Sudden Frequency Deviations Caused by Solar Flares
Part II ~ Instrumentation and Observations

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2-1. Instrumentation

The following equipment was used for sudden frequency deviation observations (figure 1):

- PC with internal stereo soundcard running Windows XP, later upgraded to Windows 7, and synchronized to UTC using Network Time Protocol (NTP)
- Argo {Argo} and R_Meteor {R_Meteor} software
- Icom R-75 general coverage receivers x2
- KMA Antennas KMA1832, 8-element HF log periodic antenna
- Stridsberg Engineering MCA-104M 4-port receiver multicoupler

Note: Links in braces { } and references in brackets [ ] are provided in **section 2-7**.

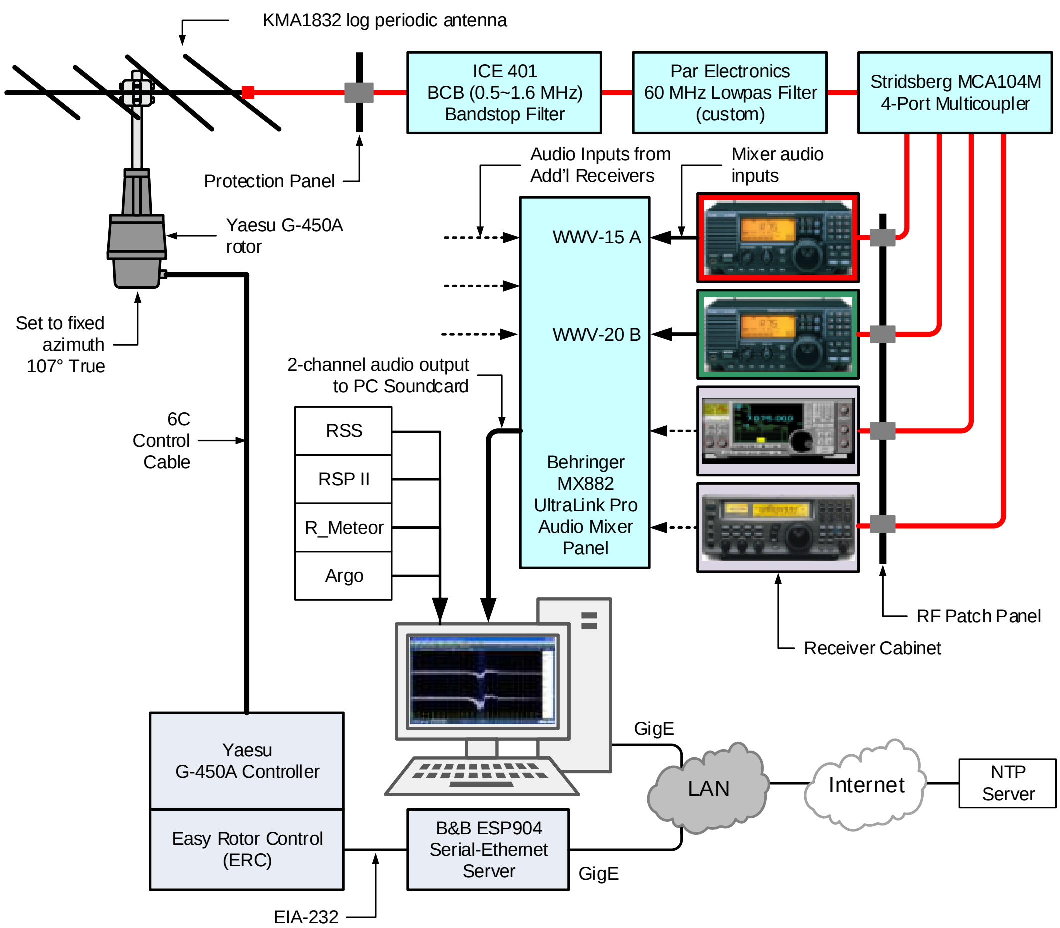

Figure 1 ~ Instrumentation block diagram. Only R-75 receivers A and B were used to record data.

I initially used both Argo and R_Meteor software to process the receiver audio outputs. Both programs were new to me so I initially used both to provide a cross-check. Both programs display and save the data in a similar way but Argo has built-in file transfer protocol (FTP) capability, which I use to upload the display images to my website {Meteor}. I eventually closed R_Meteor and used only Argo.

The Icom R-75 receivers were operated in lower sideband (LSB) mode with the automatic gain control (AGC) disabled. The receivers each have the high stability oven-controlled crystal oscillator (OCXO, option p/n CR-282) with advertised stability ±0.5 ppm (±7.5 Hz at 15 MHz). The receivers were turned on for the entire study period. The R-75 uses a product detector for the single-sideband modes. The receiver main oscillator provides a stable 30 MHz RF source for a direct digital synthesis (DDS) beat frequency oscillator (BFO) with 455 kHz output. The DDS output is fed along with the 455 kHz intermediate frequency (IF) output to a mixer to provide the SSB audio frequency (AF) output. The AF output is a very stable tone with the receiver tuning offset from the WWV carrier frequency by about 1 kHz. It is this AF that is processed and displayed.

I noted fractional hertz variations due to receiver temperature changes but these were smooth and had a characteristic time of around 15 minutes. Sudden frequency deviations and other transient phenomena were easy to spot on the Argo display, which spans 13 minutes.

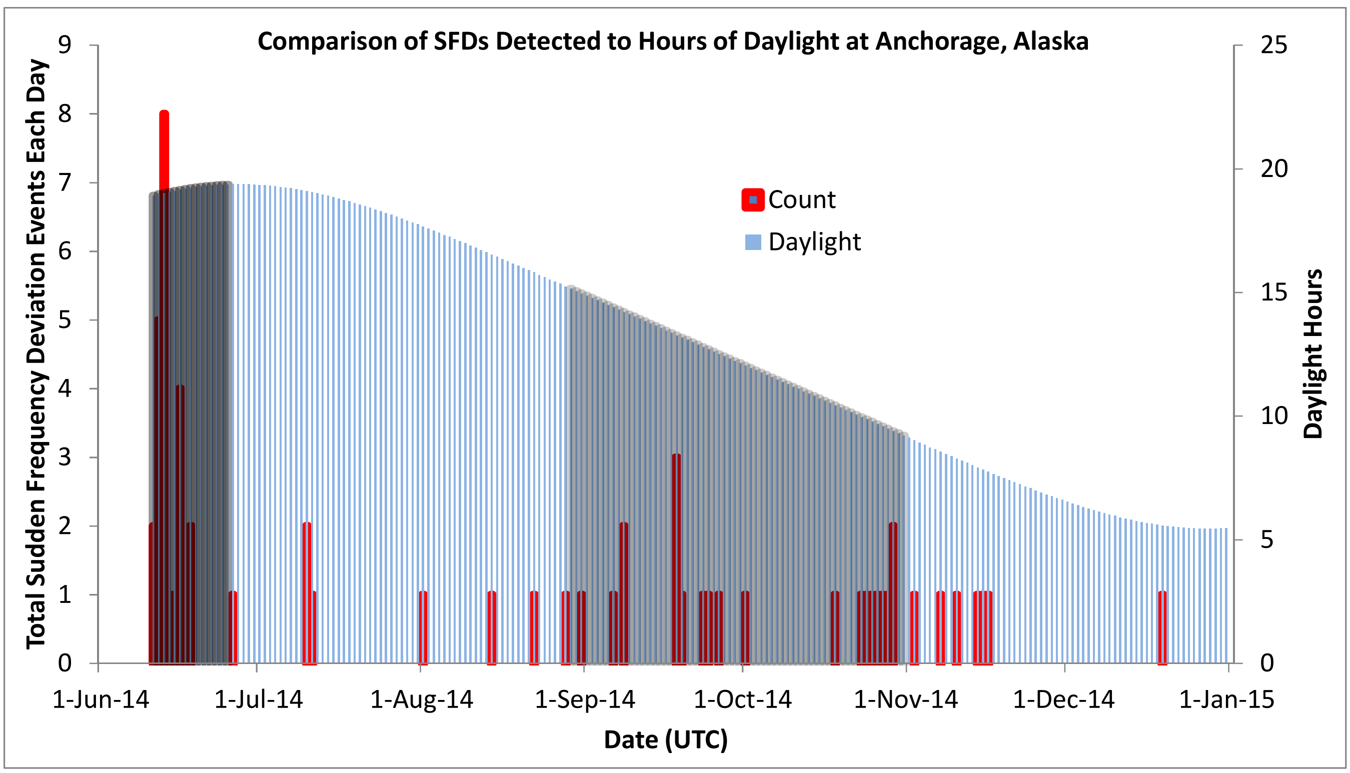

Figure 2 ~ Comparison of Sudden Frequency Deviations Detected at Anchorage, Alaska and Hours of Daylight

I initially tuned the receivers to 15, 20 or 25 MHz with the antenna pointed toward Boulder, Colorado (107° true azimuth) where WWV is located. I eventually abandoned 25 MHz due to sporadic reception and monitored only 15 and 20 MHz for the remaining measurements. Because of propagation conditions, I sometimes heard the WWVH station on Kauai on 15 MHz even though its true azimuth is 194°, almost a right-angle to the main antenna beam and close to a theoretical null in its pattern. It was impossible to discriminate or separate WWV and WWVH during the unattended automated measurements.

The receiver frequency offset was adjusted on each receiver to show separate signal traces for each receiver on the Argo and R_Meteor displays. The smallest tuning step of the R-75 is 10 Hz so the Argo trace can be adjusted only in 10 Hz increments. Argo was set to QRSS 10 mode, which provides about 40 Hz displayed bandwidth. The frequency scale tick-marks on the Argo chart are 1 Hz and fractional Hz variations are easy to see. R_Meteor was set to 50 Hz displayed bandwidth but the display has no frequency scale or grid.

2-2. Observations

When I started this study in June 2014, the days were quite long – up to almost 19.5 hours – and the Sun dipped only a few degrees below the northern horizon at night (although, around the Summer Solstice, the sky does not get dark). The end of the study was 31 December 2014, and the daylight hours were quite short. The winter Sun in late December does not rise more than about 5° above Anchorage's southern horizon and observations were limited to only a few hours. Only one SFD was observed during December. A comparison of the number of SFDs with the number of daylight hours (figure 2) did not yield any enlightening information.

The solar cycle 24 sunspot number peaked in February 2014 and then declined to about 75% of its peak value by the end of the study (figure 3). During the study period the total number of reported C, M and X class x-ray flares was 1092 (I made no count of optical flares). I detected 64 sudden frequency deviations at Anchorage, Alaska directly related to both x-ray and optical flares.

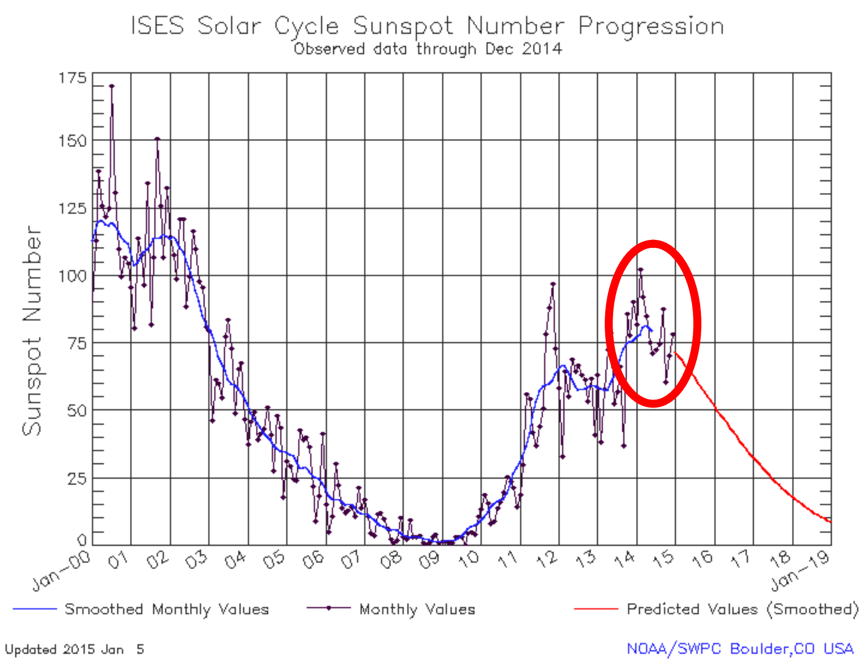

Figure 3 ~ Solar cycle 24 sunspot number progression. The circle shows 2014. Source: {NOAA}

Most sudden frequency deviations observed at Anchorage were characterized by a sudden frequency increase, peak and then decay of the received frequency to its pre-flare value. The deviations sometimes had several peaks and usually but not always reached negative values during the decaying portion. The start-to-maximum time generally was 1 minute, more or less, and the maximum deviation observed was 9 Hz. There was no clear correspondence between flare x-ray class and the peak frequency deviation but, generally, stronger flares caused higher deviations.

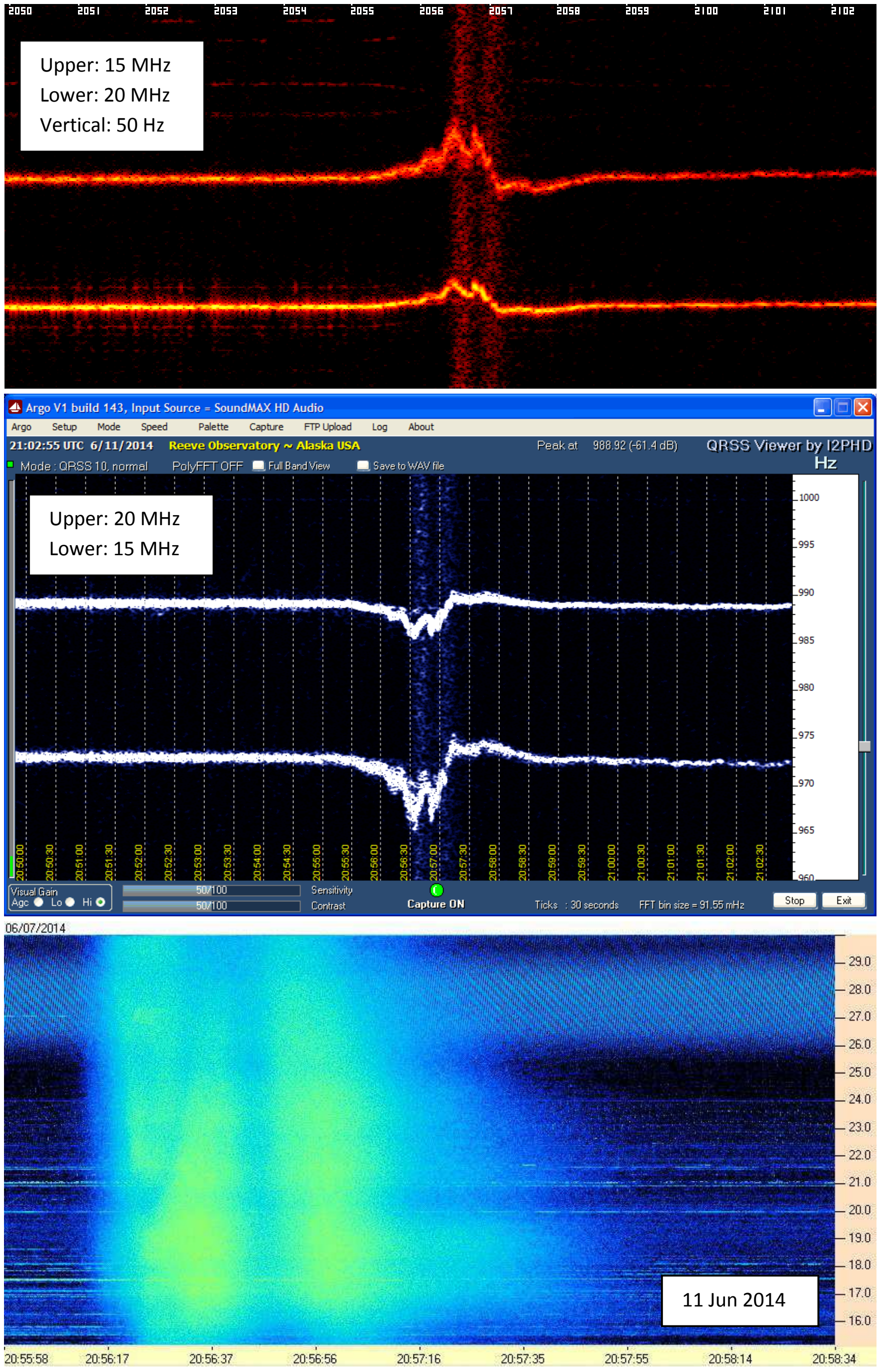

Figure 3 ~ Comparison of R_Meteor (upper) and Argo (middle) displays of a sudden frequency deviation at 2056 on 11 June 2014. A spectrogram (lower) shows solar radio bursts received at the same time from 15 to 30 MHz. The R_Meteor display shows the leading edge of the SDF rising to indicate an increase in received carrier frequency. The Argo display is inverted. Both displays are correct in terms of the technical setup, but the R_Meteor is more intuitive. The radio spectrogram shows two closely spaced bursts, which may correspond to the two peaks in the SFD. Note that the time scales of the SFD charts cover 12 minutes while the time scale of the spectrogram is only about 2.5 minutes.

In the Argo chart images shown in the next section, the onset of an SFD is indicated by a downward trace to a lower indicated frequency on the right-hand scale. Since the receivers were set to LSB and then tuned about 1 kHz offset above the carrier, the indicated direction of the deviation on the Argo charts is reversed – in other words, a decrease in audio output frequency corresponds to an increase in received carrier frequency. The situation is opposite with Radio_Meteor (figure 3).

During the study period Argo produced almost 60 000 images. The images were placed into weekly folders corresponding to the Space Weather Prediction Center (SWPC) Weekly Event Reports and then examined for the tell-tale signature of an SFD. It was possible to process the images for one week in < 15 minutes. Each candidate image was copied to another folder for additional visual analysis and comparison to the Event Reports. Some statistics are provided (table 1) and each SFD that correlated with the Event Report is tabulated (table 2). Representative sudden frequency deviation charts in chronological order and with annotations are provided in the next section. These are a subset of all SFDs observed. A complete set of all chart images is contained in Part II-A of this paper {SFD-P2a}.

Table 1 ~ Data summary for sudden frequency deviations observed at Anchorage, Alaska
11 June to 31 December 2014
Observatory coordinates: N61° 11’ 58.0”, W149° 57’ 22.9”

Item	Description	Value
1	Total observed sudden frequency deviations	64
2	Accompanied by x-ray class flare	51/64 = 80%
3	Accompanied by optical flare	38/64 = 59%
4	Accompanied by either x-ray class or optical flare	64/64 = 100%
5	Received with Sun below local horizon	13/64 = 20%
6	Maximum observed frequency deviation, 15 MHz	9 Hz
7	Maximum observed frequency deviation, 20 MHz	4 Hz
8	Highest x-ray class flare observed with SFD	X3.1
9	Lowest x-ray class flare observed with SFD	B6.3
10	Month with most observed SFDs	26 in June
11	Month with least observed SFDs	1 in December
12	Total daylight observation time	2621 h
13	History of observations and activity	See figure 4
14	Total number of reported C, M and X class x-ray flares	1092

Table 2 ~ Sudden Frequency Deviations Received at Anchorage, Alaska between 11 June and 31 December 2014
See key at end of table for explanation of column labels.

Day	Month	Time	Peak	Class	Optical	AZ/EL		Day	Month	Time	Peak	Class	Optical	AZ/EL
11	Jun	0944	0937	—	SF	356/–6		28	Aug	0524	0520	—	SF	293/–1
11	Jun	2056	2103	M3.9	SF	157/+50		31	Aug	1732	1733	C2.2	—	106/+18
12	Jun	1601	1603	C7.8	1N	79/+20		6	Sep	1745	1748	C4.7	SF	111/+18
12	Jun	1808	1813	M1.3	—	107/+35		8	Sep	0009	0011	C5.1	—	218/+29
12	Jun	2001	2003	M1.1	—	138/+47		8	Sep	1903	1907	C2.1	SF	130/+26
12	Jun	2106	2113	M1.0	—	160/+51		15	Sep	2047	2051	C2.3	SF	160/+30
12	Jun	2348	2349	—	SF	218/+48		18	Sep	0106	0112	C1.4	—	232/+21
13	Jun	0034	0033	—	SF	232/+44		18	Sep	0839	0841	M1.2	SN	339/–25
13	Jun	0343	0339	C9.9	—	278/+22		18	Sep	1727	1730	C3.4	—	110/+12
13	Jun	1523	1524	C2.4	SF	71/+26		19	Sep	1355	1352	C1.4	—	63/–13
13	Jun	1617	1619	C2.1	SF	82/+22		23	Sep	2307	2309	M2.3	2B	201/+27
13	Jun	1652	1655	C3.3	SF	89/+26		24	Sep	1749	1750	C7.0	1N	116/+13
13	Jun	1816	1817	—	SF	109/+36		26	Sep	0426	0430	—	SF	277/–5
13	Jun	2015	2017	C9.0	SF	143/+48		1	Oct	0532	0540	—	SF	291/–15
13	Jun	2058	2101	C4.1	SF	157/+51		18	Oct	0116	0107	C5.0	—	232/+8
14	Jun	0754	0737	—	SF	331/–2		20	Oct	1858	1902	M1.4	—	138/+11
15	Jun	2353	0001	M1.0	—	220/+47		20	Oct	1957	2004	M1.7	—	153/+15
16	Jun	1452	1452	C1.9	SF	64/+13		20	Oct	2246	2246	M1.2	—	196/+17
16	Jun	1844	1843	—	SF	116/+40		24	Oct	2110	2115	X3.1	3B	171/+17
16	Jun	1918	1918	C2.9	SF	125/+43		25	Oct	2322	2326	C8.4	—	205/+14
16	Jun	2148	2151	C2.3	SF	175/+52		26	Oct	1808	1815	M4.2	—	128/+5
17	Jun	0626	0627	—	SF	312/+5		27	Oct	1736	1740	M1.4	—	121/+1
18	Jun	0643	0652	—	SF	316/+3		28	Oct	0239	0242	M3.4	1B	250/–4
18	Jun	1622	1625	C1.8	SF	83/+23		29	Oct	1849	1850	M1.3	—	137/+8
26	Jun	0906	0918	C2.2	—	347/–5		29	Oct	2121	2122	M2.3	—	174/+15
10	Jul	2104	2113	C7.4	—	158/+50		2	Nov	0219	0159	—	SF	245/–3
10	Jul	2231	2234	M1.5	—	189/+51		7	Nov	1637	1639	C7.0	—	109/–8
11	Jul	0042	0044	C4.6	SN	233/+43		10	Nov	0221	0222	C7.6	SB	244/–5
1	Aug	1759	1813	M1.5	—	109/+29		14	Nov	2006	2011	C3.3	—	157/+8
14	Aug	0431	0420	B6.3	SF	283/+9		15	Nov	2043	2046	M3.7	1N	165/+9
22	Aug	0003	0006	C6.6	SF	217/+36		16	Nov	0228	0226	—	SF	245/–8
25	Aug	2011	2021	M3.9	—	146/+34		20	Dec	2032	2035	C5.6	SF	160/+4

Key to column labels:

Day — Day when the SFD occurred. Some SFDs occurred close to end of day and extended into the next day
Month — Month when the SFD occurred
Time — UTC time-of-day when the SFD occurred
Peak — UTC time of maximum flare x-ray flux reported by SWPC. Some flares started close to end of day but maximum occurred the next day
Class — Flare x-ray class reported by SWPC. A dash – indicates none reported
Optical — Flare optical importance reported by SWPC as follows:
1B, 2B, 3B: Importance 1, 2 and 3, Brilliant
1N: Importance 1, Normal
SB: Brilliant subflare
SF: Faint subflare
—: None reported
AZ/EL — AZimuth/ELevation (°) of Sun at Anchorage, Alaska at time of SFD; negative elevations indicate Sun below horizon

2-3. Sudden Frequency Deviation Charts

The Argo charts (figure 5) are a subset of all charts. The lower trace is 15 MHz and upper trace is 20 MHz. Only sudden frequency deviations with corresponding x-ray or optical characteristics as reported by SWPC are shown. Frequency deviations are shown inverted on the Argo charts; that is, a downward slope indicates a received frequency increase. The time span of all charts is 13 minutes, and most charts have 30 s tick-marks but some have 1 min tick-marks. The frequency scale on the right of each chart indicates the offset of the receiver frequency from the carrier frequency. The absolute value of the offset has no specific meaning.

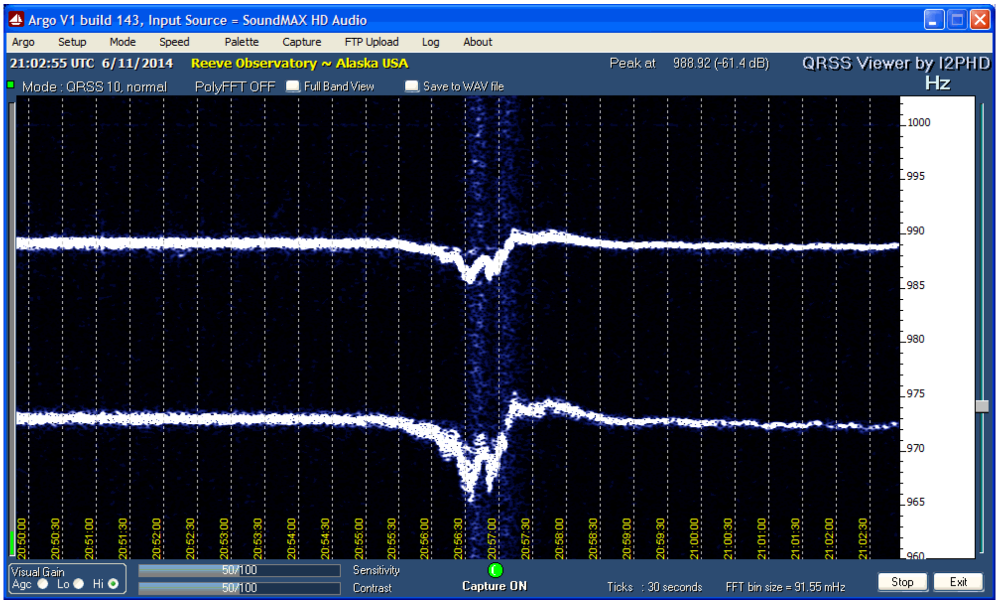

Figure 5-1

2056 UTC
11 Jun 2014
M3.9 : SF

7 Hz at 15 MHz
4 Hz at 20 MHz
Double-peak

AZ/EL: 157/+50

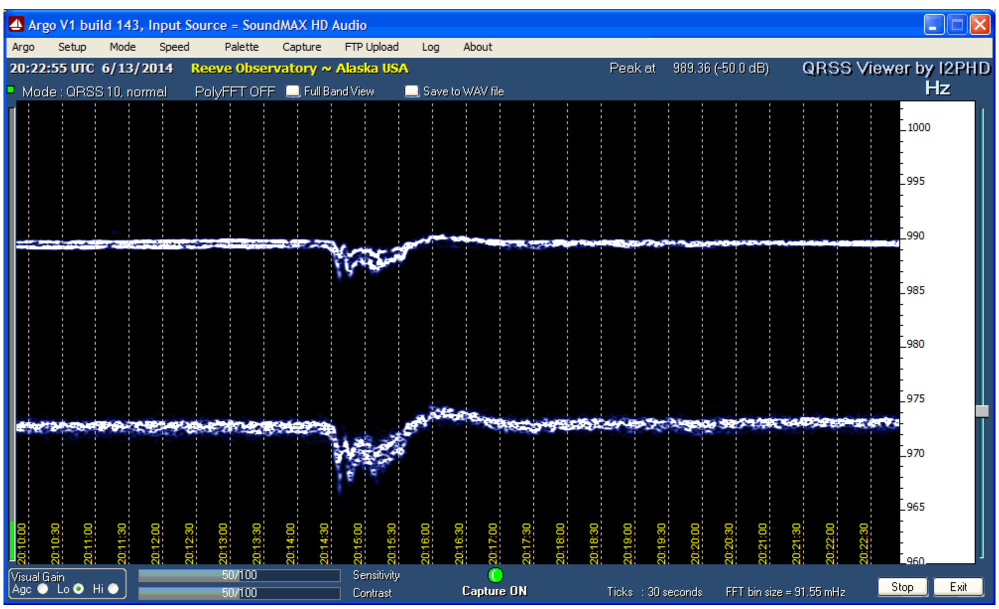

Figure 5-2

2015 UTC
13 Jun 2014
C9.0 : SF

Two carriers are present at 20 MHz. The trace for 15 MHz appears to show multiple carriers during the burst

AZ/EL: 143/+48

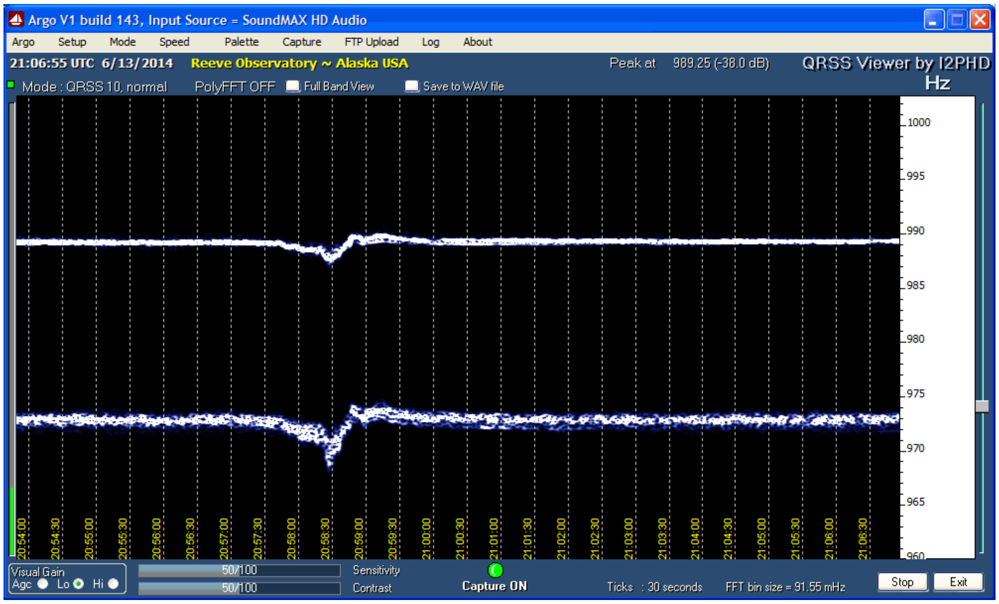

Figure 5-3

2058 UTC
13 Jun 2014
C4.1 : SF

AZ/EL: 157/+51

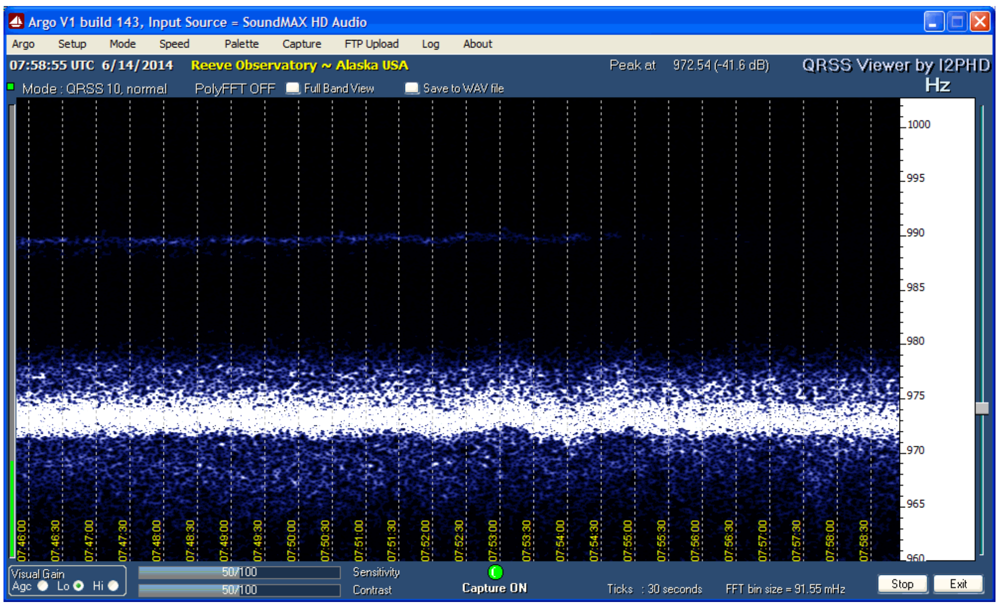

Figure 5-4

0754 UTC
14 Jun 2014
— : SF

Noise with Sun below horizon

AZ/EL: 331/–2

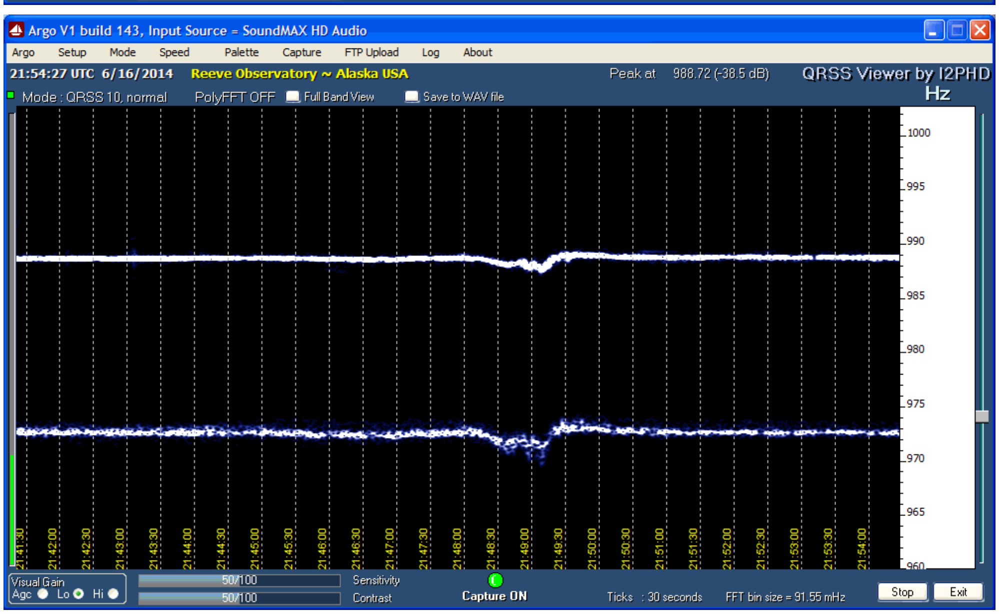

Figure 5-5

2148 UTC
16 Jun 2014
C2.3 : SF

No sudden onset and very little overshoot

AZ/EL: 175/+52

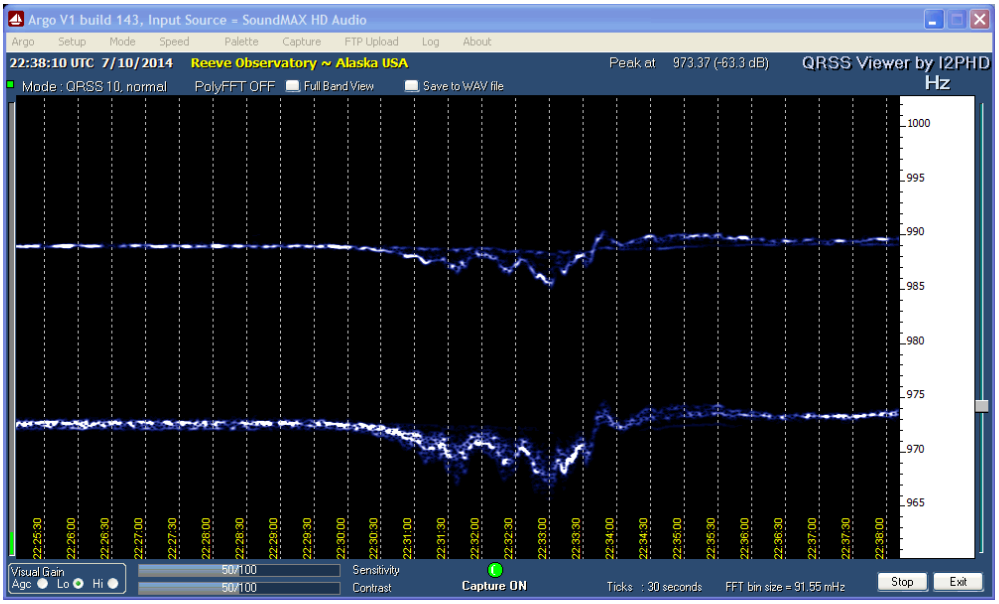

Figure 5-6

2231 UTC
10 Jul 2014
M1.5 : —

Weak reception at mid-afternoon

AZ/EL: 189/+51

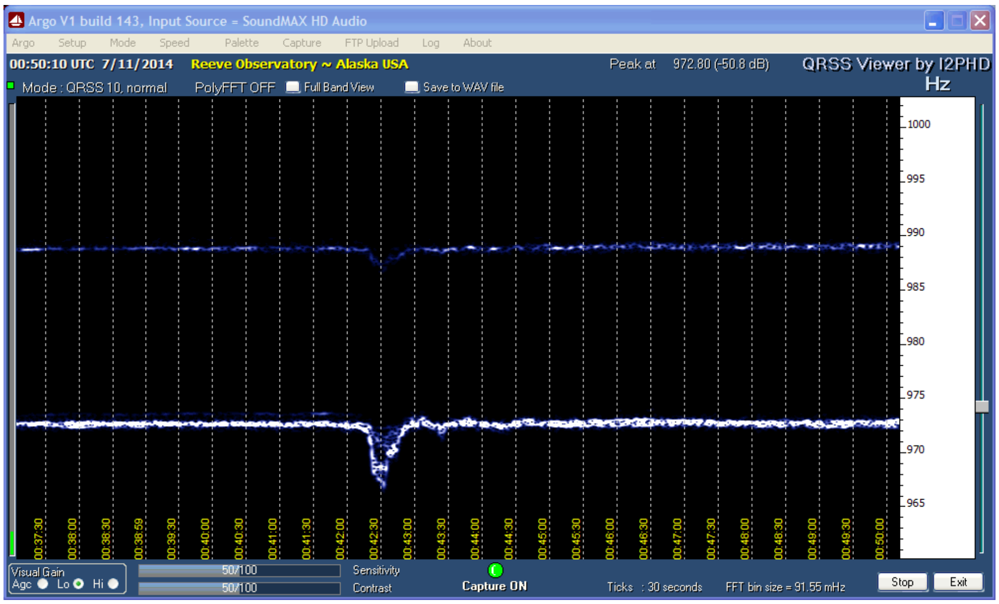

Figure 5-7

0042 UTC
11 Jul 2014
C4.6 : SN

SFD at 15 MHz only
Deviation 6 Hz

AZ/EL: 233/+43

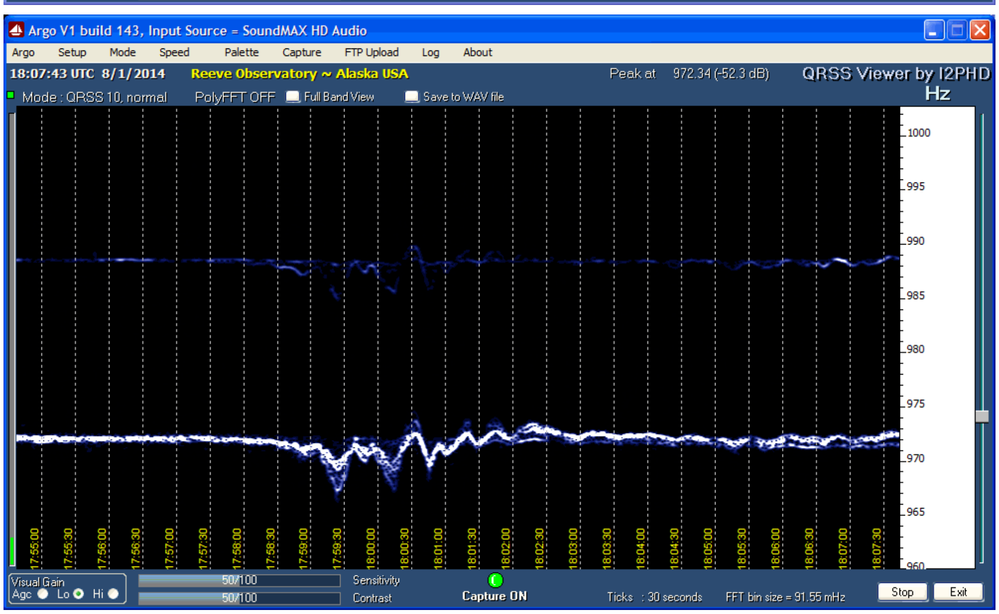

Figure 5-8

1759 UTC
1 Aug 2014
M1.5 : —

Ongoing frequency deviation > 4 minutes

AZ/EL: 106/+29

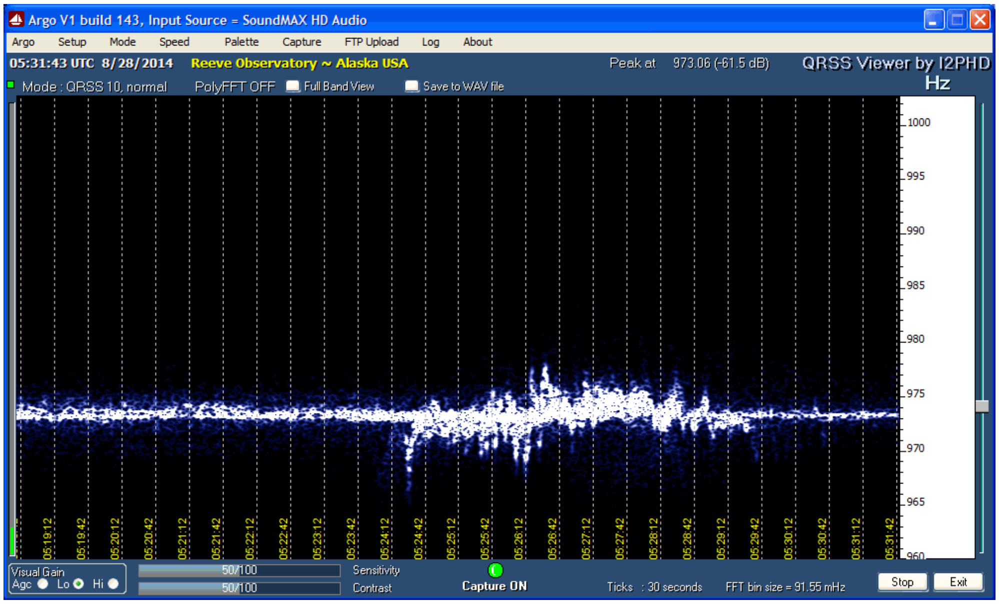

Figure 5-9

0524 UTC
28 Aug 2014
— : SF

Appears to be a 2nd carrier superposed on original 15 MHz carrier

AZ/EL: 293/–1

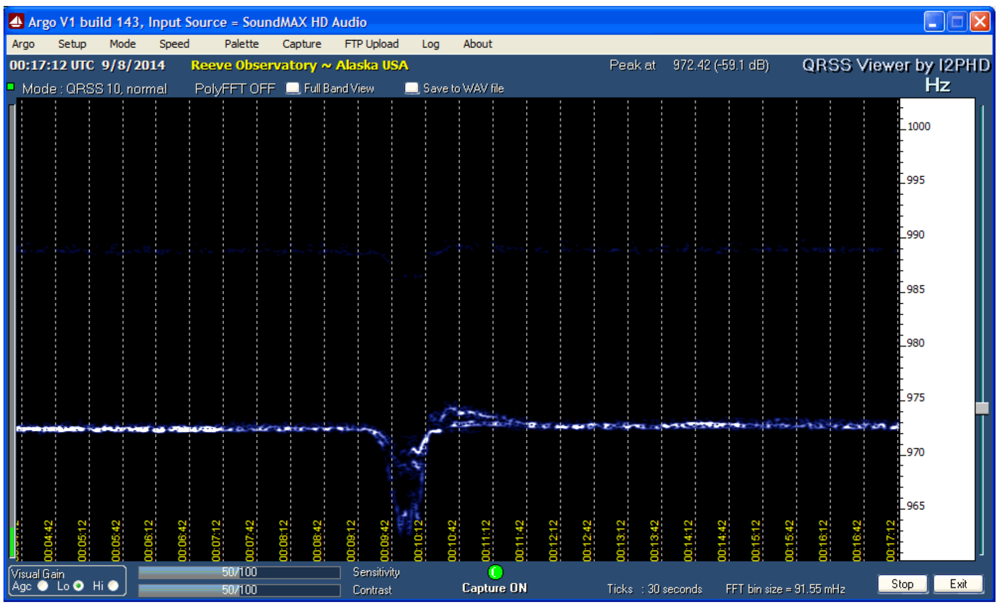

Figure 5-10

0009 UTC
8 Sep 2014
C5.1 : —

Deviation ~9 Hz at 15 MHz

AZ/EL: 218/+29

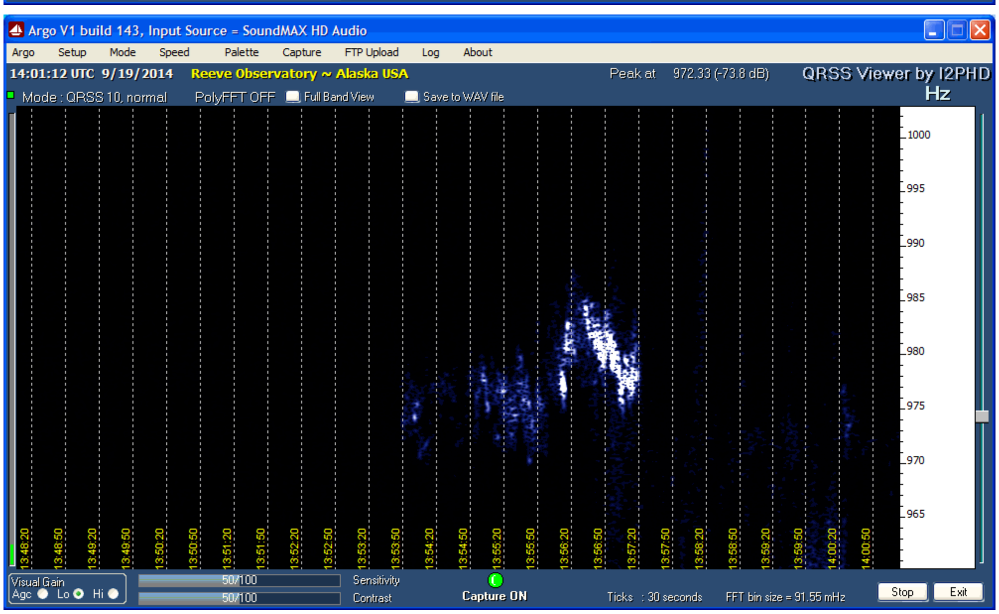

Figure 5-11

1355 UTC
19 Sep 2014
C1.4 : —

Flare enhanced propagation ~2 h before local sunrise

AZ/EL: 63/–13

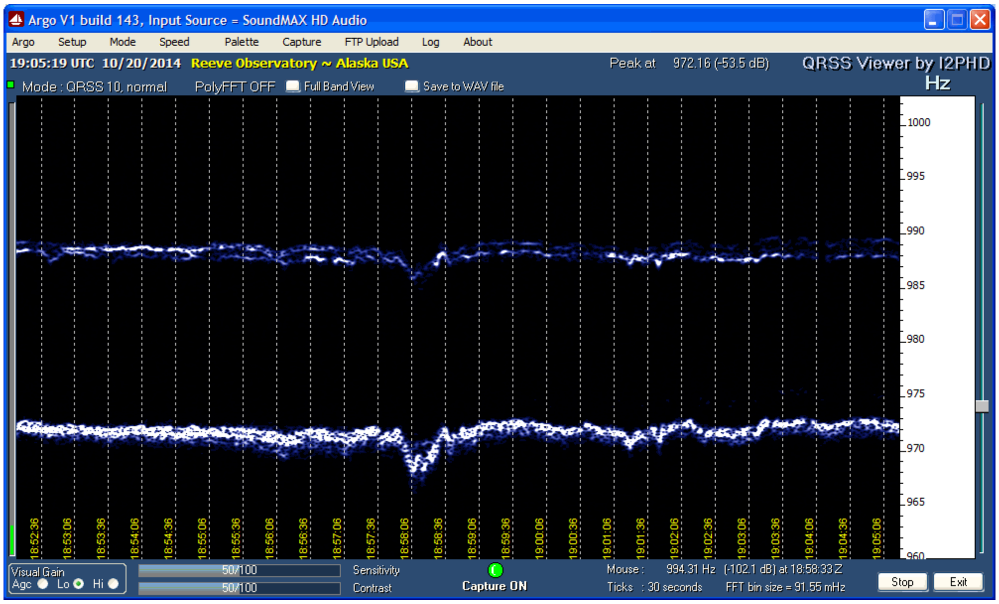

Figure 5-12

1858 UTC
20 Oct 2014
M1.4 : —

Frequency disturbances lasting > 7 minutes

AZ/EL: 138/+11

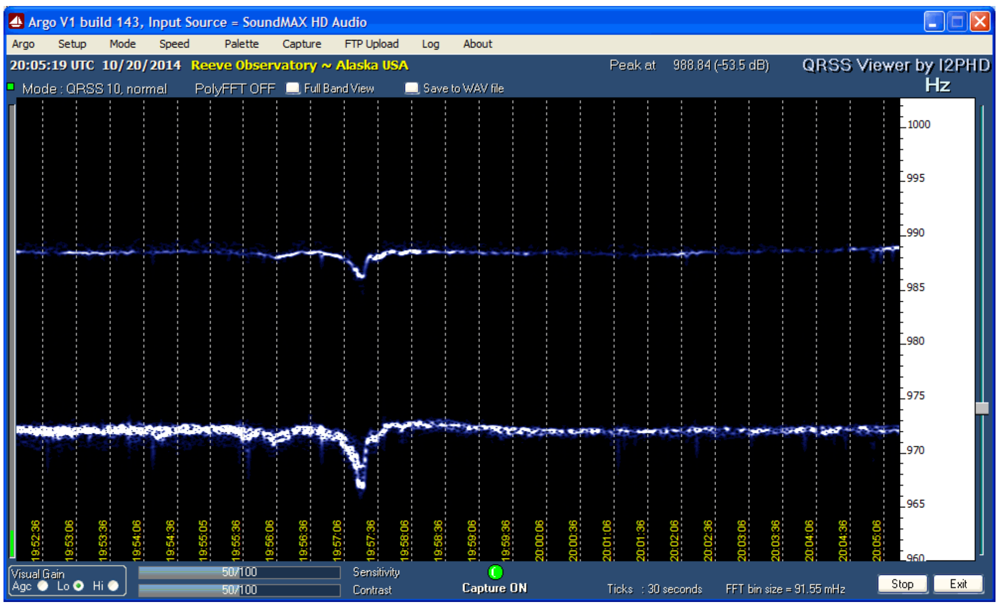

Figure 5-13

1957 UTC
20 Oct 2014
M1.7 : —

Frequency deviation 6 Hz at 15 MHz and 2 Hz at 20 MHz

AZ/EL: 153/+15

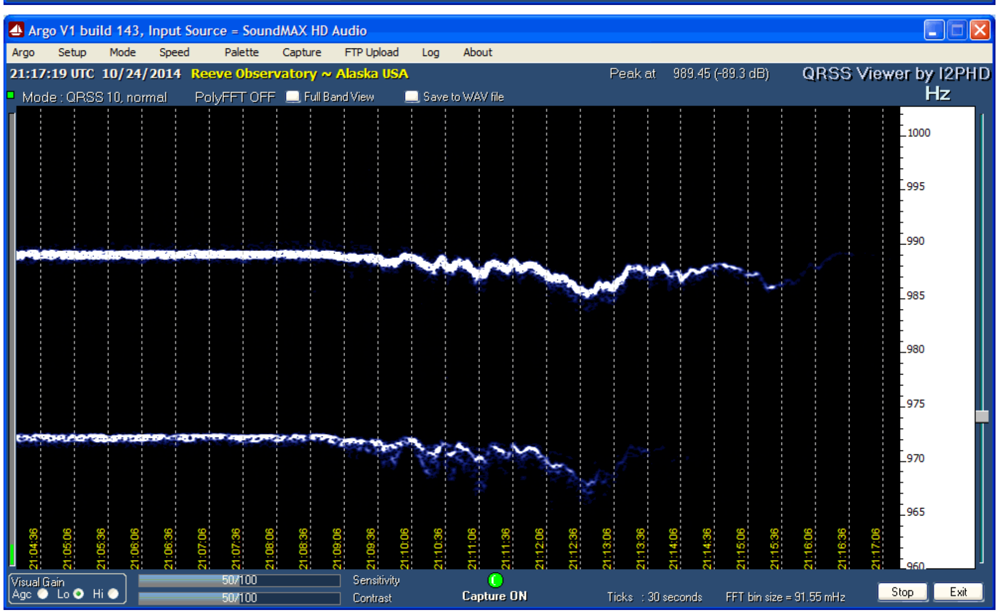

Figure 5-14

2110 UTC
24 Oct 2014
X3.1 : 3B

Flare, SFD and Radio Blackout due to D-region absorption

AZ/EL: 171/+17

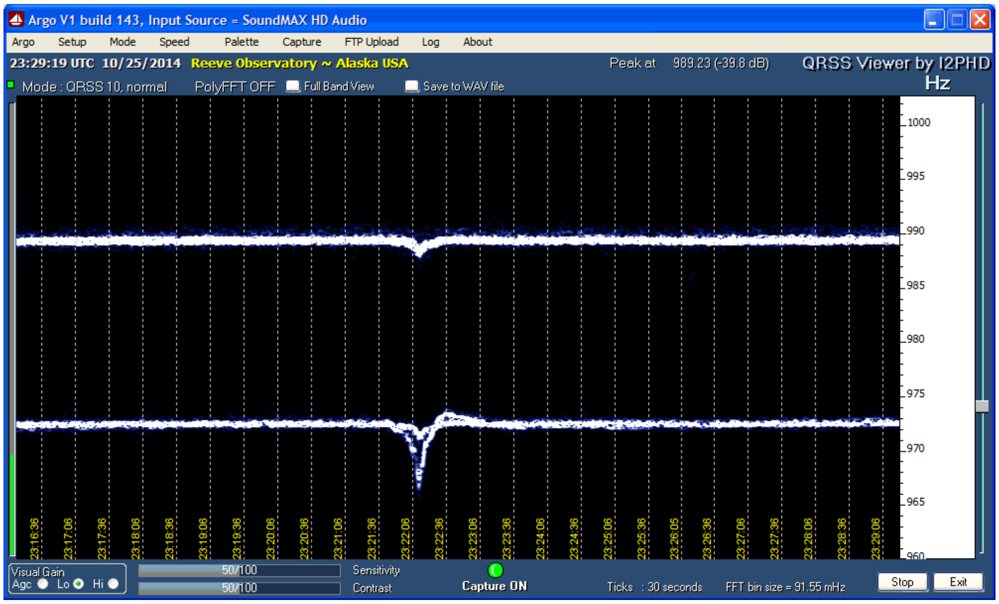

Figure 5-15

2322 UTC
25 Oct 2014
C8.4 : —

2 modes at 15 MHz
Frequency deviation 6 Hz

AZ/EL: 205/+14

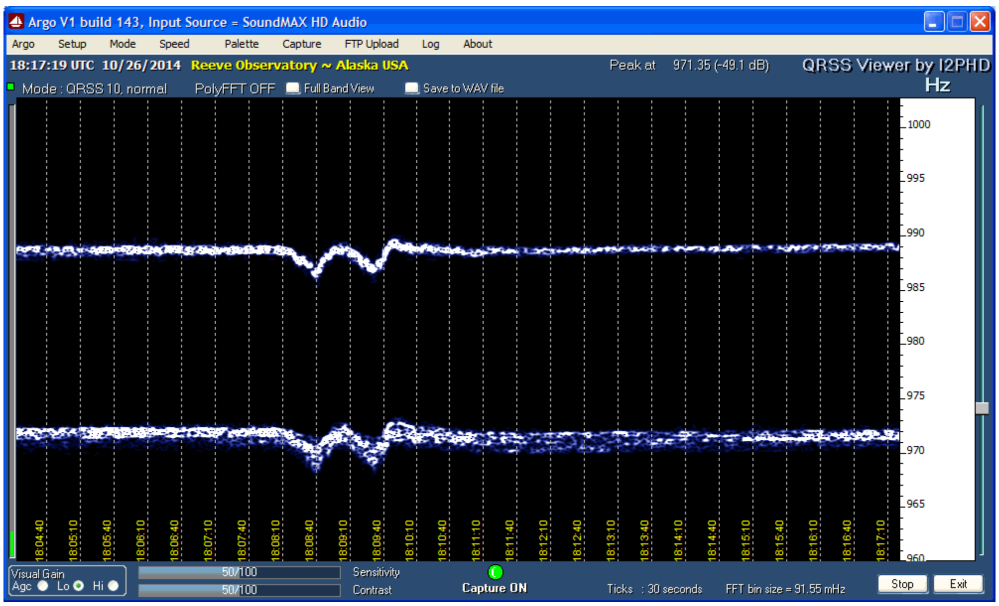

Figure 5-16

1808 UTC
26 Oct 2014
M4.2 : —

Almost equal frequency deviation at 15 and 20 MHz

AZ/EL: 128/+5

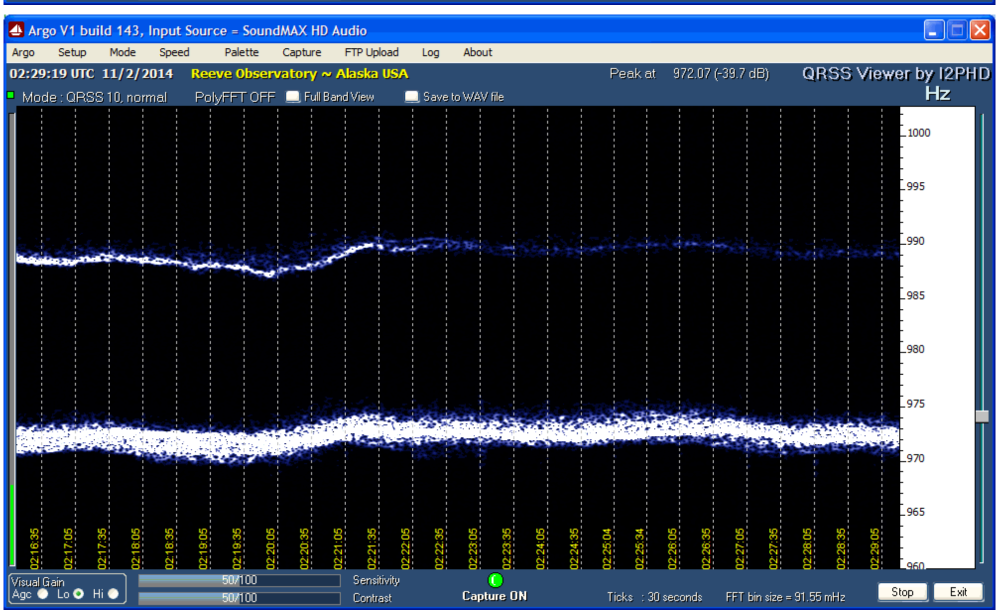

Figure 5-17

0219 UTC
2 Nov 2014
— : SF

Flare, SFD and radio blackout at 20 MHz

AZ/EL: 245/–3

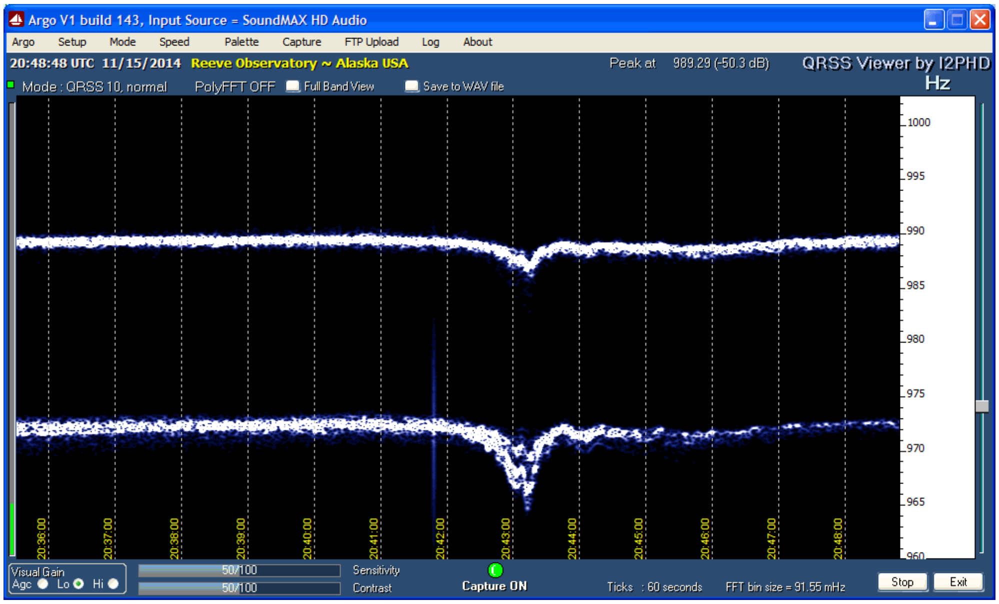

Figure 5-18

2043 UTC
15 Nov 2014
M3.7 : 1N

Frequency deviation 8 Hz at 15 MHz

AZ/EL: 165/+9

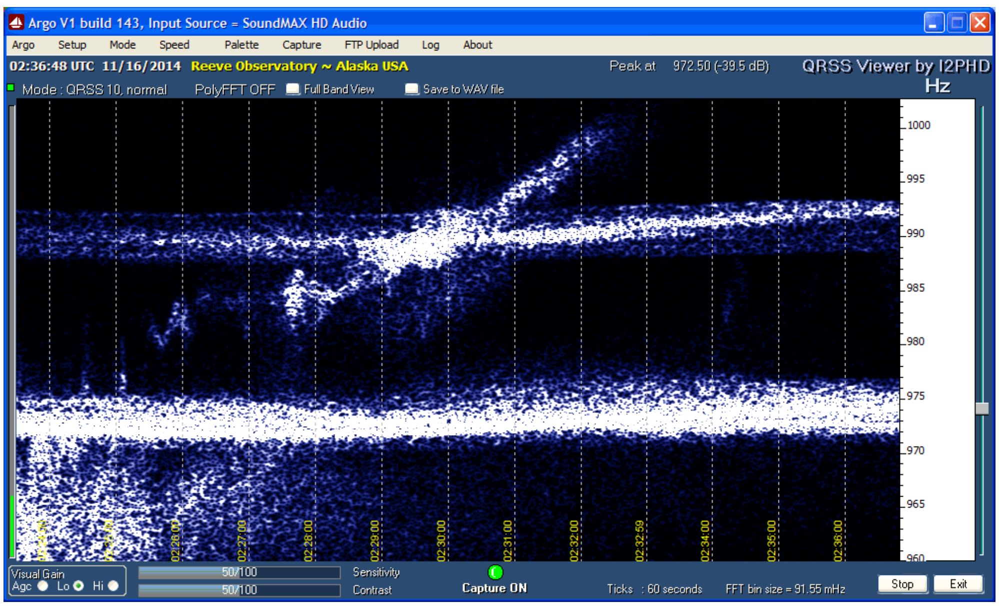

Figure 5-19

0228 UTC
16 Nov 2014
— : SF

Unknown 2nd carrier below 15 MHz and passing through 20 MHz

AZ/EL: 245/–8

2-4. Observations Related to Sudden Frequency Deviations

Some sudden frequency deviations were accompanied by a radio blackout (figure 6). During a radio blackout x-rays and extreme ultraviolet rays from a solar flare ionize the lower part of the dayside ionosphere. Radio waves directed into this region are absorbed before they reach the upper ionosphere, where they are normally reflected or refracted. The length of a radio blackout depends on the frequency and other conditions. For the observations discussed here, a radio blackout generally started within a few minutes after the onset of a sudden frequency deviation and lasted tens of minutes to over an hour and generally lasted longer at 15 MHz than 20 MHz.

A significant percentage (21%) of sudden frequency deviations were observed when the Sun was below the local horizon, some while it was east of Anchorage toward Boulder and some while west of Anchorage. The maximum negative elevation was 25° on 18 September when the Sun was at a true azimuth of 339°. Even though the Sun dropped below the local horizon, it still illuminated the upper ionosphere for a while afterwards. The ionization was sufficient to support propagation but only at 15 MHz in most cases. It should be noted that the ionosphere along the propagation path between Boulder and Anchorage plays a more important role than the ionosphere directly over Anchorage.

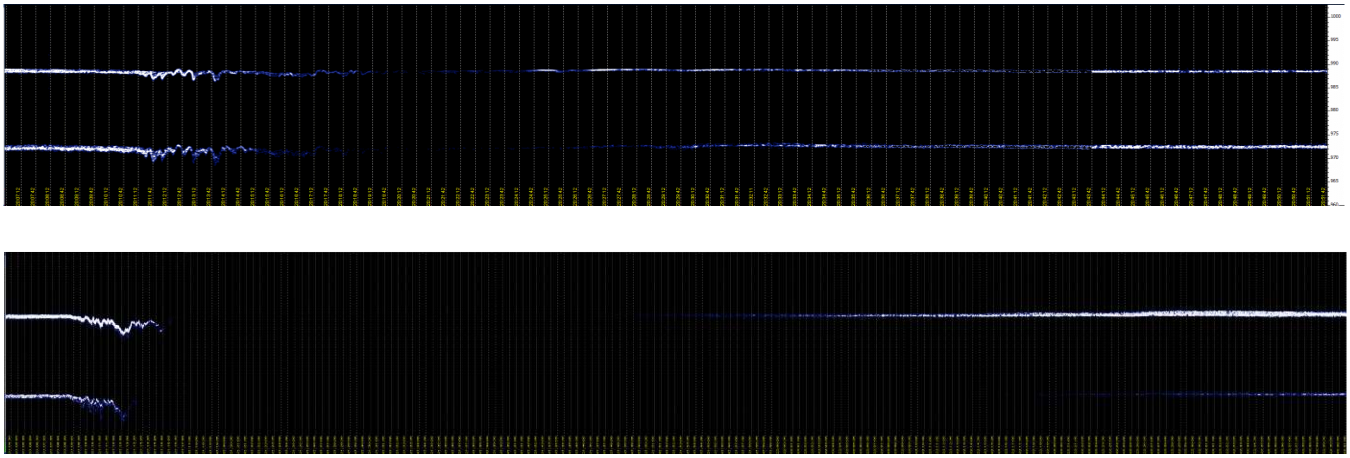

Figure 6 ~ Upper: Radio blackout at 15 (lower trace) and 20 MHz on 25 August 2014; total chart span is 44 min; Lower: Radio blackout at 15 (lower trace) and 20 MHz on 24 October 2014; total chart span is 1 h 35 min. Both charts are composites of several individual Argo charts.

2-5. Other Observed Phenomena during the Study

I noted some sudden frequency deviations that had no corresponding x-ray or optical flare. The R-75 receivers have never shown transient frequency deviations by themselves, and both Argo and R_Meteor displayed the same indications. The source of these anomalous events is unknown. They could have been due to instrumentation, terrestrial effects, ionospheric variations such as sporadic-E or SFDs associated with unreported flares. Some anomalous events appear to be related to the effects of sunrise and sunset. The anomalies observed included

- Short duration off-frequency bursts
- Sporadic receptions, mostly at 20 MHz
- Split signal traces
- Noise bursts
- Sunset noise
- Frequency deviations with no corresponding reported solar flare
- Frequency deviations near sunset
- Frequency striations with up to five separate traces on the center frequency

Some examples follow (figure 7).

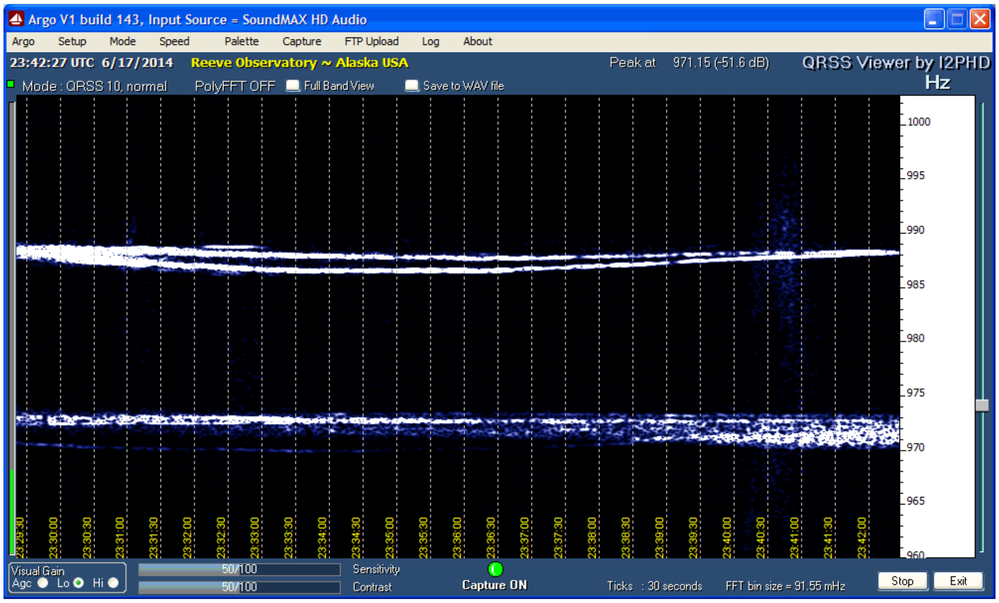

Figure 7-1

2334 UTC
17 Jun 2014

Striations at both 15 and 20 MHz

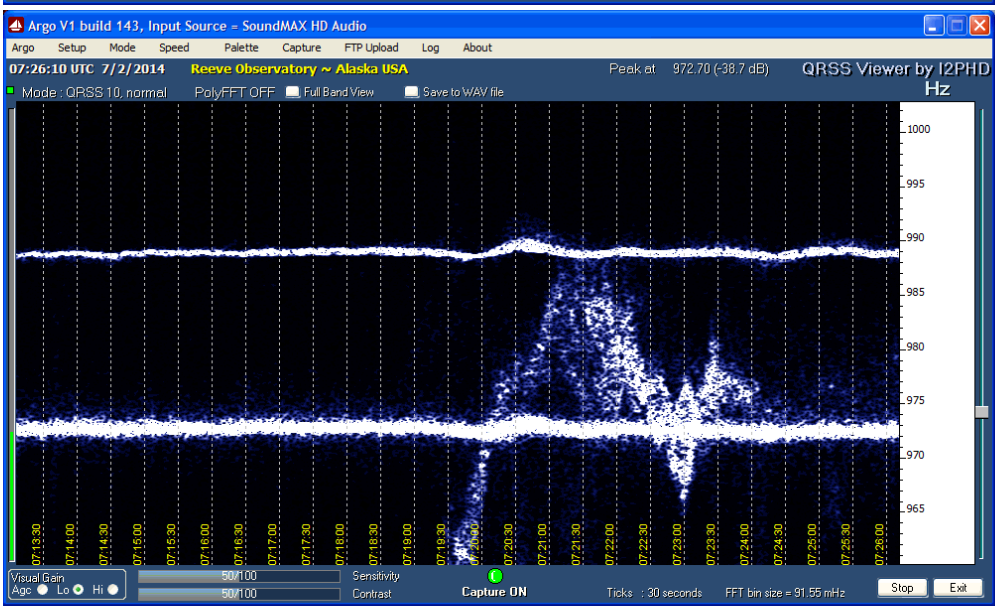

Figure 7-2

0720 UTC
2 Jul 2014

Unknown interference

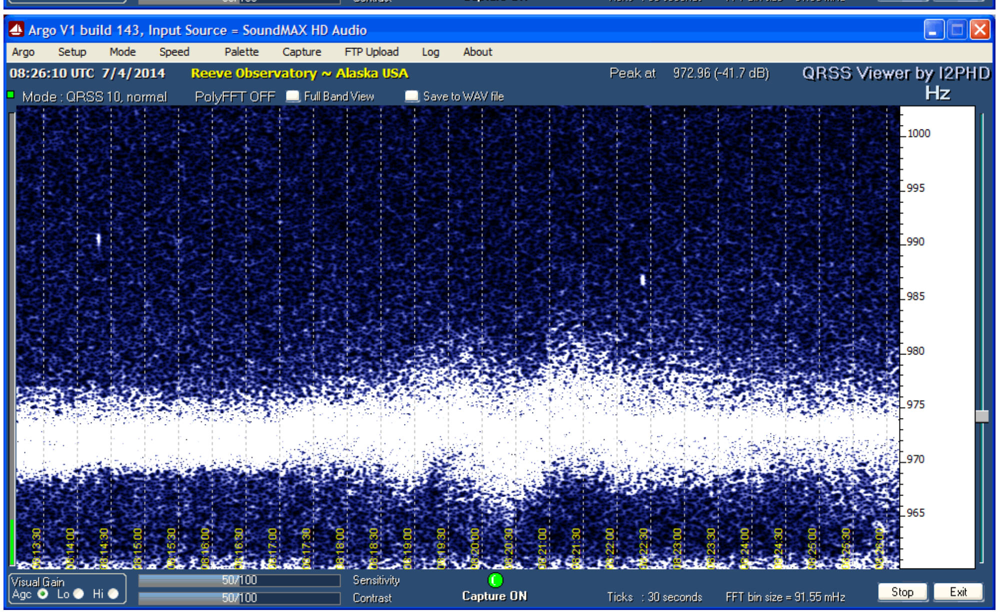

Figure 7-3

0819 UTC
4 Jul 2014

Very noisy received carrier

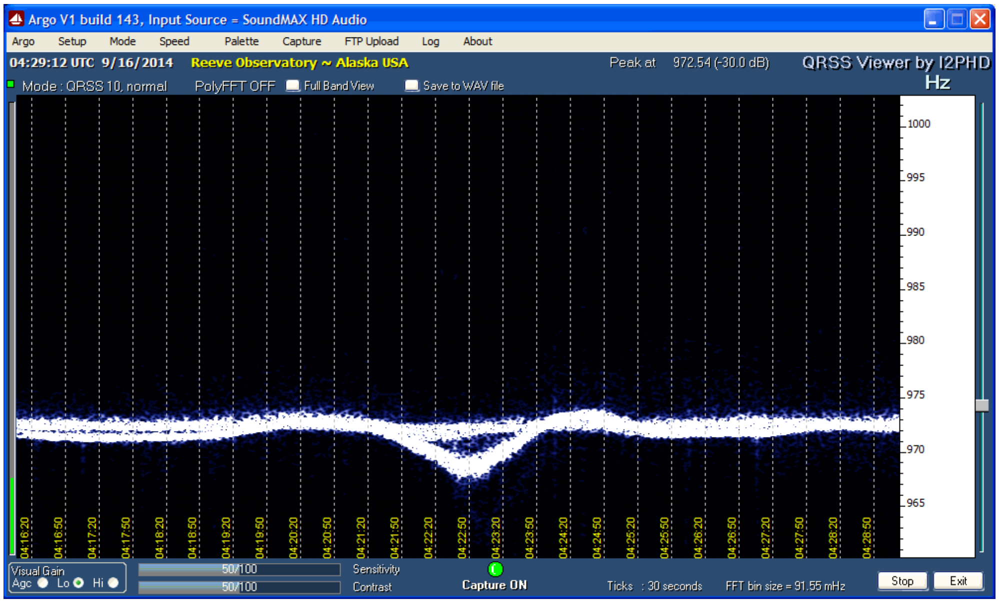

Figure 7-4

0421 UTC
16 Sep 2014

Striation at 15 MHz
at local sunset

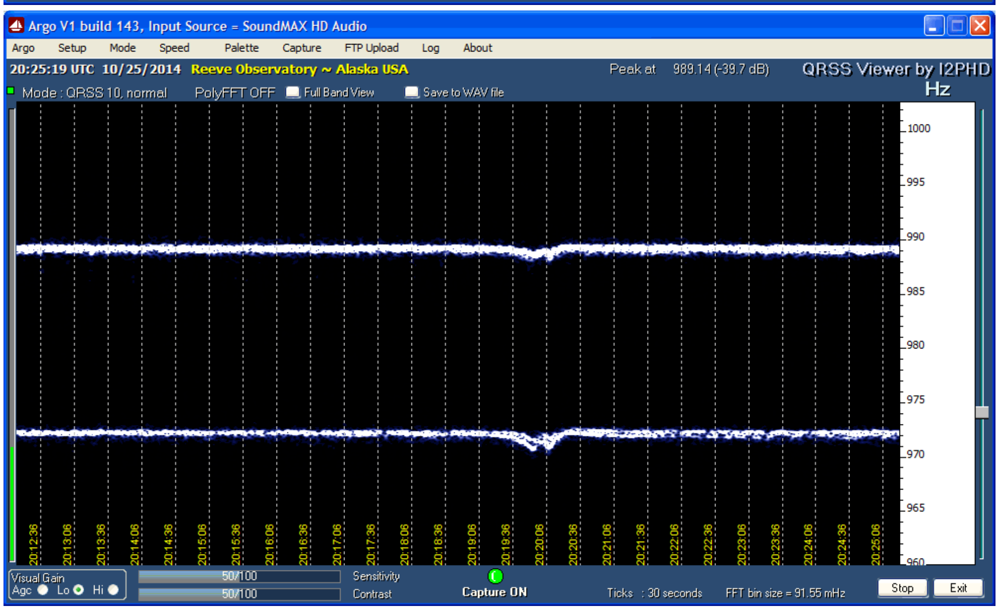

Figure 7-5

2019 UTC
25 Oct 2014

Weak SFD with no
reported solar flare,
typical of several

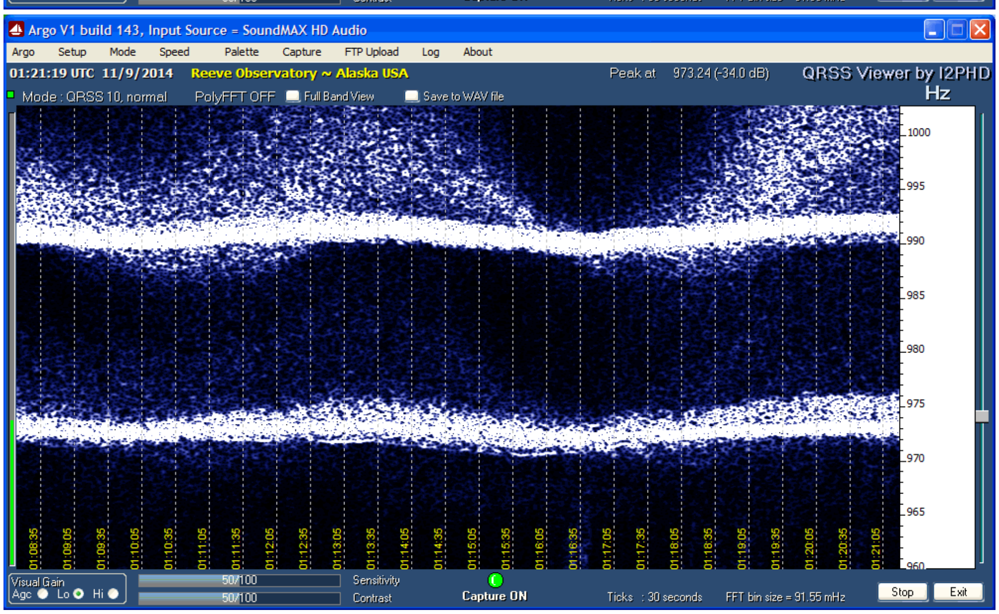

Figure 7-6

0112 UTC
9 Nov 2014

Noise and other
anomalies at local
sunset

2-6. Conclusions

Sudden frequency deviations result from rapid changes to Earth's ionosphere. Two conditions are attributed to sudden frequency deviations – rapid change of the electron density in the ionosphere below the reflection region and rapid vertical movement of the reflection region itself. SFDs are relatively easy to detect with an ordinary HF receiver and antenna system that is tuned to a fixed frequency transmitting station far enough away to ensure sky wave propagation.

During the study period of about 2621 daylight hours, 64 sudden frequency deviations were observed at Anchorage, Alaska. All were associated with an x-ray or optical solar flare reported by Space Weather Prediction Center but some SFDs occurred without a corresponding flare. On the other hand, during the study period there were many flares that did not cause a detectable sudden frequency deviation. Therefore, neither the x-ray characteristics nor the optical characteristics alone determine if a sudden frequency deviation will occur or will be detected. Many other factors are involved including the propagation path characteristics and time of day.

2-7. Web Links

{Argo} http://www.weaksignals.com/
{EVENTS} ftp://ftp.swpc.noaa.gov/pub/indices/events/
{Meteor} http://www.reeve.com/Meteor/Meteor_simple.html
{NOAA} http://www.swpc.noaa.gov/products/solar-cycle-progression
{R_Meteor} https://www.coaa.co.uk/r_meteor.htm
{SFD-P2a} http://www.reeve.com/Documents/Articles%20Papers/Reeve_SuddenFreqDevMeas_P2A_Obs.pdf

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0.2 (Retained only representative images, others moved to Part II-A, 19 Jan 2015)

0.3 (Add'l revisions to clean up, 21 Jan 2015)

0.4 (Completion of 1st draft, 23 Jan 2015)

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