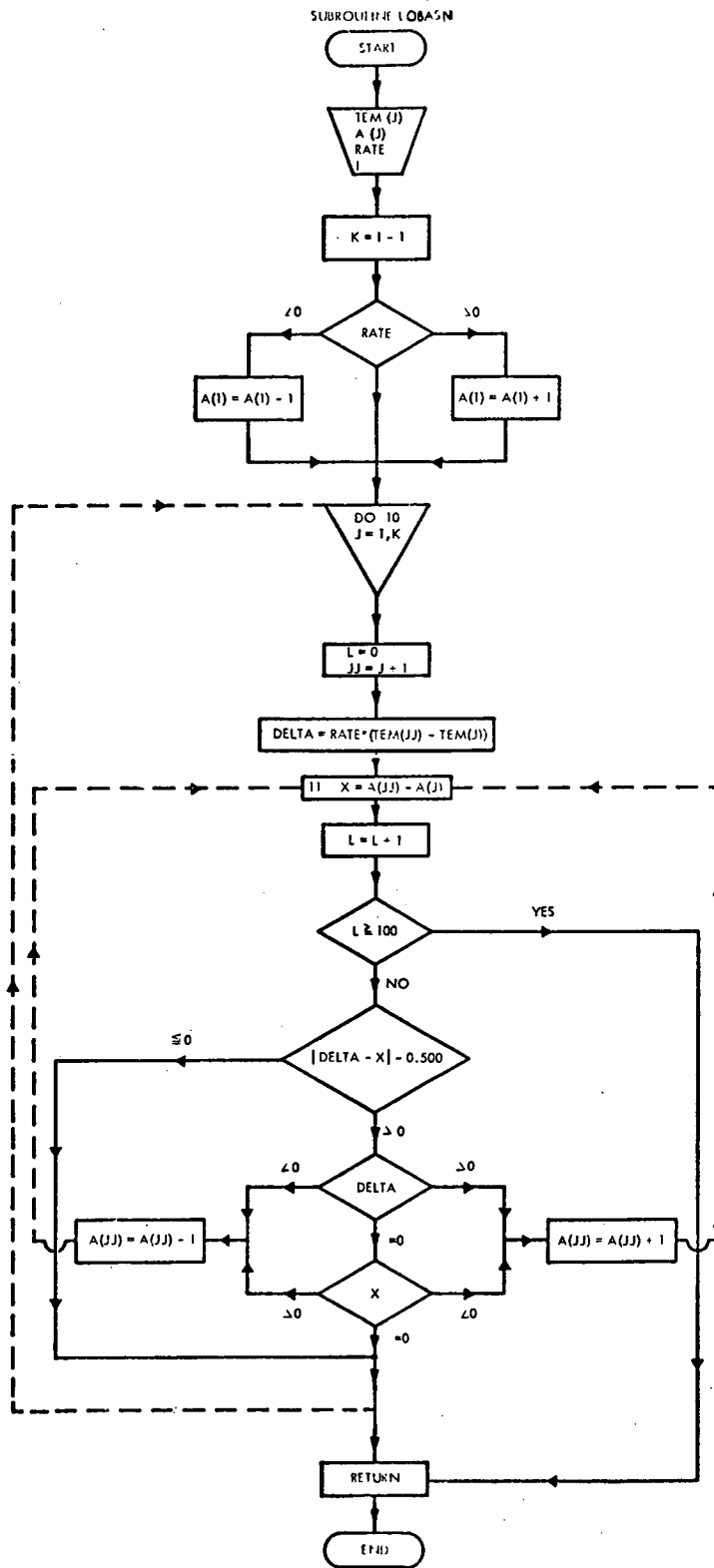


Figure 5-2.—Subroutine LOBASN.

In this manner, the absolute values (correct integers) are not needed because differences are taken which render the relative values sufficient. Because LSQQUA solves for the coefficients α , β , and γ , the RATE, assumed to be zero in LOBASN, can be estimated from

$$\frac{dR}{dT} = \beta + 2\gamma T$$

This equation for the phase difference rate is a pointwise condition; that is, the phase difference rate is constantly changing over the trajectory. For subroutine LOBASN, we are concerned with the average phase difference over the entire interval. Using the conventional time average bracket notation, the average rate is given by

$$\text{RATE} = \left\langle \frac{dR}{dt} \right\rangle = \langle \beta + 2\gamma T \rangle$$

where the angle bracket notation is defined as

$$\langle X \rangle = \frac{\int X dt}{\int dt}$$

Therefore,

$$\begin{aligned} \text{RATE} &= \langle \beta + 2\gamma T \rangle \\ &= \langle \beta \rangle + \langle 2\gamma T \rangle \\ &= \beta + 2\gamma \langle T \rangle \end{aligned}$$

because β and γ are constants.

Finally, because the referenced time scale is essentially symmetric with respect to the midframe, $\langle T \rangle = 0$. Thus, the average phase difference rate of change RATE is approximately equal to β .

Fine Baselines

When the compressed and counter-corrected fine data enter LOBASN, the least-square quadratic solutions for the ambiguity data have already been made. In other words, when the east-west fine data enter LOBASN, the values of β already have been calculated in LSQQUA for the east-west medium and east-west coarse baselines (similarly for the north-south data). Therefore, estimates of the absolute phase-difference rates are available from the above approximation for the ambiguity baselines. Through the use of the proportionality between the phase-difference rate and the baseline length, the main program estimates the fine phase-difference rate from the average of the two ambiguity phase-difference rates before LOBASN is entered:

$$\text{RATE}_{\text{fine}} = \begin{cases} \frac{46[(\text{RATE}_{\text{coarse}}/3.5) + (\text{RATE}_{\text{medium}}/4.0)]}{2} & \text{for the equatorial set} \\ \frac{57[(\text{RATE}_{\text{coarse}}/3.5) + (\text{RATE}_{\text{medium}}/4.0)]}{2} & \text{for the polar set} \end{cases}$$

where

$$\text{RATE}_{\text{coarse}} = \beta_{\text{coarse}}$$

$$\text{RATE}_{\text{medium}} = \beta_{\text{medium}}$$

Because the ambiguity rates employed are approximations of the absolute ambiguity rates, the resulting fine rates are approximations to the absolute fine rates of the phase differences. Thus, multiplication of this fine rate for the phase differences and the time interval between two frames yields an estimate of the difference of the phase differences between the two frames; that is,

$$\text{RATE} * \Delta T = \frac{\Delta R}{\Delta T} * \Delta T = \Delta R$$

The program statement $\text{DELTA} = \text{RATE} * (\text{TEM}(\text{JJ}) - \text{TEM}(\text{J}))$ embodies this calculation for the successive frames J and JJ = J + 1. Comparison of this estimated difference DELTA with the observed difference between the phase differences of two successive frames, namely, $X = \text{EEWF}(\text{JJ}) - \text{EEWF}(\text{J})$ for the east-west fine data, serves as a control or test to examine the possibility of the data having entered a new phase cycle (or lobe) in going to the next frame. The actual test examines the absolute value of the difference of the estimated and observed values of the difference of the phase differences of two successive frames— $\text{IF}(\text{ABS}(\text{DELTA}-X) - 0.500) 10, 10, 6$ —to see if half a lobe (or phase cycle) is exceeded. Two points should be made concerning the fine data distinct from the ambiguity data.

First, because the fine phase differences vary much more rapidly than the ambiguity phase differences, the comparison of the change in phase difference for successive fine frames can exceed one-half phase cycles. (Phase difference rate is proportional to baseline length.) In other words, the basic operating assumption for the ambiguity baselines is not necessarily valid for the fine data. Therefore, the entrance into a new lobe or phase cycle for the fine data must use an estimated value DELTA to first remove the uncertainty due to the natural difference between the phase differences for successive fine frames.

Second, the process hinges upon the somewhat more subtle fact that even though the recorded phase differences are relative rather than absolute, the difference of successive, proper, relative phase differences is absolute. This can be seen easily by comparison of the differences of successive values for the relative and absolute columns given in table 5-1. The actual incrementing or decrementing of the fine phase differences is otherwise exactly the same as for the ambiguity baselines.

Later, in the preprocessor, when the artificial one-half wavelength baseline has been constructed from the medium and coarse data, the proper absolute integers for the ambiguities are readily established from the eighth and seventh multiples, respectively, of the phase difference for the one-half wavelength baseline.

In the printed Minitrack preprocessor output, the phase-difference rates for each of the fine baselines are not the above-mentioned rates but refined rates determined from a differential correction of a Taylor series expansion of the phase difference as a function of time. This correction is discussed in the main preprocessor description.

Finally, when the Minitrack phase differences for each of the six baselines with their associated residuals are printed for all of the data frames, the relative rather than the absolute values are represented.

SUBROUTINE NORMAL.

The Minitrack phase readings for both the fine and ambiguity arrays are recorded in fractions of a phase cycle, and the integral number of phase cycles is truncated; therefore, a restoration process is necessary to retrieve the original numerical sequencing. This is performed by subroutine NORMAL. The subroutine list is

SUBROUTINE NORMAL (N, IIN, AREA)

The subroutine is called 20 times in the main program of MIN-B:

```
CALL NORMAL (IDIF1) for E-W fine
CALL NORMAL (IDIF2) for E-W fine
CALL NORMAL (IDIF3) for E-W fine
CALL NORMAL (IDIF4) for E-W fine
CALL NORMAL (IDIF1) for N-S fine
CALL NORMAL (IDIF2) for N-S fine
CALL NORMAL (IDIF3) for N-S fine
CALL NORMAL (IDIF4) for N-S fine
CALL NORMAL (AB)
CALL NORMAL (BC)
CALL NORMAL (EAB4)
CALL NORMAL (EBC4)
CALL NORMAL (EAB3)
CALL NORMAL (EBC3)
CALL NORMAL (FE)
CALL NORMAL (FN)
CALL NORMAL (EWMER)
CALL NORMAL (EWCER)
CALL NORMAL (SNMER)
CALL NORMAL (SNCER)
```

Let us consider the following example for the five fine phase readings of one frame of data for the east-west baseline (table 5-2).

Table 5-2.—Fine Phase Reading Examples

Variable name	Actual phase cycle	Minitrack phase cycle recorded
EWF1	2.90	0.90
EWF2	2.95	.95
EWF3	3.05	.05
EWF4	3.20	.20
EWF5	3.40	.40

To consolidate the above five values for this frame into one effective value by using the compression formula, four differences are produced by taking successive pairs of the east-west fine readings from the data available; that is,

$$\begin{aligned} \text{IDIF1} &= 0.05 \\ \text{IDIF2} &= -0.90 \\ \text{IDIF3} &= 0.15 \\ \text{IDIF4} &= 0.20 \end{aligned}$$

Because it is assumed that the difference between two successive phase readings cannot be greater than 0.500 for any satellite above a height of 120 km, a difference greater than 0.500 in absolute value must of necessity indicate the beginning of a new phase cycle. The assignment of subroutine NORMAL is to rectify the distorted result for quantities such as IDIF2 so that IDIF2 is made to equal 0.10, thereby representing the actual phase cycle.

The scheme for accomplishing this is given in the accompanying flow diagram (fig. 5-3). Graphically, the adjusted value x_{new} as a function of the input value x_{old} is illustrated in figure 5-4. Equivalently,

$$x_{\text{new}} = \begin{cases} x_{\text{old}} + 1.0 & \text{for } -1.0 \leq x_{\text{old}} < -0.5 \\ x_{\text{old}} & \text{for } -0.5 \leq x_{\text{old}} \leq +0.5 \\ x_{\text{old}} - 1.0 & \text{for } +0.5 < x_{\text{old}} \leq +1.0 \end{cases}$$

Tracing IDIF2 through the flowchart would yield the desired result, namely IDIF2 = 0.10.

Later, in the main program subroutine, NORMAL similarly treats the one-half wavelength baselines manufactured from the difference of the medium (4.0λ) and coarse (3.5λ) arrays, namely, AB for the east-west one-half wavelength baseline and BC for the north-south one-half baseline. This is essential because physically, a one-half wavelength baseline can at most go only from -0.5λ to $+0.5\lambda$ in path difference for a satellite going from horizon to horizon.

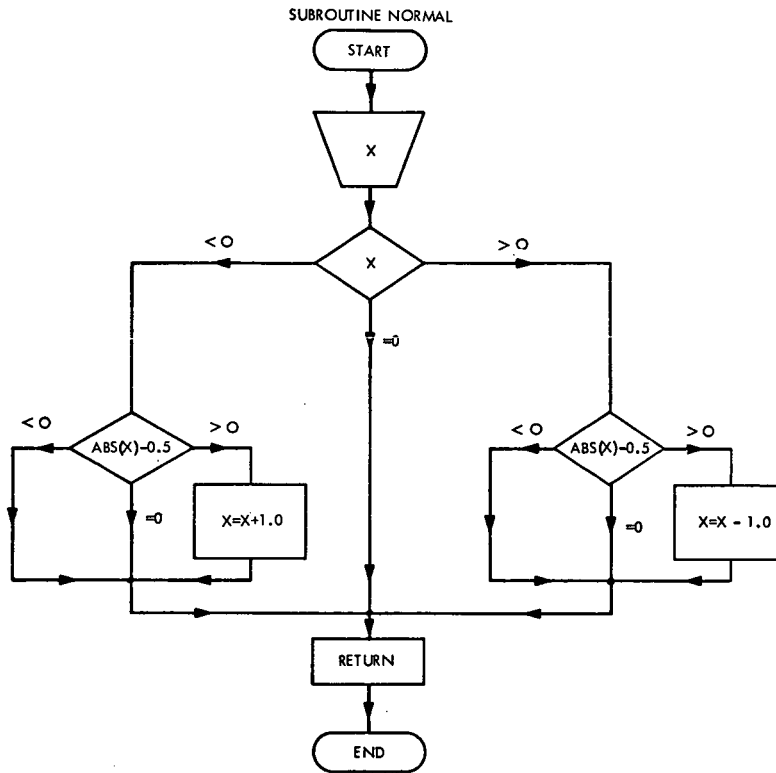


Figure 5-3.—Subroutine NORMAL.

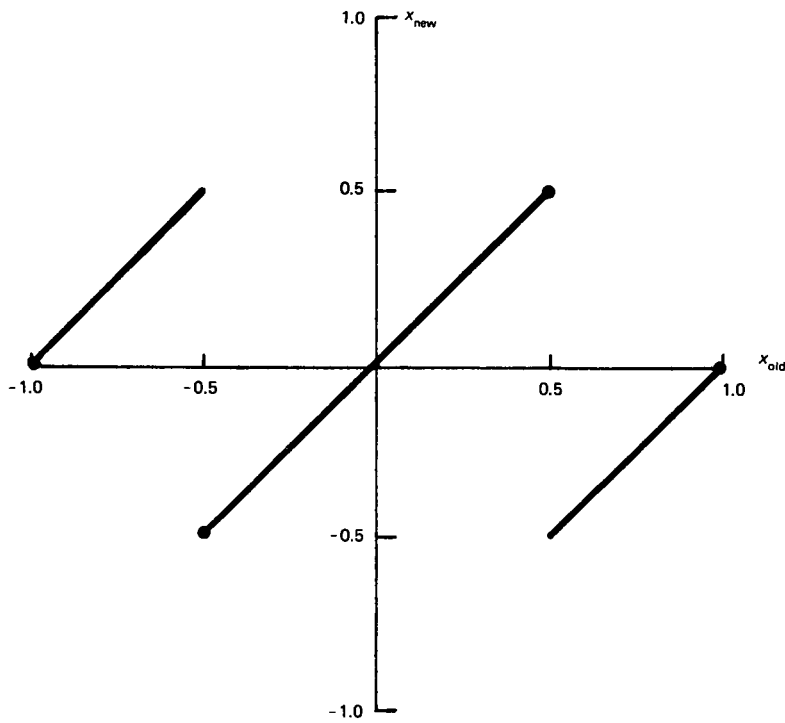


Figure 5-4.—The adjusted value x_{new} as a function of the input value x_{old} .

Subroutine NORMAL operates six additional times on the differences generated for each of the six baselines by the phase reading generated by the manufactured one-half wavelength baseline multiplied by the baseline in wavelengths (3.5, 4.0, 46.0, or 57.0) minus the corrected observed values. Finally, this subroutine checks and corrects for overflows or underflows in the four ambiguity errors EWMER, EWCER, SNMER, and SNCER.

SUBROUTINE PYRD

Subroutine PYRD (fig. 5-5) combines a three-digit running day number for the time of the midframe of the data (where January 1 = 0 and December 31 = 365 in a nonleap year) and a two-digit year number (e.g., 60 for the year 1960) into a standard six-digit calendar form for the date (YEAR/MONTH/DAY). The calling statement is

```
CALL PYRD (IYR, IDAYD(MID), YRMODA)
```

and the subroutine list is

```
SUBROUTINE PYRD (NYR, JDAY, NYMODA)
```

This subroutine is called only once, see volume 2, page 16.

Example:

```
Input:  NYR = 60 (Note 1960 a leap year)
        JDAY = 61
Output:  6 0 0 3 0 1
        Yr Mo Day
Answer:  Represents March 1, 1960
```

SUBROUTINE ZERO

Subroutine ZERO converts an input digital value IIN of N characters in length into its appropriate hexadecimal representation and stores it in the one-dimensional array AREA for transfer to and subsequent use in Program OBS-B (referred to as B). The subroutine list is

```
SUBROUTINE ZERO (N, IIN, AREA)
```

The subroutine is called 22 times in the main program of MIN-B:

```
CALL ZERO (4, INO, IENO)
CALL ZERO (4, ISO, INNO)
CALL ZERO (8, IACOS, LCOS)
CALL ZERO (8, IBCOS, MCOS)
CALL ZERO (5, BOUR, IOUR)
CALL ZERO (6, ASEC, ISEC)
CALL ZERO (3, CSTA, ASTA)
CALL ZERO (7, YRMODA, ARMODA)
```

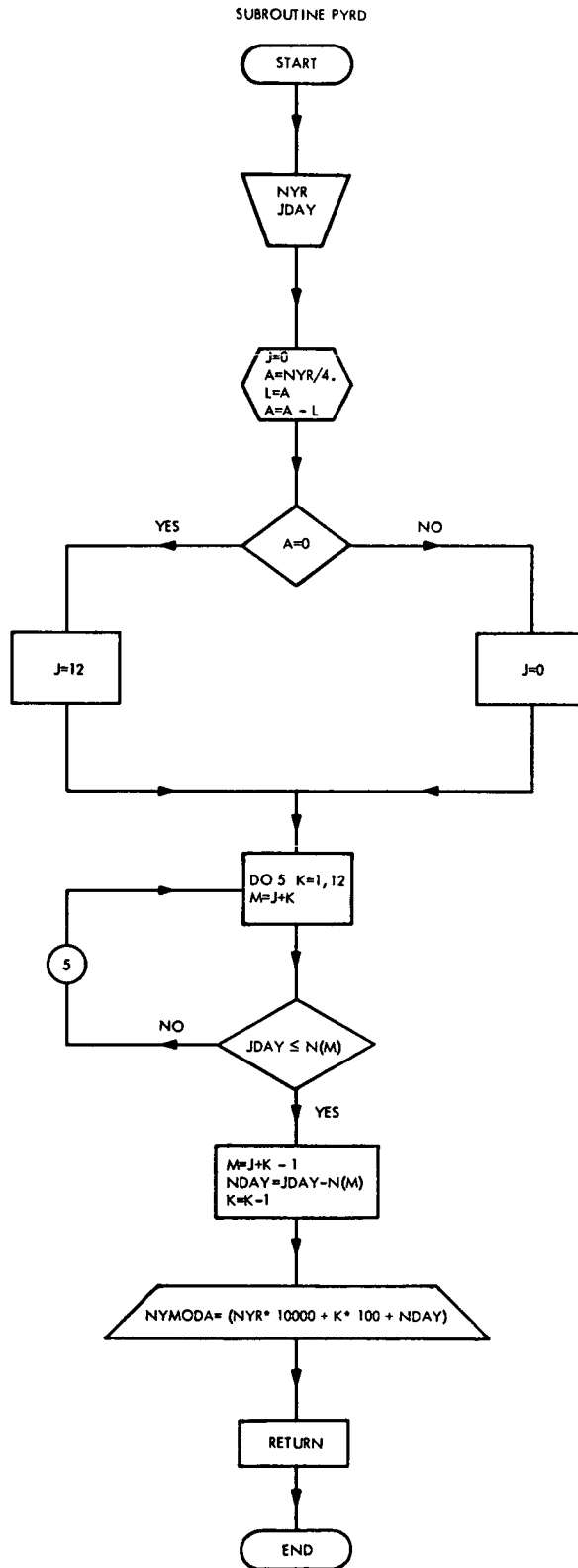


Figure 5-5.—Subroutine PYRD.

```

CALL ZERO (7, HOUR, AOUR)
CALL ZERO (7, IELOBE, IALOB)
CALL ZERO (4, IEWMER, IAWMER)
CALL ZERO (4, IEWCER, DAWCER)
CALL ZERO (7, INLOBE, IBLOBE)
CALL ZERO (7, IERATE, IARATE)
CALL ZERO (7, INRATE, IBRATE)
CALL ZERO (7, IEACC, IAACC)
CALL ZERO (7, INACC, IBACC)
CALL ZERO (6, IEWFE, IAEWFE)
CALL ZERO (6, INSFE, IANSFE)
CALL ZERO (4, ISNMER, IBNMER)
CALL ZERO (4, ISNCER, IBNCER)
CALL ZERO (3, K, IFIT)

```

The value N equals the number of base 10 positions required for IIN, including one for the sign (e.g., $N = 4$ for IIN = -379). The value IIN must be a signed integer less than 10^7 ; that is, IIN = $|\pm 9,999, 999|$. If the entry is outside this range, asterisks in hexadecimal form are automatically entered in the output array AREA. This array is dimensioned 80, but, at most, 8 can be used, as can be seen by examining the trace of the dummy index IJ (fig. 5-6).

Example:

Input:	IIN = - 379
	N = 4
Output (in hexadecimal):	AREA(1) = minus sign
	AREA(2) = 3
	AREA(3) = 7
	AREA(4) = 9

SUBROUTINE DCOUNT

Subroutine DCOUNT (*Day Count*) converts the calendar form into a running day number for the year, with the epoch being January 1 of that year. The subroutine list is

```
SUBROUTINE DCOUNT(IDATE)
```

The subroutine is called twice in the main program of MIN-B:

```

CALL DCOUNT (BDATE)
CALL DCOUNT (BDATE)

```

The input date IDATE is in a six-digit form XXXXXX representing the usual calendar notation: YEAR/MONTH/DAY. (See fig. 5-7.)

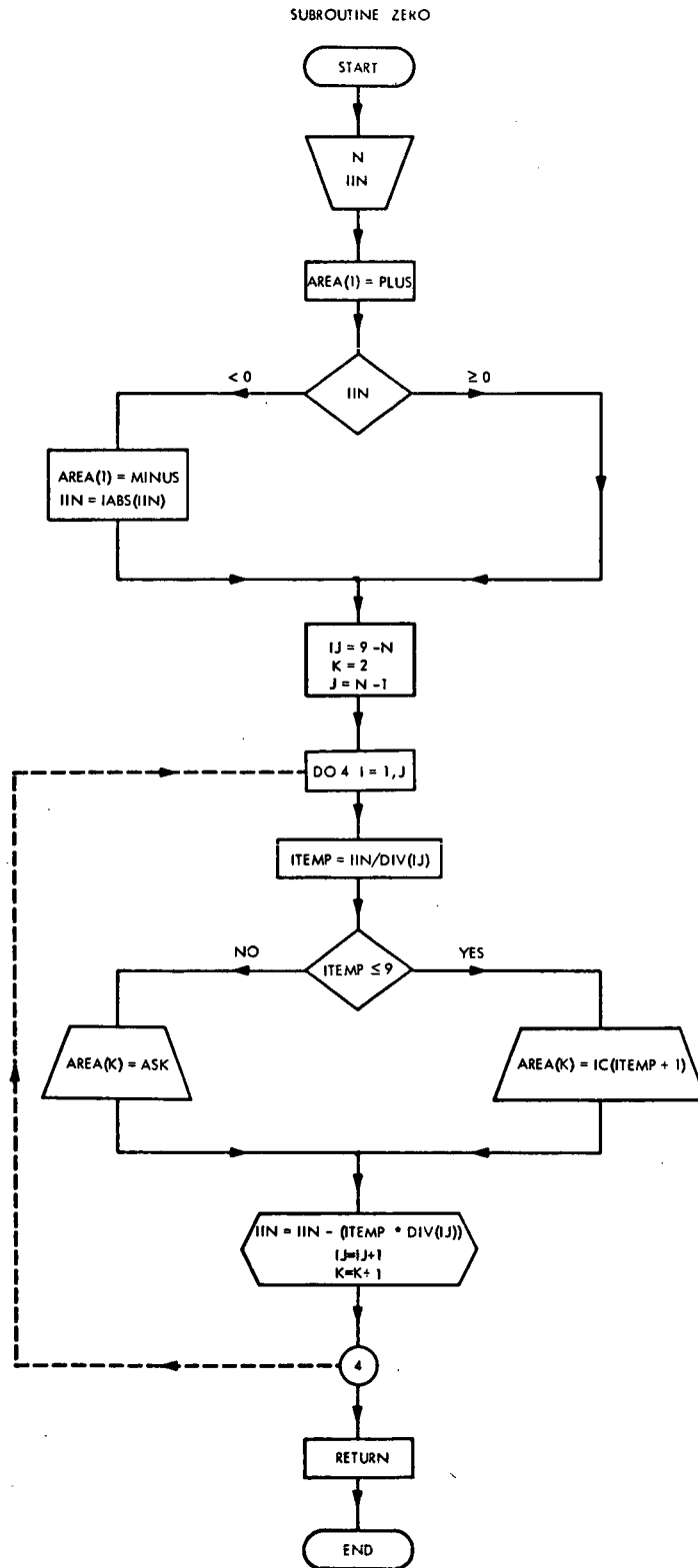


Figure 5-6.—Subroutine ZERO.

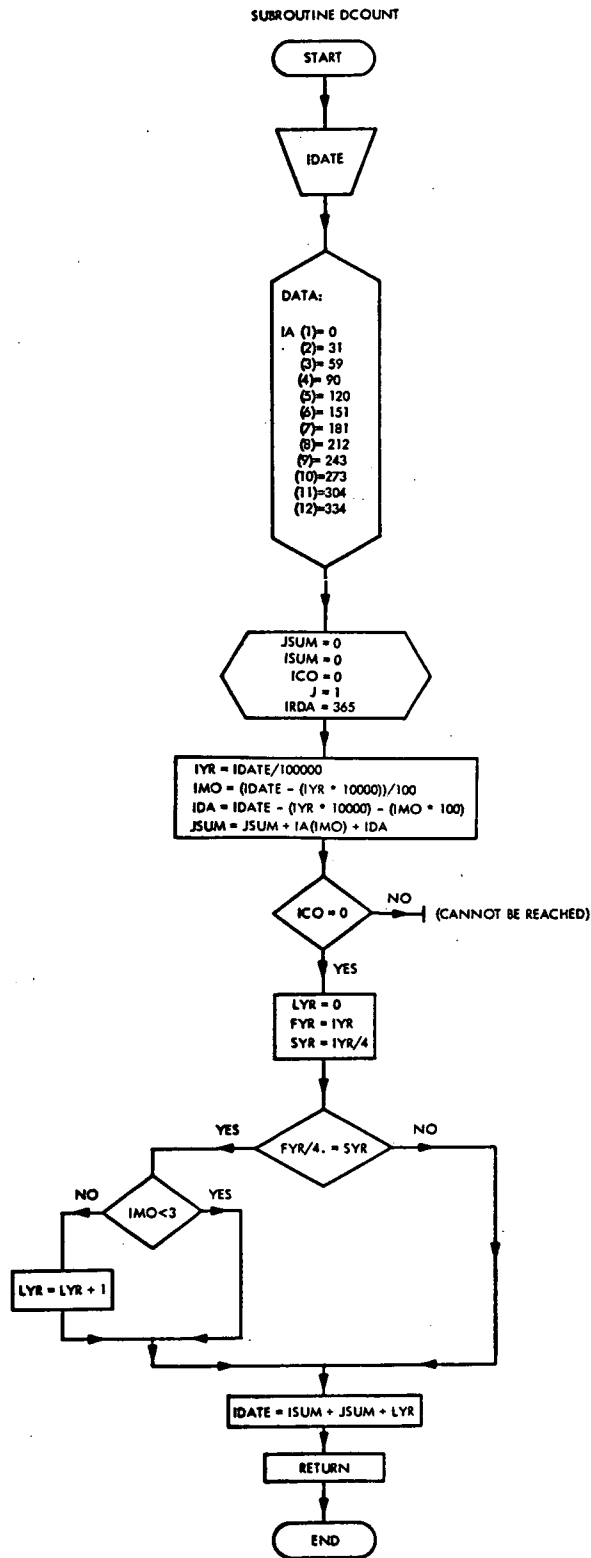


Figure 5-7.—Subroutine DCOUNT.

Example:

Input: IDATE = 600301, representing March 1, 1960

Output: IDATE = 61, representing the 61st day of the year 1960

The original six digits in IDATE are lost when replaced by the three-digit day number. In essence, this means the year is lost in this notation. Provision is made to increment the day count by one for any day beyond the last day in February during a leap year. A leap year is defined when $IYR/4$ has an exact integral value; however, any century year divisible by 400 is not a leap year even though $IYR/4$ is an exact integer. This will have a practical application only in the year 2000.

Between statements EFN1 and EFN4, the statements are inaccessible with the present form of the subroutine. They are probably a carryover from a previous form of the routine in which this segment computed a running day number for some earlier epoch than the first of the present year. Provision was then made to employ 365 or 366 days for the previous year/day count.

Section 6

DATA SMOOTHING

COMPRESSION OF FINE DATA

The fine data determine the ultimate accuracy of the Minitrack system. Precautions must be taken, therefore, to insure that the fine data do not contain excessive random errors.

The accumulation of Minitrack data for a given satellite pass is not distributed uniformly among the six active baselines. Each frame of data, regardless of which frame rate has been preselected by the operator, will sample each of the four ambiguity baselines only once, whereas each of the two fine baselines will have been sampled five times per frame.

The fine data errors include not only the inherent difficulties of small sample statistics and interference from other radiofrequency emission sources but also the vagaries of the data bit handling in such components as the digitizer. The apparent redundancy of the 5-to-1 ratio of fine to ambiguity readings per data frame allows the preprocessor to apply a smoothing process to the fine data. In so doing, the system reduces the effect of random error in the fine data.

In the preprocessor this smoothing process is embodied in a single FORTRAN statement for each fine baseline. In numerical analysis, this standard process is known as the five-point compression formula. The five fine readings in each frame are uniformly spaced in time. In essence, these are smoothed to one value at the center of the frame-sampling time interval. For this analysis, the phase differences $a_i (i = 1, \dots, 5)$ as a function of time t_i are most conveniently handled in the form presented in table 6-1.

These phase differences a_i must be at least the relative phase differences as discussed in the section covering subroutine NORMAL. That is, the phase differences must have their relative integers attached. Also, the time scale in the function table shown is for convenience.

Table 6-1.— a_i as a Function of t_i

Independent variable	Index value i				
	1	2	3	4	5
a_i	a_1	a_2	a_3	a_4	a_5
t_i	-2	-1	0	1	2

Actually, the five fine readings are taken at 0.2-s intervals during each data frame. Therefore, with the origin of the time scale at the beginning of the frame, the five readings represent $t = 0, 0.2, 0.4, 0.6,$ and 0.8 s.

Actually, the preprocessor will accommodate any of seven frame rates (1, 2, 10, 20, 60, 120, or 600 s/frame). The frame rate is chosen so that 31 data frames will essentially cover the half-power rectangle of the antenna pattern projected upon the celestial sphere. However, regardless of which frame rate is selected, the five fine readings per frame are sampled in the first second of each frame.

The smoothing process yields a value for the phase difference at the center value of time, namely, $t = 0.4$ s. Translating the time origin to the center value yields $t = -0.4, -0.2, 0, 0.2, 0.4$. Only a scale factor of 5 separates these values and the table values. In the following discussion, it will be shown that this difference is irrelevant in obtaining the smoothed value of the phase difference at the center. It must be noted, however, that 0.4 s will have to be added to the frame time (which refers to the beginning of the frame) to associate the correct time with the smoothed center value. The only criterion for these considerations will be that the data are uniformly spaced in time.

The object is to obtain a smoothed value of the phase difference at the center of the time interval, namely, \bar{a}_3 . For the present form of the preprocessor, the smoothing function is represented by the cubic polynomial

$$a_i = \alpha + \beta t_i + \gamma t_i^2 + \delta t_i^3$$

where $i = 1, \dots, 5$

At this point, the usual procedure would be to use the five data pairs (a_i, t_i) in a least-squares solution to determine the four parameters $\alpha, \beta, \gamma,$ and δ . Because the time at the center value is $t_3 = 0$, the expression for the smoothed phase difference reduces to $\bar{a}_3 = \alpha$. This approach requires a least-squares cubic fit to be made for each of the 31 possible data frames for each fine baseline. These computations would tax the computer unnecessarily. Therefore, the preprocessor uses a single expression algorithm—the compression formula—which incorporates the concept of the least-squares fitting but does not actually perform all of the calculations required in the standard approach.

In understanding the algorithm derived in this section, the reader should keep in mind a relatively recent change in the preprocessing routine. Originally, a second-degree or quadratic polynomial was employed to represent the phase difference as a function of time for the entire string of 31 data frames instead of the present cubic polynomial. It would seem appropriate to use the same degree polynomial for smoothing the five fine readings per frame as assumed for the fitting of all of the frame values. Therefore, when the change to a least-squares cubic fit for the 31 data frames was included in the preprocessor, the compression algorithm should have been changed. However, because the center value of the five points is chosen, both the five-point quadratic and the five-point cubic compression formulas are the same.

In deriving the more general expression, let us use the ordinary definition of the "best" cubic approximation as that one which minimizes the sum of the squares of the residuals r_i , namely,

$$\sigma^2 = \sum_{i=1}^5 r_i^2 = \sum_{i=1}^5 (a_i - \alpha - \beta t_i - \gamma t_i^2 - \delta t_i^3)^2$$

with respect to the four parameters α , β , γ , and δ .

Through the use of the five integer values of t given in the previous table, the residuals are

$$r_1 = a_1 - (\alpha - 2\beta + 4\gamma - 8\delta)$$

$$r_2 = a_2 - (\alpha - \beta + \gamma - \delta)$$

$$r_3 = a_3 - \alpha$$

$$r_4 = a_4 - (\alpha + \beta + \gamma + \delta)$$

$$r_5 = a_5 - (\alpha + 2\beta + 4\gamma + 8\delta)$$

Some economy of notation results if this problem is posed in matrix notation. This is equivalent to asking for the vector $(\alpha, \beta, \gamma, \delta)$, which minimizes the length of the following error vector formed from the residual equations above:

$$\mathbf{e} = \begin{bmatrix} r_1 \\ r_2 \\ r_3 \\ r_4 \\ r_5 \end{bmatrix} = \begin{bmatrix} a_1 \\ a_2 \\ a_3 \\ a_4 \\ a_5 \end{bmatrix} - \begin{bmatrix} 1 & -2 & 4 & -8 \\ 1 & -1 & 1 & -1 \\ 1 & 0 & 0 & 0 \\ 1 & 1 & 1 & 1 \\ 1 & 2 & 4 & 8 \end{bmatrix} \begin{bmatrix} \alpha \\ \beta \\ \gamma \\ \delta \end{bmatrix}$$

where $\sigma^2 = (\text{length } \mathbf{e})^2 = \|\mathbf{e}\|^2 = \mathbf{e} \cdot \mathbf{e}$

The normal equations to reduce the system to 4×4 are formed in the standard manner by differentiating the expression for σ^2 with respect to each of the four parameters α , β , γ , and δ and setting the derivatives equal to zero to obtain the minimum conditions:

$$\begin{bmatrix} N & \sum t & \sum t^2 & \sum t^3 \\ \sum t & \sum t^2 & \sum t^3 & \sum t^4 \\ \sum t^2 & \sum t^3 & \sum t^4 & \sum t^5 \\ \sum t^3 & \sum t^4 & \sum t^5 & \sum t^6 \end{bmatrix} \begin{bmatrix} \alpha \\ \beta \\ \gamma \\ \delta \end{bmatrix} = \begin{bmatrix} \sum a \\ \sum at \\ \sum at^2 \\ \sum at^3 \end{bmatrix}$$

Through the use of the tabular values for a and t ,

$$\begin{bmatrix} 5 & 0 & 10 & 0 \\ 0 & 10 & 0 & 34 \\ 10 & 0 & 34 & 0 \\ 0 & 34 & 0 & 130 \end{bmatrix} \begin{bmatrix} \alpha \\ \beta \\ \gamma \\ \delta \end{bmatrix} = \begin{bmatrix} a_1 + a_2 + a_3 + a_4 + a_5 \\ 2(a_5 - a_1) + (a_4 - a_2) \\ 4(a_5 + a_1) + (a_4 + a_2) \\ 8(a_5 - a_1) + (a_4 - a_2) \end{bmatrix}$$

To solve for the four desired parameters, the first matrix in the preceding equation (which we denote by \mathbf{A} below) must be inverted. Using the definition of the inverse of a matrix as the adjoint of that matrix divided by the norm of the matrix yields

$$\mathbf{A}^{-1} = \frac{\text{adj. } \mathbf{A}}{\|\mathbf{A}\|}$$

$$= \frac{\begin{bmatrix} 4896 & 0 & -1440 & 0 \\ 0 & 9100 & 0 & -2380 \\ -1440 & 0 & 720 & 0 \\ 0 & -2380 & 0 & 1700 \end{bmatrix}}{10\ 080}$$

$$= \begin{bmatrix} \frac{17}{35} & 0 & \frac{-1}{7} & 0 \\ 0 & \frac{65}{72} & 0 & \frac{-17}{72} \\ \frac{-1}{7} & 0 & \frac{1}{14} & 0 \\ 0 & \frac{-17}{72} & 0 & \frac{5}{72} \end{bmatrix}$$

Therefore,

$$\begin{bmatrix} \alpha \\ \beta \\ \gamma \\ \delta \end{bmatrix} = \begin{bmatrix} \frac{17}{35} & 0 & \frac{-1}{7} & 0 \\ 0 & \frac{65}{72} & 0 & \frac{-17}{72} \\ \frac{-1}{7} & 0 & \frac{1}{14} & 0 \\ 0 & \frac{-17}{72} & 0 & \frac{5}{72} \end{bmatrix} \begin{bmatrix} a_1 + a_2 + a_3 + a_4 + a_5 \\ 2(a_5 - a_1) + (a_4 - a_2) \\ 4(a_5 + a_1) + (a_4 + a_2) \\ 8(a_5 - a_1) + (a_4 - a_2) \end{bmatrix}$$

After performing the indicated matrix multiplication, the individual parameters are given by

$$\alpha = \frac{17}{35} a_3 - \frac{3}{35} (a_5 + a_1) + \frac{12}{35} (a_4 + a_2)$$

$$\beta = \frac{-1}{12} (a_5 - a_1) + \frac{2}{3} (a_4 - a_2)$$

$$\gamma = \frac{-1}{7} a_3 + \frac{1}{7} (a_5 + a_1) - \frac{1}{14} (a_4 + a_2)$$

$$\delta = \frac{1}{12} (a_5 - a_1) - \frac{1}{6} (a_4 - a_2)$$

However, as indicated before, because the expression for the smoothed phase difference reduces to $\bar{a}_3 = \alpha$ at the center value $t_3 = 0$, only the expression for α above is needed.

The solution for the smoothed value if a quadratic rather than a cubic equation is assumed can easily be derived from the above just by eliminating the last column and last row from the normal equations matrix to yield the appropriate 3×3 system with the unknown parameters α , β , and γ . Doing this produces values of α and γ that are exactly the same as those derived for the cubic fit; only β is different:

$$\beta = \frac{1}{5}(a_5 - a_1) + \frac{1}{10}(a_4 - a_2)$$

However, because the smoothed value is given by $\alpha = \bar{a}_3$ only, this is of no consequence for the five-point compression formulas; the cubic and quadratic five-point compression formulas are the same. In the preprocessor, the compression formula has a somewhat different form than

$$\alpha = \bar{a}_3 = \frac{17}{35}a_3 - \frac{31}{35}(a_5 + a_1) + \frac{12}{35}(a_4 + a_2)$$

With some algebraic manipulation, this can be written as

$$\alpha = \bar{a}_3 = a_3 + \frac{9(a_4 - a_3 - a_3 + a_2) - 3(a_5 - a_4 - a_2 + a_1)}{35}$$

or, equivalently,

$$\alpha = \bar{a}_3 = a_3 + \frac{9(\text{IDIF3} - \text{IDIF2}) - 3(\text{IDIF4} - \text{IDIF1})}{35}$$

where the four differences between pairs of successive values of the five fine phase readings have been formed:

$$\text{IDIF1} = a_2 - a_1$$

$$\text{IDIF2} = a_3 - a_2$$

$$\text{IDIF3} = a_4 - a_3$$

$$\text{IDIF4} = a_5 - a_4$$

In the preprocessor, these differences go through subroutine `NORMAL` before they are used in the calculation of \bar{a}_3 in order to guarantee that the proper relative sequence of the phase readings is retained if a new phase cycle has been entered. (See the subsection on subroutine `NORMAL` in sec. 5.)

A cursory examination of the propagation of the normal equations matrix would show that a higher order polynomial would not produce the same smoothed values for the matrix element $A_{15}^{-1} \neq 0$. Of course, with five data points per line, these higher order polynomials would include just a fourth- and a fifth-degree one. However, for meaningful results over a

large range of input values, a ratio of 2:1 is usually recommended for the number of data points to the degree of the polynomial.

In step 6(8) of the MIN-B program description, it was indicated that the five phase readings for each fine baseline were smoothed or compressed to a single value at the time center just as the data frames were treated. The underlying premise for this similarity in data handling is probably not justified. When the Minitrack station is tracking a satellite, the satellite is moving through the antenna-field pattern so that at least one of the two orthogonal baselines should register a phase difference a which varies with time t . As derived above, the compression formula for the cubic polynomial relating these two variables accounts for this time variation. However, the $K_{s,2}$ calibration readings are acquired by inputting a common, constant signal to the receivers. Neither a moving satellite nor an antenna-field pattern is involved. Hence, the deliberate use of a cubic polynomial of time to smooth the calibration data is not immediately obvious. A simple arithmetic average of the five readings would probably be more straightforward and realistic.

LEAST-SQUARES FITTING ERRORS

An effort has been made to analyze the errors introduced by the polynomial smoothing techniques used in the Minitrack preprocessing computer program. The analysis described in the following paragraphs deals with the mathematical data smoothing done by the preprocessing program on the 31-frame Minitrack message. In the smoothing subroutines, a few estimated values are generated from many tracking observations. We have constructed a FORTRAN IV Minitrack simulator for use on a computer time-sharing system that answers the question of how well certain ideal (or noiseless) consecutive interferometer phase readings may be approximated by the smoothing subroutines of the Minitrack preprocessor. A listing of the simulation program is given later in this chapter. The intraframe five-point compression formula of the preprocessor is examined in another section.

Only two simplifications of real Earth-orbital space flight have been introduced into the computer simulation. These are that the satellite moves in a circular orbit and that the Earth on which the station is placed does not rotate. We are prepared to demonstrate that neither of these restrictions has appreciable effect upon our conclusions. The Earth rate, at worst, for a 1-s frame time, can lengthen the observational arc by about 0.14° , which is

$$(360^\circ \times 31)/(24 \times 3600)$$

We shall see later that lengthening the observed arc is the primary source of fitting inaccuracies. Therefore, the Earth rate can easily be related to some change in satellite altitude and thus be accounted for.

Although the effect of orbit eccentricity on fitting error has not been specifically explored, experience indicates that such eccentricity would have little impact on the results. The Minitrack interferometer is not sensitive to changes in spacecraft altitude except as they affect the rate of change of the cone angle. The only way the effect of eccentricity could

enter the Minitrack message phase readings, therefore, is through a failure of these readings to balance around the midpoint of the message time interval. This is the second most important error source in smoothing. In the brief period of 31 s (the most commonly used data message length), it is unlikely that significant changes due to eccentricity will take place.

The preprocessing program used a quadratic polynomial smoothing approximation until only recently, when a cubic polynomial in time, namely,

$$\alpha + \beta T + \gamma T^2 + \delta T^3$$

replaced it. We shall consider certain questions in the light of both the cubic and quadratic approximations. Any number of pairs of direction cosines may be requested from the OBS-B preprocessing program. The location of the samples in the fitting interval varies with the number of samples requested. Because the error as a function of time for a fixed approximation depends upon the sample locations in the tracking interval, the number of pairs requested (preprocessor term IPTS) is a significant parameter in the estimation of the residual. If only one point is requested, the center point will be sampled. If two points are requested, the center point and the end point on the descending arc of the projected trajectory are sampled. If three points are requested, the end points plus center point will be provided by the processing program.

In general, the fit will be worse at the end points.¹ Further, the fitting error of a polynomial of degree n can be expected to be smallest in the vicinity of the roots of the Legendre polynomial of degree $n + 1$. This means, among other things, that the center point is an excellent point at which to sample a quadratic fit because the Legendre polynomial of degree 3 is zero at the center point, but the center point is not an optimal choice for a cubic fit because the Legendre polynomial of degree 4 has a local maximum at the center point. This will be borne out in the numerical data, which show the cubic fit to be a much better overall approximation than the quadratic fit although it has the same residual at the center as exhibited by the quadratic fit.

Most of the illustrations deal with the case of a satellite whose ground track passes directly down a baseline. This adequately exhibits the worst possible errors because it will be shown that for a fixed altitude orbit, such an orientation leads to the largest residuals. These cases will also show that with one exception the errors for a "balanced" pass can be related directly to the range of magnitude of the observed angle.

The cases to be considered first are

- (1) The orbit plane contains the baseline in question.
- (2) The orbit plane passes through the station center at 10° to the baseline in question.
- (3) The orbit and the great-circle planes through the baseline are inclined at 5° with the line of nodes 90° from the station.

¹Bodo Kruger: *Filter Properties of Least Squares Fitted Polynomials*. NASA TM X-63-321, 1968.

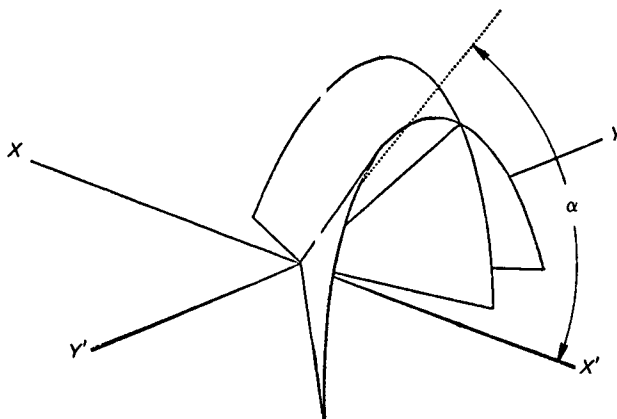


Figure 6-1.—Double cone intersection.

- (4) Case (2) on the other baseline.
- (5) Case (3) on the other baseline.

Figure 6-1 defines the cone angle α that is related to the direction cosine in the Minitrack interferometer system.

Figure 6-2 shows the cone angle α as a function of time for the 200-mile-altitude orbit containing the baseline. Notice that the arc goes well beyond the null points of the antenna pattern, which are at about 85° or 86° . More comment on this will be made later. Essentially, the cone angle for this run is a linear function of time, centered on 90° . Because of this, the problem is essentially the same as fitting $\sin t$ for t in the interval $[-(20/57.3), (20/57.3)]$ with a cubic or quadratic polynomial. (For the orbits under analysis, we are considering the segment occurring 15 temporal s before zenith and 15 s after zenith. This works out to be approximately -20° through $+20^\circ$ of arc centered about zenith. The constant 57.3 converts the notation to equivalence in radians.)

Figure 6-3 shows the error $(\cos \alpha - \cos \alpha)$ obtained from the quadratic fit. To express this in a more meaningful way, the error has been multiplied by 57 300, which yields an estimate of the residual in Minitrack fine counts (0.001°).

The residuals are grossly too large. A quadratic fit could be used for this satellite only if the sampling were done at the center point of a precisely centered arc. As we would expect from the analysis,² the error curve follows a scaled, third-degree Legendre polynomial.

Figure 6-4 shows the error from the cubic fit. Residuals have been tremendously reduced. The error at the end points, however, is still, at nine fine counts, hardly acceptable in the light of inherent Minitrack capabilities. Thus, for such a satellite, only the center point should be sampled. The error curve for the cubic fit is not a fourth-order Legendre polynomial but a fifth-order Legendre polynomial. To explain this, it is only necessary to

²Bodo Kruger: *Filter Properties of Least Squares Fitted Polynomials*. NASA TM X-63-321, 1968.

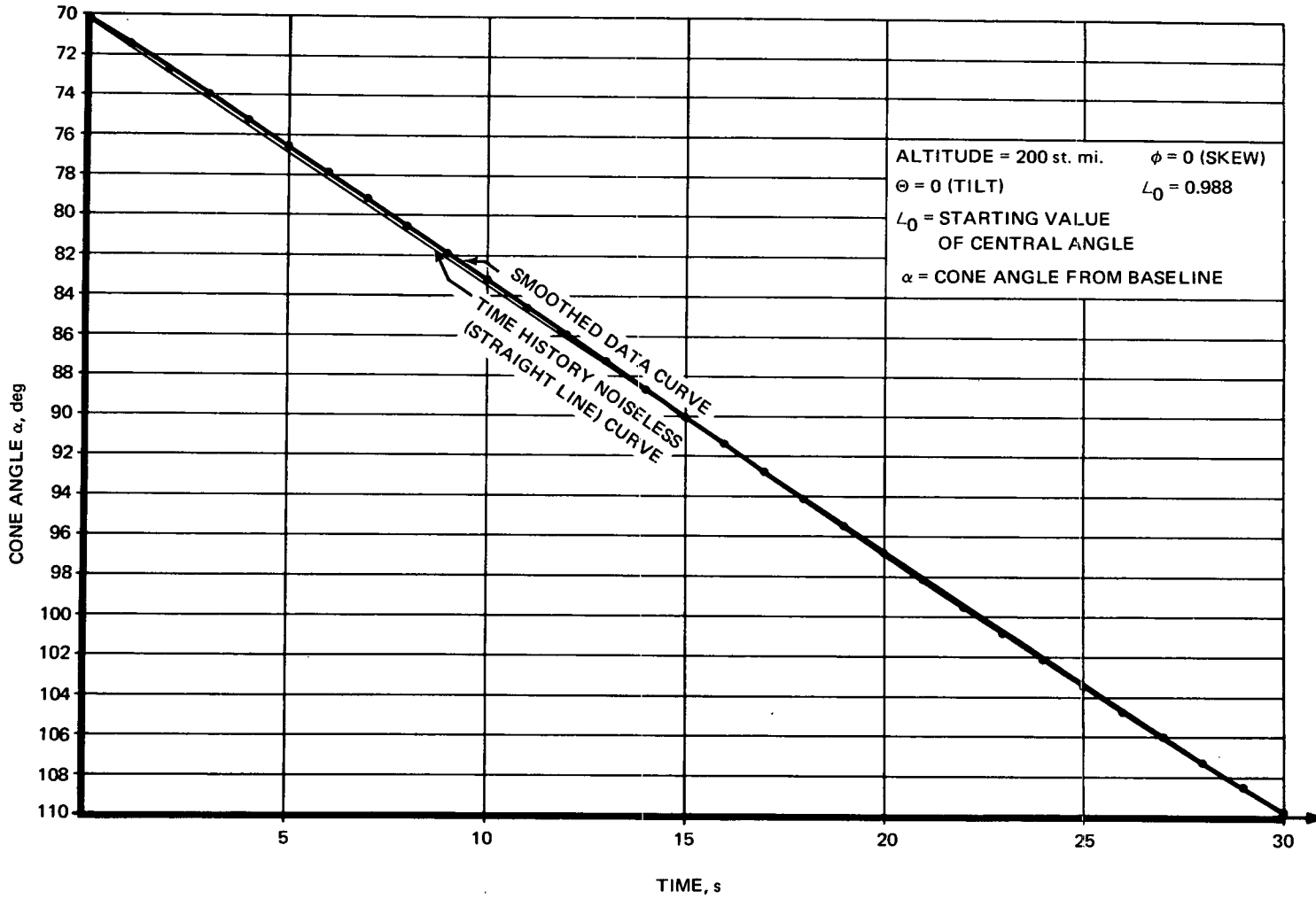


Figure 6-2.—Minitrack cone angle to satellite on circular orbit as a function of time.

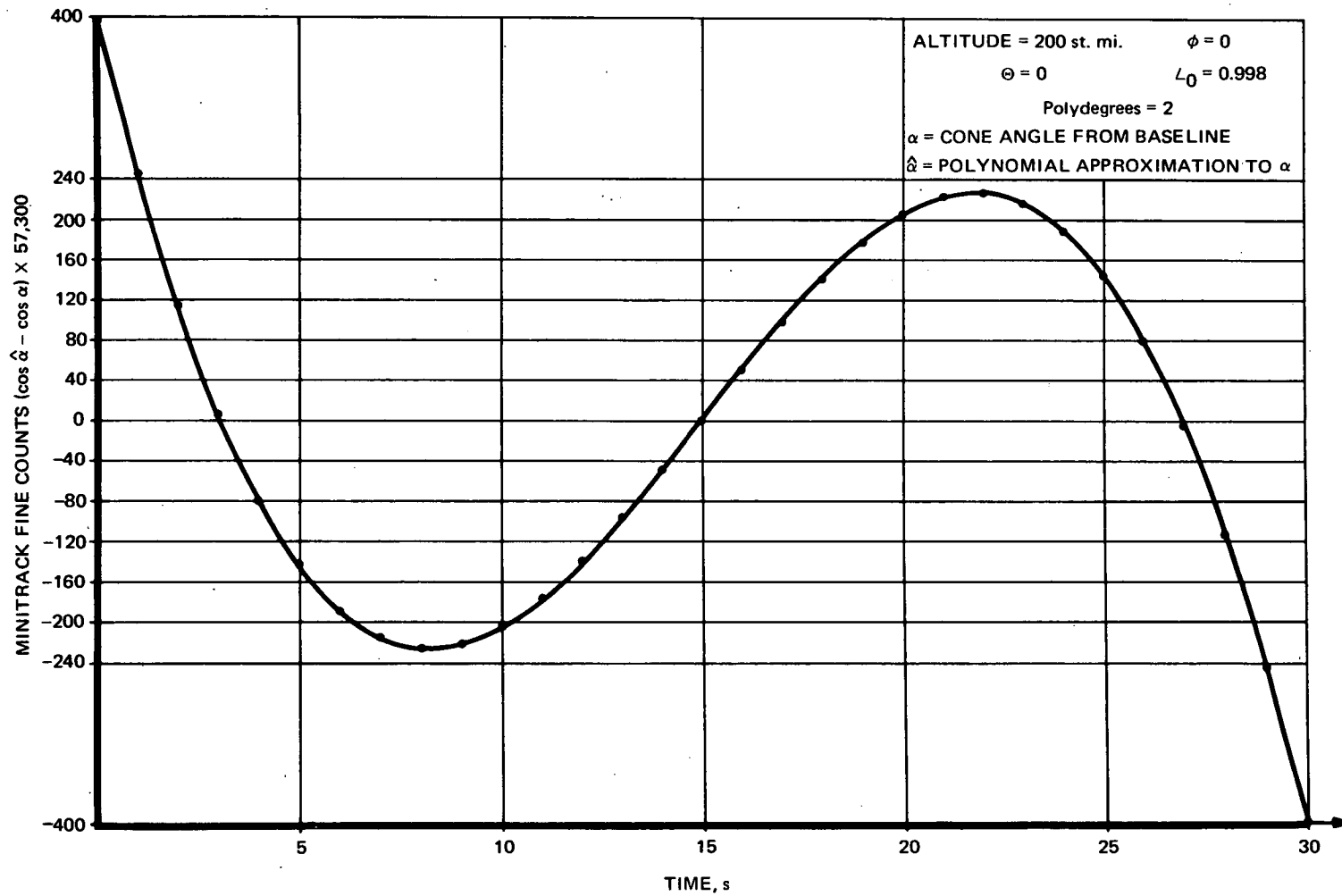


Figure 6-3.—Second-degree polynomial fitting error for circular orbit satellite of figure 6-1.

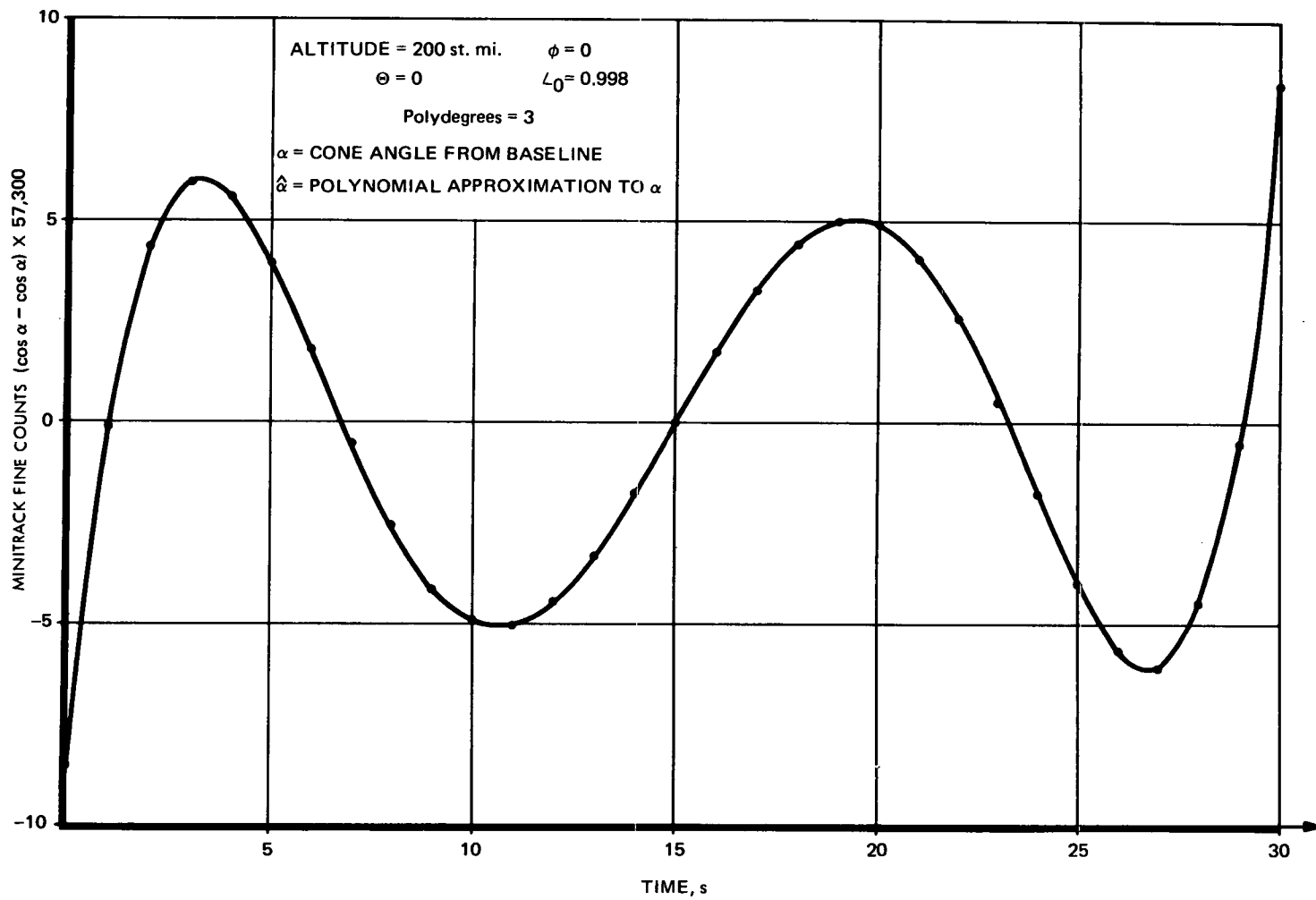


Figure 6-4.—Third-degree polynomial fitting error for circular orbit satellite of figure 6-1.

observe that the sine function, when accurately centered on the midpoint, as it is here, contains no fourth-degree term. The error, therefore, is expressed by the next higher degree polynomial. This also helps to explain why the cubic fit is so very much better than the quadratic fit. Perhaps this can be made even clearer by pointing out that the error of a first-order fit is less than half a fine count different from the function in figure 6-3. That is, a linear fit would have been just as good as a quadratic fit for this pass.

For the second case, when the orbit passes through the station zenith, but at an angle of 10° to the baseline, virtually no change takes place. The cone angle spread decreases from $\pm 19.8^\circ$ to $\pm 19.5^\circ$. This reduces the error in the fit, but not significantly. For the quadratic fit, maximum error decreases from 401 fine counts to 395 fine counts. For the cubic fit, maximum error decreases from 8.5 fine counts to 8.4 fine counts.

For the third case, when the orbit is tilted 5° away from the baseline, the net effect is to decrease the arc, again with little change in the analysis explained in the previous paragraphs. The arc decreases to $\pm 10^\circ$. In the quadratic case, this reduces the maximum error to 52 fine counts; in the cubic case the maximum error reduces to less than a fine count. These effects appear to be caused entirely by the decrease in the length of the fitting arc.

For the fourth case, the observed rule is violated. That is, that the length of the observed arc (range of Minitrack cone angle) determines the error magnitude. The fourth case shows an observed angular range of $\pm 3.39^\circ$. For a pass coming directly down the baseline (a satellite of 1100-statute-mile altitude, with a starting central angle of 0.736°), this range would give a maximum residual of only 1.7 fine counts for a quadratic fit. However, for this range on the nondominant baseline, caused by a ground track skewed to the dominant baseline, the maximum residual is 70.2 fine counts for a quadratic fit.

In this description we refer to dominant and nondominant. The term "dominant" will refer to the east-west reading or baseline if the equatorial pair is being used, or to the north-south reading or baseline if the polar pair is being used. In general then, the dominant baseline is the one that has an angle of less than 45° to the space vehicle ground track. It is also the set of readings that usually will pass through a null. The nondominant reading or baseline is the other of the pair.

The time history of the cone angle for the fourth case is shown as the heavy curved graph in figure 6-5. The time history of the cone angle for the pass of equal range but going directly down the baseline also is given in figure 6-5. The differences do not appear significant on the graph, but we must recall that one fine count is approximately 0.001° .

Notice that the down-the-baseline trace is a straight line, whereas the fourth case trace has a visible curve. Further, observe that the curvature is such that it will be accentuated when the cosine function is applied. This causes the error to be much larger than expected. In fact, the observed error of 70.2 fine counts is what would be obtained from a down-the-baseline pass with a cone angle range of $\pm 11.4^\circ$ (altitude of 350.0 statute miles and starting central angle of 0.94°).

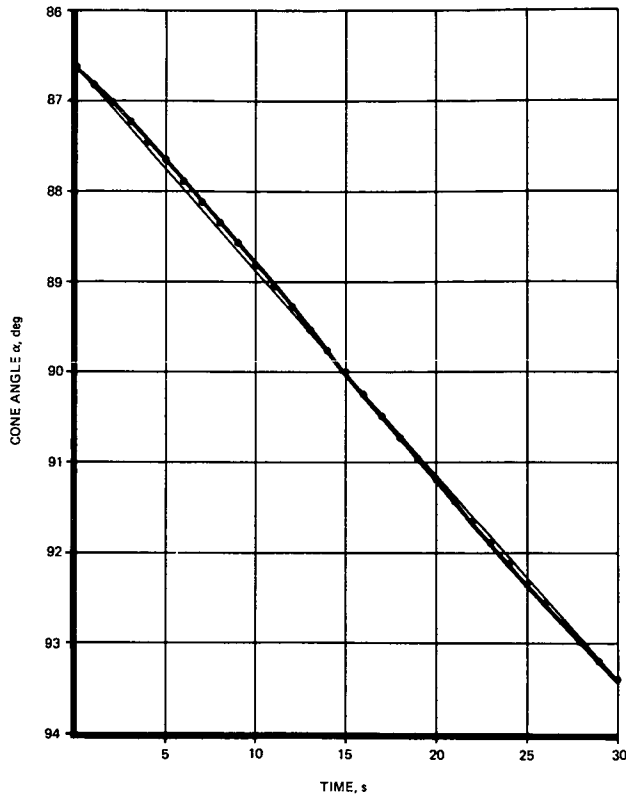


Figure 6-5.—Minitrack cone angle to fourth satellite case fitting error.

The physical causes of this nonlinearity are found in the manner in which the satellite cuts through the Minitrack cones. On the dominant antenna, it cuts the cones within 45° of normality, which tends to give a uniform rate. On the nondominant antenna, there is a tendency for the satellite, after cutting cones at a uniform rate, to become more nearly parallel to the cones, which causes the rate to change with time. This is fairly easy to see by referring to figure 6-1. Observe that if the satellite passes directly down the baseline, it remains in the degenerate cone, which is the zero-phase plane of the nondominant baseline.

In spite of the increased sensitivity of the fit to such a pass, it remains valid to investigate the residuals by investigating single-axis, down-the-baseline passes because, after all, the larger residuals occur on the dominant baseline. The cubic fit residual for this fourth case pass was only 1.5 fine counts.

For the fifth case, which is for the nondominant antenna, the orbit is tilted by 5° . The cone angle for this pass is shown in figure 6-6. Observe that this is an *even* function of time with respect to the midpoint. Therefore, the cubic fit and quadratic fit should be the same. This holds true, and the maximum residual for each is about 3.0 fine counts. Henceforth, only down-the-baseline runs will be considered.

The most important cause of large residuals is attempting to fit too large a range of cone angle. The second most important influence is the "balance" of the arc; that is, how

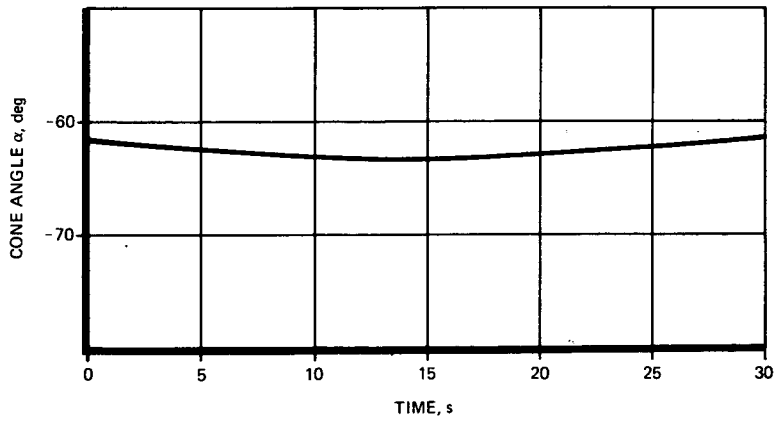


Figure 6-6.—Minitrack cone angle to fifth satellite case fitting error, 5° orbit tilt, nondominant antenna pair.

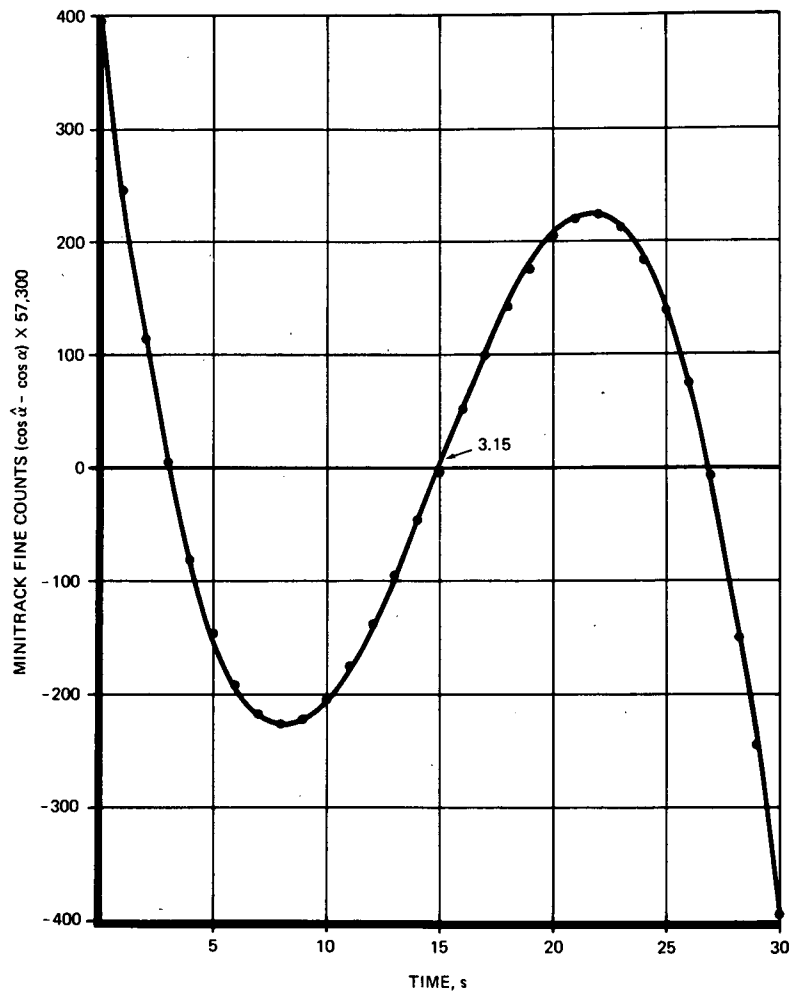


Figure 6-7.—Quadratic fitting error for first case displaced by 1 s.

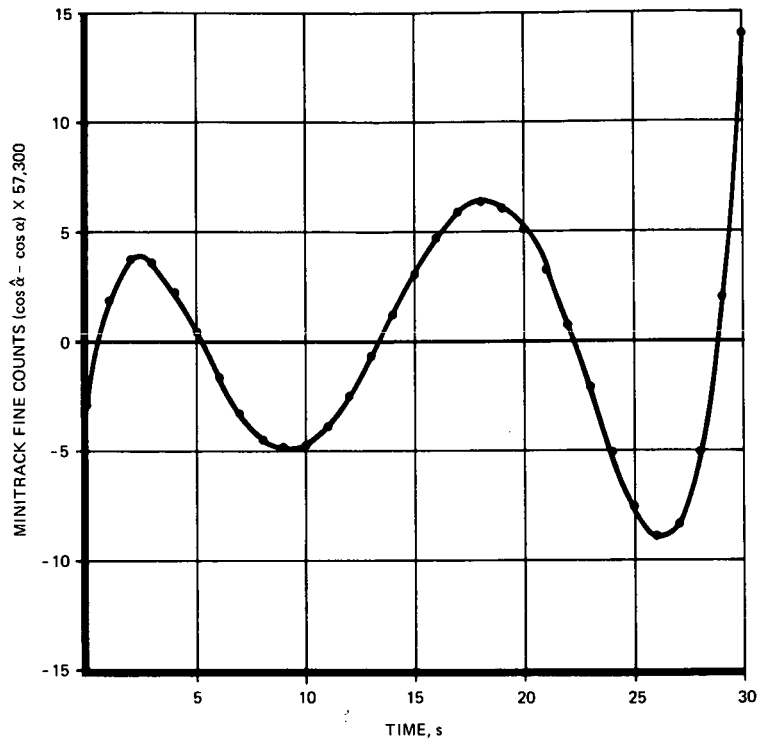


Figure 6-8.—Cubic fitting error for first case displaced by 1 s.

closely the center frame approximates the null point of the direction cosine. In this connection, we recall that the operational techniques at the Minitrack site are designed to place the midpoint of the 31 frames to within one frame interval of the baseline crossover time. As a result, this study will be restricted to passes that are “out of balance” by one frame at most.

Consider the first case run displaced by 1 s. The residuals for the quadratic fit are plotted in figure 6-7, and the residuals for the cubic fit are plotted in figure 6-8. The interesting point is that the error at the midpoint for both fits is the same despite the fact that the overall cubic fit is much better than the overall quadratic fit. This is explained, of course, by the fact previously referred to (i.e., that the center point is a good point at which to sample a quadratic approximation, whereas it is not so good a point at which to sample for a cubic fit).

In figure 6-8, the error curve is shifting toward a Legendre polynomial of the fourth degree. As the arc becomes even more off-balance, the fourth-degree terms will be more significant, and the residual at the center point and end points will continue to increase. The quadratic error at the center point will be approximately that of the cubic fit (in this case 3.1554 versus 3.1545), but the cubic end point errors will be much smaller.

As in the balanced arc cases, the results are essentially the same for the first and second cases.

Because the arcs for the third and fourth cases are quite short, the 1-s lag introduces no significant error change.

In the fifth case, the increase in residual is insignificant for the cubic fit. The quadratic fit becomes poorer and increases the end point residual to 4.3 fine counts. This is caused by the introduction of third-order terms that the cubic can handle but the quadratic cannot.

Because the hardware errors of the Minitrack system appear in practice to be slightly more than 2.0 fine counts, that value will be considered as an allowable residual. The unbalancing of the arc will be increased to 2 s to allow for some extra carelessness on the part of the operator and to account for all noncircular orbits of interest. This value is based on the relationship between the angular rate at any radius for a parabolic orbit and a circular orbit, a ratio of 2. Because we have doubled the probable unbalancing of an arc of a circular orbit, we should be quite conservative with orbits with eccentricity as high as 1 (i.e., parabolic orbits).

The following important questions concerning fit procedures for the cubic approximation can now be treated:

- (1) At what arc length does the center point become unacceptable?
- (2) At what arc length do the end points become unacceptable?
- (3) What is the graphic representation of the magnitude of the residuals on the dominant axis as a function of arc length?
- (4) What can be said about residuals on the nondominant axis?

The answers to all these questions are available in figure 6-9.

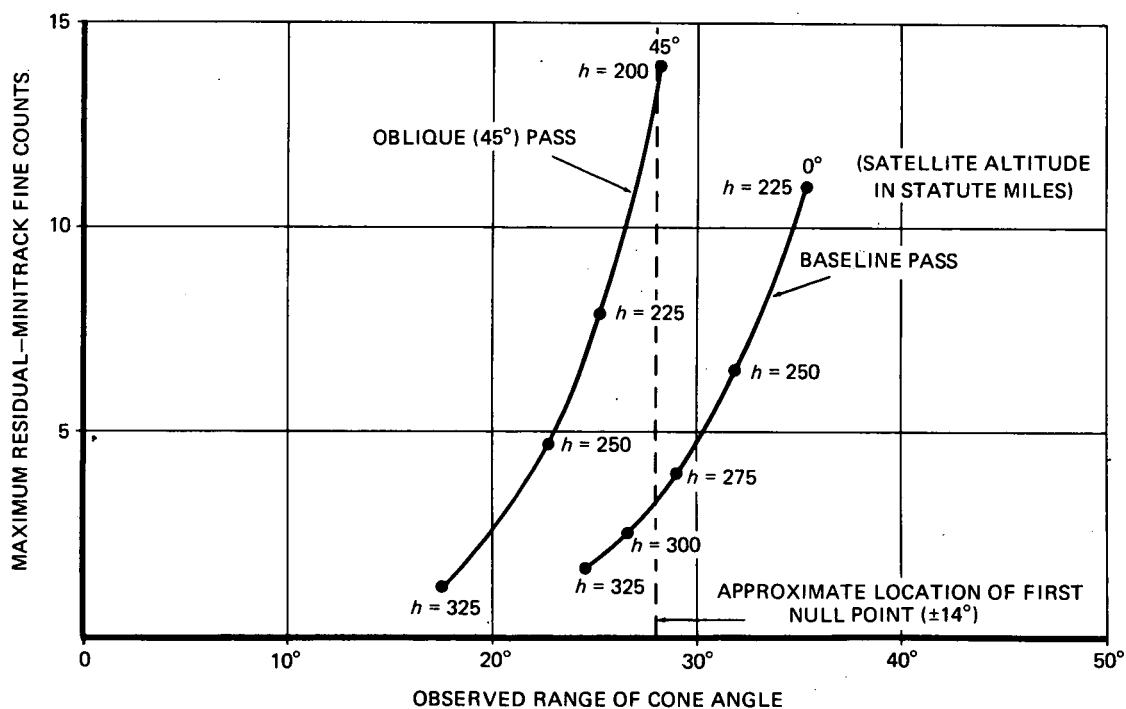


Figure 6-9.—Error residual of a cubic polynomial fit.

The residuals or errors that are plotted are the maximum absolute value difference between real values and polynomial approximation as obtained from a cubic polynomial fit. These errors occur, of course, at the end of the fitting interval. For convenience, the errors have been expressed in Minitrack fine counts, as in previous figures.

All residuals are obtained from arcs that are out of balance by 2 s. The errors for the same arc unbalanced by 1 s may be obtained with an accuracy of nearly two decimal places by dividing the plotted errors by 1.4. To about the same accuracy, the errors at the center point of these arcs can be obtained by dividing the given numbers by 3.1.

The curve on the right, marked 0° , gives the residuals for an arc passing directly down the baseline (that is, one making an angle of 0° with the baseline). The independent variable is then the total angle through which the spacecraft, as seen from the station, passes in 30 s. For instance, a satellite with an altitude of 275 statute miles shows a cone angle range of about 29° . This corresponds to the cone angle extremes of 77.4° and 106.4° .

The left-hand curve, marked 45° , gives the residuals for an arc intersecting the baseline at about 44° . Such a pass will give the maximum residuals for a given range of cone angle. Notice that here the arc is not the total arc over the station, but only the arc as seen by the dominant baseline. For instance, the total arc over the station for both satellites having $h = 250$ is the same, about 32° . In the pass at an angle of 45° , however, the observed range is only 22.7° , or about $0.707 \times 32.0^\circ$.

The vertical line on figure 6-9 shows the approximate location of the antenna lobe null. As is stated elsewhere in this report, great care should be exercised in using Minitrack data obtained from runs that extend beyond this point. If we assume that all runs are obtained from passes lying within this region, the theoretical limits on end point residuals are easy to see; after using the divisor 3.1 to obtain center point residuals, we find that virtually all satellites can be handled with less than three Minitrack fine counts error at the center point.

All the results of this study indicate that residuals on the nondominant baseline will be less than those on the dominant baseline.

Some remarks should be made concerning the selection of sample points. We have mentioned that the center point is not an optimal point for sampling a cubic fit. In general (that is, with no knowledge of the particular case), this is true, and we should evaluate the fit at the zeros of $P_4(x)$. This yields $x_1 = 2.1$ s; $x_2 = 9.9$ s; $x_3 = 20.1$ s; and $x_4 = 27.9$ s. In particular, we might choose to evaluate the fit at x_2 or x_3 rather than at the center point. However, in this application, we know that the arc will be rather accurately centered; thus, the error at the center point will be small. As a tactical consideration (from fig. 6-8) then, the x_2 and x_3 points will remain worse than $t = 15$ for the full magnitude of unbalancing that we expect. Therefore, it does not make sense to change the present procedure of favoring midpoint sampling.

With regard to the end point sampling, however, there is no doubt that residuals could be reduced considerably by sampling at the 3rd and 29th frames rather than at the 1st and 31st. The only disadvantage to this is that it does not maximize the time between

observations (observability) for the use of the ODP. This consideration is not covered in the present investigation, but it seems hardly possible that it could outweigh the reduction of end point residuals to the same magnitude as those at the center point.

THE SMOOTHING SIMULATOR

A listing of the computer program that was developed for simulation and evaluation of the Minitrack preprocessing program smoothing routines is reproduced here (fig. 6-10). This time-sharing FORTRAN IV program may be copied in machine-readable form by anyone wishing to perform additional analyses of the smoothing functions of the Minitrack preprocessor. The program in eight-level, ASCII code in 1-in., punched paper tape may be obtained from the authors.

As discussed in the chapter on the preprocessor data smoothing, this simulator answers questions on how well ideal consecutive interferometer phase readings are approximated by the smoothing subroutines of the preprocessing program. In essence, the simulator possesses the equations that describe the temporal and spatial positions of spacecraft in circular orbit about the Earth at any inclination and skew angle to a Minitrack interferometer antenna pair baseline. The simulation program then operates the same least-squares polynomial fitting procedures used in the Minitrack preprocessing program and attempts thereby to approximate the circular orbit. A residual is generated for each data point in the tracking arc. This residual, then, is an indicator of the goodness of fit of the polynomial and measures a specific kind of error in the Minitrack system, one that is introduced by the data processing itself.

In running the Minitrack smoothing simulator, the operator may select the degree of the smoothing polynomial, the skew angle of the orbit (i.e., the angle between the dominant baseline and the suborbital track), the tilt angle of the orbit (i.e., the angle between the station zenith and the orbital plane), the altitude of the spacecraft, and the starting central angle, which controls the "centering" of the 31-frame message on the baseline crossing. Each run of the program simulates one noiseless data Minitrack pass under the conditions set by the five inputs controlled by the experimenter. Any or all of these input orbital pass and smoothing conditions may be varied to evaluate the residuals of each case desired.

The simulator duplicates all the elements of orbital space flight significant to Minitrack tracking and the smoothing evaluation. The limitation to circular orbits only and the neglect of the Earth's rotational effects have no bearing on the significance of the simulation.

We have duplicated a sample run of the simulator to illustrate the format (fig. 6-11). At RUN, the program asks for each of the five independent variables:

- (1) The number 4 is inputted to indicate the order of the fitting (smoothing) polynomial plus one (or, specifically, the number of terms in the polynomial). In this case, the number 4 sets up the simulator for the cubic fit condition.
- (2) The number 0.1746 is a 10° skew angle expressed in radians.

```

850 SUBROUTINE GINV2 (A,U,AFLAG,ATEMP,MR,NR,NC)
860 DIMENSION A(MR,NC),U(NC,NC),AFLAG(NC),ATEMP(NC)
870 D0 10 I = 1, NC
880 D0 5 J = 1, NC
890 U(I,J) = 0
900 U(J,I) = 0
910 5 CONTINUE
920 10 U(I,I) = 1.
930 CALL DOT(A(1,1), A(1,1), NR, FAC)
940 FAC = 1.0/SQRT(FAC)
950 D0 15 I = 1, NR
960 15 A(I,1)=A(I,1)*FAC
970 D0 20 I = 1, NC
980 20 U(1,I)=U(1,I)*FAC
990 AFLAG(1)=1.0
1000 * TOL IS THE THRESHOLD ZERO.
1010 TOL = 1.E-12
1020 D0100 J=2,NC
1030 J = J
1040 CALL DOT(A(1,J), A(1,J), NR, DOT1)
1050 JM1 = J-1
1060 D0 50 L=1,2
1070 D0 30 K=1,JM1
1080 L=L
1090 K = K
1100 J=J
1110 CALL DOT(A(1,J), A(1,K), NR, ATEMP(K) )
1120 30 CONTINUE
1130 D0 45 K=1,JM1
1140 D0 35 I=1,NR
1150 35 A(I,J)=A(I,J)-ATEMP(K)*A(I,K)*AFLAG(K)
1160 D0 40 I=1,NC
1170 40 U(I,J)=U(I,J)-ATEMP(K)*U(I,K)
1180 45 CONTINUE
1190 50 CONTINUE
1200 J = J
1210 CALL DOT(A(1,J), A(1,J), NR, DOT2 )
1220 IF(DOT2/DOT1)-TOL) 55,55,70
1230 55 D0 60 I=1,JM1
1240 ATEMP(I)=0.0
1250 D0 60 K=1,I
1260 60 ATEMP(I)=ATEMP(I)+U(K,I)*U(K,J)
1270 D0 65 I=1,NR
1280 A(1,J)=0.0
1290 D0 65 K=1,JM1
1300 65 A(1,J)=A(1,J)-A(1,K)*ATEMP(K)*AFLAG(K)
1310 AFLAG(J)=0.0
1320 J = J
1330 CALL DOT(U(1,J), U(1,J), NC, FAC)
1340 FAC = 1.0/SQRT(FAC)
1350 D0 75
1360 70 AFLAG(J) = 1.0
1370 FAC= 1.0/SQRT(DOT2)
1380 75 D0 80 I=1,NR
1390 80 A(I,J) = A(I,J)*FAC
1400 D0 85 I=1,NC
1410 85 U(I,J) = U(I,J)*FAC
1420 100 CONTINUE
1430 D0 130 J=1,NC
1440 D0 130 I=1,NR
1450 FAC=0.0
1460 D0 120 K=J,NC
1470 120 FAC=FAC+A(I,K)*U(J,K)
1480 130 A(I,J) = FAC
1490 RANK=0
1500 D0 132 J=1,NC
1510 RANK=RANK+AFLAG(J)
1520 132 CONTINUE
1530 WRITE(9,133) RANK
1540 133 FORMAT( 3X,7HRANK = .,1E15.8)
1550 RETURN
1560 END
1570 SUBROUTINE DOT(X,Y,NR,FAC)
1580 DIMENSION X(50),Y(50)
1590 FAC = 0
1600 D0 900 I = 1,NR
1610 FAC = FAC + X(I)*Y(I)
1620 900 CONTINUE
1630 RETURN
1640 END

```

Figure 6-10.—The smoothing simulator program.

```

10 DIMENSION A(50,20), AFLAG(20), ATEMP(20), U(20,20)
20 DIMENSION ALFA(31), DELT(31)
30 DIMENSION B(5), CDELT(31), FCDELT(31)
40 * MINITRACK SIMULATOR
50 * THE VARIABLE K IS THE DEGREE OF THE FIT POLY PLUS ONE.
60 * AT PRESENT K MAY TAKE THE VALUES 2, 3, 4.
70 READ(9,397) K
80 397 FORMAT(I5)
90 DO 160 I = 1,5
100 B(I) = 0
110 160 CONTINUE
120 READ(9,396) THETA
130 CSTH = COS(THETA)
140 SNTH = SIN(THETA)
150 READ(9,396) PHI
160 CSPH = COS(PHI)
170 SNPH = SIN(PHI)
180 * PHI IS THE ANGLE BETWEEN ZENITH AND ORBIT PLANE
190 * THETA IS THE ANGLE BETWEEN THE ORBIT PLANE AND THE BASELINE
200 DO 100 I = 1,31
210 A(I,1) = 1.
220 XI = 1
230 A(I,2) = XI - 16.
240 A(I,3) = A(I,2)**2
250 A(I,4) = A(I,2)*A(I,3)
260 100 CONTINUE
270 READ(9,396) H
280 396 FORMAT(E20.8)
290 READ(9,396) X
300 CALL GIRV2(A,U,AFLAG,ATEMP,50,31,K)
310 * THE VARIABLE X IS THE STARTING VALUE OF THE CENTRAL ANGLE.
320 * THE CENTRAL ANGLE STARTS AT X AND DECREASES.
330 ALFA(1) = X/57.29578
340 XOM = (5280.0*(3960.0+H))**3
350 XOM = 1.0/SQRT(XOM/1.4E16)
360 WRITE(9,396) XOM
370 150 DO 200 I = 1,31
380 XI = I
390 * THE VARIABLE XOM IS THE ORBITAL ANGULAR RATE IN RAD/SEC.
400 ALFA(I) = ALFA(1) - (XI-1.)*XOM
410 X = SIN(ALFA(I))
420 Y = COS(ALFA(I))
430 * THE VARIABLE H IS THE ALTITUDE OF THE ORBIT IN STATUTE MILES.
440 R1 = 3960.0 + H
450 X3 = R1*Y+CSPH - 3960.0
460 X = R1*X
470 X2 = R1*Y*SNPH
480 X1 = X*CSTH - X2*SNTH
490 X2 = X*SNTH + X2*CSTH
500 CDELT(I) = X1/SQRT(X1*X1+X2*X2+X3*X3)
510 DELT(I) = CDELT(I)/SQRT(1.0-CDELT(I)**2)
520 DEL(I) = ATAN(CDELT(I))
530 200 CONTINUE
540 DO 300 I = 1, K
550 B(I) = 0
560 DO 310 J = 1, 31
570 B(I) = A(J,I)*CDELT(J) + B(I)
580 310 CONTINUE
590 WRITE(9,399) B(I)
600 300 CONTINUE
610 DO 400 I = 1,31
620 XI = I
630 X = (XI-16.)
640 FCDELT(I) = X*(X*(X*(X*(4) + B(3) ) + B(2) ) + B(1)
650 ERRFC = 57300.*(FCDELT(I)-CDELT(I))
660 * ERRFC IS THE RESIDUAL IN FINE COUNTS
670 Y = DELT(I)*57.29578
680 X = ALFA(I)*57.29578
690 * X AND Y ARE RESPECTIVELY THE SATELLITE CENTRAL ANGLE
700 * AND DECLINATION ANGLE.
710 WRITE(9,399)X,Y,I
720 399 FORMAT(X,2E15.6,I5)
730 * CDELT AND FCDELT ARE THE SINES OF THE ACTUAL AND THE
740 * FITTED DECLINATION ANGLE.
750 WRITE(9,395)CDELT(I), FCDELT(I),ERRFC
760 395 FORMAT(X,3E15.6)
770 WRITE(9,398)
780 398 FORMAT(X)
790 400 CONTINUE
800 WRITE(9,398)
810 WRITE(9,398)
820 ALFA(1) = ALFA(2)
830 GO TO 150
840 END

```

Figure 6-10 (concluded).—The smoothing simulator program.


```

I 4
I 0.1746
I 0.0
I 200.
I 0.922144

```

```

RANK = 0.40000000F 01
0.11494050E-02
-0.234269E-01
-0.234945E-01
0.167499E-04
0.576096E-05
0.922144E 00 0.182627E 02 1
0.313374E 00 0.313325E 00 -0.279034E 01

0.856288E 00 0.170344E 02 2
0.292945E 00 0.292979E 00 0.191942E 01

0.790432E 00 0.157903E 02 3
0.272118E 00 0.272182E 00 0.369540E 01

0.724576E 00 0.145312E 02 4
0.250907E 00 0.250970E 00 0.359636E 01

0.658720E 00 0.132580E 02 5
0.229336E 00 0.229376E 00 0.228999E 01

0.592864E 00 0.119717E 02 6
0.207428E 00 0.207436E 00 0.452533E 00

0.527008E 00 0.106734E 02 7
0.185210E 00 0.185164E 00 -0.149080E 01

0.461152E 00 0.936420E 01 8
0.162709E 00 0.162654E 00 -0.317286E 01

0.395296E 00 0.804537E 01 9
0.139957E 00 0.139881E 00 -0.434944E 01

0.329440E 00 0.671808E 01 10
0.116984E 00 0.116900E 00 -0.480710E 01

0.263583E 00 0.538378E 01 11
0.938264E-01 0.937453E-01 -0.465170E 01

0.197727E 00 0.404368E 01 12
0.705170E-01 0.704511E-01 -0.377908E 01

0.131871E 00 0.269929E 01 13
0.470942E-01 0.470522E-01 -0.240483E 01

0.660153E-01 0.135292E 01 14
0.235950E-01 0.235832E-01 -0.673464E 00

0.159229E-03 0.324165E-02 15
0.569265E-04 0.786556E-04 0.124509E 01

-0.656968E-01 -0.134549E 01 16
-0.234811E-01 -0.234269E-01 0.310626E 01

-0.131553E 00 -0.262979E 01 17
-0.469807E-01 -0.468988E-01 0.469226E 01

-0.197409E 00 -0.403719E 01 18
-0.704040E-01 -0.703026E-01 0.580694E 01

-0.263265E 00 -0.537728E 01 19
-0.937136E-01 -0.936037E-01 0.629534E 01

-0.329121E 00 -0.671167E 01 20
-0.116873E 00 -0.116768E 00 0.605114E 01

-0.394977E 00 -0.803897E 01 21
-0.139847E 00 -0.139760E 00 0.499494E 01

-0.460833E 00 -0.935789E 01 22
-0.162601E 00 -0.162545E 00 0.319506E 01

-0.526689E 00 -0.106671E 02 23
-0.185102E 00 -0.185090E 00 0.695023E 00

-0.592545E 00 -0.119655E 02 24
-0.207322E 00 -0.207359E 00 -0.212093E 01

-0.650401E 00 -0.132518E 02 25
-0.229231E 00 -0.229318E 00 -0.499153E 01

-0.724257E 00 -0.145250E 02 26
-0.250803E 00 -0.250932E 00 -0.739422E 01

-0.790113E 00 -0.157642E 02 27
-0.272015E 00 -0.272167E 00 -0.669547E 01

-0.855970E 00 -0.170294E 02 28
-0.292845E 00 -0.292988E 00 -0.821732E 01

-0.921826E 00 -0.182567E 02 29
-0.313275E 00 -0.313361E 00 -0.492493E 01

-0.987681E 00 -0.194683E 02 30
-0.333285E 00 -0.333251E 00 0.197407E 01

-0.105354E 01 -0.206427E 02 31
-0.352866E 00 -0.352823E 00 0.138902E 02

```

Figure 6-11.—Smoothing simulator sample results.

- (3) The number 0.0 is a zero tilt angle. This input must be expressed in radians.
- (4) The number 200. is the altitude of the spacecraft in statute miles.
- (5) The number 0.922144 is the starting central angle in degrees. This is the situation in the text in which the arc is out of balance by 1 s. If a balanced arc is desired, the number 0.988 should be used.

In the course of processing, the simulator generates the six consecutive numbers down the page after the word RANK:

- (1) The rank, namely, order of polynomial plus one, just inputted
- (2) The angular rate of the satellite in circular orbit as a function of the Earth's central angle in radians per second
- (3) The constant term of the fitting polynomial
- (4) The first-degree term of the polynomial (rate)
- (5) The second-degree term of the polynomial (acceleration)
- (6) The third-degree term of the polynomial (jerks)

The remainder of the printout is the bulk of the outputted data arranged in batches of six numbers each, a batch for each of the 31 frames of the Minitrack message. The following numbers are exhibited from left to right on the top row of each batch:

- (1) The central angle of the spacecraft from culmination in degrees
- (2) The complement of the cone angle in degrees
- (3) The frame (batch) number

On the second row of each batch, from left to right, may be seen—

- (1) The cosine of the cone angle (direction cosine)
- (2) The fitted cosine of the cone angle
- (3) The residual in Minitrack fine counts (57 300 times the value of the fitted cosine of the cone angle minus the cosine of the cone angle)

Section 7

GLOSSARIES

PROGRAM MIN-B

AB. (1) The phase of the east-west artificial half-wavelength baseline obtained by subtraction of the coarse (4.0λ) and medium (3.5λ) baseline phase readings;

$$AB = EWMBB - EWCBB$$

(2) For all later operations, the integer in **AB** is truncated by the use of **LDIF** and goes through subroutine **NORMAL** so that only the decimal portion is used. (See also **BC**.)

AB3. Estimated phase reading for the east-west coarse (3.5λ) baseline determined from the artificial half-wavelength baseline;

$$AB3 = AB*7$$

(See also **BC3**.)

AB4. Estimated phase reading for the east-west medium (4.0λ) baseline determined from the artificial half-wavelength baseline;

$$AB4 = AB*8$$

(See also **BC4**.)

ABB. Twice the phase difference of the east-west artificial half-wavelength baseline,

$$AB*2,$$

or equivalently, the phase difference for a unit-wavelength baseline. (See also **ABC**.)

ABC. Twice the phase difference of the north-south artificial half-wavelength baseline,

$$BC*2,$$

or equivalently, the phase difference for a unit-wavelength baseline.

ACORE. The phase reading per unit wavelength of the east-west artificial 7.5λ baseline;

$$ACORE = \frac{CORE}{7.5}$$

(See also **ACORN**.)

Preceding page blank

ACORN. The phase reading per unit wavelength of the north-south artificial 7.5λ baseline;

$$\text{ACORN} = \frac{\text{CORN}}{7.5}$$

(See also **ACORE.**)

ACOS. The direction cosine of the satellite with respect to the east-west baseline at the midframe;

$$\text{ACOS} = \frac{\text{EWLOBE}}{(\text{FREQ}/136.) * \text{ANT}}$$

(See also **BCOS.**)

ADE. The phase reading per unit wavelength of the east-west medium baseline;

$$\text{ADE} = \frac{\text{DE}}{4}$$

(See also **AFG.**)

ADE3. The phase reading per unit wavelength of the east-west coarse baseline;

$$\text{ADE3} = \frac{\text{DE3}}{3.5}$$

(See also **AFG3.**)

AEWLOB. The phase reading per unit wavelength of the east-west fine baseline;

$$\text{AEWLOB} = \frac{\text{EWLOBE}}{\text{ANT}}$$

(See also **ASNLOB.**)

AFG. The phase reading per unit wavelength of the north-south medium baseline;

$$\text{AFG} = \frac{\text{FG}}{4}$$

(See also **ADE.**)

AFG3. The phase reading per unit wavelength of the north-south coarse baseline;

$$\text{AFG3} = \frac{\text{FG3}}{3.5}$$

(See also **ADE3.**)

ALPHA. Constant coefficient in both the least-squares quadratic solution for the ambiguity phase readings and the least-squares cubic solution for the fine phase readings:

$$\text{phase}_{\text{amb}} = \alpha + \beta T + \gamma T^2$$

$$\text{phase}_{\text{fine}} = \alpha + \beta T + \gamma T^2 + \delta T^3$$

hence, it is used for all six baselines. (See also EWCB, EWCC, EWMB, EWMC, SNCB, SNCC, SNMB, SNMC, EWFB, EWFC, EWFE, SNFB, SNFC, SNFE.)

AM. (1) The fitted phase reading for the east-west medium baseline equal to the raw phase reading at the midframe time EWMA plus the phase reading of the east-west medium baseline at the desired frame time relative to the midframe time which is calculated from the least-squares fit of the east-west medium raw data;

$$\text{AM} = \text{EWMD}(\text{MID}) + \alpha + \beta T + \gamma T^2$$

(2) The deviation of the above AM from the raw phase reading of the actual (Ith) frame desired;

$$\text{AM} = \text{EWMD}(\text{I}) - \text{AM}$$

(See also AN, AO, AP, AQ, AR.)

AMIN. Number of minutes of the east-west fine time (EWFT) for the midframe starting at the beginning of the day of observation (includes only the minutes after the hour; therefore, AMIN < 60). (See also HOUR, SECN.)

AN. Similar to AM except applies to the east-west coarse baseline. (See also AO, AP, AQ, AR.)

ANT. Length of the fine baseline in vacuum wavelengths; i.e.,

$$\text{ANT} = \begin{cases} 57.0 & \text{for the polar array (ANTD} = 2) \\ 46.0 & \text{for the equatorial array (ANTD} = 1) \end{cases}$$

ANTD. Single-digit discriminator formed from the input data array DATA, which specifies which of the two fine antenna-array baseline configurations was employed;

$$\text{ANTD} = \text{DATA}(54) = \begin{cases} 1 & \text{for the equatorial array} \\ 2 & \text{for the polar array} \end{cases}$$

(See also ANT.)

AO. Similar to AM except applies to the east-west fine baseline. (See also AN, AP, AQ, AR.)

AOUR. A seven-element array for storing and transferring to the second program OBS-B the six-digit time of day HOUR after HOUR has been converted to hexadecimal form in subroutine ZERO.

AP. Similar to **AM** except applies to the north-south medium baseline. (See also **AN, AO, AQ, AR.**)

AQ. Similar to **AM** except applies to the north-south coarse baseline. (See also **AN, AO, AP, AR.**)

AR. Similar to **AM** except applies to the north-south fine baseline. (See also **AN, AO, AP, AQ.**)

ARMODA. A seven-element array for storing and transferring to the second program **OBS-B** the six-digit calendar date **YRMODA**, which gives the year, month, and day of the satellite pass. The array **ARMODA** stores **YRMODA** in hexadecimal form (subroutine **ZERO.**)

ASEC. Number of milliseconds of the east-west fine time (**EWFT**) for the midframe starting at the beginning of the day of observation (includes just the milliseconds after the hour and minute **HOUR** and **AMIN**; thus, $ASEC < 60,000$).

Defining statement: $ASEC = SECN * 1000$

(See also **SECN, HOUR, AMIN.**)

ASK. The hexadecimal representation (**Z5C404040**) for an asterisk that is entered in the program through a data statement used as a code for the use of a narrowband filter. (See also **AST(1).**)

ASNLOB. The phase reading per unit wavelength of the north-south fine baseline;

$$ASNLOB = \frac{SNLOBE}{ANT.}$$

(See also **AEWLOB.**)

AST(1). Coded indicator for the filter used in the calibration frame;

$$AST(1) = \begin{cases} SPA & \text{for a 10-Hz filter if } CANT = 2 \\ ASK & \text{for a narrowband filter if } CANT > 2 \\ PER & \text{for a 2-Hz filter if } CANT = 0 \end{cases}$$

(See also **CANT.**)

AST(2). Array identifier;

$$AST(2) = \begin{cases} POL & \text{if } ANT = 57.0 \\ EQ & \text{if } ANT = 46.0 \end{cases}$$

AST(3). A coded element to indicate the frame rate used in taking the data;

$$\text{AST}(3) = \begin{cases} \text{F1 if 1 frame/s} \\ \text{F2 if 1 frame/2 s} \\ \text{F3 if 1 frame/10 s} \\ \text{F4 if 1 frame/20 s} \\ \text{F5 if 1 frame/60 s} \\ \text{F6 if 1 frame/120 s} \\ \text{F7 if 1 frame/600 s} \end{cases}$$

AST(4). (1) Indicator of the quality of the scatter or standard deviations for the north-south baselines from the least-square fits of the north-south phase data. If either the standard deviation **SD** of the north-south fine data is greater than 0.05 phase unit or the deviation of the north-south coarse or medium data, **ISNCER** and **ISNMER**, is greater than 0.50 phase unit in absolute value, the indicator **AST(4) = F2** is set which implies an intermediate quality data. If none of the three limits is exceeded, the indicator **AST(4) = SPA** is set which implies high-quality data. (2) If **AST(4) = F2** and **AST(6) = F1**, then **AST(4)** and **AST(6)** are set equal to **F3**. This implies a low-quality data set. (See also **AST(6)**, **F1**, **F2**, **SPA**, **ISNMER**, **ISNCER**.)

AST(6). Similar to **AST(4)** but applies to the east-west baselines occurring earlier in program; however,

$$\text{AST}(6) = \begin{cases} \text{F1 if east-west medium or coarse phase count is 100} \\ \text{F2 if north-south medium or coarse phase count is 100} \end{cases}$$

(See also **AST(4)**, **IEWMER**, **IEWCER**.)

ASTA. A three-element array used for the storage and subsequent transfer of the Minitrack station identification number to program **OBS-B**. This identification number in the form of term **CSTA** is a hexadecimal output of subroutine **ZERO**. (See also **CSTA**.)

BC. (1) The phase of the north-south artificial half-wavelength baseline obtained by subtraction of the coarse (4.0λ) and medium (3.5λ) baseline phase readings;

$$\text{BC} = \text{SNMBB} - \text{SNCBB}$$

(2) For all later operations the integer portion of **BC** is truncated by the use of **LDIF** and goes through subroutine **NORMAL** so that only the decimal portion is used. (See also **AB**.)

BCOS. The direction cosine with respect to the north-south baseline at the midframe;

$$\text{BCOS} = \frac{\text{SNLOBE}}{\text{ANT} * \text{FREQ}/136.}$$

BC3. Estimated phase reading for the north-south coarse (3.5λ) baseline determined from the artificial half-wavelength baseline;

$$\text{BC3} = \text{BC} * 7$$

(See also **AB3**.)

BC4. Estimated phase reading for the north-south medium (4.0λ) baseline determined from the artificial half-wavelength baseline;

$$AB4 = AB*8$$

(See also **AB4**.)

BIN. Hexadecimal representation (**ZFO**) for a zero which is entered in the program through a **DATA** statement.

BOUR. A single variable constructed to store both the number of hours **HOUR** and the number of minutes **AMIN** of the east-west fine time (**EWFT**);

$$BOUR = HOUR*100 + AMIN$$

(i.e., 3 hours 49 minutes = 0349 = **BOUR**)

C0, C1, C2, C3, C4, C5, C6, C7, C8. Input station coefficients determined from a previous calibration process for each station for the antenna-field correction for the fine phase resulting from the position of the satellite within the interferometer array pattern. Four sets are needed, east-west and north-south equatorial baselines and east-west and north-south polar baselines.

CANT. Single-digit filter indicator for the calibration frame read from the input tape data array (**CANT** = **DATA(54)**). The filter is a manually operated Minitrack equipment option. The technician indicates in the Minitrack message which filter he has used for each pass.

$$CANT = \begin{cases} 0 & \text{if 2-Hz filter used} \\ 2 & \text{if 10-Hz filter used} \\ 3 & \text{if narrowband filter used} \end{cases}$$

CEWC. (1) The raw phase reading of the east-west coarse baseline for the calibration frame (form **.XX**). (2) The same notation is used after the algebraic combination with the station bias $K_c - K_1$ for the east-west coarse baseline (given by **EW**);

$$CEWC = EW(L) + CEWC.$$

(3) The same notation is used after the incrementation to include the east-west coarse cable-length-inequality phase correction **CLEWC**,

$$CEWC = \frac{(CLEWC(L))}{.846*(136.5 - \text{FREQ}) + CEWC}$$

(See also **CEWM, CNSC, CNSM**.)

CEWF1, CEWF2, CEWF3, CEWF4, CEWF5. (1) The five raw phase readings of the east-west fine baseline in the calibration frame (form **.XXX**). (2) The same notation is used after the algebraic addition with the east-west fine station bias (either **EWFEQ** or **EWFP** for the equatorial or polar arrays, respectively). (3) The five corrected values

from definition (2) are combined into one value by the compression formula represented by **CEWF1**. (See also **CNSF1**, . . . , **CNSF5**.)

CEWM. Similar to **CEWC** except that **CEWM** refers to the east-west medium baseline reading in the calibration frame with its own particular station bias **EWM** and cable-length inequality **CLEWMC** (form .XX).

CLEWC. Cable-length inequality for the east-west coarse baseline given in feet. A positive number implies that the cable for the east array is longer than that for the west array. A negative number signifies that the west array cable is longer. (No such inequality exists for the two cables of each fine baseline, which are cut and pruned to the same electrical length.)

$$\text{Correction} = \frac{\text{cable-length inequality}}{\text{velocity of propagation}} \times (136.5 - \text{FREQ}) \times 10^6 \quad \text{cycles}$$

(See also **CLEWM**, **CLNSC**, **CLNSM**.)

CLEWM. Similar to **CLEWC** except applies to the cable-length inequality for the east-west medium baseline.

CLNSC. Similar to **CLEWC** except applies to the cable-length inequality for the north-south coarse baseline.

CLNSM. Similar to **CLEWC** except applies to the cable-length inequality for the north-south medium baseline.

CNSC. Similar to **CEWC** except refers to the north-south coarse baseline phase reading in the calibration frame with its own particular station bias **NSC** and cable-length inequality **CLNSC** (form .XX).

CNSF1, **CNSF2**, **CNSF3**, **CNSF4**, **CNSF5**. (1) The five raw phase readings of the north-south fine baseline in the calibration frame (form .XXX). (2) Same notation used after algebraic addition with the north-south fine station bias (either **NSFEQ** or **NSFPO** for the equatorial or polar arrays, respectively). (3) The five corrected values from definition (2) are combined into one value by the compression formula represented by **CNSF1**. (See also **CEWF1**, . . . , **CEWF5**.)

CLNSM. Similar to **CEWC** except refers to the north-south medium baseline phase reading in the calibration frame with its own particular station bias **NSM** and cable-length inequality **CLNSM** (form .XX).

CORE. The absolute phase reading for the east-west artificial 7.5λ baseline constructed from the sum of the absolute phases of the medium (4.0λ) and coarse (3.5λ) baselines;

$$\text{CORE} = \text{DE} + \text{DE3}$$

(See also **CORN**.)

COREF. Estimated east-west fine phase reading determined from the artificial 7.5λ baseline and the direct proportionality of phase and baselength;

$$\text{COREF} = \frac{\text{CORE*ANT}}{7.5}$$

(See also **CORNF.**)

CORN. The absolute phase reading for the north-south artificial 7.5λ baseline constructed from the sum of the absolute phases of the medium (4.0λ) and coarse (3.5λ) baselines;

$$\text{CORN} = \text{FG} + \text{FG3}$$

(See also **CORE.**)

CORNF. Estimated north-south fine phase reading determined from the artificial 7.5λ baseline and the direct proportionality of phase and base length;

$$\text{CORNF} = \frac{\text{CORN*CANT}}{7.5}$$

(See also **COREF.**)

CSTA. A two-digit station identification number formed from the calibration line of the input data tape for the purpose of verifying **KSTA** from the input cards. (See also **ASTA.**)

D. Auxiliary variable used to convert the coarse, medium, and fine phase readings in their alphameric form in the array **DATA** to usable numeric quantities in all the calibration and data frames.

DATA. An alphameric array, 65×1 , for storing the input tape data. It is used to verify the format of the satellite identification line, the internal calibration frame, and up to 31 data frames for each pass of each satellite.

DATE. A six-digit integer representing the calendar form of date (YEAR/MONTH/DAY). It represents the date on which the last station calibration was performed.

DE. Absolute phase difference for the east-west medium baseline (4.0λ) calculated from

$$\text{DE} = \text{AB4} - \text{EAB4}$$

(See also **FG.**)

DE3. Absolute phase difference for the east-west coarse baseline (3.5λ) calculated from

$$\text{DE3} = \text{AB3} - \text{EAB3}$$

(See also **FG3.**)

EAB3. (1) The difference of the phase reading for the east-west coarse baseline (3.5λ) estimated from the artificial half-wavelength baseline (interpolated to the time of the east-west fine reading of the particular data frame) and the measured phase reading for



the east-west coarse baseline (with the station calibration correction added and the reading interpolated to the time of the east-west fine reading of the particular data frame);

$$EAB3 = AB3 - EWCBB$$

(2) Later integer portion truncated by use of LDIF so that only decimal portion of phase is left. (See also EBC3.)

EAB4. Similar to EAB3 except applies to the east-west medium baseline;

$$EAB4 = AB4 - EWMBB$$

(See also EBC4.)

EBC3. Similar to EAB3 except applies to the north-south coarse baseline;

$$EBC3 = BC3 - SNCBB$$

(See also EAB3.)

EBC4. Similar to EAB3 except applies to the north-south medium baseline;

$$EBC4 = BC4 - SNMBB$$

(See also EAB4.)

EEWF. (1) A single compressed value of the five raw phase readings EWF1, . . . , EWF5 for the east-west fine array calculated from the compression formula

$$EEWF(K) = \frac{EWF3 + 9(IDIF3 - IDIF2) - 3(IDIF4 - IDIF1)}{4}$$

where

$$IDIF1 = EWF2 - EWF1$$

$$IDIF2 = EWF3 - EWF2$$

$$IDIF3 = EWF4 - EWF3$$

$$IDIF4 = EWF5 - EWF4$$

and the IDIF's have gone through subroutine NORMAL. (2) Same notation after the counter-delay correction (actual time required for counters to "count" the phase reading);

$$EEWF(K) = EEWF(K) - .05 * IDIF5 * EWF3$$

where

$$IDIF5 = \frac{IDIF1 + IDIF2 + IDIF3 + IDIF4}{4}$$

(See also ENSF.)

ENA. Initial number of frames of data going into the least-squares quadratic solution for the east-west medium phase readings before any frames are deleted by the sigma-rejection process. (ENA is made equal to INN in subroutine LSQQUA.) (See also ENB, ENE, ENX.)

ENB. Same as **ENA** except applies to the east-west coarse data.

ENC. Initial number of frames of data going in the least-squares cubic solution for the east-west fine phase readings before any frames are deleted by the sigma-rejection process. (**ENC** is made equal to **INN** in subroutine **LSCUB**.) (See also **ENF**.)

END. Represents a period (.) which is used as the last character in every calibration and data frame of the Minitrack message;

$$\text{END} = \text{DATA}(65).$$

ENE. Same as **ENA** except applies to the north-south coarse data.

ENF. Same as **ENC** except applies to the north-south fine data.

ENSF. Similar to **EEWF** except applies to the single compressed value for the five raw phase readings for the north-south fine array **NSF1**, . . . , **NSF5**; the **IDIF**'s are defined in terms of these five values analogously to those in the definition of **EEWF**.

ENX. Same as **ENA** except applies to the north-south medium baseline.

EOA. Final number of frames of data going into the least-squares quadratic solution for the east-west medium phase readings after the sigma-rejection process. (**EOA** is made equal to **IOT** in subroutine **LSQUA**.) (See also **EOB**, **EOD**, **EOE**.)

EOB. Same as **EOA** except applies to east-west coarse baseline.

EOC. Final number of frames of data going into the least-squares cubic solution for the east-west fine phase readings after the sigma-rejection process. (**EOC** is made equal to **IOT** in subroutine **LSCUB**.) (See also **EOF**.)

EOD. Same as **EOA** except applies to the north-south medium baseline.

EOE. Same as **EOA** except applies to the north-south coarse baseline.

EOF. Same as **EOC** except applies to the north-south fine baseline.

EQ. Hexadecimal representation **ZC5404040** (the letter **E** followed by three blanks) used to verify the selection of the equatorial fine array when used for the satellite pass. (See also **POL**.)

EWC. Station bias $K_c - K_{s1}$ for the east-west coarse baseline for each station from previous calibration procedures. **EWC** represents the phase shift caused by both the antennas and the feed lines of the east-west coarse pair. (See also **NSC**, **EWM**, **NSM**.)

EWCA. (1) A translated value for the east-west coarse phase reading,

$$\text{EWCA} = \text{EWCD}(\text{MID}) + \text{ALPHA},$$

where **EWCD(MID)** is the raw phase reading of the midframe and **ALPHA** is the constant coefficient of the least-squares quadratic solution for the east-west coarse phase readings. (2) Later represents the east-west coarse phase reading interpolated for the time of the east-west fine time **EWFT**;

$$EWCA = EWCA + EWCB*(EWFT - EWCT) + EWCC*[(EWFT - EWCT)**2]$$

(See also SNMA, EWMA, SNCA.)

EWCB. Main routine variable name for the linear term coefficient β in the least-squares quadratic solution (subroutine LSQQUA);

$$\text{phase} = \alpha + \beta T + \gamma T^2$$

for the east-west coarse baseline. (See also EWMB, SNCB, SNMB.)

EWCB. (1) The “final” east-west coarse phase reading given by the difference of the east-west coarse phase EWCA (interpolated to the time of east-west fine time) and the total station calibration bias CEWC (i.e., $K_{s2} + K_c - K_{s1}$);

$$EWCB = EWCA - CEWC$$

(2) Later truncated by LDIF so that only the decimal portion remains. (See also EWMBB, SNCBB, SNMBB.)

EWCC. Main routine variable name for the quadratic term coefficient γ in the least-squares quadratic solution (subroutine LSQQUA)

$$\text{phase} = \alpha + \beta T + \gamma T^2$$

for the east-west coarse baseline. (See also EWMC, SNCC, SNMC.)

EWCD. Raw phase reading for the east-west coarse baseline. (See also EWMD, NSCD, NSMD.)

EWCE. East-west coarse error, where the error is the difference of the calculated and “observed” values. The calculated values are based on the absolute fine phase reading EWLOBE, and the observed values are based on the absolute values DE3 from the coarse data;

$$EWCE = \frac{3.5}{ANT} * EWLOBE - DE3$$

EWCT. An adjusted time in seconds for the east-west coarse midframe time relative to the arbitrary zero point, the east-west fine midframe time, where the adjustment is required because of the real-time digitizer sequencing pattern and a filter delay within the system;

$$EWCT = TIM(MID) + 0.05$$

(See also EWMT, SNCT, SNMT, EWFT, SNFT.)

EW1, EW2, EW3, EW4, EW5. The five raw phase readings for the east-west fine baseline for each data frame whether the polar or equatorial array is used.

EWFA. (1) A translated value for the east-west fine phase reading,

$$\text{EWFA} = \text{EEWF}(\text{MID}) + \text{ALPHA},$$

where **EEWF(MID)** is the single compressed value for the five fine raw phase readings for the midframe of data. (2) The value in definition (1) corrected for the fine filter delay **XKFA** for the east-west fine baseline. Thus, this value has compression, counter delay, and filter delay corrections included. (See also **SNFA**.)

EWFB. (1) The coefficient β of the linear term in the least-squares cubic fit (subroutine **LSCUB**) to the east-west fine data. (2) The phase rate for the east-west fine baseline which is the coefficient of the first-derivative term (ΔT term) in the Taylor expansion of phase as a function of time in the neighborhood of the east-west midframe time where the filter delay **XKFA** for the east-west fine baseline has been accounted for.

$$\text{EWFB} = \text{EWB} + 2.*\text{EWFC}*(-\text{XKFA}) + 3.*\text{EWFE}*(-\text{XKFA})^2$$

(See also **SNFB**, **EWFC**, **SNFC**, **EWFE**, **SNFE**.)

EWFBF. The final east-west fine phase reading determined from the fine raw data with compression, counter delay, filter delay (**EWFA**), and calibration correction (**CEWF1**) applied:

$$\text{EWFBF} = \text{EWFA} - \text{CEWF1}$$

(See also **SNFBF**, **EWMBF**, **SNMBF**, **EWCBF**, **SNCBF**.)

EWFC. (1) The coefficient γ of the quadratic term in the least-squares cubic fit (subroutine **LSCUB**) to the east-west fine data. (2) The phase acceleration for the east-west fine baseline, which is the coefficient of the second-derivative term (ΔT)² in the Taylor expansion of phase as a function of time in the neighborhood of the east-west midframe time where the filter delay **XKFA** has been accounted for:

$$\text{EWFC} = \text{EWFC} + 3.*\text{EWFE}*(-\text{XKFA})$$

(See also **SNFC**, **EWFB**, **SNFB**, **EWFE**, **SNFE**.)

EWFE. (1) The coefficient δ of the cubic term in the least-squares cubic fit (subroutine **LSCUB**) to the east-west fine data. (2) The phase rate of change of acceleration for the east-west fine baseline, which is the coefficient of the third-derivative term (ΔT)³ in the Taylor expansion of phase as a function of time in the neighborhood of the east-west midframe time where the filter delay **XKFA** has been accounted for. (See also **SNFE**, **EWFB**, **SNFB**, **EWFC**, **SNFC**.)

EWFEQ. Station bias ($K_c - K_{s1}$) for the east-west fine equatorial baseline for each station from previous calibration procedures represents the phase shift caused by both the antennas and the feed lines of the east-west fine pair. (See also **EWFPQ**, **NSFEQ**, **NSFPQ**.)

EWFP0. Similar to **EWFEQ** except applies to the east-west fine polar baseline. (See **EWFEQ**.)

EWFT. (1) The corrected time in seconds for the east-west fine midframe time,

$$\text{EWFT} = \text{TIM}(\text{MID})$$

where this east-west fine midframe time has been arbitrarily chosen as the time origin for the system. (2) If $\text{EWFT} > 86,400$,

$$\text{EWFT} = \text{EWFT} - 86,400$$

to signify that the data have carried into the next day.

EWLOBE. Absolute phase difference for the east-west fine baseline at the time of midframe **EWFT**;

$$\text{EWLOBE} = \text{COREF} - \text{FE}$$

FE is definition (2) after going through subroutine **NORMAL**. (See also **SNLOBE**, **DE**, **FG**, **DE3**, **FG3**.)

EWM. Similar to **EWC** except applies to the east-west medium phase reading. (See also **EWC**, **NSC**, **NSM**.)

EWMA. (1) A translated value for the east-west medium phase reading,

$$\text{EWMA} = \text{EWMD}(\text{MID}) + \text{ALPHA}$$

where **EWMD(MID)** is the raw phase reading of the midframe and **ALPHA** is the constant coefficient of the least-squares quadratic solution for the east-west medium phase readings. (2) The east-west medium phase reading interpolated for the time of the east-west fine time **EWFT**.

$$\text{EWMA} = \text{EWMA} + \text{EWMB} * (\text{EWFT} - \text{EWMT}) + \text{EWMC} * [(\text{EWFT} - \text{EWMT}) ** 2]$$

(See also **SNMA**, **EWCA**, **SNCA**.)

EWMB. Similar to **EWCB** except applies to the east-west medium baseline.

EWMBB. Similar to **EWCB** except applies to the east-west medium baseline.

EWMC. Similar to **EWCC** except applies to the east-west medium baseline.

EWMD. Raw phase reading for the east-west medium baseline. (See also **EWCD**, **NSCD**, **NSMD**, **EW1**, . . . , **EW5**, **NS1**, . . . , **NS5**.)

EWMER. East-west medium error where the error is the difference of the calculated and observed values. The calculated values are for the east-west medium baseline based on the absolute east-west fine phase reading **EWLOBE** and the observed values are based on the absolute phase value for the east-west medium phase reading **DE** determined from the ambiguity baselines alone.

$$EWMER = \left(\frac{4.0}{ANT} * EWLOBE \right) - DE$$

EWMT. An adjusted time in seconds for the east-west medium midframe time relative to the arbitrary zero point, the east-west fine midframe time, where the adjustment is required because of the real-time digitizer sequencing pattern and a filter delay within the system:

$$EWMT = TIM(MID) - 0.15$$

(See also EWCT, SNCT, SNMT, EWFT, SNFT.)

- F1.** Hexadecimal representation (ZC1404040) for the letter **A** followed by 3 blanks.
- F2.** Hexadecimal representation (ZC2404040) for the letter **B** followed by 3 blanks.
- F3.** Hexadecimal representation (ZC3404040) for the letter **C** followed by 3 blanks.
- F4.** Hexadecimal representation (ZC4404040) for the letter **D** followed by 3 blanks.
- F5.** Hexadecimal representation (ZC 5404040) for the letter **E** followed by 3 blanks.
- F6.** Hexadecimal representation (ZC6404040) for the letter **F** followed by 3 blanks.
- F7.** Hexadecimal representation (ZC7404040) for the letter **G** followed by 3 blanks. **F1** to **F7** are codes which indicate the frame rate used to register the Minitrack data on tape. (See AST(3).)
- FE.** (1) Difference of the east-west fine phase reading estimated from the 7.5λ baseline constructed from the medium and coarse data (**COREF**) and the final east-west fine baseline reading determined from the fine raw data:

$$FE = COREF - EWFBB$$

(See also FN.) (2) Later truncated by the use of **LDIF** to isolate the decimal portion of **FE**. (See also FN.)

- FG.** Absolute phase difference for the north-south medium baseline (4.0λ) calculated from

$$FG = BC4 - EBC4$$

(See also DE.)

- FG3.** Absolute phase difference for the north-south coarse baseline (3.5λ) calculated from

$$FG3 = BC3 - EBC3$$

(See also DE3.)

- FN.** Similar to **FE** except applies to the north-south fine baseline:

$$FN = CORNF - SNFBB$$

FREQ. Designates which one of four satellite transmitter frequencies is to be used according to the keys **IFIX** and **ILINK**. These frequencies are not fixed; the four can vary from satellite to satellite.

$$\text{FREQ} = \begin{cases} \text{FRQ1 if ILINK} = 1, \text{IFIX} \neq 2 \\ \text{FRQ2 if ILINK} = 2, \text{IFIX} \neq 2 \\ \text{FRQ3 if ILINK} = 3, \text{IFIX} \neq 2 \\ \text{FRQ4 if ILINK} = 4, \text{IFIX} \neq 2 \\ \text{FRQ1 if IFIX} = 2 \end{cases}$$

FRQ1. See **FREQ**.

FRQ2. See **FREQ**.

FRQ3. See **FREQ**.

FRQ4. See **FREQ**.

HORD. An indexed integer variable designating the hour of the day of the Minitrack message frame start time. (See also **SECD** and **MIND**.)

HOUR. (1) Number of hours in east-west fine time:

$$\text{HOUR} = \frac{\text{EWFT}}{3600}$$

(2) Later, combines the hours, minutes, and seconds of the east-west fine time into one six-digit entry for transfer to program **OBS-B**;

$$\text{HOUR} = \text{HOUR} * 1000 + \text{AMIN} * 100 + \text{SECN}$$

I. A dummy index used to designate the time **TIM** of the Ith frame of data (**TIM(I)**).

IAACC. An output of subroutine **ZERO**. A seven-element array that stores **IEACC** in hexadecimal form. (See **IEACC**, **IBACC**.)

IACOS. The east-west direction cosine **ACOS** converted to an integer and rounded off,

$$\text{IACOS} = \text{ACOS} * 1000000 + 0.5$$

(See **ACOS**, **IBCOS**.)

IAEWFE. An output of subroutine **ZERO**. A six-element array that stores **IEWFE** in hexadecimal form. (See **IEWFE**, **IANSFE**.)

IALOBE. An output of subroutine **ZERO**. A seven-element array that stores the absolute east-west fine phase reading in integer form **IELOBE** in hexadecimal form. (See **IELOBE**, **IBLOBE**.)

IAMP. The hexadecimal representation **Z50** for an ampersand (&) used as a check for the first character of the satellite identification line unless the next line or frame of data is read.

- IANSFE.** An output of subroutine **ZERO**. A six-element array that stores **INSFE** in hexadecimal form. (See **INSFE**, **IAEWFE**.)
- IANT.** A single letter code, **P** or **E**, for distinguishing between polar and equatorial fine data, respectively.
- IAO.** A term set equal to 2., no apparent function in **MIN-B** but used later in program **OBS-B**. (See also **IBO**.)
- IARATE.** An output of subroutine **ZERO**. A seven-element array that stores **IERATE** in hexadecimal form. (See **IERATE**, **IBRATE**.)
- IAWCER.** An output of subroutine **ZERO**. A four-element array that stores **IEWCER**, which is the east-west coarse error **EW CER** in integer form, in hexadecimal form. (See **IEWCER**, **EW CER**, **IBNCER**.)
- IAWMER.** A term similar to **IAWCER** except applies to the east-west medium error **IEWMER** in integer form. (See **IAWCER**.)
- IB.** An internal counter employed to check the time sequence of the data frames. **IB** indicates the number of frames for which the one frame per second rate is used for a given satellite pass. (See also **IC**, **ID**, **IE**, **IF**, **IG**, **IH**.)
- IBACC.** An output of subroutine **ZERO**. A seven-element array that stores **INACC** in hexadecimal form. (See **INACC**, **IAACC**.)
- IBCOS.** The north-south direction cosine **BCOS** converted to an integer and rounded off;
- $$IBCOS = BCOS * 100000 + 0.5$$
- IBLOBE.** An output of subroutine **ZERO**. A seven-element array that stores the absolute north-south fine phase reading in integer form **INLOBE** in hexadecimal form. (See **INLOBE**, **IALLOBE**.)
- IBNCER.** A term similar to **IAWCER** except applies to the north-south coarse error **ISNCER**. (See **IAWCER**, **ISNCER**.)
- IBNMER.** A term similar to **IAWCER** except applies to the north-south medium error **ISNMER**. (See **IAWCER**, **ISNMER**.)
- IBO.** A term set equal to 3., no apparent function in program **MIN-B** but used later in program **OBS-B**. (See also **IAO**.)
- IBRATE.** An output of subroutine **ZERO**. A seven-element array that stores **INRATE** in hexadecimal form. (See **INRATE**, **IARATE**.)
- IC.** A term similar to **IB** that counts the number of Minitrack message frames employed in final computation whenever a frame rate of one frame per 2 s was used. (See also **IB**, **ID**, **IE**, **IF**, **IG**, **IH**.)

ID. A term similar to **IB** that counts the number of Minitrack message frames employed in final computation whenever a frame rate of one frame per 10 s was used. (See also **IB, IC, IE, IF, IG, IH.**)

IDAYD. (1) A three-digit integer representing the day of the year (from 0 to 365 in non-leap year) for the frame start. An input for subroutine **PYRD**. (See also **SECD, MIND, HORD.**) (2) Later **IDAYD(1) = IDAYD(MID)** to identify the numbered day of the midframe.

IDIF. The filter delay correction in seconds of time. (See **XKFA, XKFB.**)

IDIF1, IDIF2, IDIF3, IDIF4. Compression formula variables for the fine readings, that is, four differences formed from pairs of successive values of the five fine readings for each frame for both the east-west and north-south baselines and for both the calibration and data frames.

$$\text{IDIF1} = \text{EWF2} - \text{EWF1}, \text{NSF2} - \text{NSF1}, \text{CEWF2} - \text{CEWF1}, \text{CNSF2} - \text{CNSF1}$$

.
.
.

$$\text{IDIF4} = \text{EWF5} - \text{EWF4}, \text{NSF5} - \text{NSF4}, \text{CEWF5} - \text{CEWF4}, \text{CNSF5} - \text{CNSF4}$$

IDIF5. Arithmetic average of the four normalized differences $(\text{IDIF1} + \text{IDIF2} + \text{IDIF3} + \text{IDIF4})/4$ for both the east-west and north-south fine baselines separately.

IDT. Two-digit input number representing the year of the satellite pass;

$$\text{IYR} = \text{IDT}$$

IE. The term similar to **IB** that counts the number of Minitrack message frames employed in final computation whenever a frame rate of one frame per 20 s was used. (See also **IB, IC, ID, IF, IG, IH.**)

IEACC. A modified integer form of **EWFC**, the coefficient for the phase acceleration term $(\Delta T)^2$ in the Taylor expansion for the phase difference in the neighborhood of the midframe for the east-west baseline, where the independent variable has been changed by the inclusion of **TILI** (number of seconds per frame) so that the acceleration is now per square frame instead of per square second:

$$\text{IEACC} = \text{EWFC} * 10^7 * (\text{TILI})^2$$

This value is transferred to program **OBS-B** where it is converted to floating-point form by a **FORMAT** statement under the variable name **EWACC**. (See **EWFC, IERATE, IEWFE, INACC** of **MIN-B** and **EWACC** of **OBS-B.**)

IELOBE. An integer form of absolute phase difference for the east-west fine baseline:

$$\text{IELOBE} = \text{EWLOBE} * 10000$$

(See **EWLOBE, INLOBE.**)

IENO. One-dimensional array formed in subroutine **ZERO** to store the four-digit **INO**. (See **INO**.)

IERATE. A modified integer form of **EWFB**, the coefficient for the phase rate term ΔT in the Taylor expansion for the phase difference in the neighborhood of the midframe for the east-west baseline, where the independent variable has been changed by the inclusion of **TILI** (number of seconds per frame) so that the phase rate is now per frame instead of per second.

$$\text{IERATE} = \text{EWFB} * 10^5 * \text{TILI}$$

This value is transferred to program **OBS-B** where it is converted to floating-point form by a **FORMAT** statement under the variable name **EWRATE**. (See **EWFB**, **IEACC**, **IEWFF**, **INRATE** of **MIN-B** and **EWRATE** of **OBS-B**.)

IEWCER. An integer form of the east-west coarse error **EW CER**:

$$\text{IEWCER} = \text{EW CER} * 1000$$

(See **EW CER**, **IEWMER**, **ISNMER**, **ISNCER**.)

IEWFE. A modified, integer form of **EWFE**, the coefficient for the third derivative term $(\Delta T)^3$ in the Taylor expansion for the phase difference in the neighborhood of the midframe for the east-west baseline, where the independent variable has been changed by the inclusion of **TILI** (number of seconds per frame) so that the term represents the phase difference per cubic frame instead of phase difference per cubic second.

$$\text{IEWFE} = \text{EWFE} * 10^8 * (\text{TILI})^3$$

This value is transferred to program **OBS-B** where it is converted to floating-point form by a **FORMAT** statement under the variable name **EWD**. (See **IERATE**, **IEACC**, **EWFE**, **INSFE** of **MIN-B** and **EWD** of **OBS-B**.)

IEWMER. An integer form of the east-west medium error **EW MER**:

$$\text{IEWMER} = \text{EW MER} * 1000$$

(See **IEWCER**.)

IF. A term similar to **IB** that counts the number of Minitrack message frames employed in final computation whenever a frame rate of one frame per 60 s was used. (See also **IB**, **IC**, **ID**, **IE**, **IG**, **IH**.)

IFIT. An output of subroutine **ZERO**. A three-element array in which **K**, the number of data frames used for a satellite pass, is stored in hexadecimal form.

IFIX. A single-digit input number to aid identification of the satellite transmitting frequency. (See **FREQ**.)

IG. A term similar to **IB** that counts the number of Minitrack message frames employed in final computation whenever a frame rate of one frame per 120 s was used for a given satellite pass. (See also **IB, IC, ID, IE, IF, IH.**)

IGRADE. A single-digit input number that keys the program to grade the quality of the scatter of the data about the fitted least-squares solutions for each of the six baselines.

If **IGRADE** = 1, a grading is made
If **IGRADE** ≠ 1, **AST(4) = AST(6) = SPA**

(See **AST(4), AST(6).**)

IH. A term similar to **IB** that counts the number of Minitrack message frames employed in final computation whenever a frame rate of one frame per 600 s was used. (See also **IB, IC, ID, IE, IF, IG.**)

II. A dummy index for the station number **KSTA.**

ILINK. A single-digit code to distinguish the satellite transmitting frequency. (See also **FREQ.**)

INACC. Similar to **IEACC** except that it refers to the north-south baseline.

$$\text{INACC} = \text{SNFC} * 10^7 * (\text{TILI})^2$$

(See **IEACC** of **MIN-B** for explanation and **SNRATE** of **OBS-B.**)

INLOBE. An integer form of absolute phase difference for the north-south fine baseline,

$$\text{INLOBE} = \text{SNLOBE} * 10000$$

(See **SNLOBE, IELOBE.**)

INNO. An output of subroutine **ZERO.** A four-element array in which **ISO**, the standard deviation for the cubic fit of the north-south fine data in integer form, is stored in hexadecimal form. (See **ISO, INO, IENO.**)

INO. A four-digit integer representing the standard deviation for the cubic fit to the east-west fine data **SIA.**

$$\text{INO} = \text{SIA} * 1000. + 0.5$$

(See also **ISO, IENO, INNO.**)

INRATE. Similar to **IERATE** except that it refers to the north-south baseline;

$$\text{INRATE} = \text{SNFB} * 10^5 * \text{TILI}$$

(See **IERATE, IEACC** of **MIN-B** and **SNACC, SNRATE** of **OBS-B.**)

INSFE. Similar to **IEWFE** except that it refers to the north-south baseline.

$$\text{INSFE} = \text{SNFE} * 10^8 * (\text{TILI})^3$$

(See **IEWFE** of **MIN-B** for explanation and **SND** of **OBS-B.**)

IOUR. An output of subroutine **ZERO**. A five-element array in which **BOUR**, the hours and minutes of the east-west fine time, is stored in hexadecimal form.

IQ. A dummy index for the array **DATA** used to search for the value of the indicator **ILINK**.

ISEC. A term similar to **IOUR** except stores **ASEC** of east-west fine time in hexadecimal form. (See **ASEC**, **IOUR**.)

ISNCER. An integer form of the north-south coarse error **SNCER**:

$$\text{ISNCER} = \text{SNCER} * 1000$$

(See **SNCER**, **IEWCER**.)

ISNMER. An integer form of the north-south medium baseline error **SNMER**.

$$\text{ISNMER} = \text{SNMER} * 1000$$

(See **SNMER**, **IEWMER**.)

ISO. A four-digit integer representing the standard deviation for the cubic fit to the north-south fine data **SIA**.

$$\text{ISO} = \text{SIA} * 1000. + 0.5$$

(See **INNO**, **INO**, **IENO**.)

ISTA. A two-digit station identification number formed from the individual data frames to check the quantity **KSTA** read from the identification frame. (See **KSTA**.)

ITD. Main program variable name equal to **L** generated within subroutine **LOBASN**. It is a counter whose count equals the difference of successive values of **TIM** such that if **ITD** is greater than 100, lobe assignment is not made in **LOBASN**.

ITZM. Difference in seconds of time between the frame start times of two successive frames.

IYEAR. A six-digit date number (**YEAR/MONTH/DAY**) formed from the satellite identification line.

IYR. A two-digit year number formed from the array **DATA** input for subroutine **PYRD**.

J. Dummy index for labeling the input satellite constants. (Up to 50 satellite passes can be accommodated for each running of the program.)

JK. Dummy index for labeling the basic data frames.

JL, JM. Dummy indices for labeling the appropriate input station coefficients (**C0**, **C1**, . . . , **C8**) and their identifications.

JY, JZ. Dummy indices for labeling additional data frames after **JK** is used.

K. Dummy index for reading and labeling the data frames, also used as a counter to insure that not more than 31 data frames are used for a single satellite pass.

KFA. Electronic filter delay constant in milliseconds for the east-west fine baseline, needed to set up a proper time scale for the polynomial fit to the fine data. (See also **KFB**, **T**, **XKFA**, **XKFB**.)

KFB. Similar to **KFA** except that it applies to the electronic filter for the north-south fine baseline. (See also **XKFB**, **XKFA**.)

KM. Set equal to 5, but has no apparent use in **MIN-B**.

KQ. Upper limit for the index **KS** used in the time sequence check of the data frames, established by $KQ = K - 1$.

KS. Dummy index for the time sequence check of the data frames (range 1 to **KQ**).

KSAID. Integral value for the satellite identification number (each number up to five digits and up to 50 satellites can be read in for each run of the program).

KSATCT. Internal counter for the number of satellite passes for which adequate input satellite constants have been provided.

KSTA. A two-digit station identification number where each number is associated with a station identification name read in under the variable name **STATIO**.

KZ. Index used for error messages when one of the data frames is out of sequence, the actual data time length exceeds the timecheck length, or the data will not lobe assign.

L. Dummy index for labeling the two-digit station identification numbers **KSTA(L)** where $L = 1, \dots, 12$.

LCOS. The array containing the direction cosine with respect to the east-west baseline in hexadecimal integer form. (See also **MCOS**, **IACOA**, **ACOS**.)

LDIF. An intermediate, integer variable that is set up to pick off the integer portion of a variable and leave only the decimal portion.

$$\begin{aligned}LDIF &= EWFBB \\EWFBB &= EWFBB - LDIF\end{aligned}$$

In practice, it performs this truncation for **EWFBB**, **SNFBB**, **EWMBB**, **NSMBB**, **EWCBB**, **NSCBB**, **EAB4**, **EBC4**, **EAB3**, **EBC3**.

LOBASN. A subroutine that linearizes the fine phase readings.

LSCUB. A subroutine that fits a least-squares cubic function to the fine phase readings as a function of time for each of the fine baselines.

LSQUA. A subroutine which fits a least-squares quadratic function to the ambiguity phase readings as a function of time for each of the four ambiguity baselines (east-west medium and coarse, north-south medium and coarse).

- M.** Dummy index used to identify the transmitting frequency of the satellite **FRQ1(M)**, **FRQ2(M)**, **FRQ3(M)**, **FRQ4(M)** and also the five-digit satellite number **KSAID(M)**.
- MCOS.** The array containing the direction cosine with respect to the north-south baseline in hexadecimal integer form. (See also **LCOS**, **IBCOS**, **BCOS**.)
- MID.** An integer representing the number of the middle frame of the **K** frames of data for each satellite pass. It is defined in subroutine **LSQQUA** by

$$\text{MID} = \text{L} = \frac{(\text{K} + 1)}{2} = \frac{(\text{ITO} + 1)}{2}$$

- MIND.** An indexed integer variable designating the minute of time for each frame start. (See also **SECD**, **HORD**.)
- N.** Index for checking the time sequence of the data frames. (See also **KQ**, **KS**.)
- NORMAL.** A subroutine for restoring the actual numerical sequence of the phase readings for both the fine and ambiguity baselines. This must be done because phase readings for all six baselines are recorded in fractions of a phase cycle with the integral number of phase cycles having been truncated; i.e., where X_{old} is any one of the phase difference readings, **NORMAL** yields
- $$X_{\text{new}} = \begin{cases} X_{\text{old}} + 1.0, & -1.0 \leq X_{\text{old}} < -0.5 \\ X_{\text{old}}, & -0.5 \leq X_{\text{old}} \leq +0.5 \\ X_{\text{old}} - 1.0, & +0.5 < X_{\text{old}} \leq +1.0 \end{cases}$$
- NSC.** Station bias ($K_c - K_{s1}$) for the north-south coarse baseline for each station from previous calibration procedures. Represents the phase shift caused by the antennas and the feed lines of the north-south coarse pair. (See also **NSM**, **EWC**, **EWM**.)
- NSCD.** Raw phase reading for the north-south coarse baseline. (See also **EWCD**, **EWMD**, **NSMD**.)
- NSF1, NSF2, NSF3, NSF4, NSF5.** The five raw phase readings for the north-south fine baseline for each data frame, whether the polar or equatorial baseline was used.
- NSFEQ.** Similar to **EWFEQ** except applies to the north-south fine equatorial baseline. (See also **ASFPO**, **EWFEQ**, **EWFPPO**.)
- NSFPO.** Similar to **EWFEQ** except that it applies to the north-south fine polar baseline. (See also **NSFEQ**, **EWFEQ**, **EWFPPO**.)
- NSM.** Similar to **NSC** except applies to the north-south medium baseline.
- NSMD.** Raw phase reading for the north-south medium baseline. (See also **NSCD**, **EWCD**, **EWMD**.)
- NYMODA.** Variable used in subroutine **PYRD** equivalent to **YRMODA** in main program, a six-digit date number (two digits each) **YEAR/MONTH/DAY**.

- PER.** Hexadecimal representation (**Z4B404040**) for a period (.) followed by three blanks; used as indicator for 2-Hz filter. (See **AST(1)**.)
- PEZ.** Hexadecimal representation (**Z4B**) for a period (.); used for verification of input data format. Periods are used as a data separator in 10 places in each Minitrack message calibration and data frame in columns 5, 13, 18, 26, 31, 39, 45, 53, 57, 65.
- POL.** Hexadecimal representation (**ZD7404040**) for the letter **P** followed by three blanks, used to indicate the polar array is under consideration. (See **AST(2)**.)
- PYRD.** A subroutine that combines a three-digit day of the year number for the time of the midframe of the data and a two-digit year number into a standard six-digit calendar form for the date **YEAR/MONTH/DAY**.
- RATE.** (1) When applied to the fine phase readings, it is an estimated time rate change of phase determined from the coarse and medium phase rates **EWMB** and **EWCB** for the east-west baseline or **NSMB** and **NSCB** for the north-south baseline.

$$\text{RATE} = \begin{cases} \frac{[(\text{SNMB}/4) + (\text{NSCB}/3.5)]}{2} * \text{ANT} & \text{for north-south baseline} \\ \frac{[(\text{EWMB}/4) + (\text{EWCB}/3.5)]}{2} * \text{ANT} & \text{for east-west baseline} \end{cases}$$

(2) When applied to any of the four ambiguity baselines **RATE** = 0. **RATE** is required as input to subroutine **LOBASN**.

- SA.** Standard deviation for the least-squares quadratic fit for the east-west medium baseline data. (See also **SB**, **SC**, **SD**, **SE**, **SF**, **SIA**.)
- SAT.** Forms a five-digit satellite identification number to be verified with **KSAID** from selected areas of the alphameric array **DATA** representing the satellite identification line in one of three ways:

$$\text{SAT defined by } \begin{cases} \text{ISN 0059 if DATA(7) or DATA(8) = SPX} \\ \text{ISN 0057 if DATA(4) = BIN} \\ \text{ISN 0055 otherwise} \end{cases}$$

SATT. Normally this is used as a seven-digit code for the Department of Defense satellites:
XXYYYYZZ:

XX = year

YYY = satellite number launched during the year **XX**

ZZ = numbered stage or segment of satellite **YYY** being tracked

- SB.** Standard deviation for the least-squares quadratic fit for the east-west coarse-baseline data. (See also **SA**, **SC**, **SD**, **SE**, **SF**, **SIA**.)
- SC.** Standard deviation for the least-squares cubic fit for the east-west fine-baseline data. (See also **SIA**, **SF**.)

- SD.** Standard deviation for the least-squares quadratic fit for the north-south medium baseline data. (See also **SIA**, **SA**.)
- SE.** Standard deviation for the least-squares quadratic fit for the north-south coarse-baseline data. (See also **SIA**, **SB**.)
- SECD.** An indexed, integer variable designating the second of time for the frame start (time system—GMT of date). (See also **MIND**, **HORD**.)
- SECN.** Number of seconds in east-west fine time **EWFT**;

$$\text{SECN} = (\text{EWFT} - ((\text{HOUR} * 3600) + (\text{AMIN} * 60.))).$$

(See also **HOURL**, **AMIN**, **ASEC**.)

- SF.** Standard deviation for the least-squares cubic fit for the north-south fine-baseline data. (See also **SIA**, **SC**.)
- SIA.** An intermediate variable used in the main routine to represent the standard deviations of the least-squares quadratic fits of phase differences versus time for the four ambiguity baselines and of the least-squares cubic fits of phase differences versus time for the two fine baselines. (See also **SA**, **SB**, **SC**, **SD**, **SE**, **SF**.)
- SIGN.** A predefined subprogram available in **FORTRAN IV**; **SIGN (X, Y)** = the sign of **Y** times the absolute value of **X**;

$$\begin{aligned} \text{DE} &= \text{DE} - \text{SIGN}(8.0, \text{DE}) && \text{if } \text{ABS}(\text{DE}) > 4 \\ \text{FG} &= \text{FG} - \text{SIGN}(8.0, \text{FG}) && \text{if } \text{ABS}(\text{FG}) > 4 \\ \text{DE3} &= \text{DE3} - \text{SIGN}(7.0, \text{DE3}) && \text{if } \text{ABS}(\text{DE3}) > 3.5 \\ \text{FG3} &= \text{FG3} - \text{SIGN}(7.0, \text{FG3}) && \text{if } \text{ABS}(\text{FG3}) > 3.5 \end{aligned}$$

Used to modify the absolute phase differences for the coarse and medium baselines if their natural limits are exceeded. Natural limits are $|\text{DE}| \leq 4$, $|\text{FG}| \leq 4$, $|\text{DE3}| \leq 3.5$, $|\text{FG3}| \leq 3.5$.

- SL.** Represents a sigma limit for the standard deviation of the least-squares quadratic fit to the ambiguity phase differences as a function of time (subroutine **LSQQUA**): equal to **F** in subroutine **LSQQUA**; arbitrarily set equal to **SL** = 0.01 in the main program. If $\text{sigma} \leq \text{SL}$, least-squares fit is accepted. If $\text{sigma} > \text{SL}$, least-squares fit is not accepted, sigma rejection is invoked for those points whose deviation is outside an arbitrary interval determined by the sigma multiplier **SM**, and then the fit is remade with the reduced number of data. (See **SM**, **LSQQUA**.)
- SLA.** Hexadecimal representation (**Z61404040**) for a slash (/) followed by three blanks; was used as a separator in the identification line for each satellite pass.
- SM.** Sigma multiplier, arbitrary multiplication factor of the standard deviation for each of the six baselines. If the deviation of any observed phase difference and its fitted phase difference is greater than the standard deviation times the sigma multiplier, this data point is rejected and a new fit is performed with only the data points remaining after this sigma rejection.

$$SM = \begin{cases} 2.0 & \text{for the four ambiguity baselines} \\ 2.5 & \text{for the two fine baselines} \end{cases}$$

SNCA. (1) A translated value for the north-south coarse phase reading,

$$SNCA = NSCD(MID) + ALPHA$$

where **NSCD(MID)** is the raw phase reading of the midframe and **ALPHA** is the constant coefficient of the least-squares quadratic solution **LSQQUA** for the north-south coarse phase readings. (2) Later represents the north-south coarse phase reading interpolated for the time of the east-west fine time **EWFT**

$$SNCA = SNCA + SNCB*(EWFT - SNCT) + SNCC*[(EWFT - SNCT)**2]$$

(See also **EWCA, EWMA, SNMA.**)

SNCB. Main routine variable name for the linear term coefficient β in the least-squares quadratic solution **LSQQUA**.

$$\text{Phase} = \alpha + \beta T + \gamma T^2$$

for the north-south coarse baseline. (See also **SNMB, EWCB, EWMB.**)

SNCBB. (1) The final north-south coarse phase reading given by the difference of the north-south coarse phase **SNCA** (interpolated to the east-west fine time **EWFT**) and the total station calibration bias **CNSC** (i.e., $K_{s2} + K_c - K_{s1}$):

$$SNCBB = SNCA - CNSC$$

(2) Later truncated by **LDIF** so that only the decimal portion remains. (See also **EWMBB, EWCB, SNMBB.**)

SNCC. Main routine variable name for the coefficient of the quadratic term γ in the least-squares quadratic solution **LSQQUA**

$$\text{Phase} = \alpha + \beta T + \gamma T^2$$

for the north-south coarse baseline. (See also **SNMC, EWMC, EWCC.**)

SNCER. North-south coarse error where the error is the difference of the calculated and observed values. The calculated values are for the north-south coarse baseline based on the absolute north-south fine phase reading **SNLOBE**, and the observed values are based on the absolute phase value for the north-south coarse phase reading **FG3** determined from just the ambiguity baselines

$$SNCER = \left(\frac{3.5}{ANT} * SNLOBE \right) - FG3$$

(See also **SNMER, EW CER, EW MER.**)

SNCT. An adjusted time in seconds for the north-south coarse midframe time relative to the arbitrary zero point, the east-west fine midframe time, where the adjustment is required because of the real-time digitizer sequencing pattern and a filter delay within the system

$$\text{SNCT} = \text{TIM}(\text{MID}) + 0.45$$

(See also **SNMT**, **SNFT**, **EWCT**, **EWMT**, **EWFT**.)

SNFA. (1) A translated value for the north-south fine phase reading

$$\text{SNFA} = \text{ENSF}(\text{MID}) + \text{ALPHA}$$

where **ENSF(MID)** is the single compressed value for the five fine phase readings for the midframe of data. (2) Later represents the value in definition (1) corrected for the north-south fine filter delay **XKFB**. This value has compression, counter delay, and filter delay corrections included. (See also **EWFA**.)

SNFB. (1) The coefficient β of the linear term in the least-squares cubic fit **LSCUB** to the north-south fine data. (2) Later represents the phase rate for the north-south fine baseline, which is the coefficient of the first-derivative term (ΔT term) in the Taylor expansion of phase as a function of time in the neighborhood of the east-west midframe time where the filter delay **XKFB** for the north-south fine baseline has been accounted for;

$$\text{SNFB} = \text{SNFB} + 2.*\text{SNFC}*\text{TCOR} + 3.*\text{SNFE}*\text{TCOR}**2$$

(See also **EWFB**.)

SNFBB. The final north-south fine phase reading determined from the fine raw data with compression, counter delay, filter delay (**SNFA**), and calibration correction (**CNSF1**) applied;

$$\text{SNFBB} = \text{SNFA} - \text{CNSF1}$$

(See also **EWFB**, **SNCBB**, **EWCB**, **SNM**, **EWMB**.)

SNFC. (1) The coefficient γ of the quadratic term in the least-squares cubic fit **LSCUB** to the north-south fine data. (2) Later represents the phase acceleration for the north-south fine baseline, which is the coefficient of the second-derivative term $(\Delta T)^2$ in the Taylor expansion of phase as a function of time in the neighborhood of the east-west midframe time where the filter delay **XKFB** has been accounted for,

$$\text{SNFC} = \text{SNFC} + 3.*\text{SNFE}*\text{TCOR}$$

(See also **EWFC**, **TCOR**.)

SNFE. (1) The coefficient δ of the cubic term in the least-squares cubic fit **LSCUB** to the north-south fine data. (2) Later represents the coefficient of the third-derivative term $(\Delta T)^3$ in the Taylor expansion of phase as a function of time in the neighborhood

of the east-west midframe time where the filter delay **KKFB** has been accounted for. (See also **EWFE, EWFB, SNFB, EWFC, SNFC.**)

SNFT. The time in seconds of the midframe for the north-south fine phase readings relative to **EWFT**;

$$\text{SNFT} = \text{TIM}(\text{MID})$$

(See also **EWFT.**)

SNLOBE. Absolute phase difference for the north-south fine baseline at the time of midframe **EWFT**;

$$\text{SNLOBE} = \text{CORNF} - \text{FN}$$

Note: **FN** is definition (2) after going through subroutine **NORMAL**. (See also **DE3, EWLOBE, FG, FG3, PE.**)

SNMA. (1) A translated value for the north-south medium phase reading

$$\text{SNMA} = \text{NSMD}(\text{MID}) + \text{ALPHA}$$

where **NSMD(MID)** is the raw phase reading of the midframe and **ALPHA** is the constant coefficient of the least-squares quadratic solution for the north-south medium phase readings. (2) Later represents the north-south medium phase reading interpolated to the time of the east-west fine time **EWFT**

$$\text{SNMA} = \text{SNMA} + \text{SNMB} * (\text{EWFT} - \text{SNMT}) + \text{SNMC} * [(\text{CEWFT} - \text{SNMT}) ** 2]$$

(See also **EWMA, SNCA, EWCA.**)

SNMB. Similar to **SNCB** except applies to the north-south medium baseline.

SNMBB. Similar to **SNCBB** except applies to the north-south medium baseline.

SNMC. Similar to **SNCC** except applies to the north-south medium baseline.

SNMER. North-south medium error where the error is the difference of the calculated and observed values. The calculated values are for the north-south medium baseline based on the absolute north-south fine phase reading **SNLOBE** and the observed values are based on the absolute phase value for the north-south medium phase reading **FG** determined from just the ambiguity baselines.

$$\text{SNMER} = \left(\frac{4.0}{\text{ANT}} * \text{SNLOBE} \right) - \text{FG}$$

(See also **SN CER, EW CER, EW MER.**)

SNMT. Similar to **SNCT** except applies to the north-south medium midframe time, such that the appropriate time displacement due to the sequencing pattern for collecting the data yields

$$\text{SNMT} = \text{TIM}(\text{MID}) + 0.25$$

(See also **SNCT**, **SNFT**, **EWCT**, **EWMT**, **EWFT**.)

SPA. Hexadecimal representation (**Z40404040**) for four blank spaces used for verification of input data and coding information. (See **AST(1)**.)

SPX. Hexadecimal representation (**Z40**) for a blank space. Used for verification of format in all data, identification, and calibration frames.

STAD. Two-digit station identification number formed from the array **DATA** for each data frame. (See also **KSTA**, **STATIO**.)

STATIO. Station identification name having up to six characters. As many as 10 stations can be read in for each run of the program. (See **KSTA**, **STAD**.)

T. Time in seconds of the *i*th frame relative to the time of the midframe,

$$T = \text{TIM}(I) - \text{TIM}(\text{MID})$$

so that equivalently the time origin is translated to the time of the midframe. (See also **TIM**, **EWMT**, **EWCT**, **EWFT**, **SNMT**, **SNCT**, **SNFT**.)

TCOR. Time correction in seconds for the north-south fine data relative to the east-west midframe time due to the filter delay **XKFB**

$$\begin{aligned} \text{TCOR} &= \text{EWFT} - \text{SNFT} - \text{XKFB} \\ &= \text{TIM}(\text{MID}) - \text{TIM}(\text{MID}) - \text{XKFB} \\ &= - \text{XKFB} \end{aligned}$$

(See also **XKFB**, **XKFA**, **EWFT**, **SNFT**.)

TEM. Variable name used in subroutine **LSQUA** synonymous with **TIM** in the main program. (See **TIM**.)

TILI. Floating-point quantity set equal to the number of seconds required to collect one frame of data during the actual satellite pass (i.e., 1, 2, 10, 20, 60, 120, or 600 s). (See also **AST(3)**.)

TIM. Time in seconds at the start of the *K*th frame;

$$\text{TIM}(K) = [(\text{HORD}(K)*3600.) + (60.*\text{MIND}(K))] + \text{SECD}(K)$$

X. The sum of the five single-digit values of the AGC's from columns 9, 22, 35, 49, and 61 of the calibration line (**DATA** array). The sum must be 45 because each AGC value should be 9.

XKFA. An adjusted value in seconds of the filter delay constant **KFA** in milliseconds in the east-west fine data for the *L*th station **KSTACL**;

$$\text{XKFA} = \frac{\text{KFA}(L)}{1000} + \text{IDIF}$$

where

$$\text{IDIF} = \begin{cases} 0 \text{ s, if CANT} = 1, 2, \text{ or } 3 \\ 0.120 \text{ s, if CANT} = 0 \text{ (2-Hz filter used)} \\ 0.120 \text{ s, if CANT} \neq 0, 1, 2, 3 \end{cases}$$

and CANT is the single-digit filter indicator. (See also CANT, KFA, IDIF, XKFB, KFB.)

XKFB. Similar to **XKFA** except that it applies to the north-south fine data;

$$\text{XKFB} = \frac{\text{KFB(L)}}{1000} + \text{IDIF}$$

(See **XKFA**.)

YRMODA. Output of subroutine **PYRD**, a six-digit date number, YEAR/MONTH/DAY (2 digits each). (See **NYMODA**.)

ZERO. A subroutine that converts an input digital value to its appropriate hexadecimal form and stores this converted form in a one-dimensional array for transfer to and subsequent use in program **OBS-B**.

GLOSSARY FOR PROGRAM OBS-B

A. A real variable set equal to **EWLOBE**, which is the absolute phase difference for the east-west fine baseline at the east-west fine time **EWFT** for the midframe generated in program **MIN-B**. This value is uncorrected for the antenna-field equation. (See also **B**, **AA**, **BB**.)

AA. (1) The absolute phase difference for the east-west fine baseline fitted for the appropriate frame of each of the desired output points **IPTS** by

$$\text{AA} = \text{A} + (\text{EWRATE} * \text{JT}) + (\text{EWACC} * \text{JT} ** 2) + (\text{EWD} * \text{JT} ** 3)$$

where the last three terms are the terms of the Taylor expansion of the phase difference as a function of the frame in the neighborhood of the midframe and **JT** is the frame count incremented by **IZ** to generate all of the desired output points **IPTS**. (See also **BB** (1).) (2) Later **AA** is reused as the antenna-field-corrected, absolute phase difference for the east-west baseline **C** for the appropriate frame of each of the desired output points **IPTS**; i.e., **AA** = **C**. (See **C**, **BB** (2).)

ACOS. (1) An eight-element array containing the direction cosine with respect to the east-west baseline for the midframe in hexadecimal form transferred from **MIN-B** by the variable **LCOS**. This value is uncorrected for the antenna-field equation. (See also **BCOS** (1).) (2) Later, **ACOS** represents the direction cosine with respect to the east-west baseline for each desired output point **IPTS** after the direction cosine has been adjusted to the proper frame of each output point and corrected for the antenna-field equation. The Taylor expansion is in the neighborhood of the midframe. (See **BCOS** (2).) (3) Final corrected direction cosine with respect to the east-west baseline as

in (2) but for the time (actually the frame) of crossover, where crossover is the passing of the subsatellite point across the north-south baseline, when the equatorial array is used, or the east-west baseline, when the polar array is used.

$$\text{ACOS} = \frac{\text{ZA}}{\text{FQ}}$$

where **ZA** is the absolute phase difference for the east-west baseline, when **CANT = PO**, and for the north-south baseline, when **CANT ≠ PO** (which implies equatorial array). There is no analog in **BCOS** for this definition of **ACOS**.

ANT. Length of the fine baseline in vacuum wavelengths:

$$\text{ANT} = \begin{cases} 57.0 & \text{for polar array, when CANT = PO} \\ 46.0 & \text{for equatorial array, when CANT ≠ PO} \end{cases}$$

(See **CANT**, **FQ**.)

AO. A transition variable simply set equal to **AA** (1). **AA** is reused as given in **AA** (2). (See also **BO**.)

ARMODA. (1) Output of subroutine **ZERO**. The seven-element array that stores the six-digit calendar date **YRMODA** for the frame of each desired output point **IPTS** in hexadecimal form. (See **YRMODA** (1), **ZERO**.) (2) Same as definition (1) except that it refers to the crossover point; that is, the frame during which the subsatellite point crosses the east-west baseline, when the polar array is used, or the north-south baseline, when the equatorial array is used. (See **YRMODA** (2), **ZERO**.)

ASEC. (1) Explicit integer variable that represents the number of milliseconds after the last integral minute for the frame time of each desired output point **IPTS**;

$$\text{ASEC} = \text{SEC} * 1000.$$

It also serves as input for subroutine **ZERO**. (See also **BOUR**.) (2) Similar to definition (1) but refers to the frame time of the crossover point; that is, the frame during which the subsatellite point crosses the east-west baseline, when the polar array is used, or the north-south baseline, when the equatorial array is used.

AST(1). Coded indicator for the filter used in the calibration frame

$$\text{AST}(1) = \begin{cases} \text{SPA, if 10-Hz filter is used} \\ \text{ASK, if narrowband filter is used} \\ \text{PER, if 2-Hz filter is used} \end{cases}$$

AST(1) is transferred from program **MIN-B** directly. (See **AST(2)** in **MIN-B**.)

AST(3). A coded hexadecimal element to indicate the frame rate used in collecting the fine data that are transferred with the north-south data set:

$$AST(3) = \begin{cases} F1 \text{ (represents the letter A), if 1 frame/1 s} \\ F2 \text{ (represents the letter B), if 1 frame/2 s} \\ F3 \text{ (represents the letter C), if 1 frame/10 s} \\ F4 \text{ (represents the letter D), if 1 frame/20 s} \\ F5 \text{ (represents the letter E), if 1 frame/60 s} \\ F6 \text{ (represents the letter F), if 1 frame/120 s} \\ F7 \text{ (represents the letter G), if 1 frame/600 s} \end{cases}$$

(Same as AST(3) in MIN-B.)

AST(4). Identical to AST(3) but is transferred in duplicate with the east-west data set.
(See AST(3).)

AST(6). Single-character indicator in hexadecimal form for the quality of the north-south data,

$$AST(6) = \begin{cases} SPX \text{ (represents a blank space) implies high quality.} \\ \text{Any other character implies low quality.} \end{cases}$$

Same as AST(4) in MIN-B. (See also IGRADE, AST(7).)

AST(7). Single-character indicator in hexadecimal form for the quality of the east-west data,

$$AST(7) = \begin{cases} SPX \text{ (represents a blank space) implies high quality.} \\ \text{Any other character implies low quality.} \end{cases}$$

Same as AST(6) in MIN-B. (See also IGRADE, AST(6).)

ASTA. A variable that is included in an initial DIMENSION statement but is no longer used in the program.

B. A real variable set equal to SNLOBE which is the absolute phase difference for the north-south fine baseline at the time for the midframe generated in program MIN-B. This value is uncorrected for the antenna-field equation. (See also A, BB, AA.)

BB. (1) The absolute phase difference for the north-south fine baseline fitted for the appropriate frame of each of the desired output points IPTS by

$$BB = B + (SNRATE*JT) + (SNACC*JT**2) + (SND*JT**3)$$

where the last three terms are the terms of the Taylor expansion of the phase difference as a function of the frame in the neighborhood of the midframe and JT is the frame count incremented by IZ to generate all of the desired output points IPTS. (See also AA (1).) (2) Later BB is reused as the antenna-field-corrected, absolute phase difference for the north-south baseline E for the appropriate frame of each of the desired output points IPTS; i.e.,

$$AA = C$$

(See C, AA (2).)

BCOS. (1) An eight-element array containing the direction cosine with respect to the north-south baseline for the midframe in hexadecimal form transferred from **MIN-B** by the variable **MCOS**. This value is uncorrected for the antenna-field equation. (See also **ACOS** (1).) (2) Later, **BCOS** represents the direction cosine with respect to the north-south baseline for each desired output point **IPTS** after the direction cosine has been adjusted to the proper frame of each output point (Taylor expansion in neighborhood of the midframe) and corrected for the antenna-field equation. (See **ACOS** (2).)

BDATE. (1) Six-digit calendar date (**YEAR/MONTH/DAY**) for the east-west data frame transferred from **MIN-B** where it was represented by the variable **ARMODA**. This should be equal to **JDATE** for the corresponding north-south data frame if processing is to take place. It is an input for subroutine **DCOUNT**. (2) Output of subroutine **DCOUNT** representing a three-digit running day number (1 through 365 for nonleap year) for each of the desired output points **IPTS** of each satellite pass. (Note: Since **BDATE** is the variable name for both input and output of **DCOUNT**, the year number is lost here, but was retained in the identity with **IDATE**.) (3) Similar to definition (1) except that **BDATE** applies to the date of the crossover point. That is, the frame during which the subsatellite point crosses the east-west baseline, when the polar array is used, or the north-south baseline, when the equatorial array is used. Here, also, **BDATE** becomes input and output of subroutine **DCOUNT**.

BEG. Listed as an explicit **INTEGER**. It is not used, however, in the present form of the program.

BLANK. Listed as an explicit **LOGICAL** variable with a **DIMENSION** of 80. It is not used, however, in the present form of the program.

BO. A transition variable simply set equal to **BB** (definition (1)), then **BB** is reused as given in **BB** (2). (See also **AO**.)

BOUR. (1) An explicit **INTEGER** variable that contains both the **HOURL** and **MIN** of the frame for each desired output point **IPTS**;

$$\mathbf{BOUR} = \mathbf{HOURL} * 100. + \mathbf{MIN}$$

(2) Similar to definition (1) except that it corresponds to the frame of the crossover point. The frame during which the subsatellite point crosses the east-west baseline, when the polar array is used, or the north-south baseline, when the equatorial array is used.

C. The final absolute phase difference for the east-west baseline corrected for the antenna-field equation. The phase difference was first interpolated to the frame of the desired output point **IPTS**, and the index **IM** identifies the frame and also the appropriate set of calibration constants, those referring to either east-west or north-south baseline. This equation embodies the optical calibration equation that aligns the adjusted radio data with the connected optical position obtained from the data with the Minitrack Calibration Camera at the physical center of the Minitrack configuration over the region of the

celestial sphere covered by the interferometer fan beam, approximately $10^\circ \times 80^\circ$, measured at the half-power points. Either one of two antenna-field equations is employed, depending upon the magnitudes of **CC** and **DD**, the direction cosines with respect to the east-west and north-south baselines, respectively, uncorrected for optical calibration. This is equivalent to considering whether the satellite is within the rectangular region $10^\circ \times 80^\circ$ centered at the zenith point, which, in essence, completely encompasses the half-power pattern.

For polar array CANT = PO

Case I:

$$\text{or} \quad \begin{array}{l} |\text{CC}| > 0.64279 \quad (\text{COS } \alpha > 0.64279, \alpha < 50^\circ) \\ |\text{DD}| > 0.08716 \quad (\text{COS } \beta > 0.08716, \beta < 85^\circ) \end{array}$$

where either condition implies the satellite is not within the half-power rectangle. Then

$$\text{C} = \text{CO}(\text{IM}) + \text{C1}(\text{IM}) * \text{AO} + \text{C2}(\text{IM}) * \text{BO} + \text{C3}(\text{IM}) * \text{AO} * \text{BO} \\ + \text{C7}(\text{IM}) * \text{SIN}(\text{AO} * \text{PI}) + \text{C8}(\text{IM}) * \text{COS}(\text{AO} * \text{PI})$$

Case II:

$$\text{and} \quad \begin{array}{l} |\text{CC}| < 0.64279 \quad (\text{COS } \alpha < 0.64279, \alpha > 50^\circ) \\ |\text{DD}| < 0.08716 \quad (\text{COS } \beta < 0.08716, \beta > 85^\circ) \end{array}$$

which implies the satellite is within the half-power rectangle. Further, the zenith angle γ is related to the two other direction cosines by the well-known relation,

$$\cos^2 \alpha + \cos^2 \beta + \cos^2 \gamma = 1$$

This relation with $\alpha > 50^\circ$ ($\cos^2 \alpha < 0.413179$) and $\beta > 85^\circ$ ($\cos^2 \beta < 0.007597$) implies

$$\cos \gamma = \sqrt{1 - \cos^2 \alpha - \cos^2 \beta} > 0.76107$$

$$\gamma < 40.442$$

However, it must be remembered that this last limitation on the zenith angle for the satellite is a necessary but not a sufficient condition that the satellite is within the half-power beamwidth rectangle. As a result,

$$\text{C} = \text{CO}(\text{IM}) + \text{C1}(\text{IM}) * \text{AO} + \text{C2}(\text{IM}) * \text{BO} + \text{C3}(\text{IM}) * \text{AO} * \text{BO} \\ + \text{C4}(\text{IM}) * \text{AO} ** 2 + \text{C5}(\text{IM}) * \text{BO} ** 2 + \text{C6}(\text{IM}) * \text{EE} \\ + \text{C7}(\text{IM}) * \text{SIN}(\text{AO} * \text{PI}) + \text{C8}(\text{IM}) * \text{COS}(\text{AO} * \text{PI})$$

For equatorial array CANT \neq PO

Case III:

$$|\text{CC}| > 0.08716 \quad (\text{COS } \alpha > 0.08716, \alpha < 85^\circ)$$

or

$$|DD| > 0.64279 \quad (\cos \beta > 0.64279, \beta < 50^\circ)$$

where either condition implies the satellite is not within the half-power rectangle.

Then

$$C = CO(IM) + C1(IM)*AO + C2(IM)*BO + C3(IM)*AO*BO \\ + C7(IM)*SIN(AO*PI) + C8(IM)*COS(AO*PI)$$

Case IV:

$$|CC| < 0.008716 \quad (\cos \alpha < 0.008716, \alpha > 85^\circ)$$

and

$$|DD| < 0.64279 \quad (\cos \beta < 0.64279, \beta > 50^\circ)$$

which imply the satellite is within the half-power rectangle. Further, the zenith angle γ is related to the two other direction cosines by the well-known relation

$$\cos^2 \alpha + \cos^2 \beta + \cos^2 \gamma = 1$$

This relation with $\alpha > 85^\circ$ ($\cos^2 \alpha < 0.007597$) and $\beta > 50^\circ$ ($\cos^2 \beta < 0.413179$) implies

$$\cos \gamma = \sqrt{1 - \cos^2 \alpha - \cos^2 \beta} > 0.76107$$

$$\gamma < 40.^\circ 442$$

However, it must be remembered that this last limitation on the zenith angle for the satellite is a necessary but not a sufficient condition that the satellite is within the half-power beamwidth rectangle. As a result,

$$C = CO(IM) + C1(IM)*AO + C2(IM)*BO + C3(IM)*AO*BO \\ + C4(IM)*AO**2 + C5(IM)*BO**2 + C6(IM)*EE \\ + C7(IM)*SIN(AO*PI) + C8(IM)*COS(AO*PI)$$

Note: Cases I through IV use the east-west calibration coefficients. (See IM.) (For north-south calibration coefficients, see E.)

C0, C1, C2, C3, C4, C5, C6, C7, C8. Input station coefficients determined from a previous optical-radio calibration process for each station that collectively represent the antenna-field correction for the absolute phase differences. This is due to the position of the satellite within the array pattern. Four sets are needed for each station for the east-west and north-south equatorial baselines and the east-west and north-south polar baselines. The index has four successive values. (See JL, IM.)

CANT. Single-letter array identifier for the east-west fine data.

$$CANT = \begin{cases} PO, & \text{for polar array, ANT} = 57. \\ \text{anything else,} & \text{for equatorial array, ANT} = 46. \end{cases}$$

(Same as **AST(2)** in **MIN-B** but not the same as **CANT** in **MIN-B**.) (See also **PO**, **JANT**, **ANT**.)

CC. Direction cosine with respect to the east-west baseline (that is, the cosine of the angle of elevation) formed by the radius vector to the satellite and the east-west baseline. It is positive for the two eastern octants above the horizon plane and negative for the two western octants above the horizon plane. This is for each of the desired output points **IPTS** and is uncorrected for the antenna-field equation.

$$CC = \frac{AO}{FQ} = \frac{\text{number of actual wavelengths in east-west path difference}}{\text{number of actual wavelengths in east-west baseline}}$$

This variable aids in the choice of the appropriate form of the antenna-field equation. (See **C**; see also **DD**, **AO**, **AA**, **FQ**.)

CLEWC. Cable-length inequality for the east-west coarse baseline given in feet. A positive number indicates that the cable for the east array is longer than that for the west array, whereas a negative number signifies that the west array cable is longer. (Note: No such inequality is considered to exist for the two cables of each of the fine baselines, which are cut and pruned to the same electrical length.)

$$\text{Correction (cycles)} = \frac{\text{cable-length inequality (ft)}}{\text{velocity of propagation (ft/s)}} [136.5 - \text{FREQ (MHz)}] \times 10^6$$

(Same as in **MIN-B**; see also **CLEWM**, **CLNSC**, **CLNSM**.)

CLEWM. Similar to **CLEWC** except that it applies to the cable-length inequality (in feet) for the east-west medium baseline. (See **CLEWC**.)

CLNSC. Similar to **CLEWC** except that it applies to the cable-length inequality (in feet) for the north-south coarse baseline. (See **CLEWC**.)

CLNSM. Similar to **CLEWC** except that it applies to the cable-length inequality (in feet) for the north-south medium baseline. (See **CLEWC**.)

COS. Standard **FORTRAN IV** subprogram to compute the cosine trigonometric function when the argument is in radians. **COS** is used in the antenna-field equations. (See **C**, **E**.)

CSTA. Minitrack station identification number in hexadecimal form, formed from **ASTA(2)** plus **ASTA(3)**, which are variables of **MIN-B**. It refers to the east-west data set when verification of input data is performed. (See **JSTA**.)

DATE. A six-digit integer representing the calendar form of the date (**YEAR/MONTH/DAY**) on which the last station calibration was performed and reduced. (Same as in **MIN-B**.)

DCOUNT. A subroutine of **OBS-B** that takes a six-digit calendar form of the date (**YEAR/MONTH/DAY**) and converts it into a three-digit running day number for that year (1

through 365 in a nonleap year). Here, the year number of the input is lost so that an equivalent variable is usually set up before entering the subroutine in order that the year will still be available. (See **BDATE**, **IDATE**.)

- DD**. Direction cosine with respect to the north-south baseline, that is, the cosine of the angle of elevation formed by the radius vector to the satellite and the north-south baseline. This is positive for the two northern octants above the horizon plane and negative for the two southern octants above the horizon plane. This is for each of the desired output points **IPTS** and is uncorrected for the antenna-field equation;

$$DD = \frac{BO}{FQ} = \frac{\text{number of actual wavelengths in north-south path difference}}{\text{number of actual wavelengths in north-south baseline}}$$

This variable aids in the choice of the appropriate form of the antenna-field equation (See **C**.) (See also **CC**, **BB**, **BO**, **FQ**.)

- E**. Similar to **C** but refers to the final absolute phase difference for the north-south baseline corrected for the antenna-field equation as explained under variable **C**:

For polar array CANT = PO

Case I:

$$|CC| > 0.64279 \quad (\cos \alpha > 0.64279, \alpha < 50^\circ)$$

or

$$|DD| > 0.08716 \quad (\cos \beta > 0.08716, \beta < 85^\circ)$$

where either condition implies the satellite is not within the half-power rectangle;

$$E = CO(IM) + C1(IM)*AO + C2(IM)*BO + C3(IM)*AO*BO \\ + C7(IM)*SIN(BO*PI) + C8(IM)*COS(BO*PI)$$

Case II:

$$|CC| < 0.64279 \quad (\cos \alpha < 0.64279, \alpha > 50^\circ)$$

and

$$|DD| < 0.08716 \quad (\cos \beta < 0.08716, \beta > 85^\circ)$$

which implies the satellite is within the half-power rectangle;

$$E = CO(IM) + C1(IM)*AO + C2(IM)*BO + C3(IM)*AO*BO \\ + C4(IM)*AO**2 + C5(IM)*BO**2 + C6(IM)*FF \\ + C7(IM)*SIN(BO*PI) + C8(IM)*COS(BO*PI)$$

For equatorial array CANT ≠ PO

Case III:

$$|CC| > 0.08716 \quad (\cos \alpha > 0.08716, \alpha < 85^\circ)$$

or

$$|DD| > 0.64279 \quad (\cos \beta > 0.64279, \beta < 50^\circ)$$

where either condition implies the satellite is not within the half-power rectangle;

$$E = CO(IM) + C1(IM)*AO + C2(IM)*BO + C3(IM)*AO*BO \\ + C7(IM)*SIN(BO*PI) + C8(IM)*COS(BO*PI)$$

Case IV:

$$|CC| < 0.08716 \quad (\cos \alpha < 0.0876, \alpha > 85^\circ)$$

and

$$|DD| < 0.064279 \quad (\cos \beta < 0.64279, \beta > 50^\circ)$$

which implies the satellite is within the half-power rectangle;

$$E = CO(IM) + C1(IM)*AO + C2(IM)*BO + C3(IM)*AO*BO \\ + C4(IM)*AO**2 + C5(IM)*BO**2 + C6(IM)*FF \\ + C7(IM)*SIN(BO*PI) + C8(IM)*COS(BO*PI)$$

Note: Cases I through IV use the north-south calibration coefficients (see IM); for east-west calibration coefficients and explanation, see C.

EE. Multiplicative factor of the C6 term in the polynomial expression for the antenna-field corrections, C and E;

$$EE = \begin{cases} (AO)^3, & \text{if CANT} = \text{PO (polar array)} \\ (BO)^3, & \text{if CANT} \neq \text{PO (equatorial array)} \end{cases}$$

(See also FF.)

END. An explicit INTEGER variable that is not used in the present form of the program.

EWACC. The seven-element array that contains IEACC of MIN-B (coefficient of the phase acceleration term $(\Delta T)^2$ in the Taylor expansion for the phase difference but in units of phase difference/frame/frame) transferred from MIN-B by the variable IAACC of MIN-B. (See IEACC of MIN-B and SNACC of OBS-B.)

EWC. Station bias $(K_c - K_{s1})$ for the east-west coarse baseline for each station from previous calibration procedures. This term represents the phase shift caused by both the antennas and the feed lines of the east-west coarse pair; same as in MIN-B. (See also NSC, EWM, NSM.)

EWCKER. The four-element array that contains the east-west coarse error in hexadecimal form transferred from MIN-B by the variable IAWCKER of MIN-B. (See also SNCER.)

EWD. The seven-element array that contains IEWFE of MIN-B (coefficient of the third-derivative term $(\Delta T)^3$ in the Taylor expansion of the phase difference but in units of

phase difference/frame/frame/frame) transferred from **MIN-B** by the variable **IAEWFE** of **MIN-B**. (See **IEWFE** of **MIN-B** and **SND** of **OBS-B**.)

EWFEQ. Station bias ($K_c - K_{s1}$) for the east-west fine equatorial baseline for each station from previous calibration procedures. This term represents the phase shift caused by both the antennas and the feed lines of the east-west fine pair, same as in **MIN-B**. (See also **EWFP**, **NSFEQ**, **NSFPO**.)

EWFP. Similar to **EWFEQ**, except that it applies to the east-west fine polar baseline. (See **EWFEQ**.)

EWLOBE. (1) The absolute phase difference for the east-west fine baseline at the east-west fine time **EWFT** for the midframe generated in program **MIN-B** (uncorrected for the antenna-field equation) transferred from **MIN-B** by the variable **IALOBE** of **MIN-B**. (See **A**.) (2) Later, may represent the fully corrected absolute phase difference at the crossover frame if the equatorial array is used (see **ZLOB**) or the time correction phase difference at crossover if the polar array is used. (See **ZOBE**.)

EWM. Similar to **EWC** except applies to the east-west medium phase difference station bias, same as in **MIN-B**. (See also **EWC**, **NSC**, **NSM**.)

EWMER. The four-element array that contains the east-west medium error in hexadecimal form, transferred from **MIN-B** by the variable **IAWMER**. (See also **SNMER**.)

EWRATE. (1) The seven-element array that contains **IERATE** of **MIN-B** (coefficient of the phase rate term ΔT in the Taylor expansion for the phase difference, but in units of phase difference/frame) transferred from **MIN-B** by the variable **IARATE** of **MIN-B**. (See also **SNRATE**, **EWACC**, **EWD**.) (2) Later used as the coefficient of the phase rate term (in units of phase difference/frame) as above in definition (1) but refers to the crossover point if and only if the equatorial array is used; that is, **CANT** \neq **PO**. (For explanation, see **RATE**, **ZOBE**, **ZLOB**.)

FF. Multiplicative factor of the **C6** term in the polynomial expression for the antenna-field corrections **C** and **E**;

$$FF = \begin{cases} (AO)^3, & \text{if CANT} = \text{PO (polar array)} \\ (BO)^3, & \text{if CANT} \neq \text{PO (equatorial array)} \end{cases}$$

(See also **EE**.)

FQ. Actual number of wavelengths in the fine baseline for the frequency **FREQ** based on the vacuum lengths **ANT** = 57. or 46. for a given polar or equatorial array at 136.000 MHz;

$$FQ = [(FREQ/136.)*ANT]$$

(See **FREQ**, **ANT**.)

FREQ. (1) Designates which one of four transmitter frequencies (in MHz) was used for the satellite pass (the four frequencies may vary from satellite to satellite):

$$\text{FREQ} = \begin{cases} \text{FRQ1, if ILINK} = 1 \\ \text{FRQ2, if ILINK} = 2 \\ \text{FRQ3, if ILINK} = 3 \\ \text{FRQ4, if ILINK} = 4 \end{cases}$$

(2) If

$$138. < \text{FREQ}(\text{MHz}) < 136$$

the satellite pass is not processed and another pass is read in.

FRQ1, FRQ2, FRQ3, FRQ4. See **FREQ.**

HOUR. (1) Two-digit integer variable for the hour of east-west midframe, transferred from **MIN-B** by the variable **AOUR** in **MIN-B**. (See **MIN, SEC, JHOR, JMN, JSC.**)

(2) Number of hours of the day for the frame of each desired output point **IPTS** where

$$\text{HOUR} = \text{TIMA}/3600$$

where **TIMA** is definition (2). (3) Similar to definition (2) except that it refers to the frame of crossover; that is, the frame during which the subsatellite point crosses the east-west baseline, when the polar array is used, or the north-south baseline, when the equatorial array is used.

HR. Explicit **INTEGER** variable which is not used in the present form of the program.

HRR. Explicit **INTEGER** variable which is not used in the present form of the program.

IA. A single integer plus **IB** (1 integer), **IC** (1 integer), **ID** (2 integers), **IE** (1 integer), and **IF** (1 integer), which collectively represent the seven-digit variable **SATT** (a coded satellite number and launch date) transferred from **MIN-B**. (See **SATT** of **MIN-B**.)

IACOS. (1) Integer form of **ACOS**, the final antenna-field-corrected direction cosine with respect to the east-west baseline rounded to six digits by

$$\text{IACOS} = \text{ACOS} * 1000000 + 0.5$$

for each of the desired output points **IPTS**. (See also **ACOS(1), IBCOS.**) (2) Similar to definition (1) except that it refers to the direction cosine at crossover, that is, the direction cosine with respect to the east-west baseline, if the polar array is used, or the direction cosine with respect to the north-south baseline, if the equatorial array is used. (See also **ACOS** (2).)

IANT. A single-letter code, **P** or **E**, for distinguishing between polar and equatorial fine data, respectively, same as in **MIN-B**.

IAO. (1) An integer indicator associated with an east-west data set that includes time of midframe, east-west fine, medium, and coarse phase differences, and east-west

direction cosine (uncorrected for antenna-field pattern) which was transferred from program **MIN-B**. In **MIN-B**, **IAO** should have been set equal to 2. In **OBS-B**, if in some way **IAO** \neq 2 from transfer tape (unit 2), another data set is read in and checked. (Note: A north-south data set must follow immediately after an east-west data set from unit 2 for processing to take place.) (See **IBO**.) (2) **IAO** = 9 indicates that the data set containing it refers to the time and direction cosine at the crossover frame.

IB. (1) See **IA**. (2) Later used as difference between crossover and midframe time in seconds truncated to the next lowest integral number of seconds;

$$IB = ZB$$

(See **ZB**.)

IBCOS. Integer form of **BCOS**, the final antenna-field-corrected direction cosine with respect to the north-south baseline rounded to six digits by

$$IBCOS = BCOS * 1000000 + 0.5$$

for each of the desired output points **IPTS**. (See also **IACOS** (1).)

IBO. An integer indicator associated with a north-south data set that includes time of midframe, north-south fine, medium, and coarse phase differences, and north-south direction cosine (uncorrected for antenna-field pattern) which was transferred from program **MIN-B**. In **MIN-B**, **IBO** should have been set equal to 3. In **OBS-B**, if in some way **IBO** \neq 3 from transfer tape (unit 2), another data set is read in and checked. (See note on **IAO**.)

IC. (1) See **IA**. (2) Indicator to choose one of two definitions for the variable **SAT**. (See **SAT**.)

ID. See **IA**.

IDATE. (1) Set equal to the original **BDATE**, the six-digit calendar form of the date, for the midframe of the satellite pass that was transferred from **MIN-B**. (See **BDATE**, **DCOUNT**, **JDATE**.) (2) Similar to definition (1) except that it refers to the date of the frame for the crossover point. (See **BDATE** (3).)

IE. See **IA**.

IENO. The four-digit integer in hexadecimal form representing the standard deviation for the cubic fit to the east-west fine data, same as in **MIN-B**. (See **INNO** in **OBS-B** and **IENO** and **INO** in **MIN-B**.)

IF. See **IA**.

IFIT. The three-element (**3A1**) array in which the number of data frames for the east-west baseline for a given satellite pass is stored in hexadecimal form, same as in **MIN-B**. (See also **JFIT**.)

IGRADE. Single-digit discriminator for deciding which quality of direction cosine data should be accepted from **MIN-B** and processed in **OBS-B**. If **IGRADE** = 2, any quality data are accepted and processed. If **IGRADE** \neq 2, data must be of high quality to be processed. This is indicated by **AST(7) = SPX** for the east-west data and **AST(6) = SPX** for the north-south data. If either of these conditions is not satisfied, the data are not processed. (See also **AST(6)**, **AST(7)**.)

II. Dummy index for printing the station numbers **KSTA**, same as in **MIN-B**.

ILINK. Single-digit code to select the satellite transmitting frequency, same as in **MIN-B**. (See **FREQ** for explanation.)

ILK. An integer variable set equal to the single-digit code **ILINK** that is used to isolate the satellite transmitting frequency. (See **ILINK**, **FREQ**.)

IM. (1) A dummy index for **ISTA**, range 1 through 40, which selects which one of 10 possible stations (each station has four sets of constants) is associated with it. Each station has four sets of antenna-field correction coefficients **C0**, **C1**, . . . , **C8**. Stations 3 through 10 follow the pattern of stations 1 and 2:

Station 1

East-west equatorial **C0(1)**, . . . , **C8(1)**
 North-south equatorial **C0(2)**, . . . , **C8(2)**
 East-west polar **C0(3)**, . . . , **C8(3)**
 North-south polar **C0(4)**, . . . , **C8(4)**

Station 2

East-west equatorial **C0(5)**, . . . , **C8(5)**
 North-south equatorial **C0(6)**, . . . , **C8(6)**
 East-west polar **C0(7)**, . . . , **C8(7)**
 North-south polar **C0(8)**, . . . , **C8(8)**

(2) Because the station number index refers to the set of constants **C0**, . . . , **C8** with the same index for the east-west equatorial data,

$$IM = \begin{cases} IM, & \text{if } CANT \neq PO \text{ (equatorial array used)} \\ IM + 2, & \text{if } CANT = PO \text{ (polar array used)} \end{cases}$$

(3) **IM** is incremented by **IM = IM + 1**, within the loop to evaluate the direction cosines at each of the desired output points **IPTS** to retrieve the north-south constants after an initial east-west data set has been accepted, and then decremented by **IM = IM - 1** to obtain the same relative alignment for the evaluation at the next desired output point.

INNO. The four-digit integer in hexadecimal form representing the standard deviation for the cubic fit to the north-south fine data, same as in **MIN-B**. (See **IENO** in **OBS-B** and **ISO** in **MIN-B**.)

IOUR. (1) Output of subroutine **ZERO**, the five-element array in which the hour and minute **BOUR** of the specific frame for each desired output point is stored for subsequent usage in hexadecimal form. (See **BOUR** (1).) (2) Similar to definition (1) except that it refers to the frame of the crossover point. (See **BOUR** (2).)

IPTS. Number of points for which final, corrected direction cosines are to be calculated from the uncorrected midframe value transferred from **MIN-B** and the coefficients of the Taylor expansion of the phase as a function of frame (time). The midframe point is always one of the desired final, corrected direction cosines. If **IPTS** is odd, the desired points are placed symmetrically about the midframe. (See **JT**.) If **IPTS** is even, the same points are output as for the next lowest odd integer plus the next uniformly placed (**JT**) frame on the descending arc of the satellite pass.

ISEC. (1) Output of subroutine **ZERO**, the six-element array in which the number of milliseconds **ASEC** after the last integral minute for the frame of each desired output point **IPTS** is stored for subsequent usage in hexadecimal form. (See **ASEC** (1).) (2) Similar to definition (1) except that it refers to the crossover point. (See **ASEC** (2).)

ISTA. Two-digit station identification number required as input to verify the quantity **KSTA**, which was transferred from **MIN-B**. Each station has four such entries, indexed by four successive integers where each entry represents one of the following: east-west equatorial, north-south equatorial, east-west polar, or north-south polar. (See **IM**.)

IY. Given by $IPTS - 1/2$, where **IPTS** represents the number of data points or output points for which direction cosines are to be calculated. **IY** represents the number of points on each side of the middle point when **IPTS** is odd. When **IPTS** is even, **IY** represents the number of points on each side of the two middle points. **IY** also serves as a pivotal variable for the form used to calculate **TT**, the time displacement of each point at which direction cosines are desired with respect to the east-west fine time **EWFT**. For the midframe,

$$TT = \begin{cases} 0, & \text{if } IY = 0, \text{ which implies } IPTS = 1 \text{ or } 2 \\ T*JT, & \text{if } IY \neq 0, \text{ which implies } IPTS > 2 \end{cases}$$

(See also **IPTS**, **JT**, **IZ**, **TT**, **T**.)

IYEAR. A two-digit year number that is required as input card data along with **IGRADE**. However, unlike **IGRADE**, **IYEAR** is not used in the present form of the preprocessing program.

IYR. The two-digit year number for the satellite pass under consideration formed from ($IYR = BDATE/10000$), where **BDATE** is the six-digit calendar date of the satellite pass (**YEAR/MONTH/DAY**). (See **BDATE**.)

IZ. Number of frames of data per output point, where **IPTS** is the number of output points for which direction cosines are desired:

$$IZ = \begin{cases} 1, & \text{if } IY = 0, \text{ which implies } IPTS = 1 \text{ or } 2 \\ \frac{(IFIT/2)}{IY}, & \text{if } IY \neq 0, \text{ which implies } IPTS > 2 \end{cases}$$

where **IFIT** is the number of frames of data used for the particular satellite pass. (See also **IY**, **IPTS**, **IFIT**, **JT**, **T**, **TT**.)

J. Dummy index for labeling the input satellite constants (up to 50 satellite passes can be accommodated for each running of the program) and also for some of the input station constants, same as in **MIN-B**.

JANT. Similar to **CANT** but refers to the north-south fine data. (See **CANT**.)

JDATE. The six-digit calendar form of the date for the midframe of the satellite pass that is read from the data frame input from **MIN-B** for each north-south data set. It is used for verification with **BDATE** (1), which is read in with each east-west data set. **BDATE** (1) and **IDATE** must be equal for processing to occur. (See **BDATE** (1).)

JFIT. Similar to **IFIT** except that it refers to each north-south data set transferred from **MIN-B**. Used for data verification. (See **IFIT**.)

JHOR. Similar to **HOUR** except refers to each north-south data set transferred from **MIN-B**. Must equal **HOUR** for the east-west data set so that both data sets refer to the same point in time. (See **HOUR**, **JMN**, **JSC**.)

JL, **JM**. Dummy indices for labeling the appropriate input station coefficients upon reading them in; i.e., **C0**, **C1**, . . . , **C8** and their other station identifications, same as in **MIN-B**.

JMN. Similar to **MIN** except that it refers to the north-south data set transferred from **MIN-B**. **JMN** must equal **SEC** for the east-west data set unless new data set is read in. (See **SEC**, **JHOR**, **JMN**.)

JSTA. Similar to **CSTA** but identifies with each north-south data set that is transferred from **MIN-B**. (See **CSTA**.)

JT. (1) Number of data frames preceding the middle frame or the two middle frames (depending on whether **IPTS** is odd or even, respectively) for which the first output point is to be calculated;

$$JT = \begin{cases} 0, & \text{if } IY = 0, \text{ which implies } IPTS = 1 \text{ or } 2 \\ -IZ * IY, & \text{if } IY \neq 0, \text{ which implies } IPTS > 2 \end{cases}$$

The value of **JT** is used as input to calculate the proper phase at the particular frame of the desired output point. (See **AA**, **BB**.) (2) Later, **JT** is incremented by **IZ** until all desired output points **IPTS** are calculated;

$$JT = JT + IZ.$$

(See also **IZ**, **IY**.)

- KFA.** Electronic filter delay constant in milliseconds for the east-west fine baseline, same as in **MIN-B**. (See also **KFB**.)
- KFB.** Similar to **KFA** except that it applies to the electronic filter delay in milliseconds for the north-south fine baseline, same as in **MIN-B**. (See also **KFA**.)
- KSAID.** Integral value for the satellite identification number. Each number, up to five digits and 50 satellite passes, can be read in for each run of the program, same as in **MIN-B**.
- KSATCT.** An internal counter for the number of satellite passes (satellite count) for which adequate input satellite constants have been provided, same as in **MIN-B**.
- KSTA.** A two-digit station identification number in which each number is associated with a station identification name which is read in under the variable name **STATIO**, same as in **MIN-B**. (See **STATIO**, **ISTA**, **CSTA**, **JSTA**.)
- L.** A dummy index for the variable **KSTA** used to select which of 12 stations correspond to **CSTA**.
- LCOS.** (1) Output of subroutine **ZERO**. The eight-element array that stores the final corrected direction cosine **IACOS** (in integer form) with respect to the east-west baseline for each desired output point **IPTS** stored in hexadecimal form. (See **MCOS**, **IACOS**, **IBCOS**.) (2) Similar to definition (1) except that it applies to the direction cosine at the crossover point. It is the frame during which the subsatellite point crosses the east-west baseline, when the polar array is used, or the north-south baseline, when the equatorial array is used.
- M.** (1) A dummy index used to identify the transmitting frequency of the satellite, **FRQ1(M)**, **FRQ2(M)**, **FRQ3(M)**, or **FRQ4(M)**. (2) Also used as an index for the five-digit satellite number **KSAID(M)** to identify which one of 50 satellites or satellite passes is being considered.
- MCOS.** Output of subroutine **ZERO**; the eight-element array that stores the final corrected direction cosine **IBCOS** (in integer form) with respect to the north-south baseline for each desired output point **IPTS** stored in hexadecimal form. (See also **LCOS**, **IBCOS**, **IACOS**.)
- MIN.** (1) See **HOUR** (1). (2) Later, used for the number of minutes beyond the hour for the frame of each desired output point **IPTS**;

$$\text{MIN} = \frac{\text{TIMA} - \text{HOUR} * 3600}{60}$$

where **TIMA** is definition (2). (See also **HOUR** (2), **SEC** (2).) (3) Same as definition (2) except that it refers to the crossover point; that is, the frame during which the subsatellite point crosses the east-west baseline, when the polar array is used, or the north-south baseline, when the equatorial array is used. (See **HOUR** (3), **SEC** (3).)

MN. Explicit **INTEGER** variable that has no use in the present form of the program.

MNN. Explicit **INTEGER** variable that has no use in the present form of the program.

NSC. Station bias ($K_c - K_{s1}$) for the north-south coarse baseline for each station from previous calibration procedures. Represents the phase shift caused by the antennas and the feed lines of the north-south coarse pair, same as in **MIN-B**. (See also **NSM**, **EWC**, **EWM**.)

NSFPO. Similar to **EWFEQ** except applies to the north-south fine polar baseline, same as in **MIN-B**. (See also **NSFEQ**, **EWFEQ**, **EWFPO**.)

PI. A constant used for calculating phases, that is, 2π rad/360° of electrical phase,

$$PI \ 2\pi = 6.2831853$$

PO. Hexadecimal representation (**ZD7**) for the letter **P**, entered through a **DATA** statement and used to signify that the polar array has been used. (See **CANT**.)

PYRD. A subroutine that combines a three-digit day of the year number (1 through 365 for a nonleap year) for the frame of each desired direction cosine output data point **IPTS** and a two-digit year number for the above data into a standard six-digit calendar form for the date (**YEAR/MONTH/DAY**). (See **YRMODA**.)

RATE. Coefficient of the phase rate term in the Taylor expansion for the phase difference (units of phase difference/frame) when referring only to the crossover point. Specifically,

$$RATE = \begin{cases} SNRATE \text{ (definition (3))}, & \text{if } CANT = PO \text{ (polar array)} \\ EWRATE \text{ (definition (3))}, & \text{if } CANT \neq PO \text{ (equatorial array)} \end{cases}$$

RATE is needed to calculate the time **ZB**. (See **ZB**.)

SAID. Explicit **INTEGER** variable that is not used in the present form of the preprocessing problem.

SAT. Satellite identification number formed from **IA**, **IB**, **IC**, **ID**, **IE**, and **IF** (see **IA**), which were transferred from **MIN-B** by the variable **SATT** of **MIN-B**, in one of two ways;

$$SAT = \begin{cases} IA*10000 + IB*1000 + ID*10 + IF, & \text{if } IC = 0 \\ IB*10000 + IC*1000 + ID*10 + IF, & \text{if } IC \neq 0 \end{cases}$$

SEC. (1) See **HOUR** (1). (2) See **HOUR** (2). Refers to the number of seconds beyond the last integral minute for the frame of each desired output point **IPTS**;

$$SEC = TIMA = HOUR*3600. + MIN*60.$$

where **TIMA** is definition (2). (3) Similar to definition (2) except that it refers to the frame of crossover; that is, the frame during which the subsatellite point crosses the east-west baseline, when the polar array is used, or the north-south baseline, when the equatorial array is used. (See **HOUR** (3).)

SIN. Standard FORTRAN IV subprogram to compute the sine trigonometric function when the argument is in radians. **SIN** is utilized in the antenna-field equations. (See C, E.)

SNACC. The seven-element array that contains **INACC** of **MIN-B**. **INACC** is the coefficient of the phase acceleration term (ΔT^2) in the Taylor expansion for the phase difference given in units of phase difference/frame/frame. **SNACC** is transferred from **MIN-B** by the variable **IBACC** of **MIN-B**. (See **INACC** of **MIN-B** and **EWACC**, **SND**, **EWD**, **SNRATE** (1), **EWRATE** (1) of **OBS-B**.)

SNCER. The four-element array that contains the north-south coarse error in hexadecimal form, transferred from **MIN-B** by the variable **IBNCER** of **MIN-B**. (See also **EWKER**, **SNMER**, **EWMER**.)

SND. The seven-element array that contains **INSFE** of **MIN-B**. **INSFE** is the coefficient of the third-derivative term (ΔT)³ in the Taylor expansion of the difference but in units of phase difference/frame/frame/frame. **SND** is transferred from **MIN-B** by the variable **IANSE** of **MIN-B**. (See **INSFE** of **MIN-B** and **EWD**, **SNACC**, **EWACC**, **SNRATE**, **EWRATE** of **OBS-B**.)

SNLOBE. (1) The absolute phase difference for the north-south fine baseline for the mid-frame of the data as generated in program **MIN-B** (uncorrected for the antenna-field equation), transferred from **MIN-B** by the variable **IBLOBE** of **MIN-B**. (See **B**.)
(2) Later, may represent the fully corrected absolute phase difference at the crossover frame if the equatorial array is used (see **ZLOB**) or the time correction phase difference at crossover if the polar array is used. (See **ZOBE**.)

SNMER. The four-element array that contains the north-south medium error in hexadecimal form, transferred from **MIN-B** by the variable **IBNMER** of **MIN-B**. (See also **EWMER**.)

SNRATE. (1) The seven-element array that contains **INRATE** of **MIN-B**. **INRATE** is the coefficient of the phase rate term ΔT in the Taylor expansion of the phase difference in units of phase difference/frame. **SNRATE** is transferred from **MIN-B** by the variable **IBRATE** of **MIN-B**. (See also **EWRATE**, **SNACC**, **SND**.) (2) Later, used as the coefficient of the phase rate term (in units of phase difference/frame) as above in definition (1) but refers to the crossover point if and only if the polar array is used, that is, **CANT = PO**. (For explanation, see **RATE**, **ZOBE**, **ZLOB**.)

SPA. Hexadecimal representation (**Z40**) for a single blank space entered through a **DATA** statement.

SPX. Hexadecimal representation (**Z40404040**) for four successive blank spaces entered through a **DATA** statement that is used as test for the quality of the input data. (See **IGRADE**.)

In **OBS-B** $\left\{ \begin{array}{l} \text{SPX} = 4 \text{ blanks} \\ \text{SPA} = 1 \text{ blank} \end{array} \right.$

In MIN-B $\left\{ \begin{array}{l} \text{SPX} = 1 \text{ blank} \\ \text{SPA} = 4 \text{ blanks} \end{array} \right.$

STATIO. A station identification name containing up to six characters in **A FORMAT**. As many as 10 stations can be read in for each run of the program, same as in **MIN-B**. (See also **KSTA**.)

T. Number of seconds required to record each frame of data:

$$T = \left\{ \begin{array}{l} 1 \text{ s, if } \text{AST}(4) = \text{F1} \\ 2 \text{ s, if } \text{AST}(4) = \text{F2} \\ 10 \text{ s, if } \text{AST}(4) = \text{F3} \\ 20 \text{ s, if } \text{AST}(4) = \text{F4} \\ 60 \text{ s, if } \text{AST}(4) = \text{F5} \\ 120 \text{ s, if } \text{AST}(4) = \text{F6} \\ 600 \text{ s, if } \text{AST}(4) = \text{F7} \end{array} \right.$$

(See also **AST(4)**.)

TIM. Time of day (in seconds) for the time reference point; that is, the time for the mid-frame of the east-west fine data, formed by

$$\text{TIM} = \text{HOUR} * 3600 + 60 * \text{MIN} + \text{SEC}$$

(See **HOUR (1)**.)

TIMA. (1) Time of day in seconds for the first of the output points **IPTS**;

$$\text{TIMA} = \text{TIM} + \text{TT}$$

where **TT** is definition (1). (2) If **TIMA** > 86 400 s, which implies that the frame time refers to the next day,

$$\begin{aligned} \text{TIMA} &= \text{TIMA} - 86,400 \\ \text{BDATE} &= \text{BDATE} + 1 \end{aligned}$$

The above equations alternate signs if **TIMA** < 0 s. (3) **TIMA** is later incremented by **TT** (2) to generate the times of day in seconds for the remaining output points;

$$\text{TIMA} = \text{TIMA} + \text{TT}$$

(4) Time of day in seconds for the frame of the crossover point given by

$$\text{TIMA} = \text{TIM} + \text{IB}$$

TIMC. Explicit **INTEGER** variable that is not used in the present form of the preprocessing program.

TT. (1) The first output point of **IPTS** occurs **TT** s before the middle output point(s), depending on whether **IPTS** is odd or even, respectively; that is,

$$TT = \begin{cases} 0, & \text{if } IY = 0, \text{ which implies } IPTS = 1 \text{ or } 2 \\ T*JT, & \text{if } IY \neq 0, \text{ which implies } IPTS > 2 \end{cases}$$

(See **TIMA** (1).) (2) After **TT** is used as in definition (1) for establishing the **TIMA** of the first output point, it is redefined as

$$TT = T*IZ$$

to represent the number of seconds of time per output point (i.e., the spacing in time of the output points). (See also **TIMA** (2).)

YRMODA. (1) Output of subroutine **PYRD**. It is a six-digit calendar form of the date (**YEAR/MONTH/DAY**) for the frame of each desired output point **IPTS** formed from the two-digit year number **IYR** and the three-digit day of the year number **BDATE**. (See **PYRD**, **ARMODA** (1).) (2) Similar to definition (1) except that it refers to the crossover point, that is, the frame during which the subsatellite point crosses the east-west baseline; if the polar array is used, or the north-south baseline, if the equatorial array is used.

ZA. The final corrected absolute phase difference for the crossover point needed to calculate the direction cosine at crossover from the expression

$$ACOS = \frac{ZA}{FQ}$$

ZA is represented by the algebraic sum of the phase difference for the midframe **ZLOB** plus the differential phase difference between midframe and crossover point,

$$ZA = ZLOB + \frac{ZRAT*ZB}{T}$$

where for the polar array:

$$\begin{cases} ZLOB = EWLOBE \text{ (phase difference)} \\ ZRAT = EWRATE \text{ (phase difference/frame)} \end{cases}$$

and the for the equatorial array:

$$\begin{cases} ZLOB = SNLOBE \text{ (phase difference)} \\ ZRAT = SNRATE \text{ (phase difference/frame)} \end{cases}$$

where **ZB** is the number of seconds between crossover and midframe times and **T** is the number of seconds per frame.

ZB. Difference between crossover **TIMA** and midframe **TIM** times in seconds calculated from

$$ZB = - \frac{ZOBE}{RATE} * T$$

to determine the time of crossover **TIMA** from

$$\mathbf{TIMA} = \mathbf{TIM} + \mathbf{ZB}$$

Literally, the expression for **ZB** is

$$\text{Time}_c - \text{Time}_m = \frac{\text{PD}_c - \text{PD}_m}{\text{PD/frame}} * \frac{\text{time}}{\text{frame}}$$

where *c* refers to crossover, *m* refers to midframe, PD refers to phase difference, and $\text{PD}_c = 0$ for the north-south baseline, if polar array is used, and for the east-west baseline, if equatorial array is used. (See **ZA**.)

ZERO. A subroutine that converts an input digital value to its appropriate hexadecimal form and stores this converted form in a one-dimensional array for any subsequent usage.

ZLOB. The variable used for the final corrected absolute phase difference for the midframe, which is needed to calculate the equivalent quantity for the crossover,

$$\mathbf{ZLOB} = \begin{cases} \mathbf{EWLOBE}, & \text{if polar array is used} \\ \mathbf{SNLOBE}, & \text{if equatorial array is used} \end{cases}$$

(For further explanation, see **ZA**.)

ZOBE. The variable used for the final corrected absolute phase difference for the midframe, which is needed to calculate the time of crossover,

$$\mathbf{ZOBE} = \begin{cases} \mathbf{SNLOBE}, & \text{if polar array is used} \\ \mathbf{EWLOBE}, & \text{if equatorial array is used} \end{cases}$$

(For further explanation, see **ZB**.)

ZRAT. The variable used for the phase difference rate in units of phase difference/frame in the neighborhood of the midframe, which is needed to calculate the phase difference at crossover,

$$\mathbf{ZRAT} = \begin{cases} \mathbf{EWRATE}, & \text{if polar array is used} \\ \mathbf{SNRATE}, & \text{if equatorial array is used} \end{cases}$$

(See **ZA**.)

Section 8

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