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May 7, 1998

Dear Colleague:

The five documents attached herewith comprise a report on the test measurements of emissions within the 1610.6-1613.8 MHz radio astronomy band from a satellite of the Iridium series. These tests were conducted by NRAO in cooperation with Motorola/Iridium. The five documents are as follows:

Tests of Emissions from an Iridium Satellite in the 1610.6-1613.8 MHz Radio Astronomy Band: Overview and Conclusions by NRAO.

Post-Processing of NRAO Observations of Iridium Satellites, by Motorola SATCOM.

Observations of an Iridium Satellite with the NRAO 140-ft telescope at 1610.6-1613.8 MHz. (Report on the Measurements at Green Bank.)

NRAO-VLA Data from Tests of Iridium Emissions in the RAS Band 1610.6-1613.8 MHz. (Report on the Measurements at the VLA.)

Results of Tests by NRAO/Tucson of Emission of Iridium satellites in the 1610.6-1613.8 MHz Band. (Report on the Measurements at Tucson.)

Sincerely yours,

Dick Thompson

A. Richard Thompson

Tests of Emissions from an Iridium Satellite in the 1610.6-1613.8 MHz Radio Astronomy Band: Overview and Conclusions by NRAO.

Tests of the emission from a satellite vehicle of the Iridium system in the 1610.6-1613.8 primary radio astronomy band have been made by NRAO in cooperation with Motorola/Iridium. Measurements were made independently by three NRAO groups, located at Green Bank, the VLA, and Tucson, in the last case using a small antenna of the University of Arizona. Motorola provided transits of a satellite with special software to simulate the maximum traffic load predicted for the particular area of the U.S. Tucson observed the same passes as the VLA, but for Green Bank a different set of passes on different days was used. Reports of the individual sites describing the test procedures and listing the results are attached. Here we provide an overview of the results and the conclusions that NRAO reaches from the tests. Note that intentional transmissions from Iridium satellites in L-band are all in the frequency range 1621.35-1626.5 MHz, and the emissions in the radio astronomy band are generated by intermodulation in the transmitting amplifiers that drive the elements of the phased-array antennas. The intentional transmissions are right-hand circularly polarized.

Three operating conditions of the satellite were simulated. These were with only the voice-communication channels active, voice and broadcast channels active, and only broadcast channels active. The broadcast channels are a series of frequencies that are provided to enable a user to connect to the satellite at the beginning of a call. During normal operation of the Iridium system both the voice and broadcast signals will be active. Also, it is our understanding that the broadcast signals will remain active during times of low traffic density when the system is expected to allow radio astronomy usage of the band 1610.6-1613.8 MHz without interference. During the tests the broadcast signals were activated during every 90 ms transmit/receive cycle of the satellites, whereas Motorola/Iridium tells us that in normal operation they will be activated only on every other 90 ms cycle. Thus the mean levels of the broadcast signals used in the tests is higher by 3 dB than is expected to occur in normal operation.

Antennas at Green Bank (the 140 ft.) and at the VLA that were used in the tests cannot track fast enough to follow a satellite across the sky. They were therefore set for beam transits which last for less than one second for a satellite pass near the zenith. A receiving system with a spectral resolution of 19.5 kHz was used at Green Bank, and at the VLA one with resolution of 97.7 kHz as well as a 1 MHz bandwidth system. At Tucson a smaller antenna was used which was able to track the satellite over limited ranges of the sky. With this antenna the receiver measured the power in a 2 MHz-wide band centered at 1612 MHz. In all cases the values of SPFD (spectral power flux density) listed in the tables of results are averages over time, i.e., over the complete Iridium 90 ms transmit/receive cycle. At the VLA, a total of 12 passes were observed during a period of 7 days. By repointing the antenna rapidly after a beam transit, as many as three, and in one case four, transits could be observed per pass. A total of 30 beam transits were observed at the VLA and 16 at Green Bank. At Tucson the satellite was tracked for parts of 5 passes. The interpretation of the measurements is complicated by the fact that passes occurred for many values of satellite azimuth, elevation, and range. We do not know the beam shapes of the phased array antennas on the satellites or how well the beam forming networks would work for intermodulation products in the radio astronomy band. Thus, no attempt has been made by NRAO to interpret the variation of the measured SPFD values in terms of the azimuth or elevation of the satellite.

The threshold value for detrimental interference to radio astronomy in the 1610.6-1613.8 MHz band that is appropriate in evaluating the effect of the satellite emissions is -238 dBW/m^{2}Hz. This is the value for spectral line measurements in Recommendation ITU-R RA.769, and in the ITU-R Handbook on Radio Astronomy. This figure is determined for observations with a spectral channel bandwidth of 20 kHz and an averaging time of 2000 sec. It refers to the signal received in one polarization of the radio astronomy antenna, and it is assumed that the full power of the interfering signal is received, i.e. that the polarization of the interference is matched to that of the antenna. With regard to spectral resolution, the 19.5 kHz bandwidth used at Green Bank allows direct comparison with the interference threshold. For the VLA, direct comparison with the interference threshold can be made in the case of intermodulation from the voice channels, since the records indicate that the spectrum of such emission is a continuum that varies only slowly with frequency.

Voice Communication Signals

For simplicity we will consider all of the measurements with the voice channels active as one set, including both those with the broadcast signals on and off. In Fig. 1, the peak values observed across the spectral channels are plotted against the satellite range. Since the transmission levels were set to simulate the maximum predicted levels for the particular areas, the results from Green Bank cannot be directly compared with those from the other two sites. The predicted SPFD values for emission within the radio astronomy band, estimated by Motorola/Iridium for maximum traffic conditions, are:

Green Bank	-214 dBW/m^{2}Hz
VLA Site	-223 dBW/m^{2}Hz

These values can be compared with the SPFD measurements described below.

For discussion of the VLA results we use the values for the ADS (autocorrelating digital spectrometer) since they have higher spectral resolution than those for the HTRP (high time resolution processor). The peak SPFD measured with voice channels active is -229.1 dBW/m^{2}Hz on March 6, and the mean over the radio astronomy band is -232.7 dBW/m^{2}Hz for the same beam transit. This was for a path very close to the zenith with satellite range 786 km. The lowest peak SPFD measured at the VLA was -239.7 dBW/m^{2}Hz on Feb 22, with one of the longer values of satellite range, 2076 km. This value is slightly below the interference threshold. The highest values are ~6 dB less than the maximum value of -223 dBW/m^{2}Hz predicted by Motorola for the VLA site. At Tucson, the highest measured value of the SPFD over the central 2 MHz of the radio astronomy band is -229.9 dBW/m^{2}Hz, again for a short range (890 km) measurement. As shown in Fig. 1, the values for Tucson fall within the same range as those for the VLA. The measurements at Tucson and at the VLA were made with right circular polarization for the incoming signal. In addition, some of the measurements at the VLA also included left circular polarization. For voice channels active, the levels measured for right circular polarization were higher than those for left circular by up to 11.8 db, the mean difference being 7.5 dB. Thus it appears that most of the radiated power in the emissions in the radio astronomy band is right circularly polarized. Consequently the SPFD values measured at the VLA and Tucson for right circular polarization approximately represent the full emitted power.

The observations at Green Bank were made with crossed linearly-polarized antenna feeds, and measurements were made in both polarizations. In all cases the measurements in the two polarizations were closely equal. Thus, in order to be consistent with the data from the VLA and Tucson, the values in Table 2 of the Green Bank report are the sum of the SPFD values for the two polarizations. The resulting figures represent the total emitted SPFD, that is, the SPFD that would be measured with an antenna of matched polarization.

The values in Table 2 of the Green Bank report (PSPFD column) for measurements with the communications channels active fall within the range -233.1 to -219.9 dBW/m^{2}Hz, and the highest value occurs for one of the shorter range measurements (842.5 km on March 1). All measurements are above the RA interference threshold of -238 dBW/m^{2}Hz, and the highest value is ~6 dB less than the maximum predicted value of -214 dBW/m^{2}Hz for Green Bank.

Broadcast Signals

At both Green Bank and the VLA a number of passes were recorded when only the broadcast signals were turned on. The peak values measured across the spectrum are plotted in Fig. 2. Signals within the radio astronomy band were recorded in the form of narrow bands spaced at intervals of 330 kHz, which appear as peaks in the measured frequency spectrum. Nine such peaks occur within the 1610.6-1613.8 MHz band, as shown in Fig. 3 of the Green Bank report. Measurements with the greatest spectral resolution were those made at Green Bank, and these showed the spectral width of these bands to be less than 39 kHz at the half-power level. The highest SPFD recorded for one of the peaks within the radio astronomy band is -223.3 dBW/m^{2}Hz (March 3 at 0957) for a close-range pass (790.28 km). For the same observation the average of the nine peaks in the radio astronomy band is -227 dBW/m^{2}Hz. These values are averaged over the 90 ms transmit-receive cycle of the satellite, and the observations indicate that the broadcast signals were activated for part of each cycle. No significant difference in values of SPFD were observed for the two (linear) polarizations.

The broadcast signals can also be seen in the measurements made at the VLA: see Fig. 6 of the VLA report. The highest line value is -235.6 dBW/m^{2}Hz (Feb. 25 at 0104), averaged over the full 90 ms cycle time. Since the resolution bandwidth used in the spectral measurements at the VLA is 97.7 kHz, which is a factor of at least 2.5 greater than the emission width estimated from the Green Bank observations, we should expect the corresponding value measured in a 20 kHz bandwidth to be at least 4 dB greater. However, we understand that for the broadcast channels for Green Bank the antenna panel loading of the satellite was at the "worst case level" whereas for the broadcast signals at the VLA the level was more typical of "average" loading. Thus the two sets of measurements are not directly comparable.

Conclusions

For the voice communication channels, the measurements indicate a range of values, the maxima of which are about 6 dB below the SPFD values for maximum traffic conditions at the sites concerned, as calculated by Motorola/Iridium. The Tucson and VLA values are similar. The peak SPFD values for Green Bank are about 5-10 dB higher than for the VLA, which we attribute to the higher traffic density that was being simulated for Green Bank.

For the broadcast channels, the measurements clearly indicate the presence of signals resulting from satellite emissions within the 1610.6-1613.8 MHz band. In comparing the measured values with the threshold of -238 dBW/m^{2}Hz , it should be remembered that the mean emission levels during the tests were 3 dB greater than the levels expected to be used during operation because the emission occurred every 90 ms cycle. Also, as explained above, the measured values given in the tables correspond to matched polarization values, and it can be argued that the levels received in the far sidelobes of an antenna would, on average, be 3 dB lower because of polarization mismatch. If these factors are taken into account for the VLA, and also the 4 dB correction for spectral resolution, the highest VLA measurement of the broadcast signals approximately equals interference threshold. It may also be argued that since Doppler shift of the frequency during some passes could spread the frequency over four of the 20 kHz-wide channels, the effective level of interference is thereby reduced, probably by something less than 3 dB. Finally, the effect of averaging of the SPFD levels over a 2000 second integration time cannot be evaluated from our present information. Because of the uncertainty in these mitigating factors, NRAO believes that there remains a potential that the broadcast signals, as measured at Green Bank, will exceed the detrimental threshold of interference for radio astronomy observations in spectral line mode.

File: mTN.dat X: . Y: . : May 4 17:33:07 1998

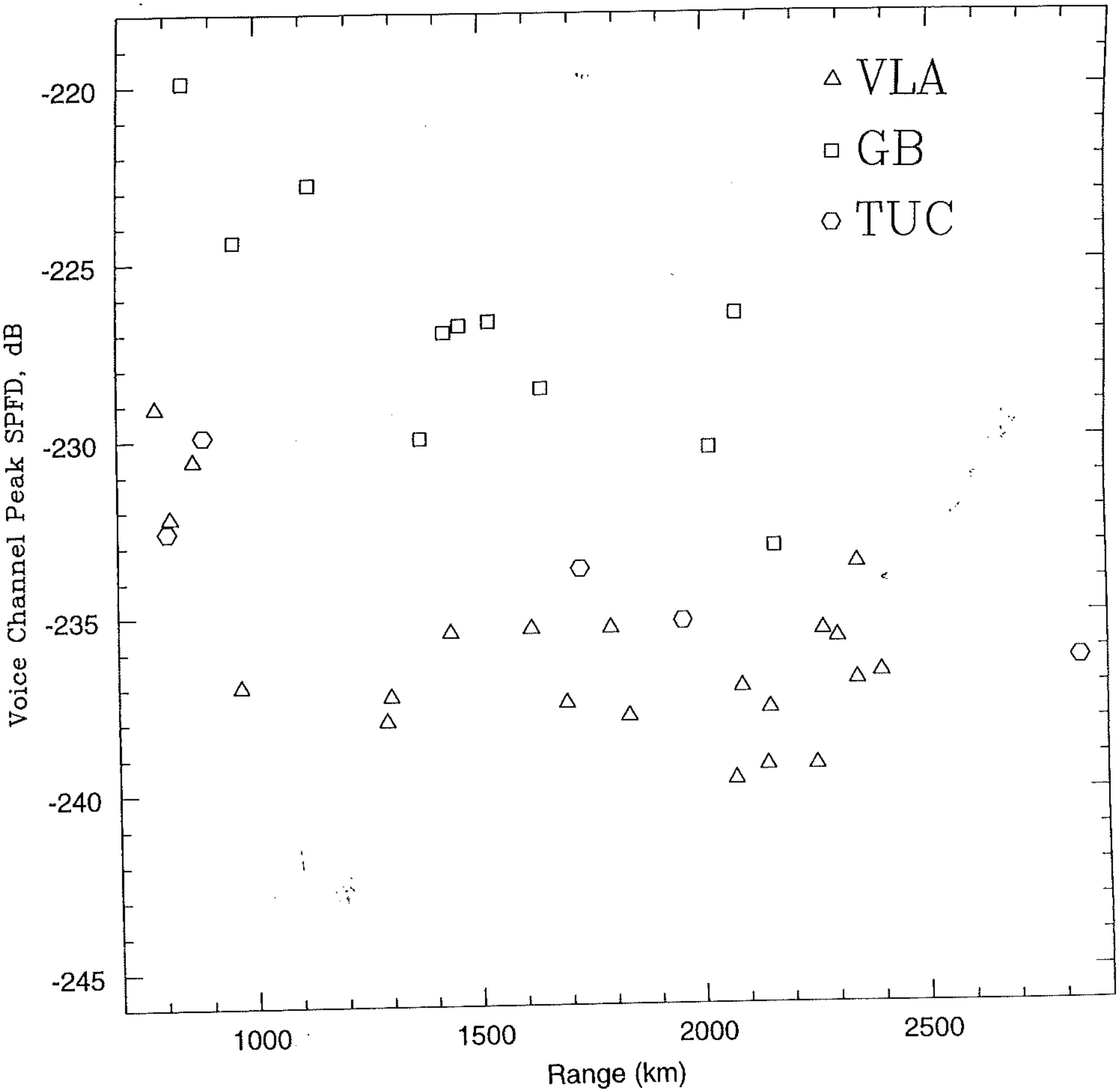

Figure 1. Measurements of the peak SPFD across the 1610.6-1613.8 MHz band for passes when voice channels were active.

File: pGB.brd X: , Y: , : May 4 17:31:58 1998

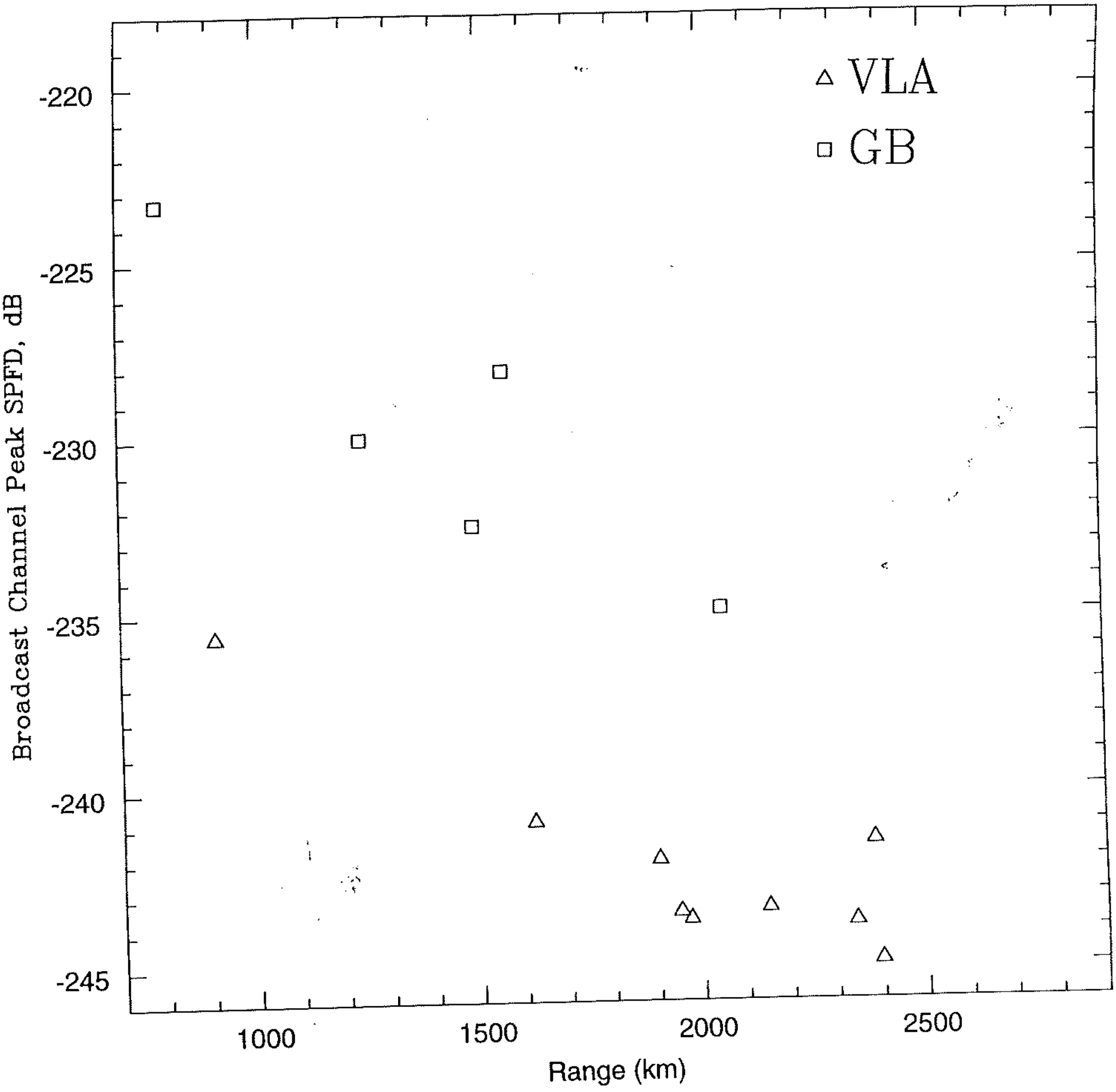

Figure 2. Measurements of the peak SPFD across the 1610.6-1613.8 MHz band for passes when only broadcast channels were active.

Post-Processing of NRAO Observations of Iridium Satellites

By: Motorola SATCOM

May 6, 1998

Abstract

The single observation test data from NRAO measurements of Iridium satellites was processed over the recommended 2000 second observation time. This processing included the projected effects of all satellites visible to the observation site, adjusted for atmospheric loss, range to the site, Doppler, and actual (rather than test) broadcast burst rate. The results are compared to the 1994 Memorandum Of Understanding between Motorola and the NRAO.

1.0 Introduction

A description of Motorola's post-processing of the NRAO data on Iridium Satellite emissions is provided in this paper. The results are compared to the June 17, 1994 Memorandum of Understanding (MOU) between the NRAO and Motorola. This MOU defines the acceptable interference levels averaged over a 2000 second observation time, and is based on the protection criteria recommended in ITU-R RA.769.

The data collected by the NRAO on Iridium satellites was confined to single satellite observations taken at specific orbital positions over the various sites. For this data to be compared to the recommended interference thresholds, it must be adjusted both spatially and temporally. The data is averaged over an observation time of 2000 seconds, as described below. The projected effects of all satellites visible to the site are included, assuming their emission performance in the RA band is similar to the tested satellite. The effects of range, atmospheric loss, Doppler, and actual (instead of test) broadcast burst rate are included.

2.0 Time Averaging Description

A model was used to compare the measurement results to the threshold levels of interference detrimental to spectral line observations as found in Recommendation ITU-R RA.769. This recommendation defines the threshold levels of interference[1] for the observation sensitivity obtained with a 2000-second averaging time. The model computes the average Spectral Power Flux Density (SPFD) from all space vehicles in view, as influenced by Doppler spreading and path loss. The contribution from each space vehicle (SV) is derived from measurements performed at Green Bank or the Very Large Array (VLA). These sites performed measurements of the peak spectral power flux density (PSPFD) from one SV at up to four points in a measured pass, each point being used for a separate computation. The computed 2000-second average SPFD levels include adjustments for the measurement channel bandwidth if different than 20 kHz. In the case of nighttime loading the averages include adjustments for the actual Iridium system broadcast rate of once every two 90 ms frames vs. the tested broadcast rate of once every frame.

The model uses tables produced by an orbit propagation program, that include elevation, Doppler offset and range loss at 1612 MHz as a function of time in 10 second increments for each SV above the horizon. The effect of broadcast intermodulation product Doppler spreading is calculated from the frequency overlap between the Doppler offset 33 kHz modulation bandwidth of the intermodulation product and the fixed 20 kHz reference measurement bandwidth. The atmospheric loss at 1612 MHz is calculated from the elevation angle. The range loss and atmospheric loss at the time of the PSPFD measurement, and the intermodulation product bandwidth and actual measurement bandwidth are used to calculate a reference PSPFD value for a 20 kHz bandwidth. In the

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[1] Conditions defined in ITU-R RA.769 are a 20 kHz receiver bandwidth, antenna noise temperature of 10 K and a receiver noise temperature of 20 K, for an observation averaging time of 2000 seconds.

nighttime cases with only broadcasts and no voice, the reference PSPFD value is reduced an additional 3 dB to account for the actual system broadcast rate. The SPFD values vs. time are calculated relative to the reference PSPFD value using the tabulated Doppler offsets, range losses and elevation angles. This is done for the length of the measured pass and for all other visible SVs for the duration of four sequential passes in the highest plane. The sum of the power from all visible SVs at each of the 10-second increments is averaged over 2000 seconds to obtain the "2000 second SPFD" value. Separate emission levels and directivity for each Main Mission Antenna (MMA) panel were not included in this model.

3.0 Results of the 2000 Second Averaging

The following tables provide computed 2000 second SPFD values for all of the measured transits with nighttime loading and for representative transits with daytime loading. The nighttime loading results differ between Green Bank and the VLA by an amount attributable to the differences in broadcast channel assignments. The highest result for nighttime loading at Green Bank occurred with a single orbital plane providing passes directly overhead and two other planes low on the horizons (3-03 09:57). A similar result occurred with two orbital planes at approximately equal elevations in the east and west (2-27 21:45). The results for nighttime loading at the VLA are consistent across various measurement ranges and elevation angles with one exception. The one measurement where Panel 0, of the MMA, was visible at the end of a pass (2-25 01:10) resulted in a higher level. The daytime loading results originally differed between cases with and without broadcasts by 1.5 to 4.7 dB, averaging about 3 dB. In order to account for this difference and the actual system broadcast rate of once every two 90 ms frames the 2000-second average values shown for the five daytime cases with broadcasts in Tables 1 and 3 (as indicated by "wb") have been reduced by 1.2 dB. The measured PSPFD value is less than the 2000-second average in cases where a high elevation pass was measured early or late in the pass at a point of great range. (See Tables 1 through 4) **Table 5 shows the estimated relative intermodulation levels produced by the broadcast channel loading for Green Bank and the VLA, based on laboratory testing.**

4.0 Conclusion

When averaged over the recommended 2000-second observation time, the aggregate SPFD of SVs in view operating with Green Bank daytime voice channel loading is less than the MOU value by a range of 14.4 dB to 19.3 dB (W/m^2/Hz). For the nighttime case -- where only broadcast channels were emitting -- the 2000-second averaged SPFD values are in a range of 0.9 dB to 4.9 dB greater than the MOU value. For the VLA, the averaged values with daytime voice channel loading are less than the MOU value by a range of 6.8 dB to 11.6 dB. For the VLA nighttime case, the results range from 19.4 dB to 14.4 dB less than the MOU values. The results range from 4.3 dB less than to 0.6 dB greater than the Recommendation ITU-R RA.769 value.

Table 1: Daytime - Green Bank (SPFD in dBW/m^2/Hz)

Date/Time (UTC)	Traffic Loading Voice channels[2]	MOU SPFD values[3] with 2000 sec. avg.	Measured SV Peak-SPFD (90 msec averaging)	Calculated System SPFD, 2000 sec. avg.[4]
2/25 22:47:30	296 - wb	-208	-230.3	-225.5
2/25 22:49:00	296 - wb	-208	-226.8	-224.9
2/26 22:14:00	296 - nb	-208	-233.1	-227.3
2/26 22:15:30	296 - nb	-208	-228.6	-225.3
3/01 22:18:30	296 - wb	-208	-219.9	-222.4
3/02 10:30:30	296 - nb	-208	-224.4	-225.8

Table 2: Nighttime - Green Bank (SPFD in dBW/m^2/Hz)

Date/Time (UTC)	Broadcast channels-no voice traffic	MOU SPFD values[3] with 2000 sec. avg.	Measured SV Peak-SPFD (90 msec averaging)	Calculated System SPFD, 2000 sec. avg.
2/27 10:33:30	GB000 - wb	-238	-232.5	-236.7
2/27 10:35:30	GB000 - wb	-238	-234.9	-236.5
2/27 21:45:00	GB000 - wb	-238	-228.1	-233.5
3/02 21:45:00	GB000 - wb	-238	-230.0	-237.1
3/03 09:57:00	GB000 - wb	-238	-223.3	-233.1

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[2] wb - with Broadcast channels, nb - no broadcast channels

[3] MOU SPFD levels in these Tables are quoted from the MOU agreement with NRAO. This MOU included simulation results published in FCC File No. 9-DSS-P-981 (87) CSS-91-010 Minor Amendment, Motorola Satellite Communication Inc., 1994. The simulation showed a -214 predicted level for Green Bank - daytime case. MOU value for Green Bank is -208. VLA MOU value is -223.

[4] 1.2 dB is subtracted from Tables 1 and 3 for "wb" Traffic Loading cases as explained above.

Table 3: Daytime – VLA (SPFD in dBW/m^2/Hz)

Date/Time (UTC)	Traffic Loading Voice channels	MOU SPFD[3] values with 2000 sec. avg.	Measured SV Peak-SPFD (90 msec averaging)	Calculated System SPFD, 2000 sec. avg.[4]
3/06 11:39:00	344 - wb	-223	-229.1	-233.0
3/06 11:44:00	344 - wb	-223	-235.7	-229.8
3/07 23:54:00	344 - nb	-223	-237.9	-233.2
3/07 23:58:00	344 - nb	-223	-232.2	-234.6

Table 4: Nighttime – VLA (SPFD in dBW/m^2/Hz)

Date/Time (UTC)	Broadcast channels- no voice traffic	MOU SPFD Values with 2000 sec. avg. [5]	Measured SV Peak-SPFD (90 msec averaging)	Calculated System SPFD, 2000 sec. avg.
2/25 01:00:00	So000 - wb	-223	-243.4	-240.4
2/25 01:04:00	So000 - wb	-223	-235.6	-240.1
2/25 01:10:00	So000 - wb	-223	-241.5	-237.4
3/04 12:43:00	So000 - wb	-223	-243.5	-242.4
3/04 12:46:00	So000 - wb	-223	-240.9	-241.4
3/05 10:28:00	So000 - wb	-223	-243.8	-241. 2
3/05 10:30:00	So000 - wb	-223	-243.7	-242.3
3/05 10:32:00	So000 - wb	-223	-242.0	-241.0
3/05 10:35:00	So000 - wb	-223	-244.9	-241.7

Table 5: Broadcast Loading

	MMA0	MMA0	MMA1	MMA1	MMA2	MMA2
	TS1	TS4	TS1	TS4	TS1	TS4
So000wb - No. of Broadcasts			8	7	9	8
Est. of relative IM level, dB			-6	-7	-9.5	-1.5
GB000wb - No. of Broadcasts	9	5	6	6		
Est. of relative IM level, dB	0	-9	-1.5	-2		

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[5] ITU-R RA.769 recommends a level of –238 dBW/m^2/Hz when averaged over an observation time of 2000 seconds.

Observations of an Iridium Satellite with the NRAO 140-Foot Telescope at 1610.6 - 1613.8 MHz

M. M. McKinnon

May 4, 1998

ABSTRACT

Observations of the Iridium satellite SV 13 were made with the NRAO 140-Foot Telescope on February 25 - March 3, 1998 to measure the spectral power flux density (SPFD) of the emissions from the satellite downlink in the radio astronomy (RA) observing band at 1610.6 - 1613.8 MHz. When the satellite transmits voice channels in its downlink, a continuum of emission appears across the RA band with the mean value of the measured SPFD ranging from -239.4 dB(watts m^{-2} Hz^{-1}) to -224.6 dB(watts m^{-2} Hz^{-1}) depending upon the distance between the satellite and the telescope. When the satellite is transmitting its broadcast channels only, the emissions in the RA band consist of many narrow band signals spaced at 333 kHz intervals. The measured SPFD of the strongest signal in a 19.5 kHz frequency channel ranges from -234.9 dB(watts m^{-2} Hz^{-1}) to -223.3 dB(watts m^{-2} Hz^{-1}).

1. Introduction.

Observations of the Iridium satellite SV 13 were made with the NRAO 140-Foot Telescope on February 25 - March 3, 1998 to measure the spectral power flux density (SPFD) of the emissions from the satellite downlink in the radio astronomy (RA) observing band at 1610.6 - 1613.8 MHz. The temporary modifications made to the telescope's L-band receiver for the observations are described in Section 2, and the satellite observations are discussed in Section 3. Data analysis procedures are reviewed in Section 4, and the results of the observations are presented in Section 5.

2. Receiver Modifications.

The telescope's L-band receiver was modified for the satellite observations because the receiver's low noise amplifiers (LNAs), the first amplifier in the RF section of the receiver, would have saturated at the power level of the satellite signal. To avoid saturation, the cryogenically-cooled LNAs were bypassed, and a sharp cutoff filter provided by Motorola was inserted in the RF signal path before the second amplifier in each polarization of the receiver. The filter passes signals in the RA band and provides more than 70 dB of attenuation at frequencies greater than about 1620 MHz. The satellite signal was not expected to saturate the modified receiver because the sum of the estimated signal power at the telescope feed (-35 dBm), filter attenuation (-70 dB), and gain of the amplifier (30 dB) was much less than the 1 dB compression point on the amplifier output (16 dBm). The gain and compression point of the amplifiers were measured in the laboratory prior to the satellite observations. Additional tests in the laboratory also showed that the response of the entire receiver (RF and IF) remained linear at the input power levels expected for the observations. At about 700 K (see Table 1), the system temperatures of the modified receiver were high because the RF amplifiers were not cooled and the Motorola filters have a high insertion loss.

3. Observations.

An Iridium satellite is above the local horizon for no more than about 15 minutes, and the 140-Foot Telescope cannot move fast enough to accurately track it. Consequently, the observations were made by parking the telescope at a predetermined azimuth and elevation and recording data when the satellite was expected to pass through the telescope beam. The satellite coordinates were estimated with current NORAD two line element sets. Under the most favorable observing geometry (when the satellite is near the horizon and its orbital plane is aligned with the longitude of the telescope), the telescope can change elevation fast enough to stay ahead of the satellite, and data can be recorded for two separate passes through the beam. The equatorial mount of the telescope prevents observations on the north horizon; therefore, most observations were made pointing to the south. Observations near the horizon also minimize the potential pointing error caused by the uncertainty in the satellite's location (cross-track error).

The telescope data were recorded with the NRAO spectral processor; a dual pipeline FFT spectrometer. The spectral processor was configured for four IF inputs of 5 MHz bandwidth each. Two IF inputs received signals from the dual linearly polarized feeds of the telescope receiver centered on a sky frequency of 1612.4 MHz, and the two remaining IF inputs received the linearly polarized signals centered on a sky frequency of 1624.0 MHz. The 5 MHz band from each IF was divided into 256 frequency channels, giving a frequency resolution of 19.5 kHz. All four spectra were recorded simultaneously at precise 15 ms intervals for a duration of 40.32 s at each telescope pointing.

The telescope gain (G) and system temperature (T_{sys}) were measured with standard observations of astronomical calibration sources when satellite observations were not being made. To calibrate the satellite data, the signal from a noise diode was injected ahead of the RF amplifiers in measurements immediately preceding and following a satellite pass. The equivalent temperatures (T_{cal}) of the noise diodes were measured in the laboratory on March 17, 1998. These properties of the telescope are tabulated for each polarization in Table 1.

The pointing and focus of the telescope were checked with standard observations of astronomical calibration sources before the satellite observing session began. The non-repeatable pointing error of the 140-Foot Telescope is 10 arcsec, and its beamwidth at a frequency of 1612 MHz is 18.6 arcmin.

The tuning of the telescope receiver was verified by injecting a test tone into the RF section of the receiver and then measuring the location of the tone in the recorded data. The tone was generated by a signal generator that was completely independent of the telescope's local oscillator. Data were recorded at three different settings of the signal generator frequency (1611, 1612, and 1613 MHz) on each of three separate occasions during the time allocated for the observations. In all nine cases, the measured frequency was identical to the setting at the signal generator, thereby verifying the tuning of the receiver.

A total of 19 satellite observations were attempted of which 16 were successful (see Table 2). Data were recorded on February 26 at 09:23 UT, but the satellite transmissions were radiated from its left panel as it headed south on the east side of the telescope. This means that the telescope was pointed towards the back side of the radiating panel, and the measured SPFD was much smaller than it would have been had the panel on the right side of the satellite been transmitting. The results from this observation are not included in Table 2. Data were also recorded on February 27 at 23:25:30 UT, but the satellite was beginning to malfunction due to "low current". The results from this observation are not included in Table 2, either. Satellite transmissions had apparently ceased altogether by the next scheduled observation on February 28 at about 10:00 UT. Coincidentally, the telescope was not able to point accurately because its control computer failed at about the same time, and no useful data were recorded.

The locations of Glonass satellites were carefully monitored during the observations. In no case did the position of a Glonass satellite coincide with that of SV 13 while satellite data were recorded. Furthermore, no evidence of emissions from a Glonass satellite were detected in the SV 13 data.

4. Data Analysis.

Figure 1a shows the raw data recorded in one polarization for the satellite observation on February 26 at 11:04 UT. The data have been averaged over a 5 MHz bandwidth centered on 1612.4 MHz. The time resolution in the figure is 15 msec. As can be seen in the figure, SV 13 passed through the telescope beam at about 20 s after data recording was started. The impulses in the data are caused by the time modulation of the satellite downlink signal. Figure 1b shows the same data in Figure 1a averaged over six consecutive time samples, giving a time resolution that is equivalent to an Iridium timeframe (90 msec). Both figures, in addition to data from the other satellite observations, show no additional temporal structure other than the main beam of the antenna and its sidelobes. This means that if any additional sources of radio emission, such as a Glonass satellite, were detected during the observation, their SPFD remained constant over the duration of the observation. Therefore, the contributions of these sources can be removed by simply subtracting the "off-beam" baseline from the "on-beam" data.

The data averaged over 5 MHz and 90 msec, such as that shown in Figure 1, were used to identify the location of the peak of the telescope beam. The raw data were then used to calculate average spectra in 90 msec intervals, and the spectrum at the beam peak was specified as the on-beam spectrum. An off-beam spectrum was subtracted from the on-beam spectrum, and the difference was divided by the off-beam spectrum to remove the shape of the instrumental bandpass. Knowing the equivalent temperature (T_{cal}) of the noise diode and the deflection it produces in a calibration scan, one can convert the units of the detected power in the spectra to units of antenna temperature, which can then be converted to units of SPFD (Janskys or watts m^{-2} Hz^{-1}) given the measured gain (G) of the telescope. Finally, the calibrated spectra from each receiver polarization were combined to produce a single spectrum of total intensity.

The data analysis procedure assumes that the satellite passes directly through the actual peak of the telescope beam. Although the two line element sets predict satellite coordinates that are accurate enough for us to acquire data, it is possible that uncertainties in the satellite orbit could cause the satellite to pass through the beam off axis where the telescope gain is substantially lower. Therefore, the calculated SPFDs should be regarded as lower limits.

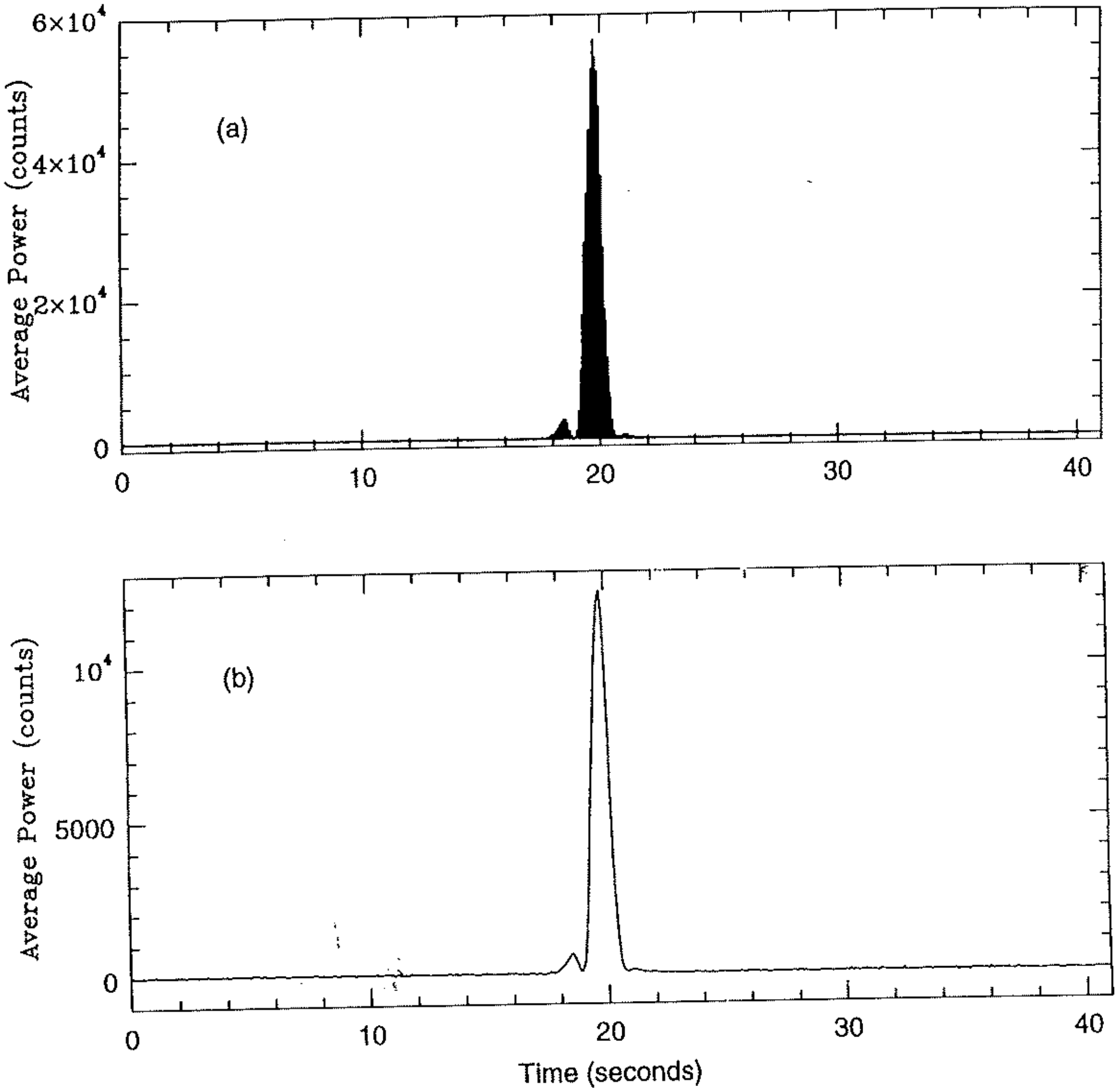


Fig. 1.— (a) The raw data recorded in a single polarization during the observation of SV 13 on February 26, 1998 at 11:04 UT. The time resolution of the data is 15 ms. The fine structure in the data is caused by the time modulation of the satellite downlink signal. (b) The same data in (a) averaged over 6 consecutive time samples to give a sampling interval that is equal to an Iridium timeframe (90 ms).

5. Results.

The measured values of the SPFD of the emissions from SV 13 in the RA band are summarized in Table 2. The date and time for each observation along with the corresponding azimuth, elevation, and range to the satellite are listed in the table. The satellite was programmed for three different loadings during the observations. The designator 296wbr in Table 2 indicates that 296 voice channels and the broadcast channels were transmitted from the satellite's right panel antenna. Similarly, 000wbr indicates that only the broadcast channels were transmitted, and 296nbl indicates that only the 296 voice channels were transmitted from the left panel antenna. The mean value of the SPFD over the RA band is listed under the column labelled MSPFD. In all cases, the units of SPFD are dB(watts m^{-2} Hz^{-1}). The peak value of the SPFD in a 19.5 kHz channel within the RA band is listed in the column labelled PSPFD. The column labelled APSPFD is relevant to cases when only the satellite's broadcast channels were transmitted and is the average of the peak SPFDs of nine narrow features that appear in the RA band (see Figure 3).

Figure 2a is an example spectrum of the emissions from SV 13 in the RA band when both the voice and broadcast channels are transmitted by the satellite. The data were recorded on February 26 at 11:04:00 UT when the range to the satellite was 1124 km. The satellite emissions appear as a continuum across the RA band with a MSPFD of −227.1 dB(watts m^{-2} Hz^{-1}). The rms noise in all spectra is −242.2 dB(watts m^{-2} Hz^{-1}). Figure 2b is an example spectrum of the SV 13 emissions when only the voice channels are transmitted by the satellite. The data were recorded on March 2 at 10:30:30 UT when the range to the satellite was 958 km. The satellite emissions in the RA band again appear as a continuum with a MSPFD of −228.0 dB(watts m^{-2} Hz^{-1}). As shown in Table 2, the mean values of the SPFD ranged from −239.4 dB(watts m^{-2} Hz^{-1}) to −224.6 dB(watts m^{-2} Hz^{-1}) depending upon the distance between the telescope and the satellite.

Figure 3 shows examples of the spectrum of the emissions from SV 13 in the RA band when only the broadcast channels are transmitted by the satellite. The emissions in the RA band consist of nine distinct features spaced at 333 ± 3 kHz intervals. The full width of the stronger features at half their peak SPFD is less than two channel widths (39 kHz). The data in Figure 3a were recorded on March 3 at 09:57:00 UT when the satellite was almost directly over the telescope. The data in Figure 3b were recorded on February 27 at 10:33:30 UT when the satellite was near the southern horizon. In both cases, the satellite was moving from north to south. The frequencies of the features in Figure 3b are about 35 kHz lower than the freqencies of the corresponding features in Figure 3b. The frequency offset is the Doppler shift caused by the satellite's change in speed along the telescope's

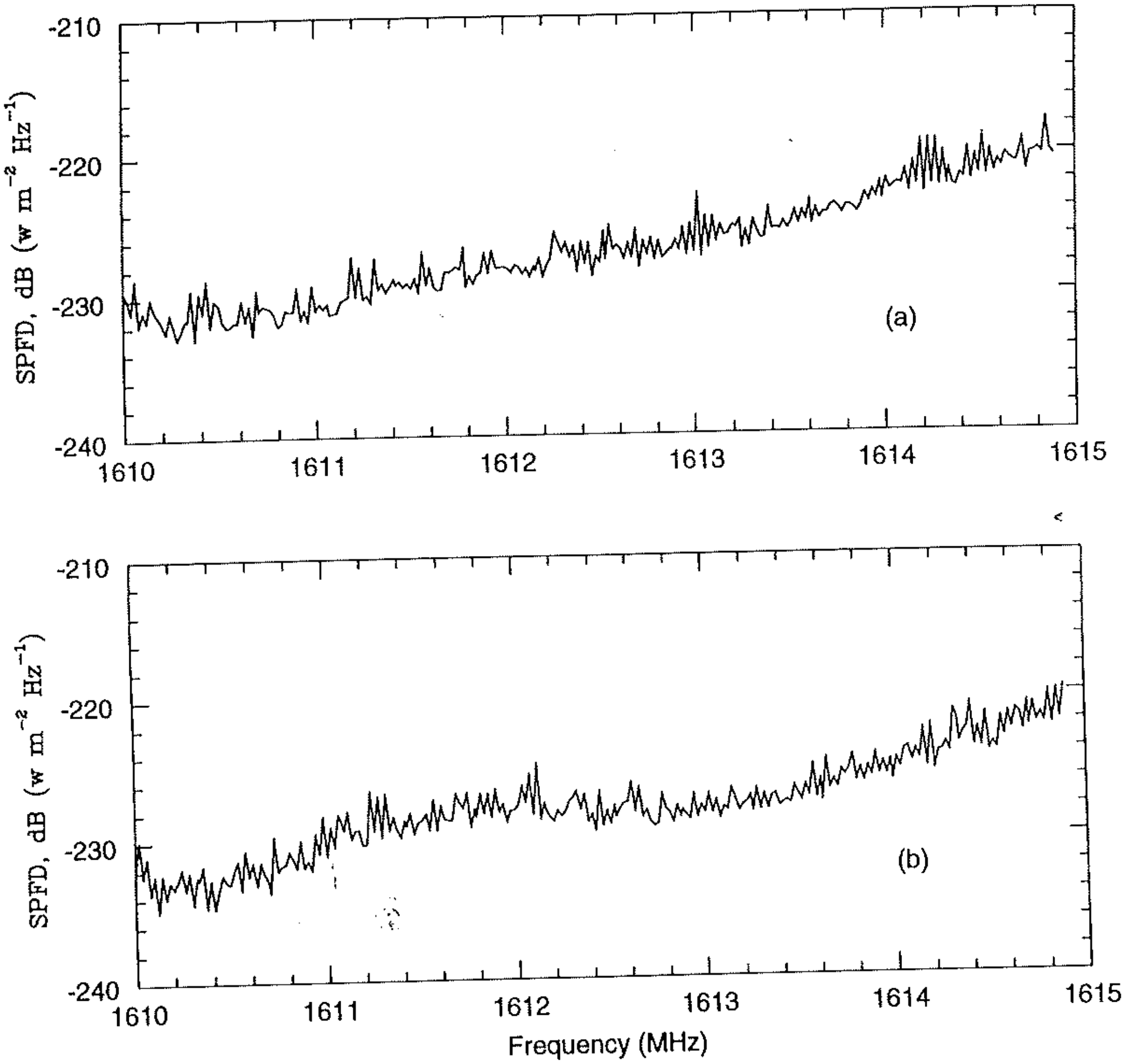


Fig. 2.— (a)The spectrum of the emissions from SV 13 in the RA band when the satellite is transmitting broadcast channels and 296 voice channels. The data were recorded on February 26, 1998 at 11:04:00 UT. (b) The spectrum of the satellite emissions when transmitting 296 voice channels only. The data were recorded on March 2, 1998 at 10:30:30 UT.

line of sight. The frequencies shift to lower values because the satellite was moving away from the telescope during the observation. If one makes the rough approximation that the frequencies in Figure 3a are the rest frequencies, the frequency shift corresponds to a velocity change of 6.5 km/s, which agrees reasonably well with the maximum change in speed along the line of sight (6.7 km/s) expected for an Iridium satellite. As shown in Table 2, the peak SPFDs of the narrow features ranged from -234.9 dB(watts m^{-2} Hz^{-1}) to -223.3 dB(watts m^{-2} Hz^{-1}).

Acknowledgments: I thank Bob Simmons and Roger Norrod for their assistance in modifying and testing the L-band receiver. I greatly appreciate Rick Fisher's technical guidance.

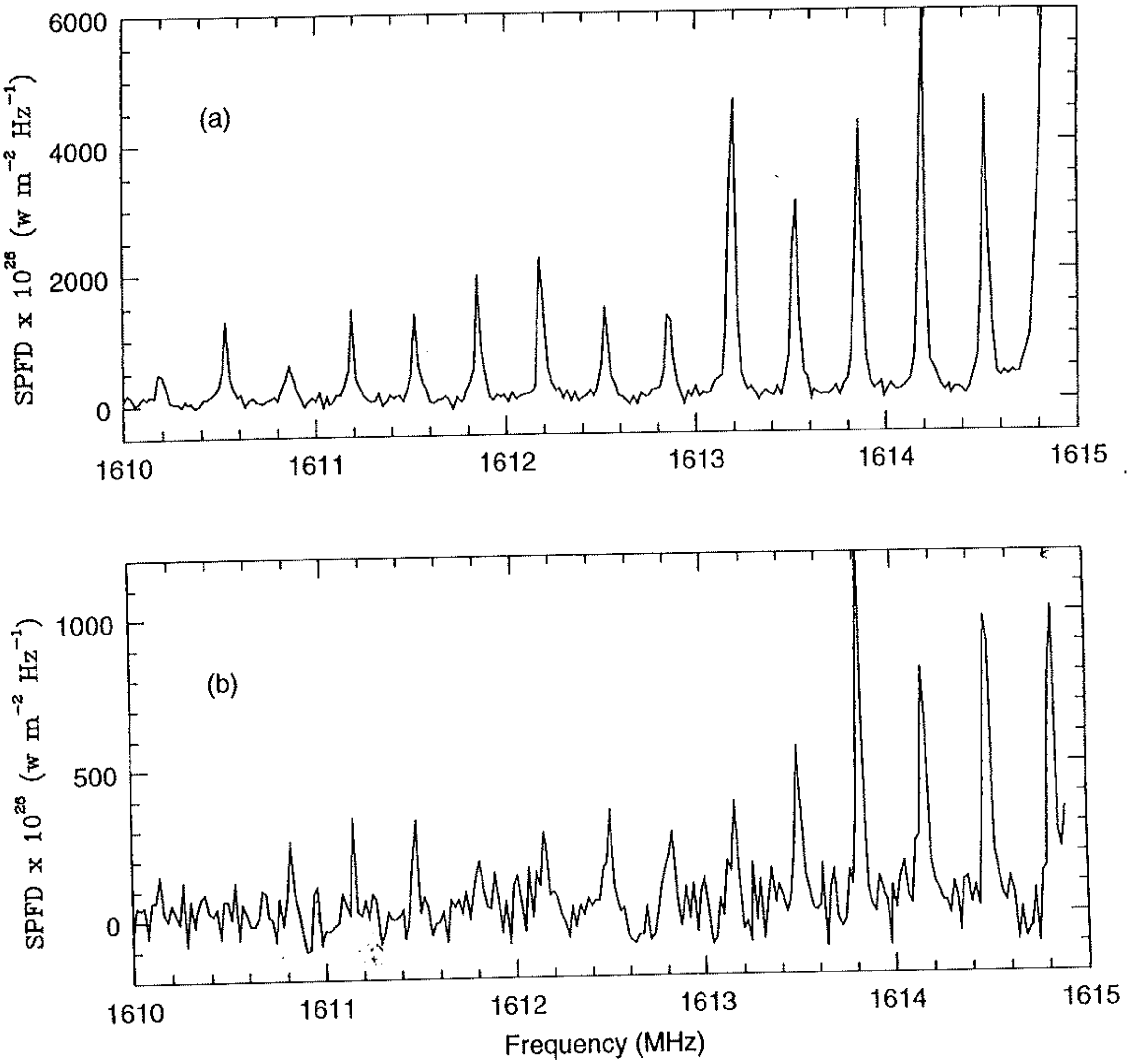


Fig. 3.— The spectrum of the emissions from SV 13 in the RA band when the satellite is transmitting broadcast channels only. The data in (a) were recorded on March 3, 1998 at 09:57:00 UT. The narrow features are less than 39 kHz wide and are spaced at 333 kHz intervals. The data in (b) were recorded on February 27, 1998 at 10:33:30 UT. The frequency offset between the corresponding features in (a) is the Doppler shift caused by the satellite's change in speed along the telescope's line of sight.

TABLE 1

CALIBRATION TEMPERATURE, SYSTEM TEMPERATURE, AND GAIN FOR EACH POLARIZATION OF THE L-BAND RECEIVER

Polarization	A	B
T_{cal} (K)	37.2	36.0
T_{sys} (K)	610	693
G (K/Jy)	0.251	0.270

TABLE 2

SUMMARY OF 140-FOOT TELESCOPE OBSERVATIONS OF IRIDIUM SV 13

Date	Time (UT)	Az (deg)	El (deg)	Range (km)	Loading	MSPFD	PSPFD	APSPFD
2-25	22:47:30	178.505	14.455	2022.44	296wbr	-235.0	-230.3	***
2-25	22:49:00	177.677	26.713	1462.78	296wbr	-232.6	-226.8	***
2-26	11:04:00	271.673	40.620	1124.25	296wbl	-227.1	-222.8	***
2-26	22:14:00	156.145	12.195	2167.32	296nbl	-239.4	-233.1	***
2-26	22:15:30	147.366	21.864	1646.39	296nbl	-234.5	-228.6	***
2-27	10:33:30	187.199	26.030	1492.61	000wbl	***	-232.5	-234.8
2-27	10:35:00	184.947	14.115	2051.25	000wbl	***	-234.9	-237.7
2-27	21:45:00	85.518	24.040	1562.70	000wbl	***	-228.1	-232.9
2-28	22:47:30	192.473	13.491	2081.94	296wbl	-234.1	-226.5	***
2-28	22:49:00	197.372	24.795	1530.13	296wbl	-231.5	-226.7	***
3-01	09:23:30	84.779	29.831	1374.74	296nbl	-234.7	-230.0	***
3-01	11:04:00	274.691	28.046	1429.20	296nbl	-231.6	-227.0	***
3-01	22:18:30	91.643	66.268	842.54	296wbl	-224.6	-219.9	***
3-02	10:30:30	274.715	52.457	958.08	296nbl	-228.0	-224.4	***
3-02	21:45:00	88.462	34.667	1242.04	000wbl	***	-230.0	-233.4
3-03	09:57:00	66.084	82.049	790.28	000wbr	***	-223.3	-227.0

NRAO-VLA DATA FROM TESTS OF IRIDIUM EMISSIONS IN THE RAS BAND 1610.6-1613.8 MHz

By the IRIDIUM testing team at the VLA: D. Bagri, L. Beno, W. Brundage, E. Callan, P. Dooley, P. Lilie, D. Polyard, B. Treacy, with extra efforts by C. Broadwell, R. Ferraro, T. Hankins and G. Taylor.

The tests used VLA antenna #4 at station W8 with a modified L-band front end. A coaxial cable connected the right circular polarization (RCP) output of the front end and post amplifiers to the test back-ends in the control building. The test back-ends which recorded spectral power data were
1) the four-section autocorrelating digital spectrometer (ADS) with 256 contiguous channels of 97.7 kHz bandwidth each, and
2) the pulsar high time resolution processor (HTRP) with 28 contiguous channels of 1000 kHz bandwidth each.

A cooled bandpass filter for the 1610.6 - 1613.8 MHz radio astronomy service (RAS) band was switched in ahead of the RCP first amplifier inside the L-band dewar. Another un-cooled bandpass filter was switched in following the left circular polarization (LCP) cooled amplifier to allow measurements of LCP through the normal VLA signal path. Otherwise the normally unfiltered system configuration might have gain-compressed which would have impaired the measurements when the satellite was in the VLA main beam. Figure 1 shows the block diagram of the VLA test system and lists characteristics of the bandpass filter, which was supplied by Motorola.

The output powers of the ADS and HTRP were recorded before, during and after the time when the test satellite vehicle (SV) transited the main beam of the VLA antenna. The data records were sorted and integrated into 45 ms SV transmit ON bins and into 45 ms SV transmit OFF bins per the synchronization timing from the radio astronomy special equipment (RASE), which Motorola supplied.

Calibration data sets were taken with the antenna main beam centered on an astronomical calibrator and again at a pointing position off the calibrator. These data sets and the known SPFD of the calibrator were used to calibrate the spectral power flux density (SPFD) scale of the IRIDIUM SV transit data sets. The calibrators and their total randomly polarized SPFD at 1612 MHz were

Cas A	1540 Jy	1.54E-23 W/m^2/Hz	-228.1 dB(W/m^2/Hz)
Cyg A	1370	1.37E-23	-228.6
Virgo A	188	1.88E-24	-237.3
3C123	43	4.30E-25	-243.7

One half of the listed calibrator SPFD was used because the VLA system received only RCP or LCP, which is one half of the total randomly polarized SPFD.

The antenna #4 peak main beam gain and all receiver system gain and bandwidth parameters were constant throughout each SV pass which consisted of calibrator - transits - calibrator. Thus, for each frequency channel, the SPFD of the SV in terms of the channel output powers Po is the simple proportion
SPFDsv(svON) = SPFDcal*[Po(svON)-Po(svOFF)]/[Po(calON)-Po(calOFF)], where the units are W/m^2/Hz. These data were converted to decibel units of dB(W/m^2/Hz)) by 10*log(SPFDsv(svON)), then converted to a 90 ms time average by subtracting 3 dB, and then listed in Table 1.

The differencing of Po(svON)-Po(svOFF) for the 45 ms ON and the 45 ms OFF cancels all GLONASS signals which remain constant over several seconds. Because the astronomical calibrator "emits" continuously with no on/off cycle, the effects of GLONASS signals could not be canceled in the calibrator data. The 10 seconds of ON calibrator data least affected by GLONASS and an equal 10 seconds of OFF calibrator data also least affected by GLONASS was selected by looking at the GLONASS spectral signature. During these calibration times, the IRIDIUM test SV was below the horizon and no other SV was emitting in L-band.

SV Loading of Voice Only:

From Table 1, the strongest peak SPFD in an ADS channel within the RAS band for this SV loading of 344 voice channels without broadcast (344), occurred 07 March at the 23:58 UTC transit. The ADS peak SPFD was -232.2 and the mean over the RAS band was -236.1 dB(W/m^2/Hz). Figure 2 shows the ADS spectra. Figure 3 shows the corresponding spectra from the HTRP in the form of a contour map and a peak and mean plot over a time span of many SV transmit cycles. Note that here the HTRP data are lower limits, because it gain-compressed internally. There was no gain compression anywhere in the ADS system at any time of taking test data.

SV Loading of Voice Plus Broadcast:

From Table 1, the strongest peak SPFD in an ADS channel within the RAS band for this SV loading of 344 voice channels with broadcast added (344wb), occurred 06 March at the 11:39 UTC transit. The ADS peak SPFD was -229.1 and the mean over the RAS band was -232.7 dB(W/m^2/Hz). Figure 4 shows the ADS spectra. Figure 5 shows the corresponding spectra from the HTRP in the form of a contour map and a peak and mean plot over a time span of many SV transmit cycles. Note that here the HTRP data are lower limits, because it gain-compressed internally. There was no gain compression anywhere in the ADS system at any time of taking test data.

SV Loading of Broadcast Only:

From Table 1, the strongest peak SPFD in an ADS channel within the RAS band for this SV loading of broadcast only (000wb), occurred 25 February at the 01:04 UTC transit. The ADS peak SPFD was -235.6 and the mean over the RAS band was -241.4 dB(W/m^2/Hz). Figure 6 shows the ADS spectra. Figure 7 shows the corresponding spectra from the HTRP in the form of a contour map and a peak and mean plot over a time span of many SV transmit cycles.

-end-

TABLE 1: VLA DATA

DATE (UTC)	Time of Transit (UTC)	SV #	SV Load [1]	SV Range (km)	AZ to SV (deg)	EL to SV (deg)	Autocorrelating Digital Spectrometer				High Time Resolution Processor (HTRP) RCP	
							RCP MSPFD [2]	RCP PSPFD [3]	LCP MSPFD [2]	LCP PSPFD [3]	MSPFD [4]	PSPFD [5]
22Feb98	18:15	22	344wb	2348	163.3	9.6	-240.2	-236.9			-239.4	-238.7
22Feb98	18:17	22	344wb	1620	154.8	22.4	-238.6	-235.4			-237.4	-237.0
22Feb98	18:25	22	344wb	2273	13.2	10.8	-238.6	-235.5			-238.3	-237.5
22Feb98	19:58	22	344wb	2401	247.0	9.0	-240.9	-236.7			-239.8	-239.1
22Feb98	20:00	22	344wb	2091	268.5	13.4	-241.2	-237.1			-239.4	-238.4
22Feb98	20:02	22	344wb	2076	294.0	13.6	-243.4	-239.7			-242.4	-240.7
25Feb98	01:00	13	000wb	2147	193.1	12.4	-246.5	-243.4			-244.2	-243.3
● 25Feb98	01:04	13	000wb	911	235.4	56.5	-241.4	-235.6			-239.2	-238.3
25Feb98	01:10	13	000wb	2385	354.9	9.2	-247.8	-241.5			-246.6	-244.2
03Mar98	11:35	13	344wb	1797	9.0	18.8	-239.3	-235.4				
03Mar98	11:39	13	344wb	868	102.5	62.6	-234.0	-230.6				
03Mar98	13:17	13	344wb	2350	301.7	9.8	-238.6	-233.6				
04Mar98	00:28	13	344	1697	203.3	20.6	-239.8	-237.5			-237.4	-236.0
04Mar98	00:32	13	344	970	300.8	50.8	-241.0	-237.0			-239.7	-237.6
04Mar98	00:36	13	344	2147	350.2	12.6	-242.2	-239.3			-240.6	-238.8
04Mar98	11:01	13	344	2153	22.7	12.6	-240.4	-237.7			-241.6	-239.7
04Mar98	11:05	13	344	1305	79.9	32.2	-241.2	-237.3			-243.0	-240.9
04Mar98	12:43	13	000wb	1948	315.1	15.9	-246.7	-243.5	-248.3	-247.3	-246.0	-245.0
04Mar98	12:46	13	000wb	1623	270.2	22.6	-244.8	-240.9	-248.6	-247.3	-244.1	-243.5
05Mar98	10:28	13	000wb	2341	38.0	9.9	-248.7	-243.8	-247.4	-246.3	-249.2	-247.9
05Mar98	10:30	13	000wb	1970	59.6	15.5	-246.2	-243.7	-247.7	-246.1	-246.3	-245.8
05Mar98	10:32	13	000wb	1902	87.3	16.7	-245.3	-242.0	-248.0	-246.0	-245.0	-244.3
05Mar98	10:35	13	000wb	2396	121.2	9.1	-247.2	-244.9	-246.5	-245.0	-247.7	-247.1
05Mar98	12:10	13	344wb	1439	325.8	27.7	-238.1	-235.5	-248.6	-247.2	> -236.7	> -235.6
05Mar98	12:14	13	344wb	1295	228.3	32.6	-241.3	-238.0	-244.9	-241.4	-239.9	-237.9
05Mar98	12:17	13	344wb	2257	203.3	10.9	-242.1	-239.3	-245.6	-241.4	-240.3	-238.3
● 06Mar98	11:39	13	344wb	786	214.5	83.4	-232.7	-229.1	-240.0	-236.6	> -233.4	> -232.5
06Mar98	11:44	13	344wb	2305	181.1	10.2	-239.8	-235.7	-248.0	-246.0	-238.3	-236.7
07Mar98	23:54	13	344	1836	190.3	17.7	-240.7	-237.9			-239.0	-237.2
● 07Mar98	23:58	13	344	817	280.6	71.1	-236.1	-232.2	-247.8	-244.0	> -234.9	> -233.0

NOTES:

[1] 000wb = Broadcast without voice channels; 344wb = 344 voice channels with broadcast; 344 = 344 voice channels without broadcast.

[2] Mean Spectral Power Flux Density [dB(W/(m^2*Hz))] over 32 channels of 97.7 kHz each, within RAS frequency band and over 90 millisec of time (one SV frame).

[3] Peak Spectral Power Flux Density [dB(W/(m^2*Hz))] within one 97.7 kHz channel within RAS band and averaged over 90 millisec of time (one SV frame).

[4] Mean Spectral Power Flux Density [dB(W/(m^2*Hz))] over 3 channels of 1000 kHz each, within RAS frequency band and over 90 millisec of time (one SV frame).

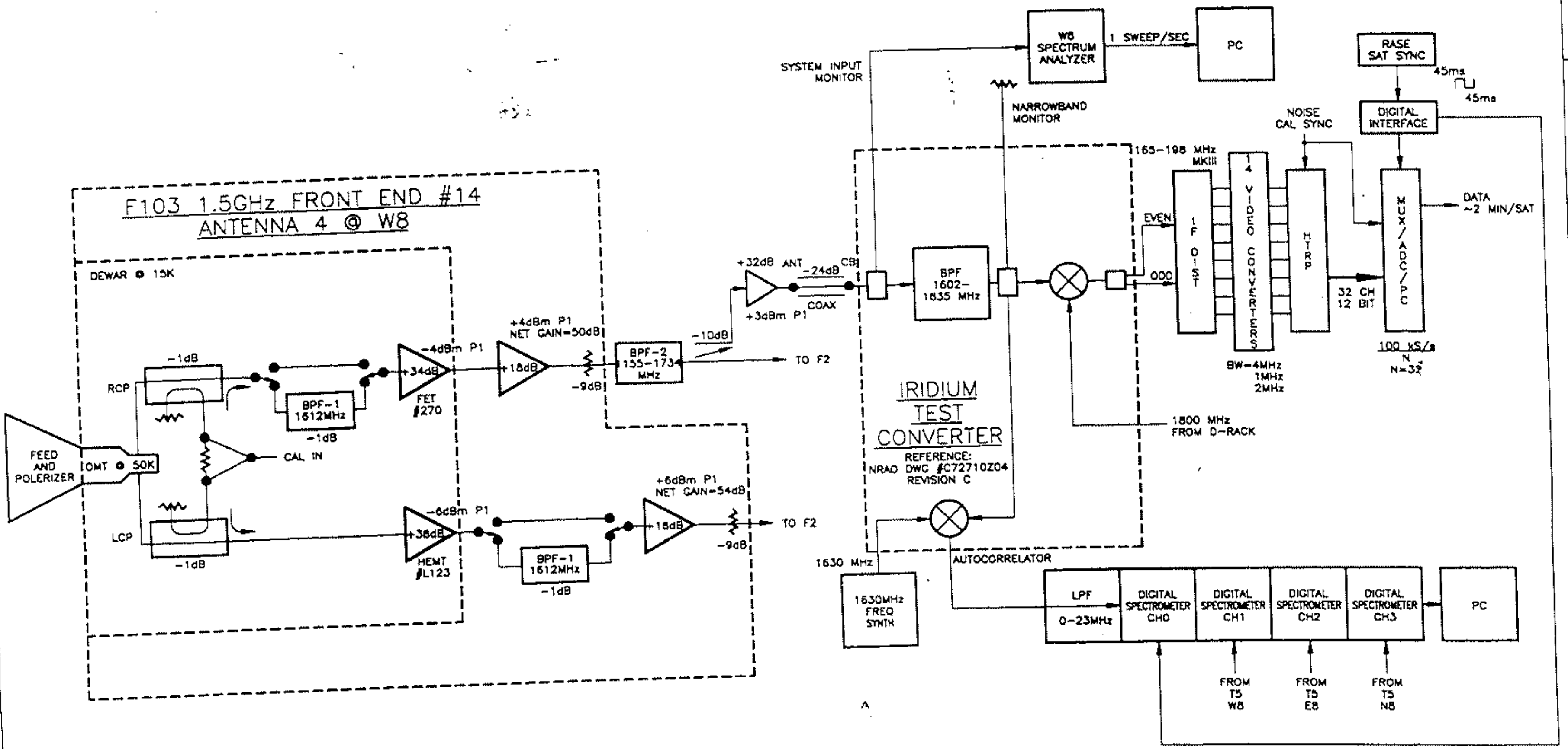
[5] Peak Spectral Power Flux Density [dB(W/(m^2*Hz))] within one 1000 kHz channel within RAS band and averaged over 90 millisec of time (one SV frame).

SV = IRIDIUM space vehicle.
RCP = Right Circular Polarization (IEEE)
LCP = Left Circular Polarization (IEEE)
RAS frequency band = 1610.6 to 1613.8 MHz.

NOTES:

1. BPF-1=BANDPASS FILTER, K&L #WSF-00025, -1dB, 1606-1616 MHz @ -3dB, 1604-1617 MHz @ -10dB, 1600-1618 MHz @ -30dB, 1621 MHz @ -70dB
2. BPF-2=BANDPASS FILTER, MFC #9097, + BANDSTOP FILTER K&L #5N45-1785/X40, -2dB, 1155-1734 MHz @ -3dB, 1139-1744 MHz @ -10dB, 1038-1760 MHz @ -40dB, 940-1770 MHz @ -60 dB

REV	DATE	DRAWN BY	APPRV'D BY	DESCRIPTION
A	7/96	K. TATE	J.CAMPBELL	MAJOR REVISIONS
B	8/96	K. TATE	J.CAMPBELL	REVISED & REDRAWN
C	1/97	K. TATE	J. CAMPELL	REMOVED VLBA TAIL-END; EXPANDED DIGITAL SPEC
D	4/22/97	K. TATE	J. CAMPELL	REVISED AND ADDED SIGNAL LEVELS
E	8/5/97	K. TATE	J. CAMPELL	ADDED SPECTRUM MONITOR; ADDED PC; MINOR CORRECTIONS
F	3/16/98	K. TATE	B.BRUNDAGE	MAJOR REVISIONS



UNLESS OTHERWISE SPECIFIED DIMENSIONS ARE IN INCHES

MATERIAL :

FINISH :

NEXT ASSEMBLY

DWG TYPE

VLA

PROJECT IRIDIUM

TITLE IRIDIUM TEST
ANTENNA 4 @ W8
BLOCK DIAGRAM

NATIONAL RADIO
ASTRONOMY
OBSERVATORY
SOCORRO, NEW MEXICO 87801

DRAWN BY K. TATE DATE 7-96

DESIGNED BY J.CAMPBELL DATE 7-96

APPROVED BY J.CAMPBELL DATE 7-96

SHEET NUMBER 1 OF 1

DRAWING NUMBER C72710Z01

REV. F

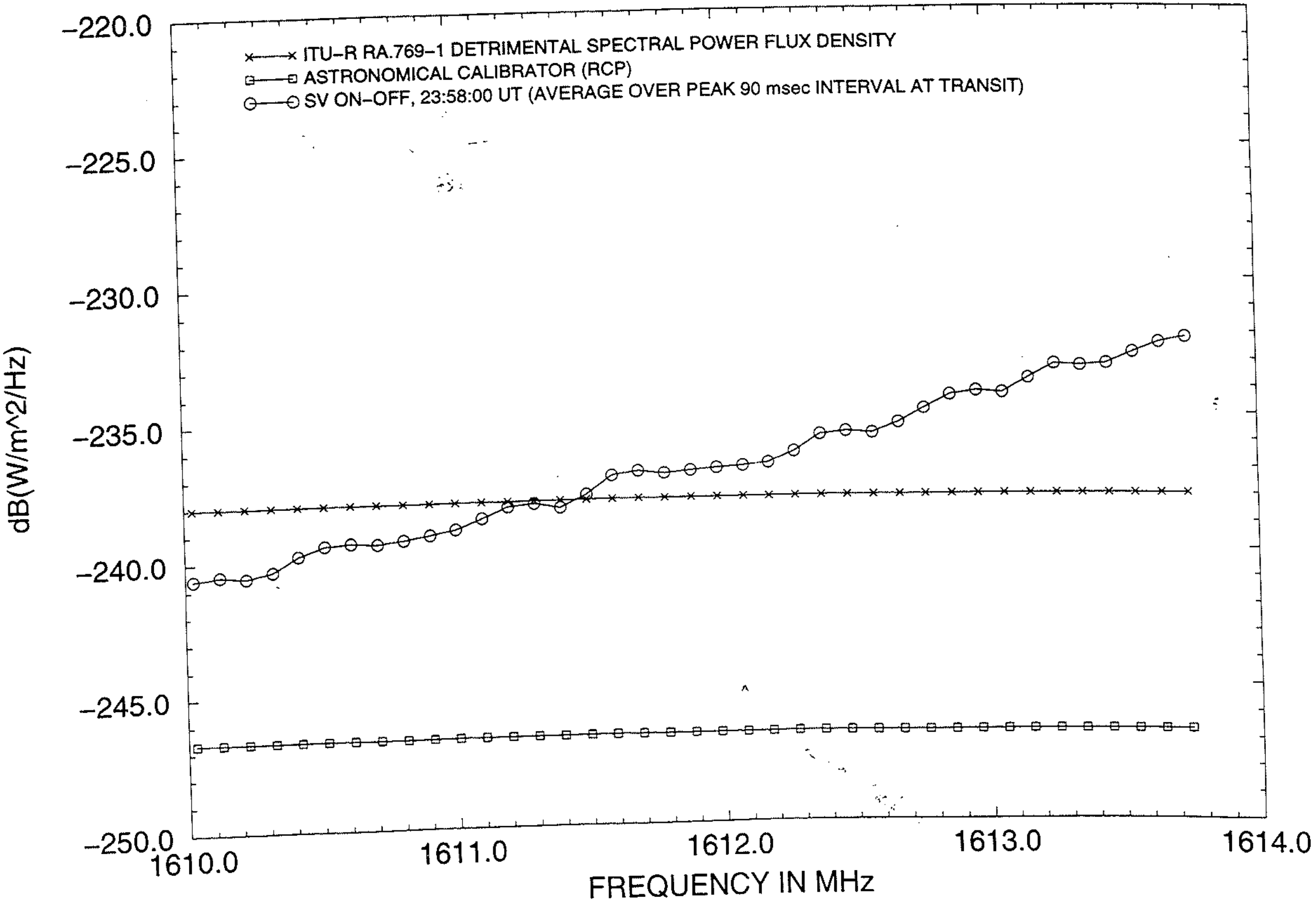
SCALE NONE

FIG. 1

ACAD : 72710Z01

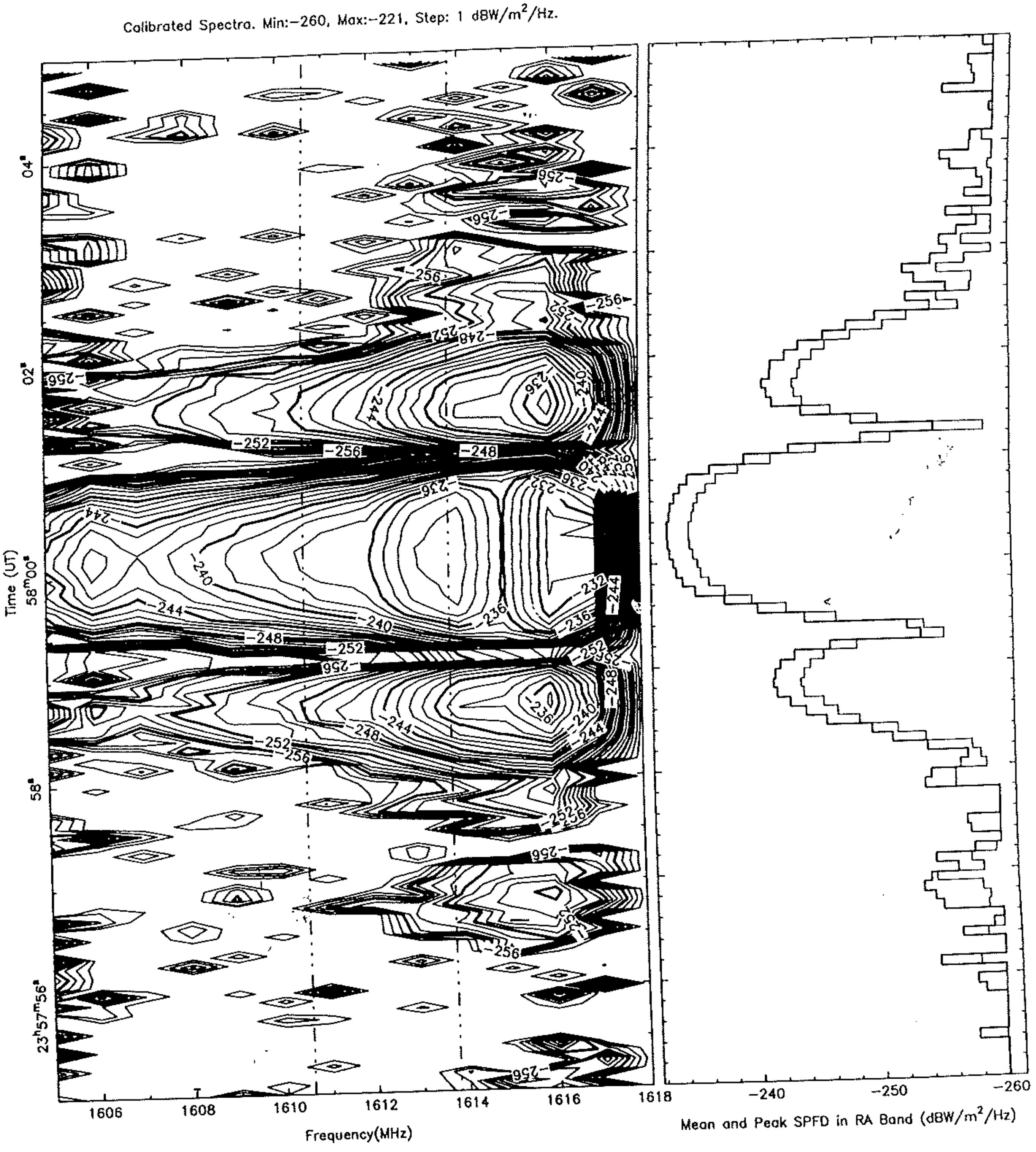
ANTENNA 4, RCP VIA IRIDIUM CONVERTER

7 MAR 1998, 3C123 CAL AND SV PASS #1, TRANSIT #2



mean= -236.1
max= -232.2

FIG. 2



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Data Prog Rev:           irid: V1.12  05 May 1998
Data Prog Run:           Tue May  5 09:32:00 1998
Data File:               /home/pogo2/irdat/19980307/IRID.000
Cal Prog Rev:            gain: V1.06  18 Mar 1998
Cal Prog Run:            Fri Apr  3 14:00:19 1998
Blank Sky Epoch (UT):    Sat Mar 07 23:10:00 1998
Blank Sky Start (UT):    23:10:10.000
Blank Sky Duration:      00:00:10.000
Calib Epoch (UT):        Sat Mar 07 23:17:00 1998
Calib Start (UT):        23:17:10.000
Calib Duration:          00:00:10.000
Blank Sky File:          /home/pogo2/irdat/19980307/1230F0F.000
On Calib File:           /home/pogo2/irdat/19980307/1230N0F.000
```

```
Freq: 1605.000-1618.000) MHz
Sample Rate:   960.01 Hz.
Plot res:   0.090000 s
RASE switching:  on
Mean SPFD in RA band:-234.9 dBW/m^2/Hz
Peak SPFD in RA band:-233.0 dBW/m^2/Hz
Iridium transit at 1998/03/07 23:58:00
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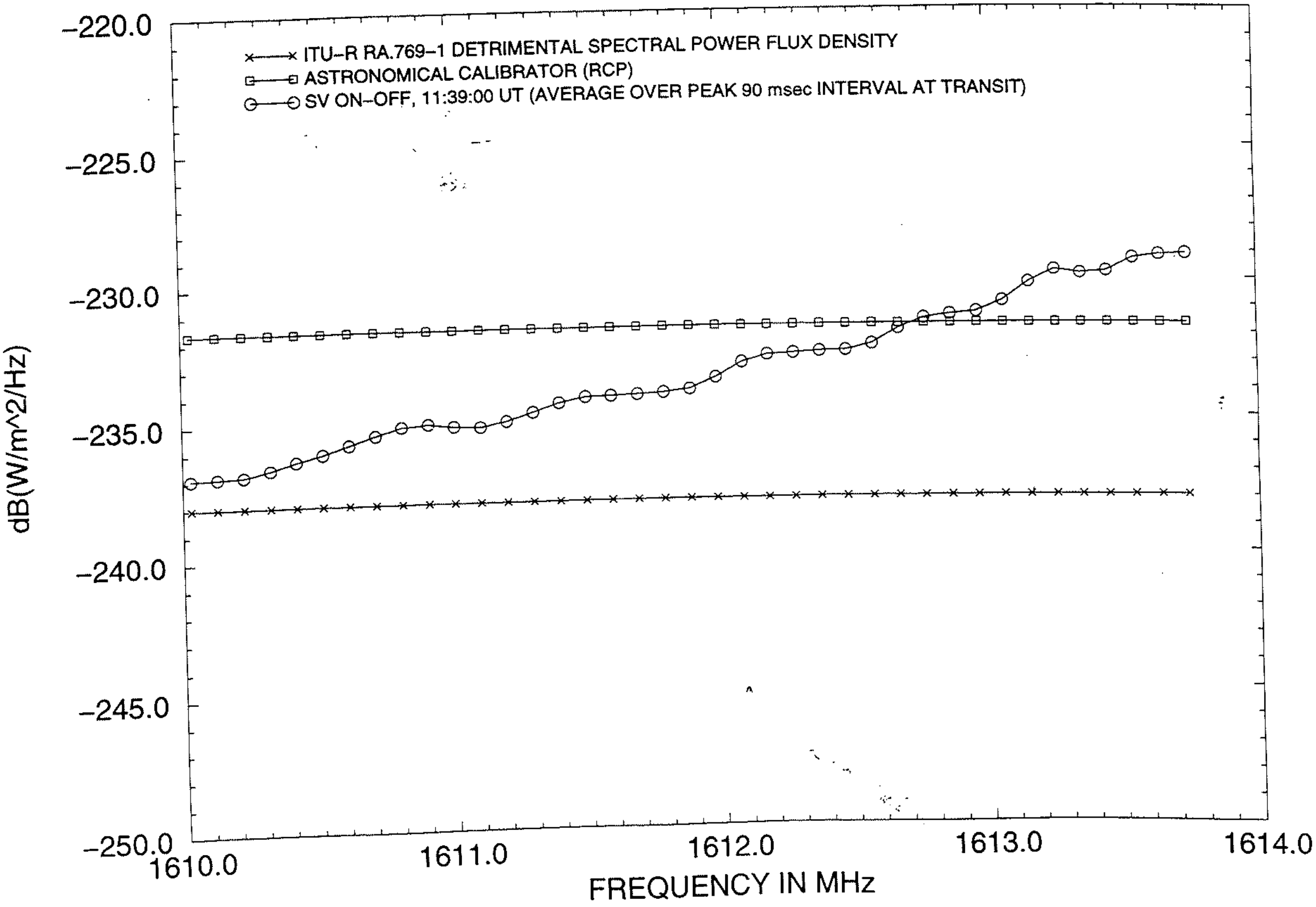
FIG. 3

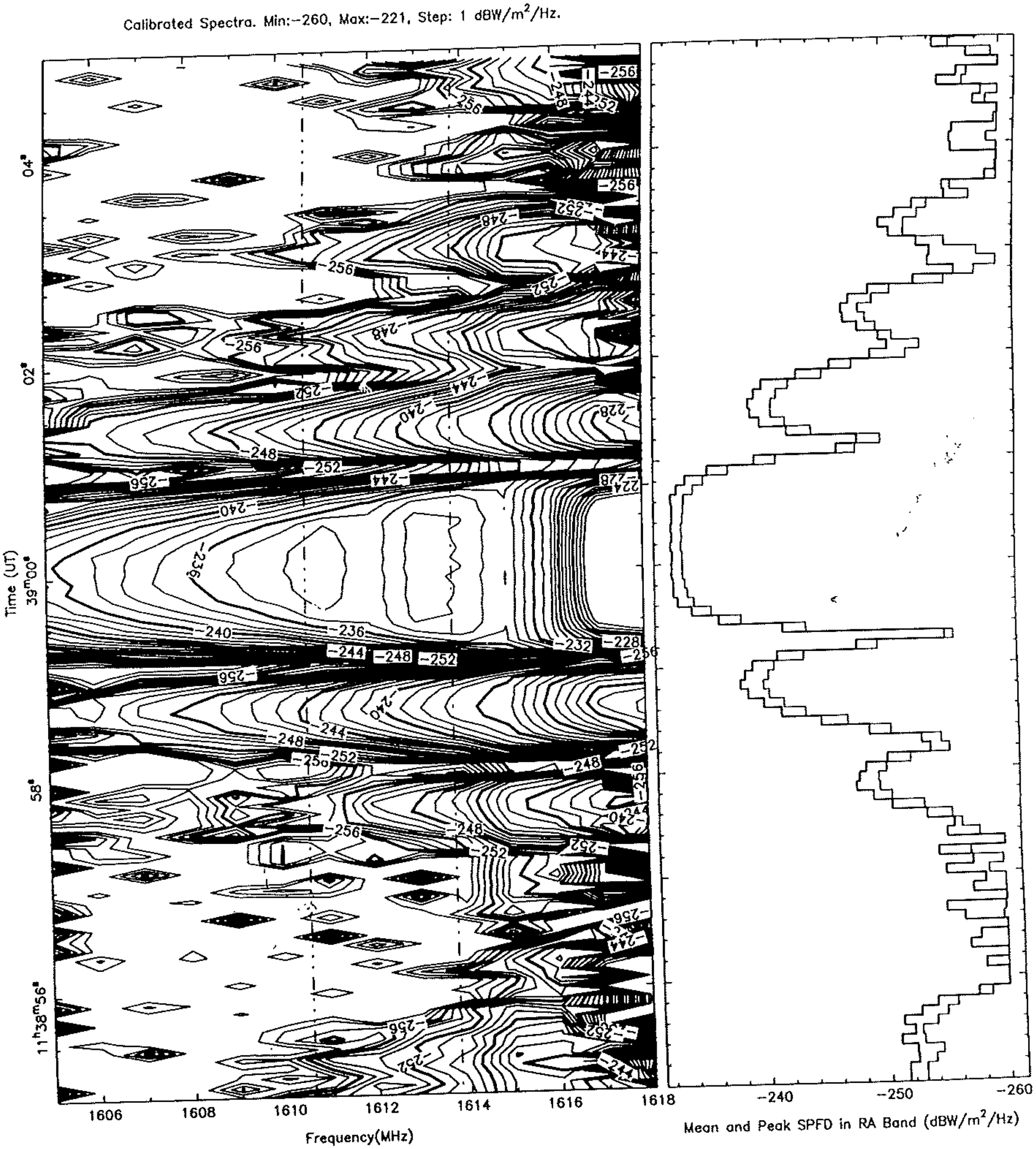
ANTENNA 4, RCP VIA IRIDIUM CONVERTER

6 MARCH 1998, CYG A CAL AND SV PASS #1, TRANSIT #1



mean= –232.7
max= –229.1

FIG. 4



Iridium tests

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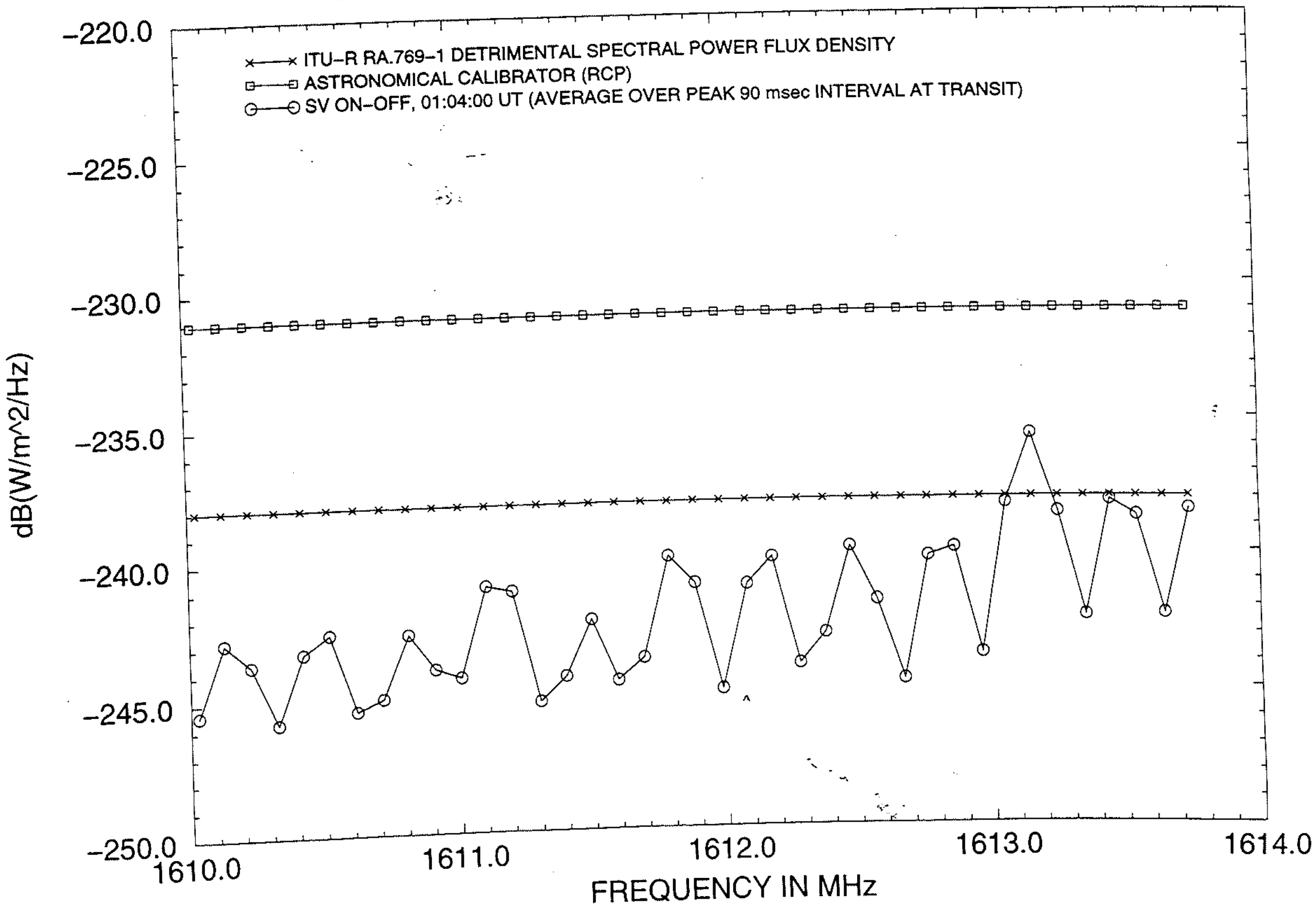
Data Prog Run:          Tue May  5 09:40:33 1998
Data File:              /home/pogo2/irdat/19980306/IRID.000
Cal Prog Rev:           gain: V1.07  10 Apr 1998
Cal Prog Run:           Fri Apr 10 10:46:16 1998
Blank Sky Epoch (UT):   Fri Mar 06 12:05:01 1998
Blank Sky Start (UT):   12:05:20.000
Blank Sky Duration:     00:00:10.000
Calib Epoch (UT):       Fri Mar 06 12:09:01 1998
Calib Start (UT):       12:09:20.000
Calib Duration:         00:00:10.000
Blank Sky File:         /home/pogo2/irdat/19980306/CYGOFOF.000
                        /home/pogo2/irdat/19980306/CYGONOF.000
```

```
Freq: 1605.000-1618.000) MHz
Sample Rate:   960.01 Hz.
Plot res:   0.090000 s
RASE switching:  on
Mean SPFD in RA band:-233.4 dBW/m2/Hz
Peak SPFD in RA band:-232.5 dBW/m2/Hz
Iridium transit at 1998/03/06 11:39:00
```

FIG. 5

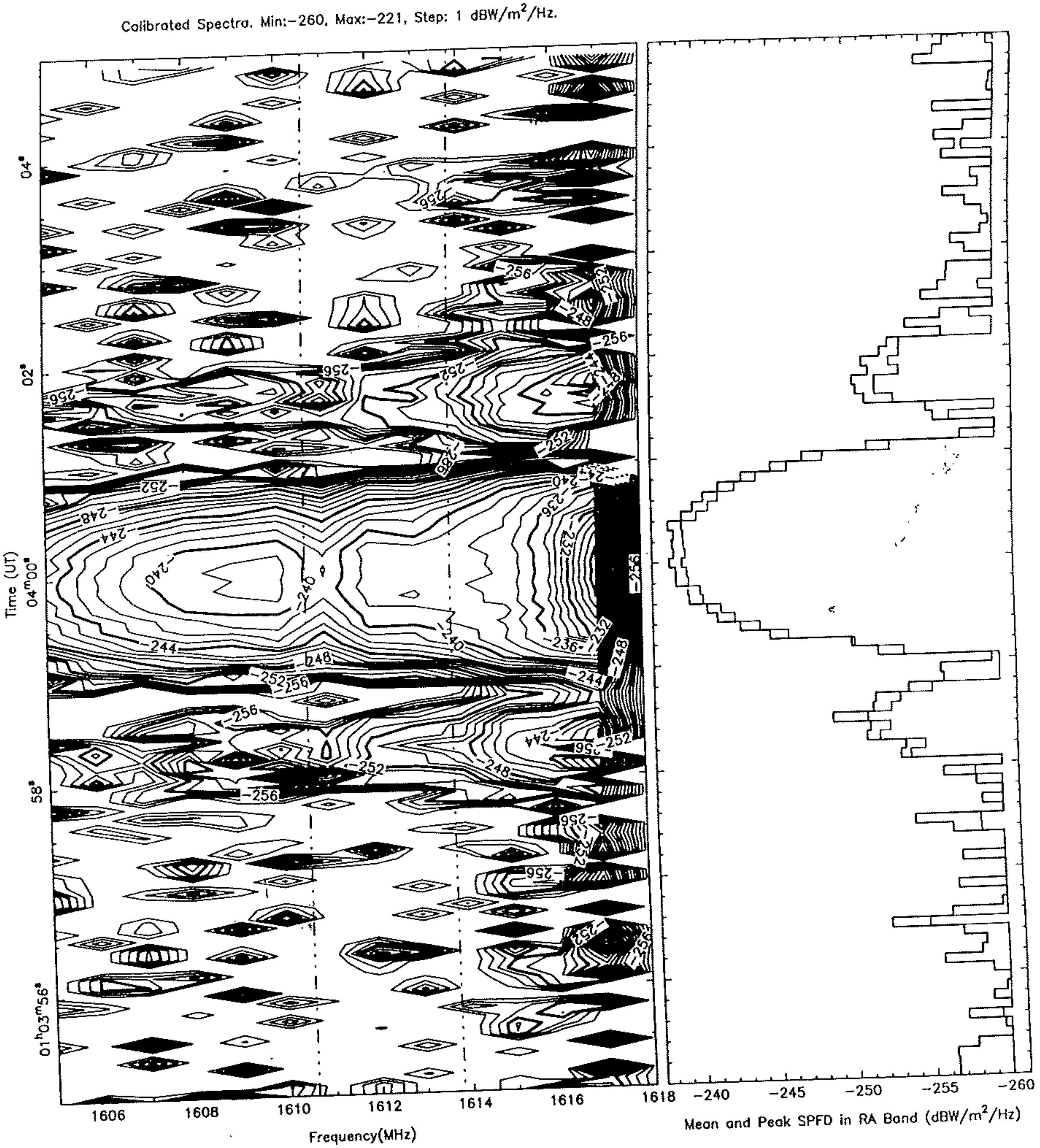
ANTENNA 4, RCP VIA IRIDIUM CONVERTER

25 feb 1998, CAS A CAL AND SV PASS #2, TRANSIT #2



mean= –241.4
max= –235.6

FIG. 6



```
Iridium tests
Data Epoch (UT):            Wed Feb 25 00:59:00 1998
Data Prog Rev:              irid: V1.12  05 May 1998
Data Prog Run:              Tue May  5 09:45:34 1998
Data File:                  /home/pogo2/irdat/24feb98/IRID225.000
Cal Prog Rev:               gain: V1.06  18 Mar 1998
Cal Prog Run:               Fri Apr  3 20:31:11 1998
Blank Sky Epoch (UT):       Wed Feb 25 01:14:00 1998
Blank Sky Start (UT):       01:14:20.000
Blank Sky Duration:         00:00:10.000
Calib Epoch (UT):           Wed Feb 25 01:17:00 1998
Calib Start (UT):           01:17:20.000
Calib Duration:             00:00:10.000
Blank Sky File:             /home/pogo2/irdat/24feb98/CASAOF.000
On Calib File:              /home/pogo2/irdat/24feb98/CASAON.000
                            /home/pogo2/irdat/24feb98/cal19980224.1
```

```
Freq: 1605.000-1618.000) MHz
Sample Rate:   960.01 Hz.
Plot res:   0.090000 s
RASE switching:  on
Mean SPFD in RA band:-239.2 dBW/m^2/Hz
Peak SPFD in RA band:-238.3 dBW/m^2/Hz
Iridium transit at 1998/02/04 01:04:00
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FIG. 7

Results of Tests by NRAO/Tucson of Emission of Iridium Satellites in the 1610.6 - 1613.8 Band

I. Introduction

This report presents an overview of the results of the recently completed, joint Motorola - NRAO tests of the Iridium satellite system's interference to radio astronomy. These observations were carried out during the latter part of February and the first part of March 1998. The report will describe the equipment and procedure used at the NRAO's downtown laboratories in Tucson, Arizona and will present the data analysis.

II. The Equipment

The tests were carried out as a collaborative effort between the University of Arizona's Steward Observatory and NRAO. Individuals actively involved in the test operations were: Dr. Darrel Emerson and Jeff Clarke of NRAO, and Henry Knoepfle of Steward Observatory. The Steward Observatory operates a small, student training, radio telescope which is installed at the campus building shared by that observatory and the NRAO downtown complex. The telescope is an ALT/AZ mounted 3.6m (12 ft.) mesh dish with a 0.375 focal ratio. The telescope has a 4 degree beam width (FWHM) at the frequency of interest. The design of this instrument, in principle, allows for fast slewing and tracking and was chosen for these tests on that basis.

Figure 1 shows the receiver system employed at the telescope for these tests. This system is designed for maximum sensitivity in a 2 MHz bandwidth centered at 1612 MHz, the center of the radio astronomy band. To make use of this instrument for the Iridium testing, it was necessary to construct a prime focus feed horn and a support quadrapod. The feed horn was based on a design by Kumar [1] which is optimized for short focus objectives and has been successfully used by NRAO. The feed horn is designed for use in two orthogonal linear polarizations and allows for use in either left hand or right hand circular polarizations. For these tests, the feed horn was always used in left hand circular polarization, making the telescope system right hand circularly polarized. A 90 degree hybrid coupler follows the feed horn and is used to select the proper polarization.

In order to assure no saturation of the first RF amplifier, due to the strong in-band transmissions from the satellite, a high order bandpass filter is placed in the signal chain after the hybrid coupler and before the first RF amplifier. This filter provides a minimum of 70dB rejection of the strong in-band satellite signal with approximately 1.3dB insertion loss at the radio astronomy center frequency. It is worth noting that the placement of this filter at this point in the system reduces the system's sensitivity by a factor of five. The first RF amplifier is a HEMT type constructed by NRAO. Its room temperature, 1600 MHz noise temperature is 25 K and the gain at that frequency is 33dB. The first RF amplifier is the last component mounted at the prime focus feed horn assembly. A length of coax feeds a second RF amplifier in the control room. A commercial ICOM brand all-band receiver is used for down conversion to an IF frequency of 10.7 MHz. To compensate for the ICOM receiver's large IF output bandwidth, and to provide further satellite in-band rejection, a 2 MHz bandwidth bandpass filter is added after the ICOM receiver. This filter provides a minimum of 40dB rejection outside the radio astronomy band. The IF signal is amplified and fed to a square law detector. The detected signal is integrated with a 1ms time constant integrator and this integrated signal is amplified by an instrumentation amplifier. The detector-integrator-instrumentation amplifier stage is a proven NRAO design.

A unit called the Radio Astronomy Special Equipment device, or RASE, allows for the detection of the satellite's in-band transmission. Only an Iridium satellite will trigger the RASE and cause it to supply a synchronized, 50% duty cycle square wave signal. This signal then represents the on-off conditions of the satellite's transmission. By sampling the RASE signal, other interfering signals can be subtracted out of the test receiver's detected signal. Therefore, the RASE signal and the receiver's detected signal voltage are sampled by two channels of an A/D converter. This device is capable of sampling both channels during a 1ms period and storing 15 minutes of this data. At the end of a data collecting period, the data is written to disk in text format. The data is in the form of a 12-bit unsigned integer.

III. Calibration

A helix antenna was wound and used to verify the polarization of the left hand polarized feed horn. The complete receiver system, without the feed horn, but with the hybrid coupler and first filter, was bench tested. These tests primarily modeled the system linearity and quantified the third order intermodulation intercept point (IP_3). The system output data was linear with input power to the limit of the test equipment employed and the IP_3 was +26dBm.

With the receiver system installed at the telescope, system noise temperature measurements were performed. A large section of L-band optimized, pyramidal absorber was used to block the feed horn as a hot load. The physical temperature of the absorber was measured with a thermocouple device. The telescope was pointed at the zenith for a cold sky temperature measurement. Sidelobe contributions to the cold sky measurements are considered to be at 290 K. These measurements resulted in a system noise temperature of approximately 165 K.

The Sun was found to be the only calibration source available with this system sensitivity. Solar flux values at 2800 MHz are available by way of WWV broadcasts and are posted hourly on the World Wide Web. A calculated spectral index of 0.71 [2] was used to convert the solar flux density at 2800 MHz to a value at 1612 MHz. With the hot/cold load measurements and the sun calibration scans, an effective aperture was obtained. The effective aperture was found from the relation:

$$(1) \qquad A_e = (2kT_A)/S$$

where: A_e is the effective aperture (m^2)
T_A is the antenna temperature (K, observed)
S is the solar flux (dB $W/m^2/Hz$, from reference (WWW))
k is the Boltzmann constant

The aperture efficiency was found to be 0.6 yielding an effective aperture of 6.3 m^2. A data count per unit of flux density is derived with the foregoing information. A minimum detectable flux density was derived with equation (1) above and substituting for T_A the value of dT from the following:

(2) $dT = (L * T_{sys})/(Bw * t)^{0.5}$

where: dT is the minimum detectable temperature variation (kelvin)
L is a loss factor due to the "on-off" switching of the integration periods (dimensionless, L = 2)
T_{sys} is the system noise temperature (Kelvin, 165 K)
Bw is the predetection bandwidth of the receiver system (Hz, Bw = 2 MHz)
t is the integration period (S)

A 1 σ level, detectable flux density of -240 dB W/m²/Hz in one second of integration was found. Typically, 10 second integrations are used in the data reduction yielding a 1 σ value of -245 dB W/m²/Hz. Because the actual satellite testing was carried out before sunrise local time, steps were taken to maintain the system gain constant and sun calibration scans were taken as soon as possible following a satellite pass. The system gain could be held constant to within 1dB over several hours. Also, sun and zenith calibration scans were taken at many other times throughout the testing period.

IV. The Data

Unfortunately, due to poor tracking and/or pointing errors of the telescope, only five partial satellite passes were observed. In all cases, the absolute pointing of the telescope may be in error. The data should then display a conservative measurement of total power. The following data sets may present averages, or integrations, of the data. These data points are obtained by averaging the data taken during a RASE condition "off," doing the same for a RASE condition "on," and subtracting. This procedure is performed for a known number of samples and a known sample rate which results in the displayed averaged, or integrated data. Using equation (1) above and solving for S, the calibrated flux density is calculated for each data set. This value assumes an average over the on periods and a 0% polarization of the signal. Corrections are made to yield data values for averages over the 90ms satellite timing frame and for the assumption of a 100% right hand circularly polarized signal.

Table 1 presents the peak values of flux density measured during each pass. The measurement was not necessarily taken at the satellite's closest approach. Therefore, this peak value does not necessarily represent the maximum power which may have fallen on this site during the satellite pass. Column 2 of the table shows the distance of the spacecraft and column 3 describes the position of the satellite, in azimuth and elevation from this site, during the measurement.

Table 2 displays the satellite's transmitter loading parameters, the direction of its track as seen from this site and the relative direction from the spacecraft's track to this site. As the spacecraft antenna configuration is known, the information in this table may provide more insight into the radiation patterns of the intermodulation signal.

By searching for the rising and falling edges of the RASE signal, the data can be separated into its framed timing format. In Figures 2 and 3, the data is displayed in 12 stacked and averaged frames. Here, the vertical scale is linear to better display the details of the signal. The units are W/m²/Hz. This view of the data may help determine the actual duty cycle and may uncover other periodicities and artifacts in the satellite transmission.

V. Conclusion

This report is meant only to present a selection of the data taken during the joint Motorola and NRAO Iridium satellite testing program. Due to problems with the telescope drive system, our initial goal of observing the satellite through complete, horizon to horizon passes, was not attained. We have presented five data sets which may help answer certain questions regarding the spectral power flux density integrated over a large bandwidth.

References

[1] Kumar, Akhileshwar (March 1978). 'Reduce Cross Polarization In Reflector-Type Antennas'. In *Microwaves*, pp. 48-51.

[2] Lang, K. R. (1974). 'Astrophysical Formulae'. pp 561.

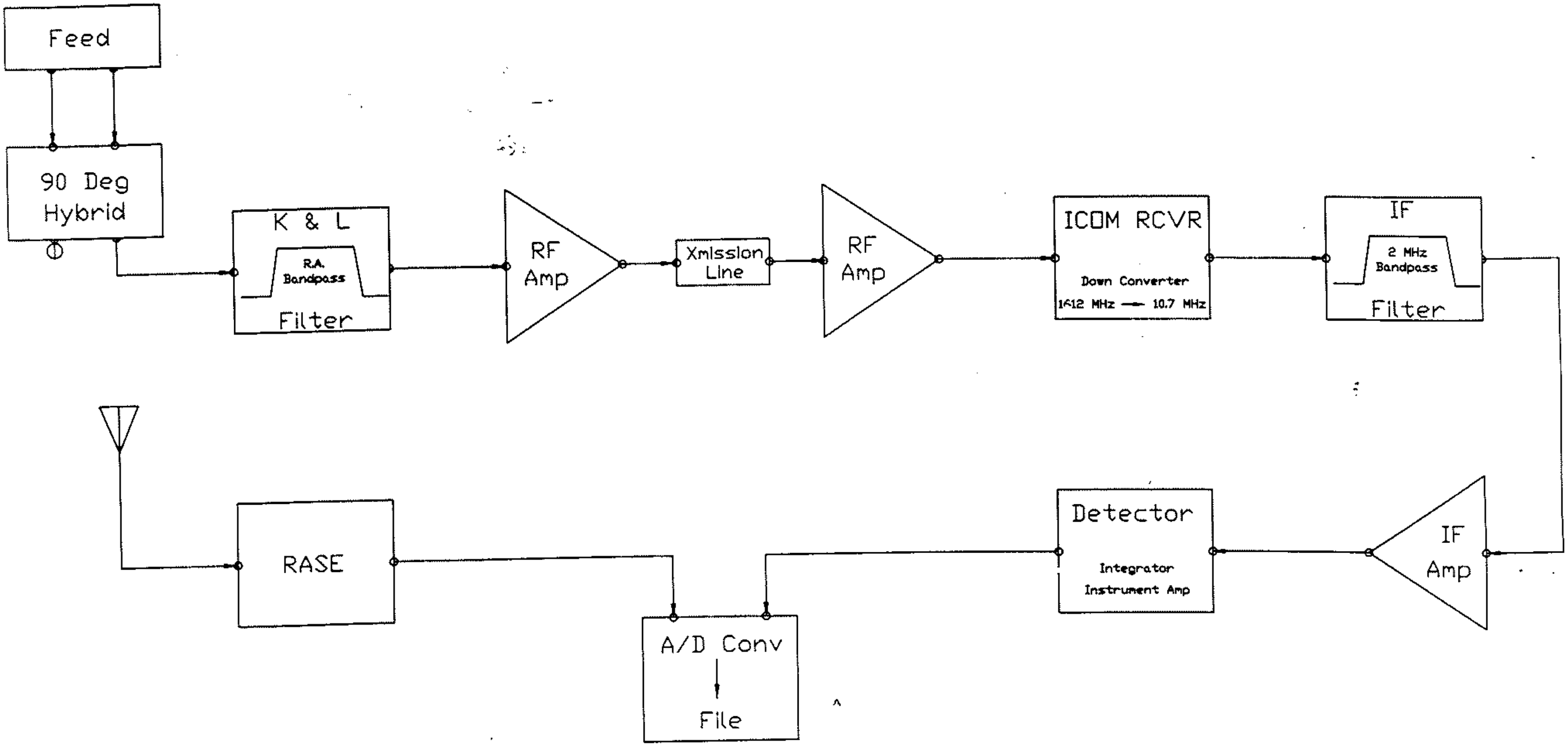


Figure 1
Receiver System Block Diagram

FIGURE 2

IRIDIUM DATA
0023 UTC 3-04-98
Loading 344nbl

Stacked Frames

Fig. 2 12 - 90 ms Frames

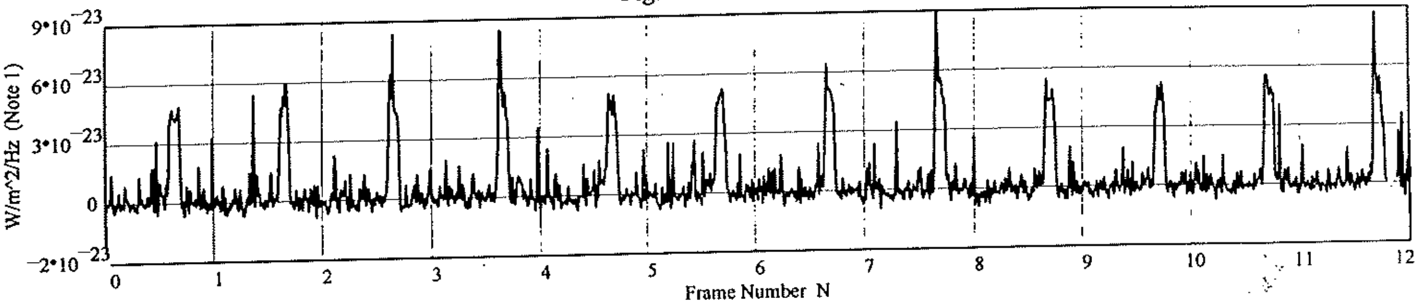
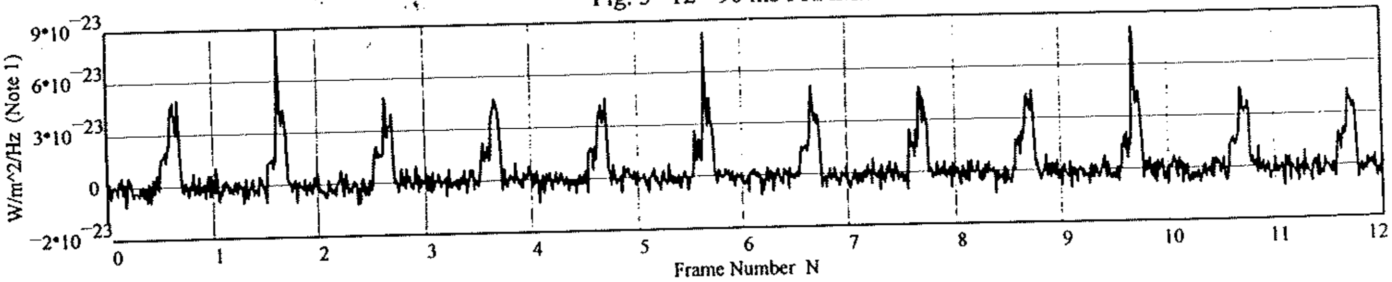


FIGURE 3

IRIDIUM DATA
1205 UTC 3-05-98
Loading 344wbr

Stacked Frames

Fig. 3 12 - 90 ms FRAMES



Note 1: Vertical scale is in units of Watts/m^2/Hz. Vertical scale is linear for clarity of detail.

Table 1
Peak Value of Flux Density
Measured Each Pass, Distance and Position

Averaged Over 90mS Frame Period, 100% RHC Polarization, 10 Sec. Integrations, 2MHz bandwidth

dB W/m²/Hz, Kilometers, Degrees

Pass Time/Date	Mean Spectral Flux Density	Distance of Satellite	AZ to Satellite	EL to Satellite
1313 3-3	-235.2 dB W/m²/Hz	1960 km	279°	16°
0023 3-4	-232.6 dB W/m²/Hz	810 km	298°	73°
1205 3-5	-229.9 dB W/m²/Hz	890 km	259°	60°
1131 3-6	-236.3 dB W/m²/Hz	2840 km	173°	10°
1239 3-7	-233.7 dB W/m²/Hz	1730 km	285°	20°

Table 2
Loading Parameters, Azimuth of Pass Start and End,
and Relative Site/Satellite Track Direction

Loading parameters [1], Degrees, Notes

Pass Time/Date	Loading [1]	Az Start	Az End	Satellite Track Direction	Relative Site Direction from Satellite Track
1313 3-3	344wbl	315°	244°	NW to SW	Site is to LEFT of satellite track
0023 3-4	344nbl	186°	358°	SW to NW	Site is to RIGHT of satellite track
1205 3-5	344wbr	350°	192°	NW to SW	Site is to LEFT of satellite track
1131 3-6	344wbl	004°	173°	NE to SE	Site is to RIGHT of satellite track
1239 3-7	344nbr	324°	231°	NW to SW	Site is to LEFT of satellite track

[1] Loading parameters from Motorola schedule of test passes, by email, dated 2-6-98.
344 = number of voice channels, wb = with broadcast channel,
nb = without broadcast channel, l = left panel illuminated, r = right panel illuminated