Application Note

Anritsu Advancing beyond

Time Difference of Arrival (TDOA)

Introduction

Time Difference of Arrival (TDOA) is a technique for geo-locating RF sources. It requires three or more remote receivers (probes) capable of detecting the signal of interest. Each probe is synchronized in time to capture corresponding I/Q data blocks. Software shifts the time signature of each I/Q data set to find the difference in the arrival time at each probe. This gives the difference in the distance of the source from each set of probes. Using several probes provides a set of curved lines that indicate solutions to the distance equations. The actual RF source sits at the intersection of these lines.

TDOA can provide a very accurate location estimate (< 100 m) in a short period of time. To successfully use TDOA it is essential to understand the type of signals that can be used, how the results depend on the geometry of the measurement (probe and source locations), what the sources of uncertainty are and how to mitigate them, and how to know if the answer is meaningful.

General Overview of a TDOA measurement

1. A modulated signal is transmitted from an unknown source.
2. The signal is captured at three or more probes at various locations around the source.
3. The signal captured at each probe is shifted in time to find a position of maximum alignment.
4. The time shift necessary to align each signal is multiplied by the speed of light to get a distance difference between each probe.
5. The distance difference is plotted as a set of hyperbolic lines.
6. The intersection of the lines indicates the location of the source

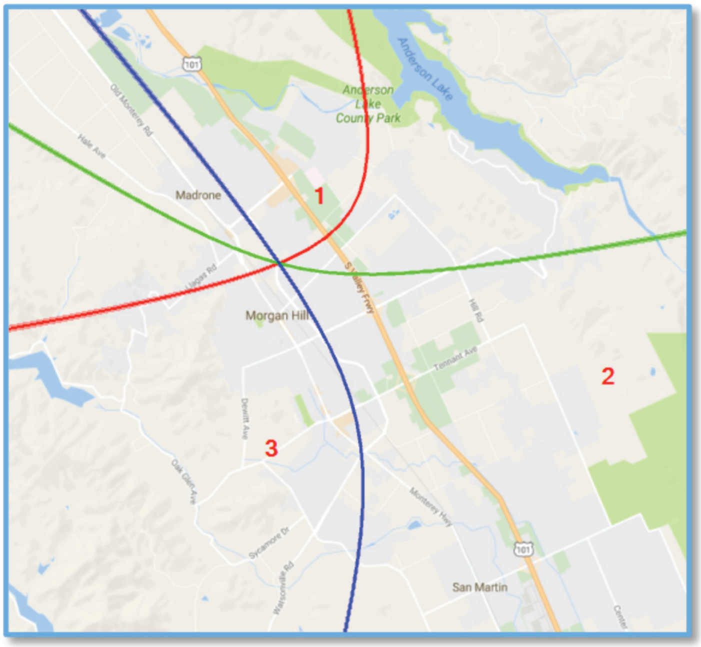


Figure 1. Map showing probe locations 1, 2 & 3. Also shown are the arcs showing continuous possible solutions for each pair of probes. The intersection of the lines is the location estimate for the RF source.

Considerations

Modulated Signals. In order to time-align the received signal at each probe, the signal must contain non-random, non-repeating structure. Many interference sources emit white noise, which lacks the structure necessary to align the signal. Simple sources, such as a sine wave generator, produce a repeating pattern that has structure, but the repeating pattern does not allow for a unique time-alignment. Repeating patterns can be aligned at multiple positions with no means of distinguishing a correct time-shift.

Modulated signals contain internal structure that can be aligned in time. Good examples of modulated signals are FM radio broadcasts and cell phone signals. For this reason, TDOA is typically used to locate rogue broadcast signals, and other communication signals that are out-of-band or otherwise unexpected.

Reflections and Signal Strength. As with most RF signal processing algorithms, the results depend on the quality of the input. Signal strength is not normally an issue, as long as the signal is clearly present. You need to be able to get a discernible I/Q diagram, but it can be rather noisy. Typically 10 to 15 dB above background is required. The capture bandwidth also needs to be narrow enough so that other modulated signals are excluded. Higher signal strength will not necessarily produce a better answer.

Multi-path signals will tend to broaden the I/Q pattern and make it more difficult to find the proper time-alignment. If the strongest component of the signal is a reflection off of some nearby surface, then the distance calculation will be the reflected signal path, rather than the direct straight-line path between the probe and source. The software cannot know this, so the result is a systematic offset to the distance calculation, equal in magnitude to the reflected distance of the signal.

Probe Synchronization. In order to do the TDOA calculation wherein each data stream is shifted in time to find the optimal signal alignment, it is necessary to capture the same signal at each probe location. Not just capturing the RF signal from the same source, but the same signal in time must be captured. If the source is a radio transmission, for instance, then each probe needs to capture the same utterance, or musical note. Special algorithms are used to obtain this synchronization.

A very high sampling rate is required to produce high spatial resolution, and this means that sufficient data must be transferred from the remote probes to the controlling computer. In order to make this as efficient as possible, it is best to have short capture times, perhaps 10’s of milliseconds. However, we need to capture the same signal at each location, so the probes must start collecting within a few milliseconds of each other. Further, the precise timing of each I/Q pair is required in the data stream so that once aligned, the time shift can be accurately calculated. A good TDOA system will produce location estimates within 100 meters of the source location. An RF signal travels 100 meters in about 300 nanoseconds. Therefore the timing of the signal must be known with very high precision.

Every I/Q sample point is not time stamped. In practice, an internal clock is synchronized once each second with GPS satellites. The internal clock tracks time between the GPS synchronization pulses. This clock needs to be very stable as it inserts a timestamp to the data stream at regular intervals. If one of the clocks drift, then it is impossible to get a good time-alignment since features lined up in one section will not align further on. Various spectrum monitors are capable of capturing I/Q data streams. Unless the spectrum monitor is designed with high precision timing, it will not work adequately for TDOA measurements.

Hyperbolic Lines. The result of a TDOA measurement is a time difference in the arrival of the signal of interest at two or more probes. The time difference is multiplied by the speed of light to give a difference in distance between each set of probes and the RF source. For two probes, the maximum distance difference is the physical distance between the probes themselves. A measured difference larger than this is not physically possible. For a set of two probes, the distance does not specify a specific location, but rather a hyperbolic line centered between the two probes (See figure 1.) Therefore, a successful TDOA measurement on two probes does not give a unique solution, but a continuous set of solutions along a hyperbolic curve.

Triangulation. Using three probes gives three sets of two probes, so a TDOA measurement of three probes will produce three hyperbola, the intersections of which yield possible locations for the RF emitter (See figure 1.) If the source is inside the triangle formed by the three probes, then you may get a single intersection point. However, it is not unusual to have a couple of intersection points for the three curved lines, especially if the source is very far outside the probe triangle. It is usually possible to use the relative receive powers at the probes to determine which intersection is the right location.

Sample Rate. Sample rate is a key factor in determining spatial resolution. Sample rate is the number of I/Q data pairs collected per second. This is by definition the temporal resolution: the spacing in time of the sample data points. The time separation is multiplied by the speed of light to get the distance separation, so the spatial resolution is directly proportional to the temporal resolution.

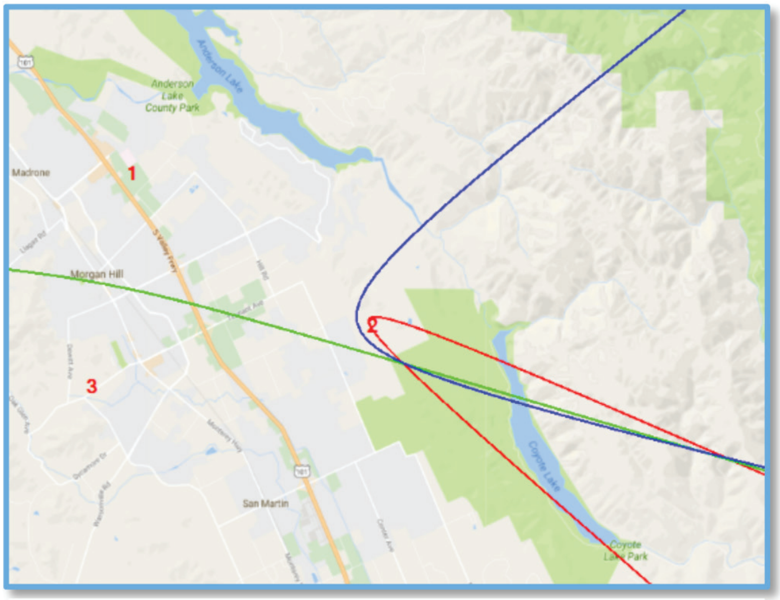


Figure 2. Notice in this image that there are two distinct locations where the three lines cross. There is not a unique solution using these three probes.

As a specific example, consider a sampling rate of 250 kHz. $250\text{ kHz} = \frac{1\ sec}{250000\ samples} = \frac{4\mu s}{\text{IQ data pair}}$. A 4 μs time resolution gives 4 μs * 3 x108 m/sec = 1.2 km per data point. A spatial resolution of 1.2 km is not very good. If the sample rate is 2.5 MHz, then we have increased the resolution of the measurement by a factor of 10, or 120 meters. That is a useful result when hunting for an interference source or rogue transmission. We will discuss below a few techniques that can improve on that further.

It is tempting to just increase the sample rate to increase the spatial resolution. Sampling at 25 MHz, according to our math above, would yield a spatial resolution of 12 meters, which would be a marvelous result, given that our search area could easily exceed 200 km2. However, there is a practical limit to how much you can increase the spatial resolution by increasing the sampling rate. This is determined by the underlying modulation rate of the signal of interest. Consider looking for an FM radio station, for instance. The audio encoded in an FM broadcast signal typically has a maximum modulation frequency of 20 kHz.

Imagine a modulated sine wave that you want to sample in order to reproduce the signal. Sampling once per period is not enough. One would probably end up with something very much like a flat line. Sampling 20 times per period would give a fair representation of the sine wave's shape. Sampling 50 times per period might be a little bit better, but sampling 1000 times per period isn't really going to give you more information. A real signal always carries some noise anyway, so there is a practical limit to the usefulness of sampling at higher and higher rates. A good rule of thumb is that sampling at 20 points per period is pretty good. Doubling that might gain something, but beyond that is pointless. So for an FM signal, a practical limit is around 500 kHz, and 250 kHz is pretty good.

Figure 3 below shows the data from two probes, one slightly ahead of the other. The dots represent sample points. There are not enough data points to accurately reproduce the shape of the curve, so the green and blue lines represent the best guess at the peak position for each set. Because the sample rate is too low, a large error is introduced. In Figure 4, the sample rate has increased and the peak positions are accurately found. Increasing the sampling rate further is not necessarily going to increase the accuracy.

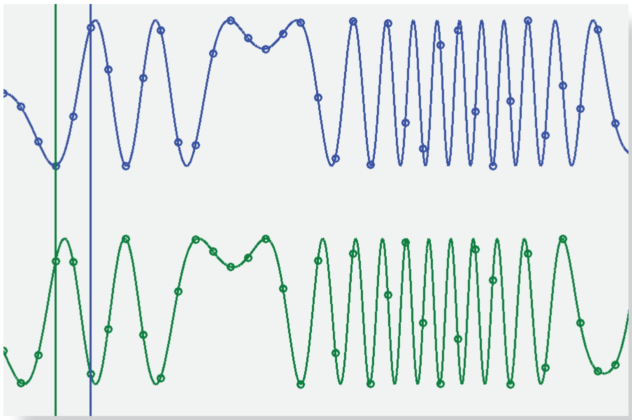


Figure 3. Two sets of data with a noticeable time shift. The sample rate, indicated by the circles on the graphs, is too low in this case to accurately determine the signal shape.

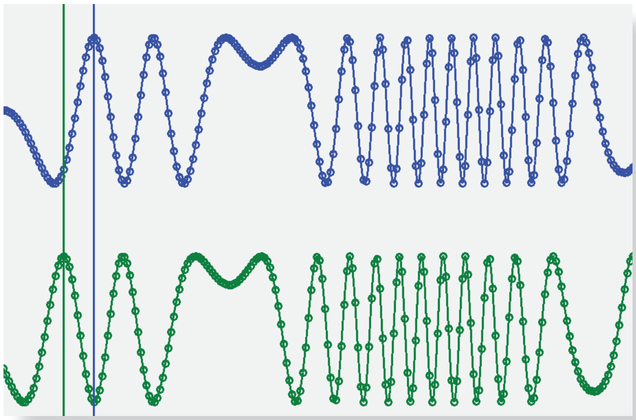


Figure 4. Two sets of data with a noticeable time shift. In this case the sampling rate is sufficient to accurately describe the underlying curve and time-align the data sets.

Cable Length. An important consideration when doing detailed timing measurements is cable length and internal timing delays. In an ideal TDOA system, the I/Q data stream is timestamped at each I/Q pair with the precisely synchronized time-of-arrival of the signal at the antenna of each probe. In practice, this is very hard to do. Errors in timing typically produce a systematic error that shifts the geo-location estimate consistently in one direction. Systematic errors cannot be eliminated with averaging. Instead, the average will consistently converge to a stable wrong answer. The error in the estimated direction and distance depends on the particular timing differences between the probes in use.

The typical speed of transmission in a coaxial cable is about 2/3 the speed of light. So for every 20 meters difference in cable length, a 30 meter offset in position is introduced. Because this error in location cannot be reduced by averaging, it may be necessary to enter cable lengths into the geo-location algorithm for each probe. Cable length may not be a significant concern if the cables are fairly uniform, or if the differences are small compared with the expected spatial resolution.

You may typically find around 100 meters of uncertainty in a TDOA measurement. If the cable lengths are within 10 meters of each other, the systematic error may not be noticeable. If there are longer differences in the cable lengths, then this should be accounted for. Remember, it is not the total cable length that is important, but the difference in cable length. Most TDOA systems will allow for entry of the cable lengths for each probe in the system, and the software calculates the differences.

Timing Delays. Of similar concern are internal delays in the probe hardware and the analog and digital paths used to capture, process, and store the I/Q data stream. This internal delay adds a systematic error that cannot be removed with signal averaging. The internal delay will vary from probe to probe and is often frequency dependent, as the center frequency and range will affect hardware and software filters in place to correctly capture the signal of interest.

The I/Q data pairs must be time stamped in the data stream in order to do the time-alignment. Any uncertainty in the clocks used to generate the timestamps will introduce uncertainty in the location estimate. Most remote probes will use a GPS signal to synchronize both the start time of the captures and the clocks used to add the time stamps. GPS chips produce a pulse-per-second (PPS) signal that is very reliable and precise. An internal clock ticks at a very high and stable frequency, and time stamps are inserted into the data stream at regular intervals based the clock tick count.

In Figure 5 notice that the signals are aligned at the green vertical line. In this case, the clocks run at slightly different rates, so the green data points are spread out more in time. When this happens, it is not possible to get a meaningful result as there is not a single time shift at which the data are all aligned in time.

Location of Emitter. The location of the RF source is also a factor in determining the accuracy of the location estimation. If the source is inside the triangle formed by the three probes, then the accuracy is expected to be high. When the emitter is behind one of the probes, even if still fairly close to the probe triangle, the uncertainty is higher. Also, for probes far away, the angle of incidence of the hyperbolic lines makes the area of uncertainty larger.

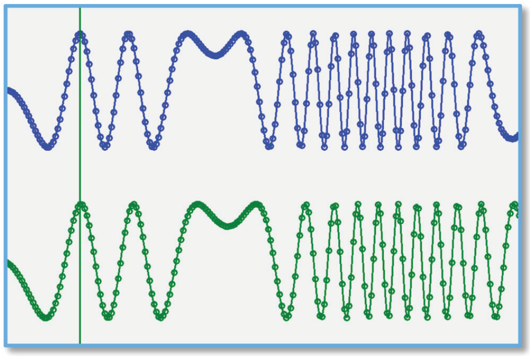
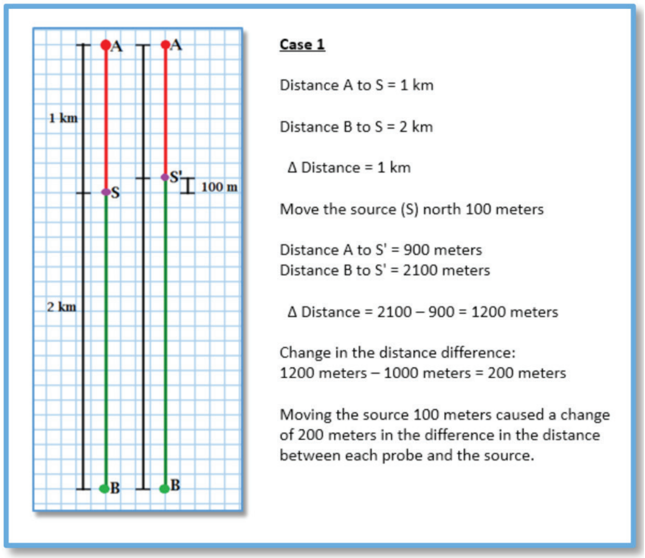


Figure 5. Effects of clock drift, showing that the data cannot be time-aligned if the sample rates do not precisely match.

Figures 6-9 show in detail how the geometry and location of the probes relative to the source effect the accuracy of the TDOA measurement. When the source is located behind a probe, it is best practice to use a more distant probe in the measurement. Signal strength is not normally a factor, as long as it is high enough above the background to be able to get a reasonable I/Q capture.



Case 1

Distance A to S = 1 km

Distance B to S = 2 km

Δ Distance = 1 km

Move the source (S) north 100 meters

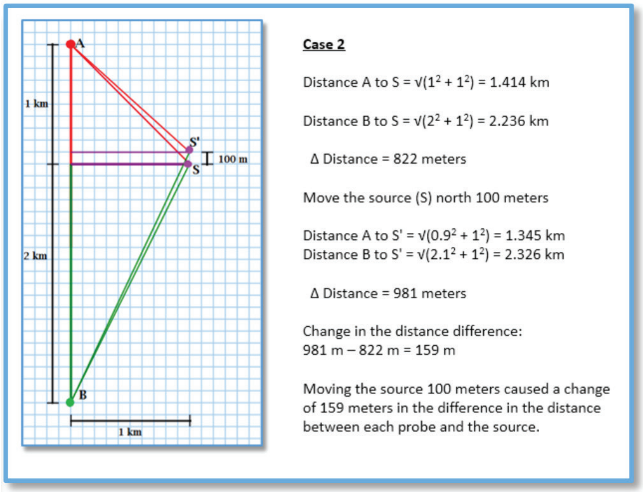
Distance A to S' = 900 meters
Distance B to S' = 2100 meters

Δ Distance = 2100 – 900 = 1200 meters

Change in the distance difference:
1200 meters – 1000 meters = 200 meters

Moving the source 100 meters caused a change of 200 meters in the difference in the distance between each probe and the source.

Figure 6. Case 1: Geometry and Location of Probes.



Case 2

Distance A to S = $\sqrt{(1^2 + 1^2)}$ = 1.414 km

Distance B to S = $\sqrt{(2^2 + 1^2)}$ = 2.236 km

Δ Distance = 822 meters

Move the source (S) north 100 meters

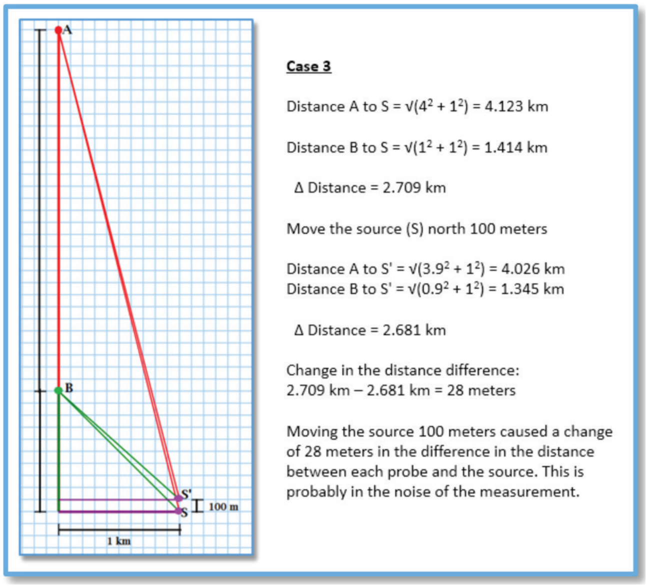
Distance A to S' = $\sqrt{(0.9^2 + 1^2)}$ = 1.345 km
Distance B to S' = $\sqrt{(2.1^2 + 1^2)}$ = 2.326 km

Δ Distance = 981 meters

Change in the distance difference:
981 m – 822 m = 159 m

Moving the source 100 meters caused a change of 159 meters in the difference in the distance between each probe and the source.

Figure 7. Case 2: Geometry and Location of Probes.



Case 3

Distance A to S = $\sqrt{(4^2 + 1^2)}$ = 4.123 km

Distance B to S = $\sqrt{(1^2 + 1^2)}$ = 1.414 km

Δ Distance = 2.709 km

Move the source (S) north 100 meters

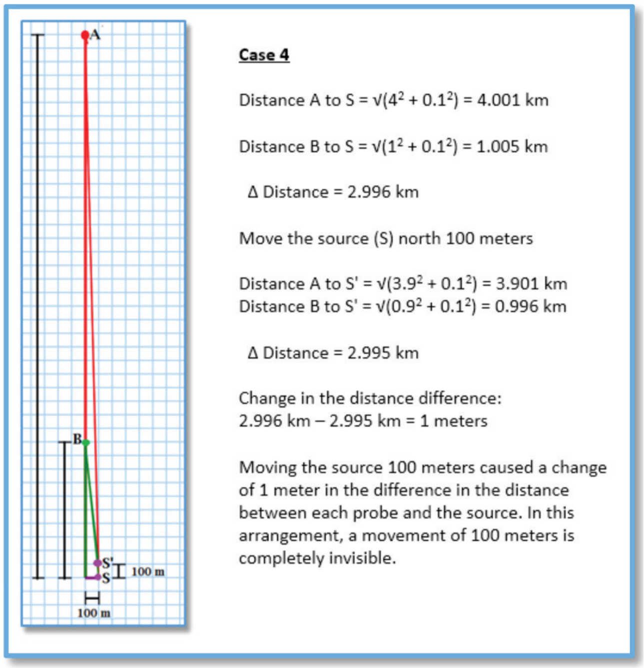
Distance A to S' = $\sqrt{(3.9^2 + 1^2)}$ = 4.026 km
Distance B to S' = $\sqrt{(0.9^2 + 1^2)}$ = 1.345 km

Δ Distance = 2.681 km

Change in the distance difference:
2.709 km – 2.681 km = 28 meters

Moving the source 100 meters caused a change of 28 meters in the difference in the distance between each probe and the source. This is probably in the noise of the measurement.

Figure 8. Case 3: Geometry and Location of Probes.



Case 4

Distance A to S = $\sqrt{(4^2 + 0.1^2)}$ = 4.001 km

Distance B to S = $\sqrt{(1^2 + 0.1^2)}$ = 1.005 km

Δ Distance = 2.996 km

Move the source (S) north 100 meters

Distance A to S' = $\sqrt{(3.9^2 + 0.1^2)}$ = 3.901 km
Distance B to S' = $\sqrt{(0.9^2 + 0.1^2)}$ = 0.996 km

Δ Distance = 2.995 km

Change in the distance difference:
2.996 km – 2.995 km = 1 meters

Moving the source 100 meters caused a change of 1 meter in the difference in the distance between each probe and the source. In this arrangement, a movement of 100 meters is completely invisible.

Figure 9. Case 4: Geometry and Location of Probes.

Referring back to figure 2, and looking at the more distant intersection of the three lines, it is seen that the blue and green lines especially, and the red line somewhat, approach each other at narrow angles. If the uncertainty in the measurement is 100 meters, then the true location of the RF source lies whenever the three lines are within 100 meters of each other. In figure 2 this is true of the blue and green lines for about 15 km. The red line crosses at a small enough angle that the actual area of possibility is more than a kilometer long. This is another case where a different probe set would be very useful so the source position is closer within the probe triangle.

Signal Averaging. Averaging is a good way to reduce random uncertainties in measurements. With TDOA this is accomplished by repeating the measurement several times and averaging the distance differences found for each probe pair. This number will vary from measurement to measurement due to statistical noise and uncertainty in the measurement data. As an example (using 250 kHz as the sampling rate), the expected uncertainties are calculated and shown here in figure 10. In this figure, N is the number of measurements taken in the averaging process.

N	Uncertainty
1	600 m
3	346 m
5	268 m
10	190 m
15	155 m
20	134 m
50	85 m

Intermittent Signals. Intermittent signals are a particular problem with TDOA. The probes all have to begin capturing at the same time, and they have to each capture a long enough data set that the overlap of the signal will be significant. To accomplish this, Anritsu implements proprietary algorithms to capture and time align each bursted signal.

Anritsu’s Solution: Vision TDOA and the MS2710xA RSM.

Anritsu provides TDOA measurements with MS2710xA Remote Spectrum Monitors (RSM) and the Vision software suite. The RSM probes have the necessary I/Q capture and precision timing features necessary to collect and transmit the timestamped I/Q data used in TDOA measurements. RSM probes can monitor and measure frequencies up to 6 GHz, with a maximum capture bandwidth of 20 MHz. RSM probes also come in a number of form factors and packages to suite a wide variety of situations. Options include multi-port enclosures that use a single receiver board to access up to 24 different antenna inputs. This provides a convenient means of deploying a single probe to cover multiple frequency ranges and tuned to specific band widths. RSM probes are also available in IP67 qualified enclosures to be mounted and operated outdoors for extended periods of time. See figures 11, 12, 13 and 14 below which shows the various models of spectrum monitors currently offered by Anritsu.

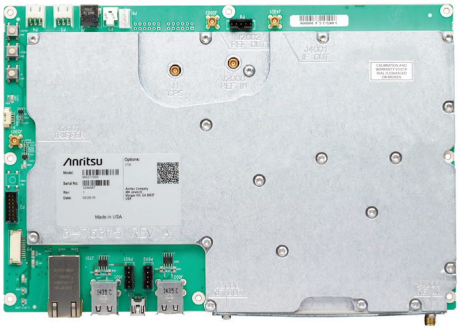


Figure 11. MS27100A OEM Model

Figure 12. MS27101A (half-rack)

Figure 13. MS27102A (IP67 Rated)

Figure 14. MS27103A (multi-port)

The Vision Software suite provides all of the necessary features to perform TDOA measurements over a wide range of frequencies and bandwidths. Vision can calibrate time delays, be used with intermittent signals, and automatically average over multiple data sets converging to a best answer for the geo-location of the RF source.

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