VLA TEST MEMORANDUM 146

Interference to
RADIO ASTRONOMY
from
GLONASS TRANSMISSIONS
in the
FREQUENCY BAND 1600 - 1615 MHz

AUGUST 1985

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INTERFERENCE TO RADIO ASTRONOMY FROM GLONASS TRANSMISSIONS IN THE FREQUENCY BAND 1600 - 1615 MHz

SUMMARY

In mid-1984 radio astronomers observing a spectral line of the hydroxyl molecule near 1612 MHz began to report an increasing incidence of interference which disrupted their observations. A set of test measurements was performed using the facilities of the Haystack Observatory, and the source of this interference has been positively identified as the GLONASS, a satellite based radionavigation system operated by the U.S.S.R.

As of December 1984 there were eight GLONASS satellites transmitting in the frequency range 1602-1616 MHz. The satellites transmit in two modes simultaneously. Both transmission modes are characterized by a $(\sin x/x)^2$ structure with a width of about 1 MHz between first nulls in one mode and a width of about 10 MHz between first nulls in the second mode. There are also narrow spike-like emission features in the nulls between the sidebands of the broad-band signal set. Both transmission modes in a given satellite are at the same center frequency, but each satellite transmits at a different center frequency. The peak power level of the emissions received at the earth was measured to be 40 dB above the power level of the cosmic radio source Cass A. The peak emission from the broad-band signal set was about 10 dB below the peak emission from the narrow-band signal set.

The results of the test measurements and a few well-documented cases of interference allow an assessment of the impact of GLONASS transmissions on astronomical spectroscopy in the frequency band 1600 - 1615 MHz. Interfering signals may be received even when the telescope is pointing many degrees away from a transmitting satellite. The narrow-band signal set has the potential to render the astronomical data useless any time the satellite is above the observatory horizon when the satellite transmitter is centered within the frequency band used by the astronomer. The broad-band signal set has a similar potential for causing interference, with the greatest impact falling on radio astronomy observations which cover several megahertz or narrow-band observations where the band falls between the center frequencies of

satellites which are above the horizon. In particular, the broad-band signal set could have devastating effects on radio astronomy observations requiring high sensitivity.

Although the impact has not been fully documented, there is a very real potential for interference to radio astronomy observations in the band 1660-1670 MHz due to the sideband emission of the broad-band signal set.

There is little the astronomers can do to avoid or correct for the interference since the frequencies of the cosmic spectral line are set by nature; since the satellites are moving, making the effects variable; and since the source of interference is moving across the sky, offering no protection from terrain shielding. The satellite operators, on the other hand, could make a number of changes in the configuration, such as shifting the center frequencies of the satellite transmitters and filtering unwanted emissions, which would greatly reduce or eliminate interference to radio astronomy observations.

It is hoped that some adjustments can be made because radio astronomy access to the frequency band 1606-1614 MHz is essential to some astrophysical problems.

INTRODUCTION

In June 1982 the Soviet Union formally advised the member countries of the International Telecommunication Union (ITU) that the U.S.S.R. was working on a project to establish a world-wide navigation satellite system to be known as "GLONASS". The system has been designed for world-wide aircraft radionavigation and is based on 9 - 12 satellites which will be positioned in three inclined planes with 3 - 4 satellites in each plane. Users of the system determine their own location according to the results of a passive measurement of the distance to each of three satellites. It is planned that each satellite will continuously transmit two signals with band diversity so as to allow for correction for ionospheric propagation error. The salient system parameters are summarized in Table 1.

An excerpt from the international frequency allocations table for the band 1559-1626.5 MHz is shown in Figure 1. The GLONASS operates in the band 1597-1610 MHz in the Radionavigation-Satellite Service (space-to-earth). In the band 1610-1617 MHz, GLONASS is operated under Footnote 732. The record of satellite launches identified with GLONASS is given in Table 2; 15 satellites assigned to this system have been launched. As will be noted later, not all 15 are active.

Radio astronomers use a band of frequencies around 1612 MHz to observe a radio frequency line emitted from a molecule called "hydroxyl" with the chemical symbol OH. This molecule is observed in hundreds of different regions of our Galaxy, and recently in other galaxies as well. By observing spectral lines from hydroxyl, radio astronomers obtain information about the chemical composition, about the temperature and density, and about the motions of the regions of space where the molecules are located. These molecules appear in space where there are no stars at all, where stars are just forming, and associated with stars in various stages of their evolution. In the aggregate, these studies provide a view of the structure of our Galaxy and the interrelationships of its various constituents. With improved instrumental sensitivity and angular resolution, these same properties are now being investigated in other galaxies.

TABLE 1: GLONASS Parameters

Down-links	
Transmit Frequencies (continuous)	1240 - 1260 MHz 1597 - 1617 MHz
Maximum Spectral Power Density	-57 db(w/Hz) at 1240-1260 MHz -44 db(w/Hz) at 1597-1617 MHz
Axial Antenna Gain	11.8 db at 1240-1260 MHz 13.3 db at 1597-1617 MHz
Satellites	
Number	9 - 12
Period	12 Hours
Altitude	20,000 KM
Orbit Inclination	63^{0}

(Satellites in three inclined planes; 3 - 4 satellites per plane)

Source: IFRB Circular 1522, Special Section AR11/a/3, 08 June 1982

TABLE 2: GLONASS Satellites

(As of December 1984)

COSMOS NO.	INTERNATIONAL DESIGNATION	LAUNCH DATE
1413	1982.100A	12 October 1982
1414	1982.100B	"
1415	1982.100C	"
1490	1983.84A	10 August 1983
1491	.84B	"
1492	.84C	"
1519	1983.127A	29 December 1983
1520	.127B	"
1521	.127C	"
1554	1984.47A	19 May 1984
1555	.47B	"
1556	.47C	"
1593	1984.95A	04 September 1984
1594	.95B	"
1595	.95C	"

Source: ITU Telecommunication Journal

MHz
1 559 — 1 626.5

Allocation to Services		
Region 1	Region 2	Region 3
1 559 — 1 610	AERONAUTICAL RADIONAVIGATION RADIONAVIGATION-SATELLITE (space-to-Earth) 722 727 730 731	
1 610 — 1 626.5	AERONAUTICAL RADIONAVIGATION 722 727 730 732 733 734	

731 *Alternative allocation:* in Sweden, the band 1 590 — 1 610 MHz is allocated to the aeronautical radionavigation service on a primary basis.

732 The band 1 610 — 1 626.5 MHz is reserved on a worldwide basis for the use and development of airborne electronic aids to air navigation and any directly associated ground-based or satellite-borne facilities. Such satellite use is subject to agreement obtained under the procedure set forth in Article 14.

733 The bands 1 610 — 1 626.5 MHz, 5 000 — 5 250 MHz and 15.4 — 15.7 GHz are also allocated to the aeronautical mobile-satellite (R) service on a primary basis. Such use is subject to agreement obtained under the procedure set forth in Article 14.

734 The band 1 610.6 — 1 613.8 MHz is also allocated to the radio astronomy service on a secondary basis for spectral line observations. In making assignments to stations of other services to which the band is allocated, administrations are urged to take all practicable steps to protect the radio astronomy service from harmful interference. Emissions from space or airborne stations can be particularly serious sources of interference to the radio astronomy service (see Nos. 343 and 344 and Article 36).

FIGURE 1: Excerpt From Radio Regulations of the International Telecommunication Union

Under the conditions encountered in space, the hydroxyl molecule produces a number of spectral lines which can readily be observed with telescopes on earth. The most important OH lines, to astronomers, result from interactions within the molecule which yield four energy levels. As the molecule changes from one energy state to another, radio frequency radiation is produced which has very specific laboratory rest frequencies of 1612.231, 1665.402, 1667.359, and 1720.530 MHz. The two center frequencies of this set are sometimes referred to as main lines and the two outer frequency transitions as satellite lines. This is simply spectroscopic terminology and has no relation to the importance of the lines to the astronomer. These four lines are also referred to as the 18-cm lines of OH. The frequencies of the lines observed at the earth will be shifted from the rest frequencies as a consequence of the motions of the OH molecules relative to the observers on earth (the Doppler effect). For example, a group of galaxies known as the Virgo cluster has a median velocity of about 1000 km/sec which shifts the 1612 MHz OH line to a frequency of 1606.8 MHz.

It is necessary to emphasize the point that to interpret the observations of the hydroxyl line radiation in terms of the physical conditions within remote parts of our Galaxy, it is necessary to measure the relative strengths of the four 18-cm OH lines. All four lines are thus equally important, and loss of a single line from the data set due to interference can impede and even prevent study of broad classes of physical phenomena. In addition, a certain class of cosmic source may radiate only in one of the 18-cm OH lines. For example, the 1612 MHz line of OH is the dominant emission line for naturally occurring masers around infrared stars. Astronomers have discovered that the conditions for Microwave Amplification by Stimulated Emission of Radiation (MASER) also exist around young stars, and that these powerful narrowband signals provide a readily detectable signature of star formation. The study of the OH emission at 1612 MHz allows astronomers and physicists to gauge such physical properties of the stars as the rate at which gas is blown off and recycled into the interstellar medium. The characteristics of the surrounding gas shells which can be measured include their size, density, and rate of expansion. Some of these characteristics cannot be inferred from any other astronomical observations. In contrast, the OH located in clouds which are not associated with any stars may emit most strongly in the lines at 1665 and 1667 MHz. Therefore observations of several spectral lines, even of the same molecular species, are essential to the derivation of reliable quantitative conclusions about the structure of the cosmos.

The requirements of the radio astronomy service for protection of observations of the 1612 MHz line of OH have been documented in the literature of the International Radio Consultative Committee (CCIR) for a number of years. CCIR Recommendation 314-3 in 1974 recommended a band from 1611.5-1612.5 MHz for these observations. Since that time, more sensitive receiver systems have been developed which allowed the scientific interest to evolve to the study of OH in other galaxies. Thus, a wider range of frequencies is now necessary to accommodate the much larger velocities (larger Doppler effect). Currently CCIR Recommendation 314-5 (1982) suggests a band from 1606.8-1613.8 MHz. This frequency band covers the velocity range +1000 km/sec to -300 km/sec which includes most of the molecular regions in our Galaxy and in nearby galaxies. Footnote 734 in the Radio Regulations (Fig. 1) provides a secondary allocation to radio astronomy in the band 1610.6-1613.8 MHz.

From about July 1984, several radio astronomy observatories in the United States reported a significant increase in the occurrence of interference around 1612 MHz. They are: The Very Large Array of the National Radio Astronomy Observatory (NRAO) in New Mexico, the National Radio Astronomy Observatory at Green Bank, West Virginia, and the Arecibo Observatory of the National Astronomy and Ionosphere Center (NAIC) in Puerto Rico. For the latter two, the interference occurred during the course of scientific observing programs, and steps were taken to document the interference but not to identify its source. Since the advent of GLONASS was known, these satellites were suspected as the source of the interference. In December 1984, test measurements specifically designed to identify the interfering source(s) were performed at the Haystack Observatory in Massachusetts. Observatory parameters are summarized in Table 3. Although the tests were performed at Haystack after the interference was documented at NRAO and Arecibo, the test measurements will be discussed first because these results could be applied in retrospect to analyze the interference.

TABLE 3: Radio Astronomy Observatory Parameters

Name/Location	Telescope Description	Type of Data Collected
1. Haystack Observatory Westford, Massachusetts 42° 37' 23" N; 71° 29' 19" W	36-m diameter parabolic reflector, fully steerable. Main beam at 1612 MHz is 21 arc min.	Specially scheduled test measurements on 04 December 1984. Spectrum analyzer frequency span of 180 MHz and 100 MHz (1520 - 1700 MHz). Spectra taken tracking satellites and 5° away.
2. National Radio Astronomy Observatory Green Bank, West Virginia 38° 26' 08" N; 79° 49' 42" W	43-m diameter parabolic reflector, fully steerable. Main beam at 1612 MHz is 18 arc min.	Documented interference during standard scientific observing program 23-24 October 1984. Spectroscopy 1611-1613.5 MHz. Spectrum analyzer 1570-1620 MHz with 100 kHz resolution bandwidth. Spectra taken at intervals spaced by 1 to 15 minutes.
3. National Astronomy & Ionosphere Center, Arecibo, Puerto Rico 18° 21' 13" N; 66° 45' 11" W	305-m diameter spherical fixed reflector. Feed is steerable over elevation 70°--90°; azimuth 0°--360°, main beam at 1612 MHz is 3 arc min.	Documented interference during standard scientific observing program 08 November 1984. Spectroscopy 1611-1613.5 MHz.

TEST MEASUREMENTS - HAYSTACK

On 04 December 1984 the Haystack Observatory facilities were used to perform a series of measurements which positively identified the source of the interfering signals which had been documented at the NRAO and Arecibo. The tests consisted of using the Haystack 36 meter diameter telescope to track all 15 of the COSMOS satellites which are identified with GLONASS. A Hewlett Packard 8566A spectrum analyzer was used to process the signals and produce spectrograms of each satellite. Transmissions were detected from 8 of the 15 satellites. In Table 4 the satellites and the measured (no Doppler corrections) center frequencies of their transmissions are identified.

Each satellite transmits on a different center frequency, and there are two sets of signals from each satellite, both of which have a $(\sin x/x)^2$ character. One signal set has a frequency separation between first nulls of about 1 MHz; the second signal set has a frequency separation between first nulls of about 10 MHz. The center frequency of each signal set appears to be identical. There are also narrow emission spikes, with about the same width as the narrow signal set, in the nulls of the sideband emission of the broader signal set.

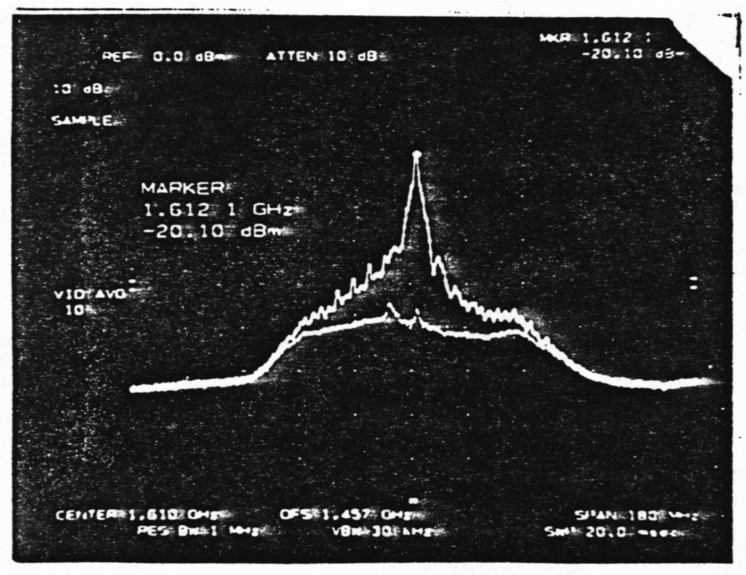
The maximum intensity of the signal at the center frequency was measured to be between 36 and 41 dB above the strength of the well known cosmic radio source Cass A; an absolute measure of the signal strength was not obtained. The 10 MHz wide signal had a peak intensity approximately 10 dB less than the narrow 1 MHz wide signal.

A representative spectrogram from the spectrum analyzer is shown in Figure 2. Figure 2A shows two traces of the spectrum analyzer. The upper trace was obtained with the telescope tracking Cosmos 1555. The lower trace was obtained with the telescope pointed 5° away from the satellite. Transmissions from GPS satellites are occassionally visible at $\sim$1575 MHz. The spectrum in Part B of Figure 2 is a higher resolution spectrogram of the signal from the same satellite.

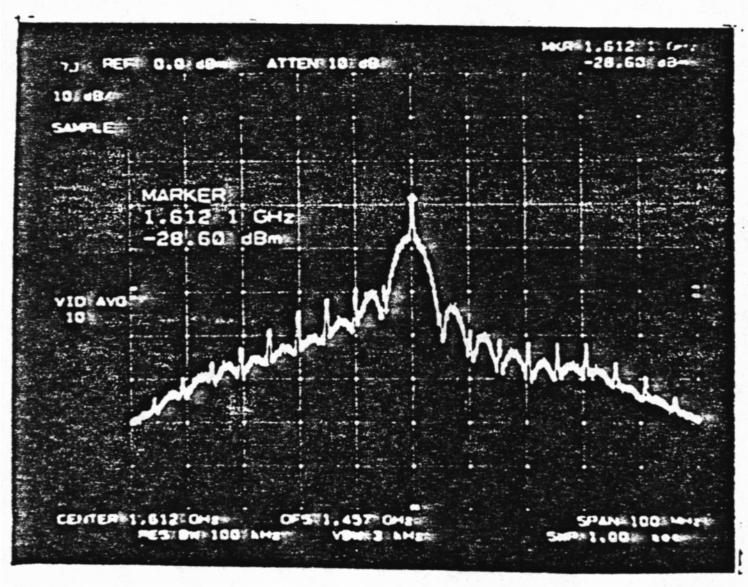
TABLE 4: Active GLONASS Satellites

COSMOS NO.	MEASURED FREQUENCY (MHz)
1491	1602.5
1519	1603.1
1490	1603.5
1554	1607.1
1593	1607.4
1595	1611.4
1555	1612.1
1520	1615.5

As of 12/84



A. Frequency Span - 180 MHz



B. Frequency Span - 100 MHz

<u>FIGURE 2</u>: Haystack Spectrum Analyzer on COSMOS 1555.
Marker Frequency = 1612.1 MHz.
Amplitude (above Cass A) ≐ 37 dB.

Figure 3A shows an idealized version of the $(\sin x/x)^2$ signals measured from the satellites; the frequency of Cosmos 1555 is used as the example. The spikes in the nulls of the broad signal set are included, but their sideband character is not known. Figure 3B shows an idealized composite of the main transmission bands of the constellation of all eight satellites from which signals were detected. The frequency bands of primary interest to radio astronomers for observations of OH are also shown on the frequency scale.

THE OBSERVED INTERFERENCE

In observations at frequencies near 1612 MHz astronomers are primarily interested in the fundamental type of observation known as spectroscopy. A spectroscopy measurement examines the detailed frequency structure of a signal within a segment of the receiver bandwidth. For example, a band of 2.5 MHz may be subdivided into 250 frequency channels giving 10 kHz per channel. At centimeter wavelengths the hardware device most often employed as a spectrometer is a digital autocorrelator.

Since the cosmic signal levels are often a small fraction of the receiver system noise, the astronomer follows a procedure where he tries to obtain a reference, or OFF, spectrum which is identical to the on-source, or ON, signal spectrum except for the source signal itself. To get a spectrum which can be analyzed for its scientific content, the astronomer subtracts the reference spectrum from the signal spectrum and normalizes that difference by the reference spectrum, (ON-OFF)/OFF. The final spectrum is often termed the "difference spectrum". Any extraneous signal which produces a different effect on the reference than on the on-source spectra, such as variability or motion, will change the shape of the difference spectrum and increase the uncertainty in the interpretation of any cosmic source signals present.

The scientific programs described in this report which were in progress when interference was documented at Green Bank and at Arecibo were following the standard observing procedure of obtaining a difference spectrum.

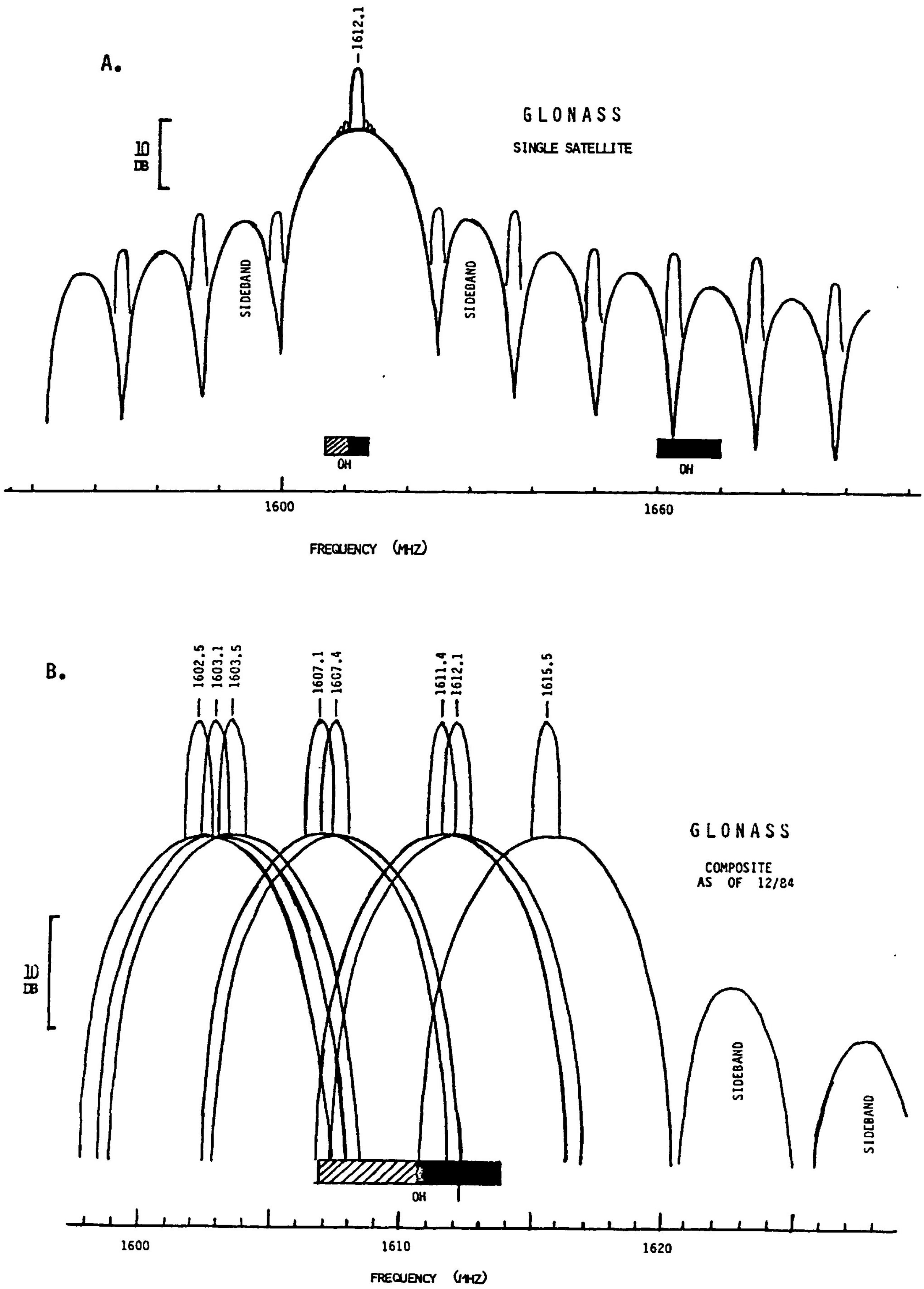


FIGURE 3: Idealized Representation of GLONASS Satellite Transmissions

NRAO -- Green Bank

The measurements at the NRAO Green Bank were made during the course of a scientific observing program on 23-24 October 1984. The receiver and autocorrelation spectrometers were configured to observe all 4 of the 18-cm OH lines simultaneously. The program followed the observing routine discussed above. Interference made any scientific data collected in the 1612 MHz quadrant of the spectrometer useless. The program was continued because data at the other 3 lines were not affected. The procedure inadvertently allowed a useful record of the effects of the interfering signals during the course of a routine observing period.

For the scientific program, the spectrometer, which was centered at about 1612 MHz, analyzed only a 2.5 MHz bandwidth, but the effects of the interference are clearly illustrated in Figure 4. The spectrograms shown are "difference" spectra obtained at two different times on 23 October 1984. Note the change in the intensity scale between parts A and B of the Figure. The noise level is the same in both spectrograms. The scale change is due to a significant change in the strength of the interference between an "OFF" and an "ON" integration. The signal appears negative because it was stronger in the "OFF" spectrum than the signal in the "ON". An interference-free spectrum is not shown here. It would simply be a flat, noisy, featureless spectrum across the 2.5 MHz analyzed band. The character of an astronomical spectral line depends on the nature of the source, but in general such a line would be significantly narrower in frequency and much weaker than any of the features in the illustrated spectrograms. The interfering signals recorded here render the data completely useless for astronomical analysis.

Soon after the interference was noticed by the scientists, the input signal was split and also fed into a spectrum analyzer which covered the frequency range 1570-1620 MHz. During the period 20:10-23:51 Universal Time (UT) on 23 October 1984, spectra over this range were obtained at intervals of 1 minute to 15 minutes. From 00:03 - 01:02 UT on 24 October 1984, the range 1597-1617 MHz was covered in the same manner. Representative spectra are displayed in Figure 5. These are not "difference" spectra. Note particularly the significant changes in signal strength that occur within 1

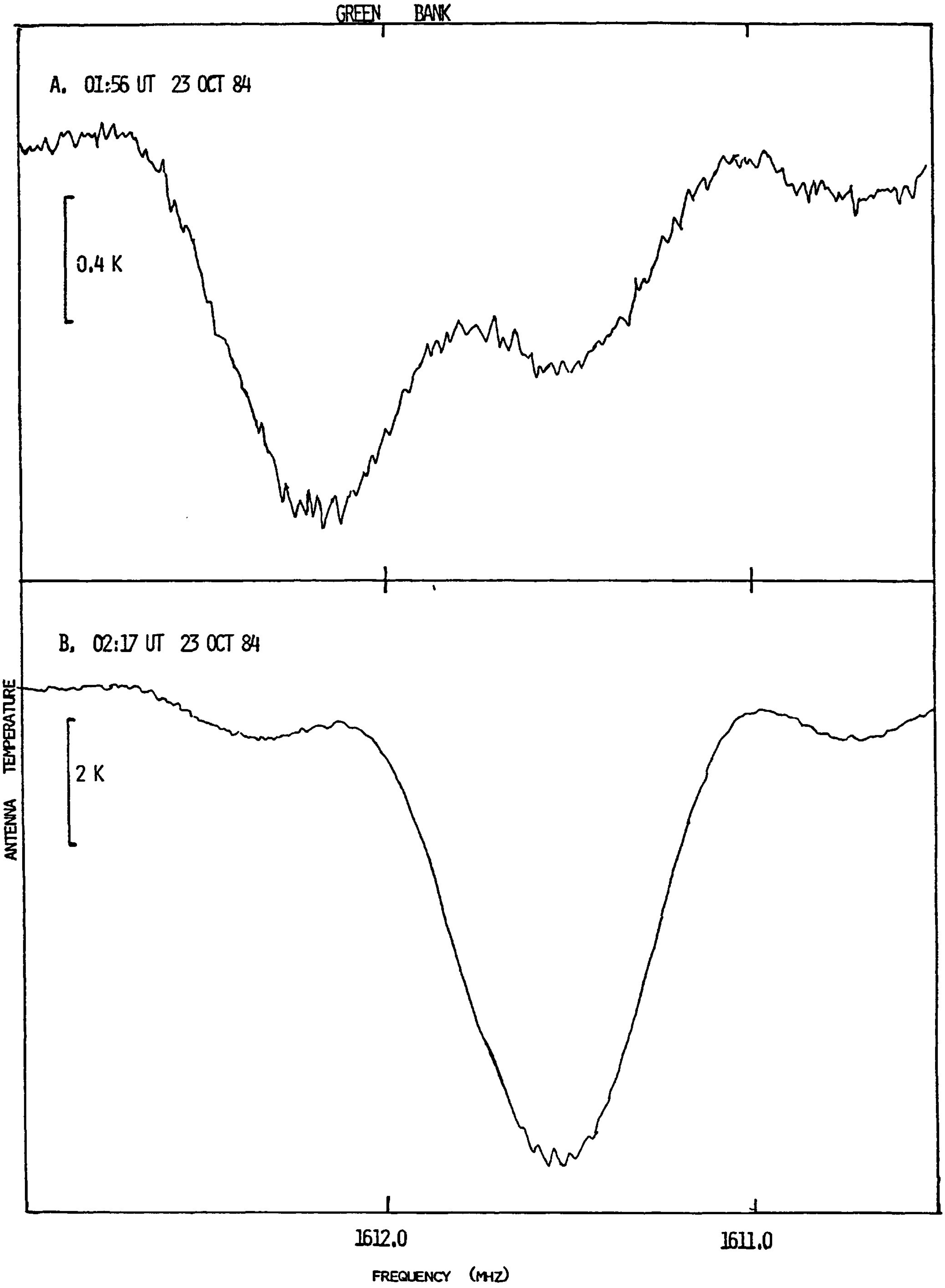
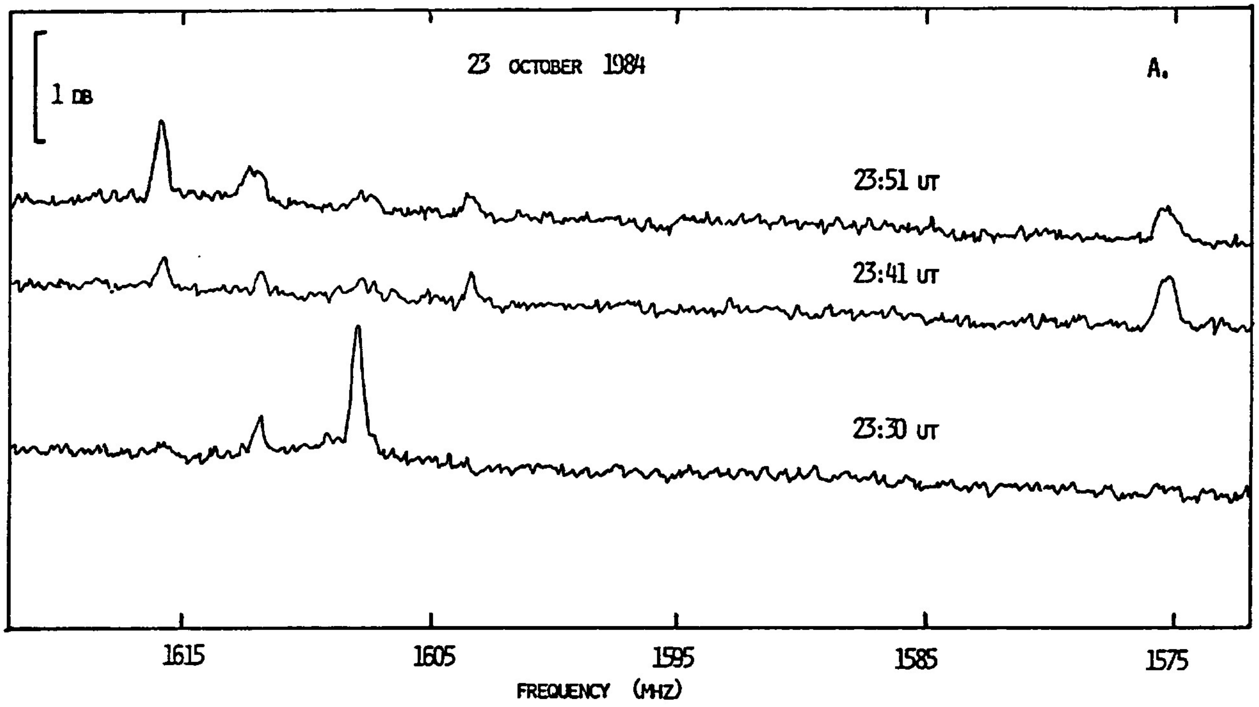


FIGURE 4: Green Bank Difference Spectra From 43-m Telescope
(5 min. on source and 5 min. reference)



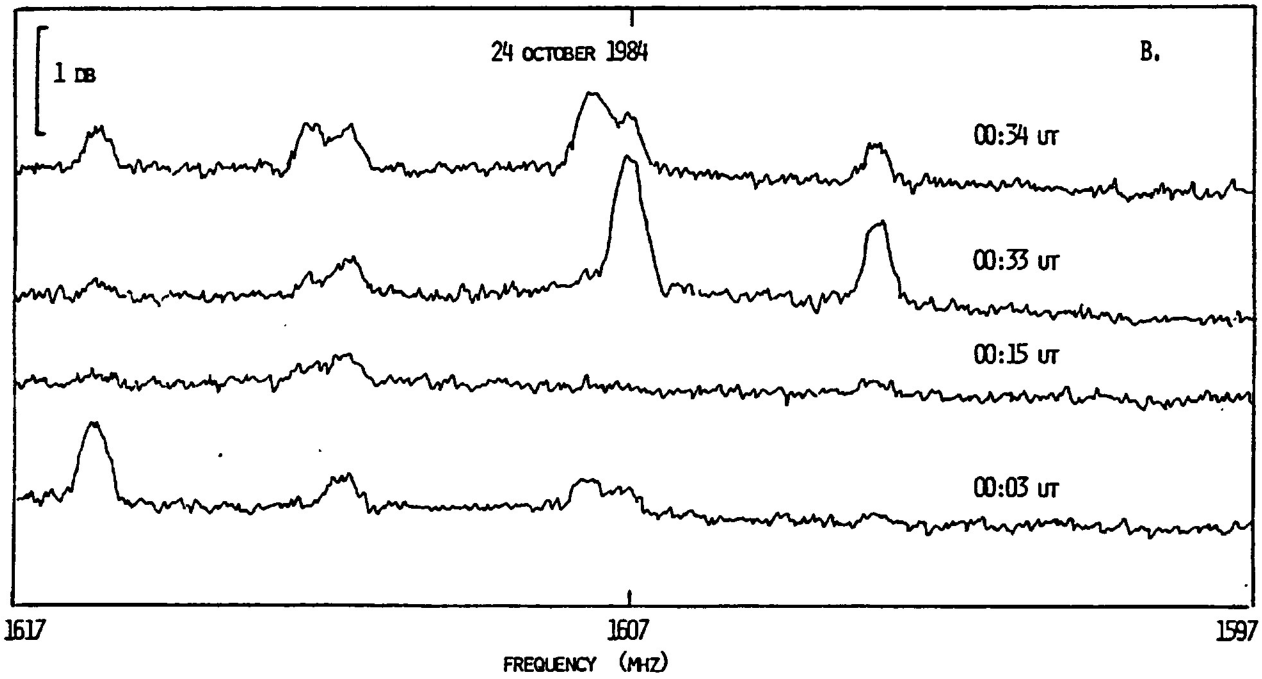


FIGURE 5: Green Bank Spectrum Analyzer

or 2 minutes. This is caused by the motion of the satellite through the antenna pattern of the telescope. The signal at 1575.4 MHz is from one or more satellites in the U.S. GPS system. It should be noted that the telescope was going through a routine observing procedure on astronomical sources throughout this time period. There was no attempt to locate the source of interference and point the telescope directly at it.

After the fact of these measurements, the ephemerides of the active GLONASS satellites were obtained, and these data were correlated with the astronomical measurements. Figure 6 shows the times between 19:00 UT 23 October 1984 and 04:00 UT 24 October 1984 when the 8 active GLONASS satellites were above the horizon (above 0^o elevation) at Green Bank, West Virginia. The vertical lines on the Figure represent examples of snapshots in time at which both spectrum analyzer spectra and the satellites' positions are available. The integer numbers at the intersection of the satellite and time lines represent the signal strengths at the frequency of that satellite at that time as measured from the spectrogram. The intensity scale is logarithmic. A "0" indicates a non-detection. A "2" is a marginal detection. Cosmos 1490 was not detected during the course of these measurements. All other satellites were detected within 40 minutes of the indicated rise time.

Figure 6 does not indicate the positions of the satellites on the sky during the time they were above the horizon. Full tracks of the satellites across the sky were not obtained, but the existing snapshot data were compiled to give an indication of the tracks in right ascension and declination units during the period 19:00-04:00 UT. Those results are shown on Figure 7. Each satellite is represented by a different symbol, and its location is shown at the specific times for which data were available. Cosmos 1490 follows Cosmos 1595 and Cosmos 1519 follows Cosmos 1555 with nearly identical tracks, but separated by about 3 minutes in time. Thus, Cosmos 1490 and 1519 were not plotted. Satellites move from left to right in the Figure as time passes. The telescope was pointed at essentially the same right ascension and declination during the entire 5 hour period, and that position is indicated on the Figure. The integers beside each satellite

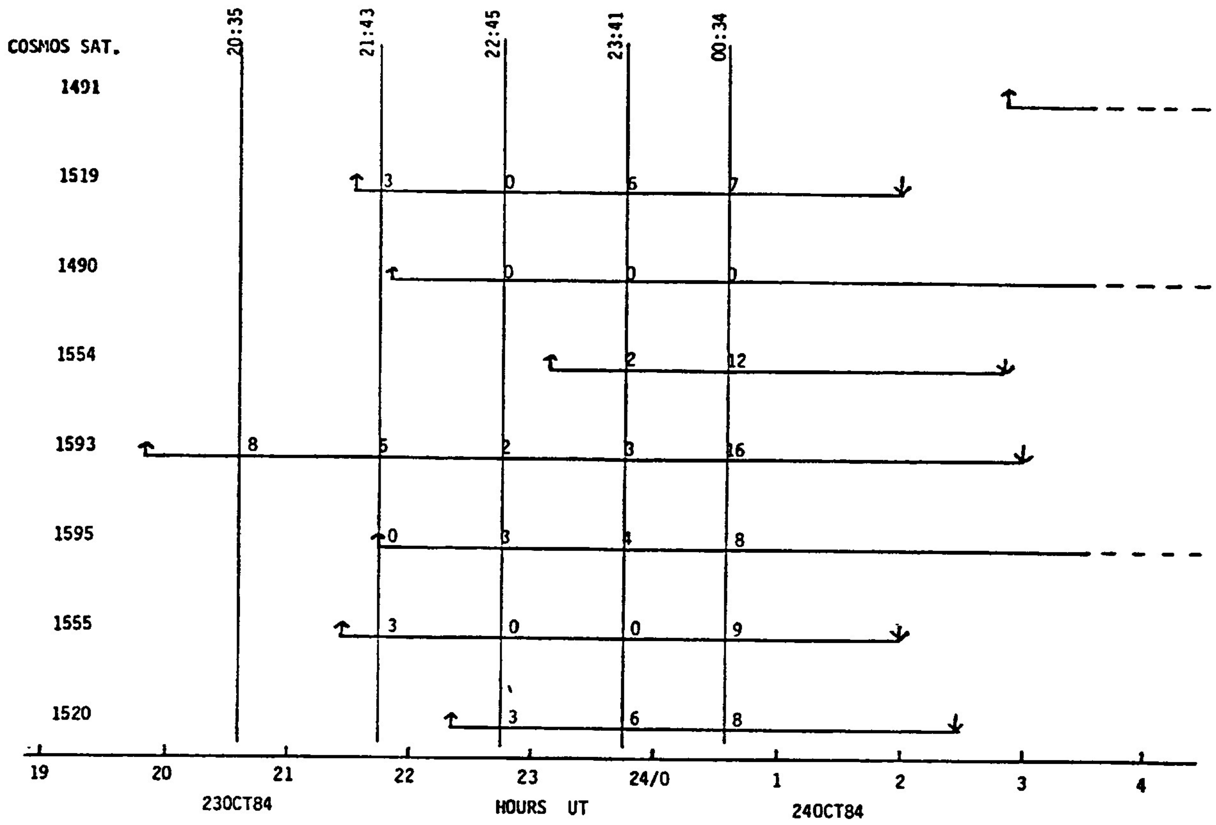


FIGURE 6: GLONASS Satellites Above Green Bank Horizon

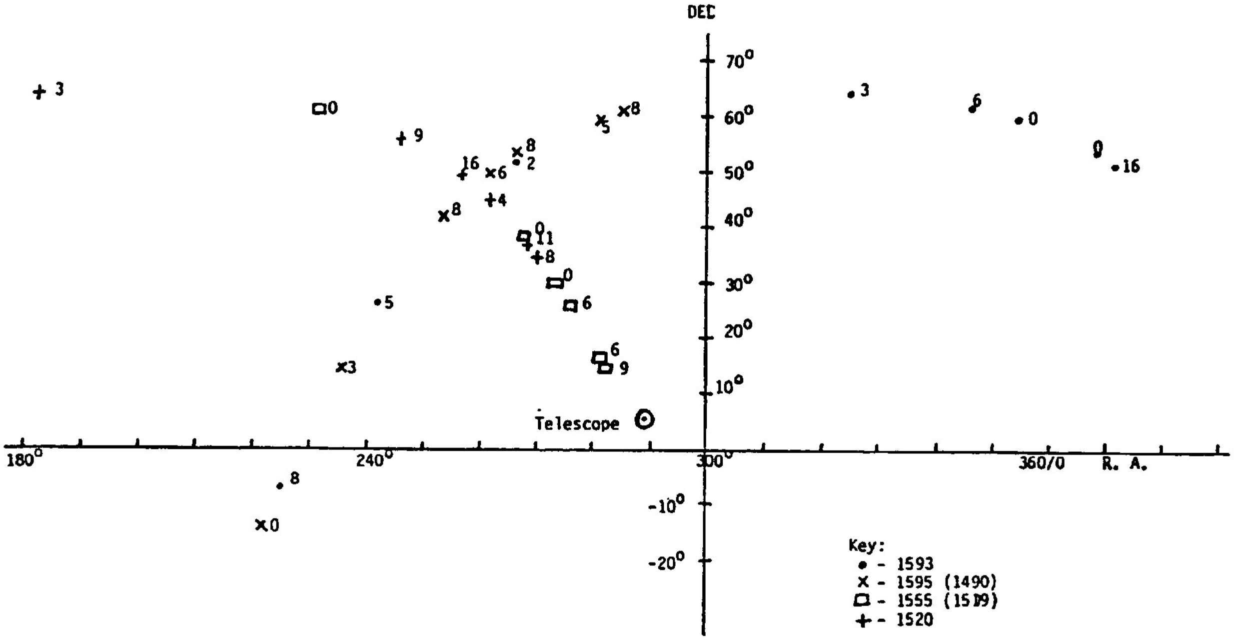


FIGURE 7: Right Ascension and Declination Positions of Satellites and Green Bank 43-m Telescope.

symbol represent the intensity of the signal from the satellite at that position, and the scale is logarithmic. It should be noted that these GLONASS satellites do not follow the same track in these coordinates from one day to the next.

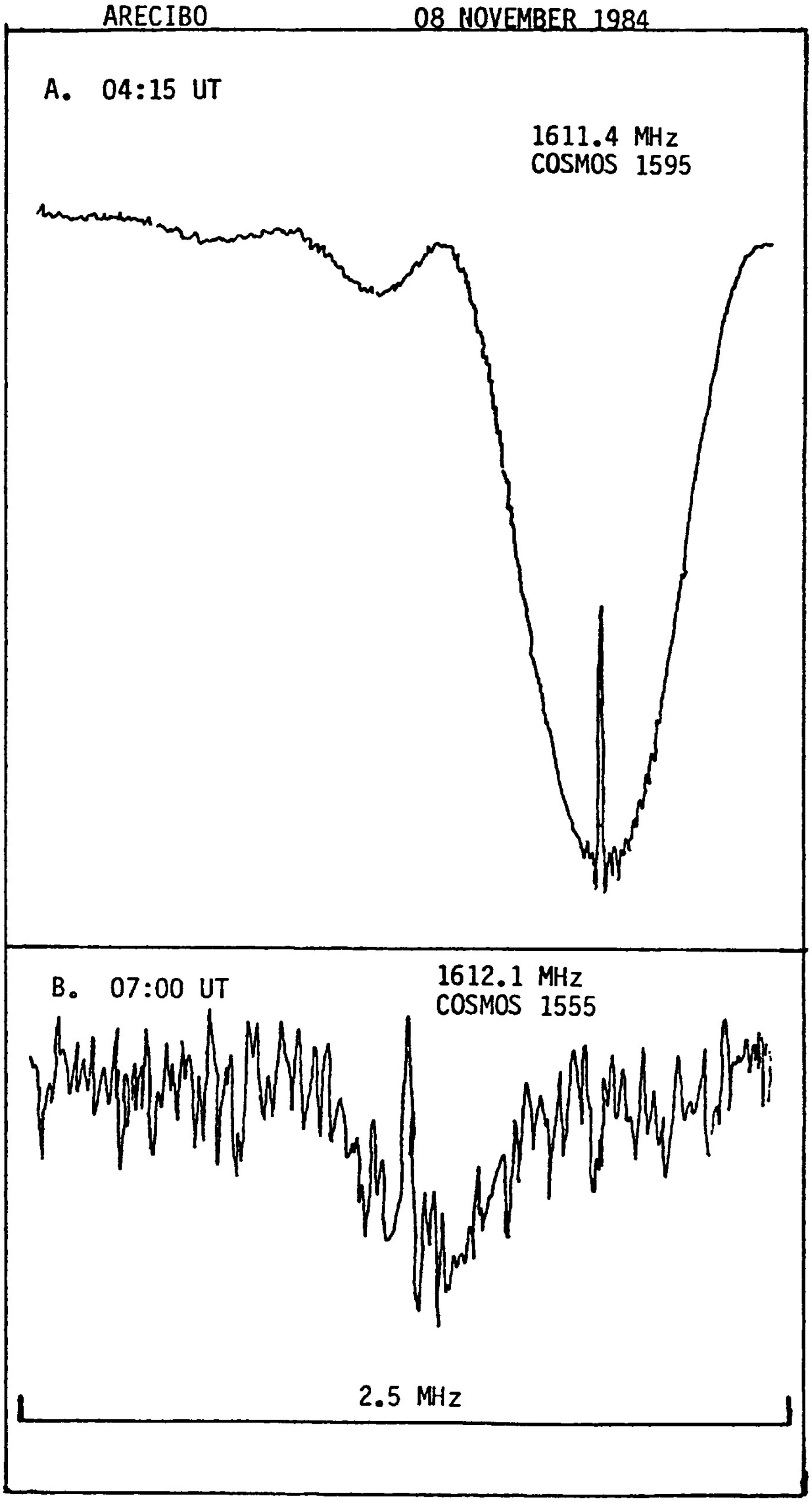
It is clear from Figure 7 that the signal strength of the interference varies significantly as the satellites pass through the sidelobe pattern of the antenna, and it may change very significantly within a minute of time. Also satellites at sky positions 60^o or more from the telescope axis may produce interference at relatively strong levels. In some cases the satellite radiation may enter the antenna feed directly (see for example the last position and strength of Cosmos 1593 in Figure 7). It is odd that Cosmos 1490 at 1603.5 MHz was not detected throughout this period since the other satellite in this pair, Cosmos 1595, was detected. The only ready explanation is that the transmitter was off on Cosmos 1490.

Only the narrow (1 MHz) signal set of GLONASS is seen in these spectrograms. The broad-band (10 MHz) signal levels are probably below the noise threshold of the spectrum analyzer spectrograms and are masked by the strong narrow signal set in the 2.5 MHz band which was analyzed by the digital autocorrelation spectrometer.

NAIC -- Arecibo

On 08 November 1984 scientists observing astronomical sources for the 1612 MHz OH line at the Arecibo Observatory suddenly experienced interference which completely obscured the astronomical data. The circumstances were very similar to those experienced at NRAO - Green Bank in October.

The spectrometer, an autocorrelator, covered a 2.5 MHz frequency band with 252 frequency channels centered at about 1612 MHz. Figure 8 shows two spectrograms taken approximately three hours apart on 08 November 1984. These spectra were obtained using the difference technique described earlier.



← FREQUENCY

FIGURE 8: Arecibo Difference Spectra
(5 min. on source and 5 min. reference)

The noise levels in both parts of the Figure are identical. The scale is suppressed in Part A because the interference is so much stronger in that spectrogram.

The interference signal is shifted in frequency between Part A and B of the Figure. Correlation of these data with the GLONASS satellite ephemerides shows that Cosmos 1595, transmitting at 1611.4 MHz, was above the Arecibo horizon at the time spectrogram A was taken. Cosmos 1555, transmitting at 1612.1 MHz, was above the horizon at the time of spectrogram B, and Cosmos 1595 had set. Presumably a spectrogram taken while both were up would show signals from both satellites.

Only the narrower 1 MHz signal set is seen in these spectrograms. The narrow signal set is too strong in the bandpass of 2.5 MHz to see indications of the broader component. The smaller lobes to the side of the strongest signal in Part A are probably sideband emission in the $(\sin x/x)^2$ satellite signal power spectrum.

Satellite ephemerides were obtained for the period of observation at Arecibo, and an analysis was made showing the locations of the satellites relative to the Arecibo Observatory at the time of the interference. The results are presented in two Figures. Figure 9 shows the times the eight active GLONASS satellites were above the horizon (0^o elevation) of the Arecibo Observatory between 3:00 and 8:00 UT 08 November 1984. The two vertical lines are the times at which the spectra in Figure 8 were obtained. Only Cosmos 1595 and Cosmos 1555 are relevant to this discussion because the receiver equipment was set to monitor only the frequency range 1611-1613.5 MHz.

Complete satellite tracks were not obtained, but representative satellite positions, in azimuth and elevation, are indicated in Figure 10. Cosmos 1490 and Cosmos 1595 are paired, as are Cosmos 1519 and Cosmos 1555. Therefore, Cosmos 1490 and 1519 were not plotted separately. Otherwise, each satellite is represented on the Figure by a different symbol. The arrows on each symbol indicate the direction of motion of the satellite. Again only Cosmos 1595 and Cosmos 1555 are of relevance to the interference data from

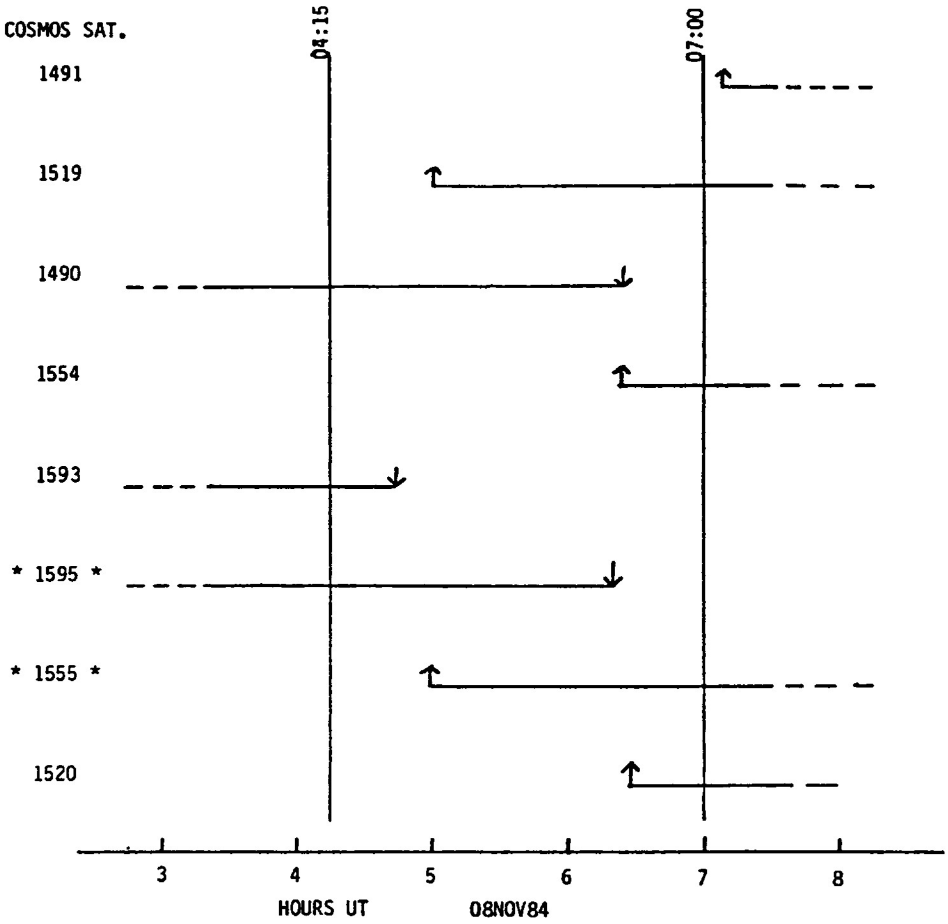


FIGURE 9: GLONASS Satellites Above Arecibo Horizon

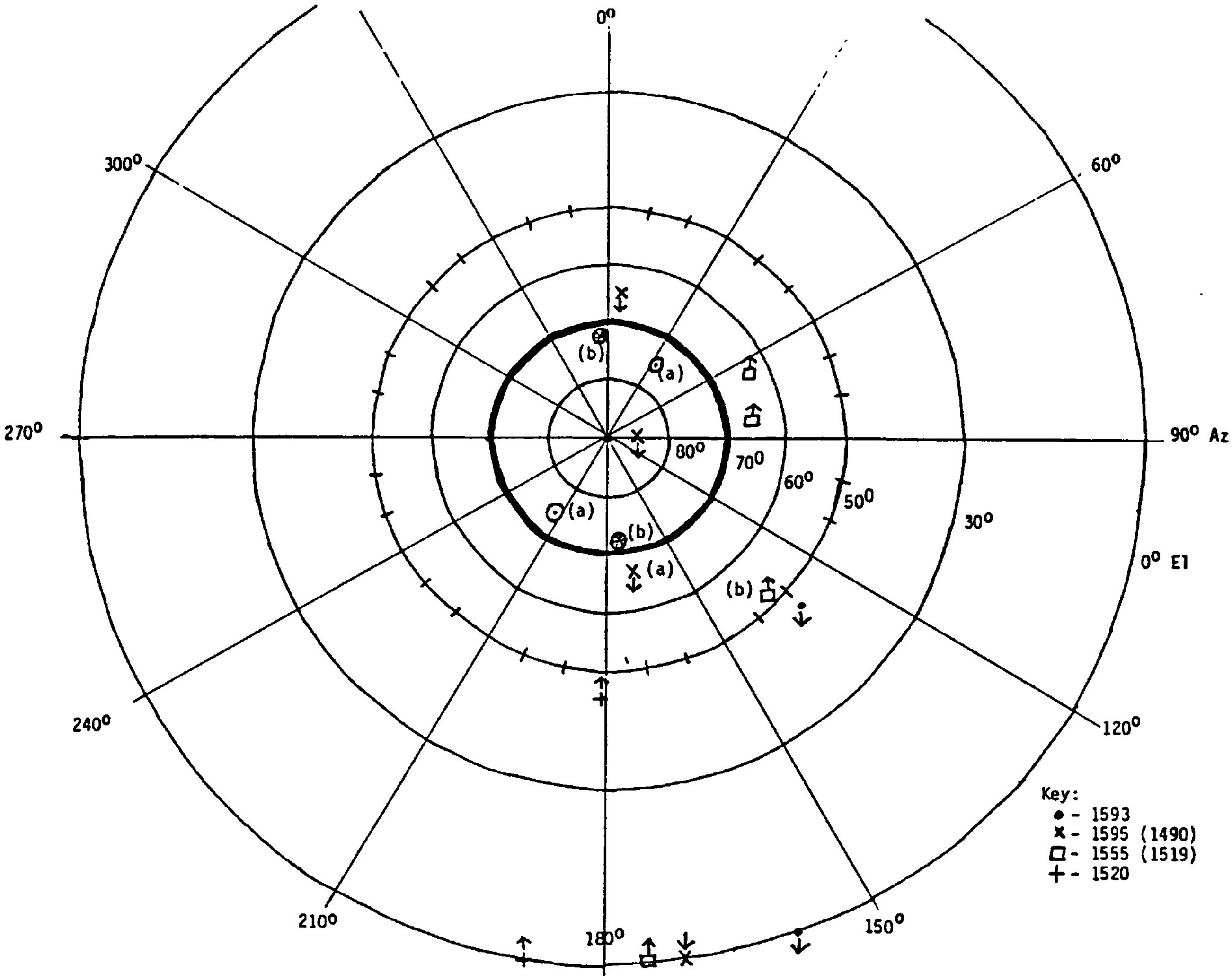


FIGURE 10: Azimuth and Elevation Positions of Satellites and Arecibo Telescope.

Arecibo. The telescope was pointed at two positions during this time period which are shown by ⊙ and ⊗ . There is an ambiguity of 180^{0} in the azimuth coordinate of the telescope at each position, since the feed moves and the reflecting surface is stationary. It is not necessary to resolve the ambiguity because satellite signals entering the feed directly may be just as much a problem than if they are first reflected off the higher gain surface and focussed into the feed. The letters beside the telescope and satellite symbols indicate the match up for telescope and satellite positions at a - 04:15 UT and b - 07:00 UT respectively. The Arecibo telescope is confined to pointing only in the area between elevation angles of 70^{0} to 90^{0}. Interference can be received from sources outside of this range through sidelobes of the antenna pattern or directly into the feed.

There are unexplained factors in these data:

1. The interference was first noted at 04:13 UT on 08 November 1984 in the midst of an observing program, and the interference seemed to appear very suddenly. Examination of the relevant satellite track shows that it was well above the Arecibo horizon before this time, although it did probably pass almost directly overhead at about this time.

2. All of the Arecibo spectra which show the interference with a width of about 1 MHz (first nulls) also have a very narrow spike in approximately, but not exactly, the middle of the interfering signal. This narrower spike was not present in the spectra which were obtained at Green Bank on a different day but from the same satellite and using approximately the same frequency resolution. Otherwise the Green Bank and Arecibo spectra look very similar.

EFFECTS OF BROAD-BAND SIGNALS

While the Haystack test measurements clearly showed the presence of a broad-band signal set with a separation between first nulls of about 10 MHz, these signals were not a factor in the interference data at Green Bank and Arecibo. This is because the observing programs, just by chance, were configured in a way which made them relatively insensitive to the broad-band signals. The bandpass of the autocorrelation spectrometers was only 2.5 MHz and much of that was filled by the narrow-band signals. The spectrum analyzer at Green Bank did cover a broad enough frequency range, but was not sensitive enough to detect the broad-band component, which has a maximum intensity about 10 dB lower than the maximum intensity of the narrower signal set.

In spite of the lack of direct data for the GLONASS, other evidence is available which shows the effects of a broad-band signal such as this on radio astronomy observations. Test measurements have been made of the L3 down-link carried on the U.S. Global Positioning Satellites, and a report is available - "The Effects of NDS Satellite Transmissions on Radio Astronomy Observations in the Frequency Band 1360-1440 MHz" (available from Pankonin). The L3 signal structure was $(\sin x/x)^2$ with a frequency separation between first nulls of 20.5 MHz centered at 1381 MHz. Figure 11 is a figure from that report. The spectrometer was an autocorrelator covering 30 MHz, and the spectrograms are difference spectra. The L3 transmitter was turned ON and OFF at controlled intervals. The effect of the transmitter being ON is clear in Part A of Figure 11. Part B of the Figure shows a spectrum free of any signals, except for the spike of unknown origin labeled x in both A and B. Of particular importance is the fact that the telescope was pointed at least 45° from the satellite at all times during the course of these measurements. Other measurements, also referenced in the same NDS report, indicate that these signals affect broader band radio astronomy spectroscopy using the Green Bank telescopes any time a satellite is above the horizon at that Observatory. This is because the Green Bank telescopes have a higher sidelobe pattern than the Arecibo telescope.

From the published data, it appears that the L3 and the GLONASS have comparable signal levels. Although the GLONASS signal is about a factor of 2 narrower in frequency spread (10 MHz versus 20 MHz), each GLONASS satellite transmits at a different frequency across the range from 1602-1616 MHz. From

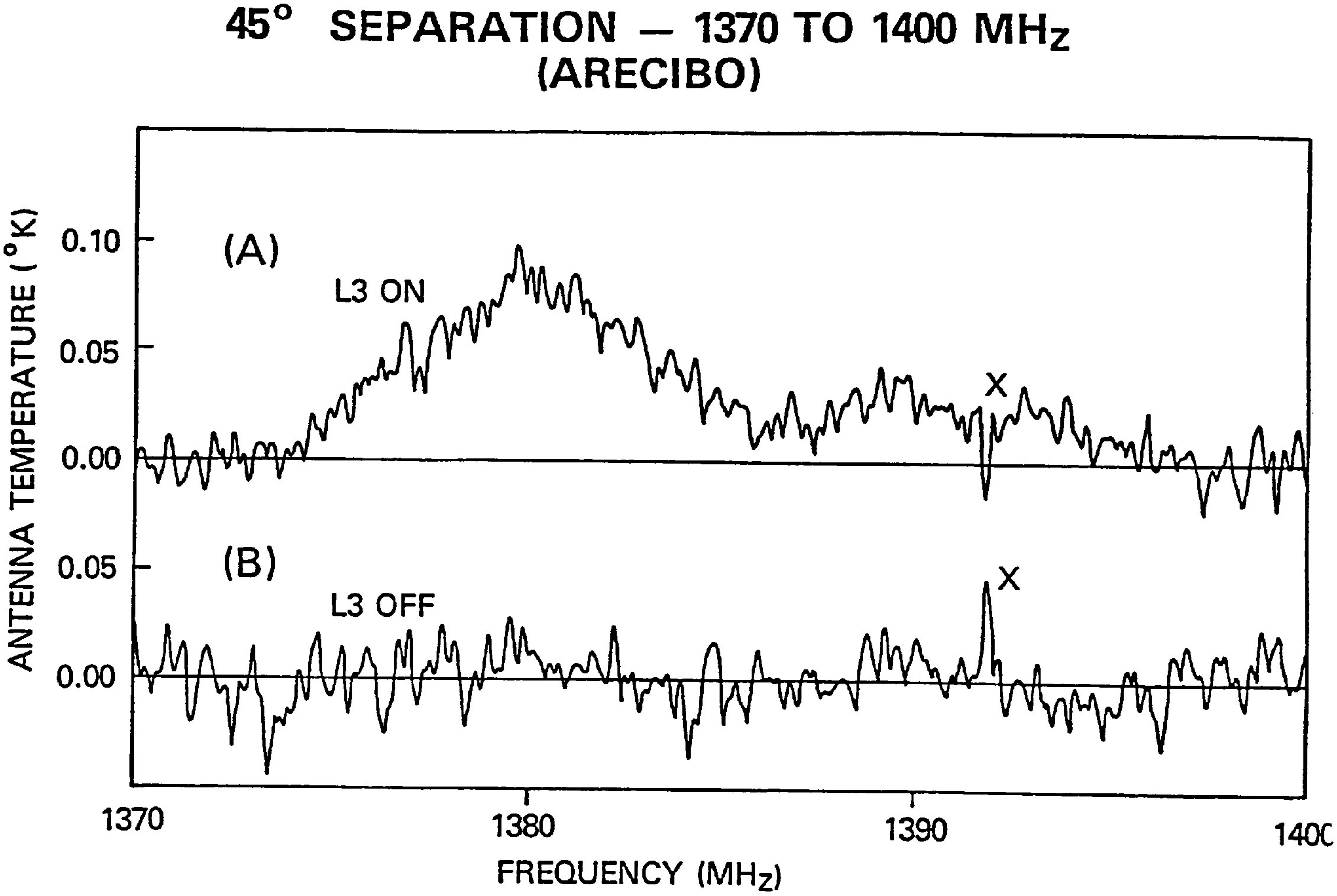


FIGURE 11: Arecibo Difference Spectra Taken With L3 Transmitter ON (A) and OFF (B).

this it is concluded that the effect of the GLONASS broad-band signal set on radio astronomy observations in the band 1600-1620 MHz will be very similar to the documented effects of L3 transmissions on radio astronomy in the band 1371-1391 MHz.

UNWANTED EMISSIONS

One consequence of the $(\sin x/x)^2$ structure of the GLONASS signals is a relatively high level of sideband emissions. For example, assume a frequency separation between first nulls of 10 MHz and no filtering or attenuation of the sidebands, then the sideband approximately 100 MHz from the carrier frequency would be 40 dB less intense than the central band maximum. Sidebands at these power levels are still strong enough to cause interference to radio astronomy observations. More specifically, the Haystack measurements indicate the sidebands from GLONASS which appear in the 1660-1670 MHz band are about 40 dB below the central broad-band maximum; 50 dB below the total emission level at the center frequency. This level is still above the guidelines for harmful interference to the radio astronomy service in this band as given in CCIR Report 224-5. To date there is no documented evidence of interference to radio astronomy from this source. However, it does remain a great concern, particularly with the fully operational GLONASS which will comprise a larger number of satellites.

CONCLUSIONS

Clearly GLONASS impacts radio astronomy operations in the frequency band 1610-1614 MHz. The interference described in this report is a regular occurrence that an observatory must deal with. The full extent of the impact depends on the type of astronomy observations and on the final configuration of the GLONASS.

The spectroscopy performed by astronomers on the 1612 MHz OH line is of two types with gradations between them. OH lines from other galaxies are observed with spectrometers covering relatively wide frequency bands, e.g.

greater than 2.5 MHz and less than 40 MHz. These observations are going to be affected by any and all of the GLONASS satellites; at least whenever any satellite is passing within 45° of the main beam of the telescope, and possibly whenever any satellite is above the observatory horizon. Furthermore, the effects on the observations will be changing continuously since the satellites are moving through the telescope antenna pattern. The signal strengths of the satellite transmissions which are received through the far sidelobes of the radio telescopes are greater than the signal strengths that are expected through the main beam from many celestial radio sources of interest. The broad-band transmissions from a fully operational GLONASS may make it impossible to do a whole class of radio astronomy research which requires broad-band spectroscopy observations.

The second type of OH line observations examines sources within our Galaxy, and the spectrometer covers a relatively narrow band, e.g. 2.5 MHz or less. These types of observations are well documented in this report. These data are primarily affected by the narrow signal set from GLONASS, and are thus impacted most severely when those satellites transmitting at center frequencies within the astronomy spectrometer bandpass are above the observatory horizon (or within 45° of the telescope main beam). The spike-like emission features which are present in the nulls between the sidebands of the broad-band signal set could also be a problem to this type of observations if the spikes happen to fall within the observed frequency band.

The effects of sideband emissions in the frequency band 1660-1670 MHz must be considered a potential problem to radio astronomy observations in that band, but the impact has not been documented.

It should be emphasized that radio astronomy programs which observe the 1612 MHz line of OH typically achieve -- indeed require -- sensitivities which far surpass the sensitivities of any of the observations presented in this report. In describing the GLONASS interference to radio astronomy, we certainly have not described situations which will only rarely occur. This satellite system, if it continues in much the same configuration as now, could have a very serious impact on this field of astrophysical research.

Radiation from the sun imposes a well-known limitation on the sensitivity of daytime radio astronomy at wavelengths of 20-25 cm. The GLONASS transmissions are approximately the same strength at the earth as solar emissions at 1600 MHz. Thus, GLONASS will be the equivalent of approximately 10 to 12 fast moving "suns" orbiting the earth day and night.

SOLUTIONS

There does not appear to be much the radio astronomers can do to avoid interference from GLONASS because the satellites are continuously transmitting in frequency bands used by the astronomers. The satellites are moving on the sky, making it impossible to predict and correct for the effects of the transmissions on radio astronomy data, and at least three satellites in the operational system will always be above the horizon of any observatory. Whenever the scientific program calls for narrow band observations, the observatory and astronomer should have access to a current set of orbital elements for the GLONASS satellites in order to schedule observations when the satellite(s) transmitting at center frequencies in the band of interest are least likely to cause interference.

There may be some indication that the current GLONASS configuration is a development phase, from the fact that some satellites are very closely spaced. If that is the case, the satellite operators may be able to make adjustments in future configurations which would be very helpful to radio astronomy. Several considerations are outlined below:

1. The ideal solution, of course, would be to move the center frequency of the transmissions down by a significant amount; 30 MHz would be best, but moving all center frequencies below 1600 MHz and filtering the sideband emission would be helpful.

2. <u>All</u> interference from the narrow-band set of transmissions would be eliminated if the entire GLONASS constellation transmitted narrow-band signals at one frequency which was centered at about 1602 MHz or below.

3. Most of the impact on narrow-band radio astronomy spectroscopy could be eliminated if there were no satellites with narrow-band signals in the frequency band 1606-1614 MHz. None transmitting in the band 1610-1613.5 MHz would be helpful.

4. If none of these adjustments are possible, then it would be very helpful if the satellites which do have narrow-band transmitters in the band 1606-1614 MHz would be closely spaced so the combination of these satellites is not above an observatory horizon an entire 24 hour day. In this case, it would be necessary for an observatory to have access to current orbital elements to schedule observations around the satellite up times.

In addition to the above considerations, the satellite operators should:

1. Incorporate filters on the transmitter to attenuate the emission levels outside the necessary bandwidth. This would avoid the potential for interference to radio astronomy observations in other bands such as 1660-1670 MHz.

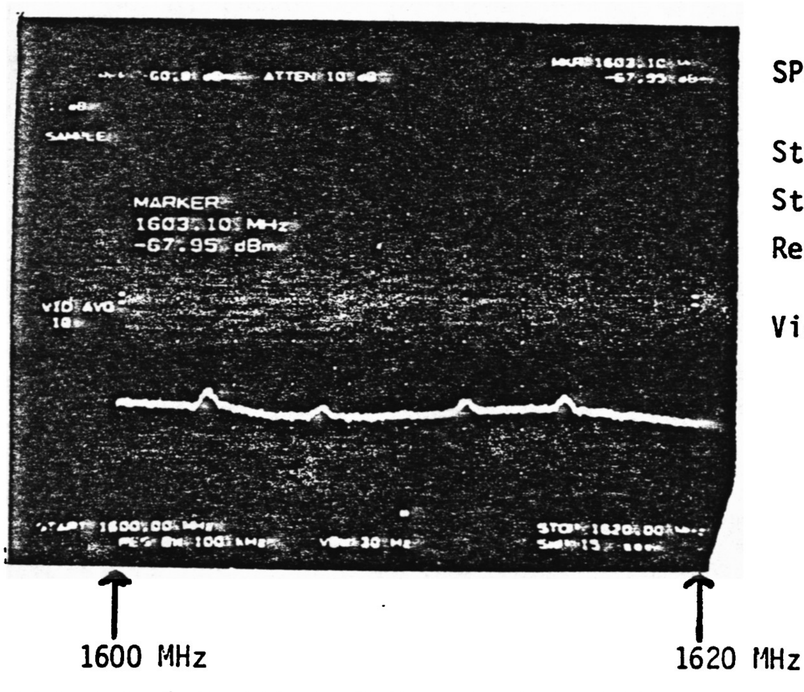
2. Eliminate or reduce the intensity of the narrow spikes in the sideband nulls. This may be most simply accomplished by the filtering suggested in 1.

3. Turn off any satellite transmitters that are not a functioning part of the navigation system, such as those on satellites no longer operational, or considered spares.

For some astrophysical problems there is no alternative to the data which are obtained through observations of the 1612 MHz OH line. Thus, access to a radio quiet band of frequencies between about 1606 and 1614 MHz is very important to astronomers. We hope that it is not too late to make adjustments in the GLONASS configuration which will allow radio astronomy continued use of this band.

ADDENDUM

The GLONASS signals are strong enough to be detected with a fairly simple and economical receiver set-up. An omnidirectional ground plane antenna was connected to a receiver which had a 200 K noise temperature. A Hewlett Packard 8566A spectrum analyzer was used to process the signals from the receiver and produce the photograph reproduced below. Seven of the GLONASS satellites were above the horizon at the time this spectrum was taken; signals from four are clearly seen. Anyone wishing to duplicate this measurement should pay close attention to the spectrum analyzer parameters given next to the spectrum.



SPECTRUM FROM GROUND PLANE ANTENNA TAKEN WHEN
COSMOS 1519, 1490, 1554, 1593, 1595, 1555, and 1520
WERE ABOVE THE HORIZON.

SPECTRUM ANALYZER
PARAMETERS

Start Freq.: 1600 MHz

Stop Freq.: 1620 MHz

Resolution Bandwidth:
100 kHz

Video Bandwidth:
30 Hz