NATIONAL RADIO ASTRONOMY OBSERVATORY
SOCORRO, NEW MEXICO
VERY LARGE ARRAY PROGRAM

VLA ELECTRONICS MEMORANDUM NO. 174

PRELIMINARY OBSERVATIONS OF THE NAVSTAR I SATELLITE

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June 1978

1.0 INTRODUCTION

The prototype satellite for the NAVSTAR Global Positioning System being developed for the Department of Defense was launched in February 1978. It transmits modulated, circularly-polarized signals at 1227·60 and 1575·42 MHz, and it is planned to deploy 24 such units during the early nineteen-eighties, to provide navigational signals at all points on the earth's surface. The satellite orbit has a period of 12 hours and a mean radius of close to 26,000 km.

The purpose of the observations described here is to measure the flux density of the satellite signals at ground level in the 1400-1427 MHz hydrogen-line band and in the vicinity of the OH lines at 1612, 1665 and 1720 MHz. The antenna used was one of those of the VLA (Very Large Array) located approximately 80 km west of Socorro, New Mexico. The standard radiometers on the antennas cover the required frequencies, but in general the array instrumentation has not been designed to facilitate the observation of fast moving satellites. The results described here are an attempt to measure the satellite radiation with the existing equipment, without development of any special hardware or software. The antennas did not track the position of the satellite continuously, and largely for this reason the results do not achieve the highest possible levels of accuracy or sensitivity.

2.0 THE OBSERVING EQUIPMENT

The antenna used in the measurements is a standard VLA antenna, which is a 25-meter-diameter reflector, shaped for high efficiency, on an altazimuth mount. The feed system is Cassegrain and the feed used for the present measurements covers a frequency range of 1350-1730 MHz and provides separate outputs for orthogonal linear polarizations. The antennas are pointed by computer control. For the present measurements the antenna did not track the satellite but was set to predicted positions a few minutes ahead of the corresponding times, so that the transit of the satellite through the beam could be observed. Predicted positions in altitude and azimuth were available at 10 minute intervals in time.[1] Operation in this mode was complicated by the fact that the control software is designed for tracking in equatorial coordinates, and for setting antennas to fixed positions it accepts altazimuth coordinates in integral numbers of degrees only. The offsets resulting from the omitted fractional parts could be allowed for in the data reduction, but it was also found that the strongest signals occurred with differences of typically half a degree between the beam and the predicted satellite position. This effect can be attributed to the pointing errors of the antennas, which are not corrected for in the non-tracking mode of operation, and to the uncertainties in the predicted satellite positions which were based on extrapolation of orbital data for periods of up to 30 days. By observing many beam transits with different offsets it was found that the strongest signal peaks tended towards a maximum value consistent with passage of the satellite close to the center of the beam. The results to be discussed are based upon these maximum values.

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[1] The positions were kindly supplied by Major C. A. Macleod, Chief Data Production Branch, North American Air Defense Command, Cheyenne Mountain Complex, Colorado 81904. The NORAD Space Defense Center number for the satellite is 10684.

A block diagram showing the relevant parts of the electronic receiving system is given in Figure 1. Separate receiving channels are used for the two planes of polarization, and these are designated channels A and C. The incoming signals are upconverted using a pump frequency of 3·2 GHz and are then amplified by a two-stage parametric amplifier with a passband of 4·5-5·0 GHz. With proper adjustment the system noise temperature is approximately 50 K. The 4·5-5·0 GHz signals are converted down to IF bands with center frequencies of 1325 and 1575 MHz for channels A and C respectively, and bandwidths of 50 MHz. The local oscillator signals for these frequency conversions are generated by units referred to as L6 modules. These are discretely tunable in alternate steps of 20 MHz and 30 MHz, so that the IF bands can be positioned to encompass any frequency in the 1350-1730 MHz input range. A calibration signal of approximately 1·8 K is provided at the input by a noise source which is switched on and off by a squarewave of frequency 9·6 Hz. A switched ALC system applied to the IF amplifiers holds the signal level constant when the noise source is off, and then maintains the same gain during each following half cycle when the noise source is on. A synchronously-switched power-law detector provides measures of both the total power level when the noise source is off, and the increase in power when it is on. These data are monitored and recorded by the control computer, and from them the system noise temperature can be obtained. The IF signals at 1325 and 1575 MHz are transmitted from the antenna to a central electronics complex by a buried TE_{01}-mode waveguide system. At the central location the signals are converted to a 0-50 MHz baseband. In the present measurements the signals were detected by monitoring the synchronous detector and ALC voltages and by displaying the 0-50 MHz signal band on a spectrum analyzer. Some further equipmental details are given in Appendix I.

3.0 OBSERVATIONS OF THE SATELLITE

Observations were made on three different days, all between the hours of 06^h and 09^h U.T. (00^h and 03^h MDT). The first observations were on June 7, 1978. Only channel C was used, and the L6 oscillator was set to 3190 MHz with which the input signal band is 1540-1590 MHz and thus includes the 1575 MHz satellite signal. The 0-50 MHz signal band was displayed on a spectrum analyzer and recorded photographically for about 10 transits of the antenna beam. After some experience with the pointing it was concluded that for the strongest observed signals the satellite was certainly within the -3 dB beam contour. Figure 2 shows a spectrum in which the signal level is about the highest observed. The following formula was used to determine the flux density from the observed signal-to-noise ratio at any frequency:

$$F = 2{\cdot}8(\alpha-1)k\ T/A \qquad (1)$$

where α is the power ratio of the signal plus noise to the noise alone, k is Boltzmann's constant, T is the system noise temperature, and A is the antenna collecting area. The factor 2·8 contains a factor of two to compensate for the mismatch between the circularly polarized signal and the linearly polarized antenna, and 1·4 to allow for 1·5 dB loss due to pointing. For the June 7 observation the system noise temperature was determined to be 75 K from the synchronous detector data, and the antenna collecting area is 255 m^2. The width of the peak of the spectrum in Figure 2 appears to result from the finite width of the signal rather than the bandwidth of the spectrum analyzer, and on the assumption that this is the case it is appropriate to express the peak signal in terms of flux density. The peak is estimated to be 36 dB above the system noise level, and using equation (1) the corresponding flux density is $4{\cdot}5 \times 10^{-20} Wm^{-2}Hz^{-1}$.

The total signal power at the input to the front end can be estimated by noting that in Figure 2 the maximum signal level is spread over about 2 MHz and there is a further component 10 MHz wide at a level of 20 dB above the system noise. These figures result in a power level of $1 \cdot 2 \times 10^{-11}$ W. The -1 dB compression point for the parametric amplifiers is 5×10^{-8} W at the input, so there is no danger of overloading the front end with the satellite signal. It can therefore be concluded that it is safe to tune the 50 MHz-wide IF band away from the satellite frequency and look for low level signals, even though the main signal remains within passband of the parametric amplifiers.

A second set of observations was made on June 10. The C channel was again tuned to cover 1575 MHz and the output displayed on a spectrum analyzer to indicate the presence of the satellite in the antenna beam. The A channel was tuned to cover the hydrogen and OH line bands using L6 frequencies given in Appendix I. The signal in the A channel was recorded on a second spectrum analyzer, and also by monitoring on a chart recorder the response to the switched noise source indicated by the synchronous detector. This voltage is proportional to the gain of the system up to the detector, and because of the action of the ALC it is inversely proportional to the total input signal, including the system noise. An increasing signal at the antenna thus causes a drop in the synchronous detector voltage.

As in the previous observations, beam transits of the satellite were observed for about three hours. No signal was detected in the A channel when it was tuned to 1390-1440 MHz or 1660-1710 MHz. When it was tuned to 1590-1640 MHz a signal was detected, and Figure 3 shows photographs of the spectrum both on and off the satellite. The strength of the satellite signal varies with a period of about 10 MHz in frequency, and near 1590 MHz it enhances the system noise level by approximately 2 dB. The synchronous detector output indicated a mean signal level over the 50 MHz bandwidth of 20% of the system noise. A measurement of the system noise temperature gave a value of 360 K for the L6 frequency used, and the mean signal strength over the 1590-1640 MHz band was found from equation (1) to be $1 \cdot 1 \times 10^{-23} \mathrm{Wm}^{-2}\mathrm{Hz}^{-1}$.

The high system noise temperature was attributed to a misadjustment made during work on the antenna electronics on the previous day and it was corrected before the next observations were made.

With the benefit of experience from the first two observing nights a final and more accurate set of observations was made on June 13. The instrumental setup was the same as used on June 10 except that the synchronous detector and the ALC voltages for channel C were also monitored on the chart recorder. These two voltages were found to give a better indication of when the satellite was in the beam then could be obtained from the spectrum analyzer display. Also during these observations it was found possible to get a better estimate of the pointing errors by observing the satellite when it was near maximum elevation and moving almost entirely in azimuth, so that it was necessary to search in elevation only.

Observations were made with the A channel tuned to 1390-1440 MHz, 1610-1660 MHz and 1690-1740 MHz. The last band was used instead of 1660-1690 MHz because of the presence of an interfering signal near 1670 MHz which was not associated with the satellite. The results are summarized in Table 1. The uncertainties in the antenna pointing, the calibration of system noise temperature, and the antenna collecting area are each estimated to be between ±1 dB and ±2 dB. The combined uncertainty resulting from these effects is ±4 dB. For the 1575 MHz and 1690-1740 MHz observations in Table 1 the uncertainty is increased to ±6 dB because in the first case only an approximate estimate of the signal level was made from the spectrum analyzer photograph, and in the second case the signal was comparable to the noise level on the chart recorder. The signal in the 1690-1740 MHz band was near the limit of detectability, but was definitely visible on two good transits of the beam.[2] No evidence of any signal was obtained in

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[2] The failure to detect a signal in the 1660-1710 MHz band on June 10 is not inconsistent with this result because of the higher system temperature on that occasion.

the 1390-1440 MHz band and the limit given is set by the noise on the chart recorder. In the final columns of Table 1 the signal levels are reduced to a range of 20,100 km which is approximately the closest approach of the satellite to the earth's surface. No correction has been made for the effect of the beam of the satellite's transmitting antenna which is presumably pointed at the center of the earth. During the measurements described the receiving location would then be 6°-11° from the center of the satellite's beam.

4.0 CONCLUSIONS

The results obtained are plotted in Figure 4 to give an indication of the overall spectrum of the radiation from the satellite. The curve for the spectrum close to the carrier frequency is taken from Figure 2. Table 2 gives the flux density levels for harmful interference to radio astronomy observations at 1420 and 1665 MHz taken from CCIR Report 224-3.[3] At 1420 MHz the measured upper limit is below the level for line radiation, but the sensitivity was not high enough to check whether the radiation is below the continuum limit. It should be very easy to obtain greater sensitivity in future measurements if the satellite is tracked continuously. At 1665 MHz the flux level determined by interpolation from the results for the 1610-1660 MHz and 1690-1740 MHz bands is -237 ± 4 $\mathrm{dBWm^{-2}Hz^{-1}}$ which is just at the level for line observations in Table 2. With the full Global Positioning System there will be four or more satellites above the horizon at all times and for isotropic reception the signal levels will be proportionately greater.

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[3] CCIR 13th Plenory Assembly, Volume 2, Space Research and Radio Astronomy, Geneva 1974.

APPENDIX I

SOME FURTHER EQUIPMENTAL DETAILS

Antenna Used: Serial No. 3

Antenna Location: DE1

F4 Modules: Model B with modified ALC circuitry.

L6 Frequencies Used

Channel A

Signal band 1390-1440 MHz : L6 frequency 3290 MHz
" " 1590-1640 MHz : " " 3490 MHz
" " 1610-1660 MHz : " " 3510 MHz
" " 1660-1710 MHz : " " 3560 MHz
" " 1690-1740 MHz : " " 3590 MHz

Channel C

Signal band 1540-1590 MHz : L6 frequency 3190 MHz

Spectrum Analyzer Used

Mainframe, Tektronix 7613

Spectrum analyzer plug-in, Tektronix 7L13

Camera, Tektronix C-59

Chart Recorder Used

Hewlett Packard 7418A with Hewlet Packard 8821A amplifier

Chart Recorder Setup

		Data Tap Addresses			
	Sensitivity*	DCS	DSA	MUX	
Channel 1 (leftmost)	0·1 V per mm	14	1	000	A channel calibration signal
Channel 2	0·05 "	14	1	020	C channel calibration signal
Channel 3	0·2 "	14	1	022	C channel ALC voltage

*Calibrated using Hewlett Packard 6115A Precision Power Supply

Signal Frequency	Date of Observation	Relative Signal Level α	System Noise Temp. T	Antenna Collecting Area A	Flux Density F $Wm^{-2}Hz^{-1}$	Satellite Range	Flux Density Corrected to a Range cf 20,100 km		
							$Wm^{-2}Hz^{-1}$	$dBWm^{-2}Hz^{-1}$	Estimated Error
1390-1440 MHz	June 13	$<1{\cdot}01$	49 K	245 m^2	$<1{\cdot}94\times10^{-25}$*	$2{\cdot}14\times10^4$ km	$<2{\cdot}2\times10^{-25}$*	<-247	
1575 MHz	June 7	$4{\cdot}0\times10^3$	75 K	255 m^2	$4{\cdot}5\times10^{-20}$	$2{\cdot}07\times10^4$ km	$4{\cdot}8\times10^{-20}$	-193	±6 dB
1610-1660 MHz	June 13	$2{\cdot}60$	66 K	255 m^2	$1{\cdot}60\times10^{-23}$	$2{\cdot}21\times10^4$ km	$1{\cdot}93\times10^{-23}$	-227	±4 dB
1690-1740 MHz	June 13	$1{\cdot}01$	44 K	255 m^2	$6{\cdot}67\times10^{-26}$	$2{\cdot}06\times10^4$ km	$7{\cdot}0\times10^{-26}$	-251	±6 dB

*Contains allowance for estimated error of ±4 dB.

Table 1: Measured flux density levels for the Navstar 1 Satellite.

FREQUENCY	FLUX DENSITY	
	LINE MEASUREMENTS	CONTINUUM MEASUREMENTS
1420 MHz (Neutral Hydrogen Line)	-237 $\mathrm{dBWm^{-2}Hz^{-1}}$	-255 $\mathrm{dBWm^{-2}Hz^{-1}}$
1665 MHz (OH Lines)	-236 $\mathrm{dBWm^{-2}Hz^{-1}}$	

Table 2: Flux density levels harmful to radio astronomy observations, from CCIR Report No. 224-3.

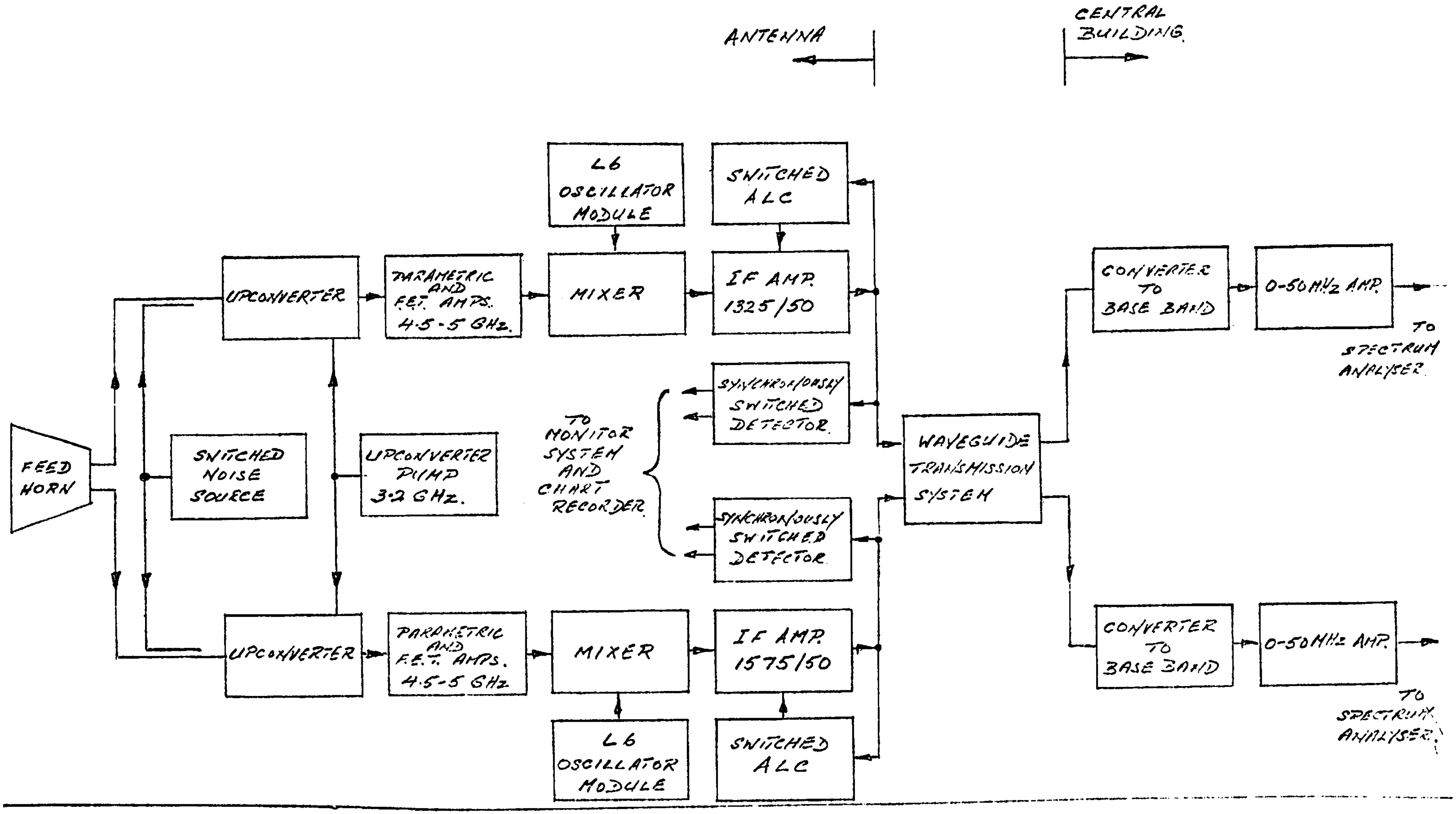

Figure 1: Simplified schematic diagram of the receiving system. The upconverters and parametric amplifiers are cryogenically cooled to 18 K to obtain a low system noise temperature.

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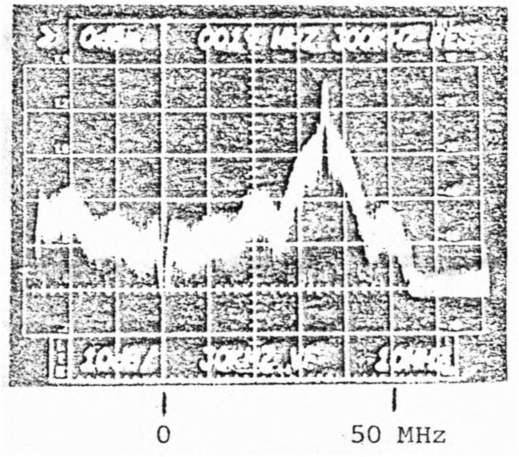
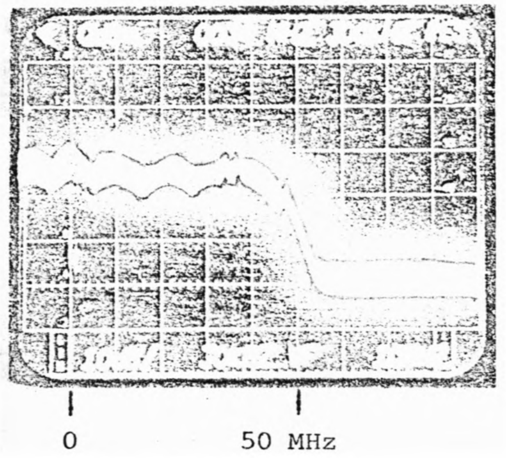
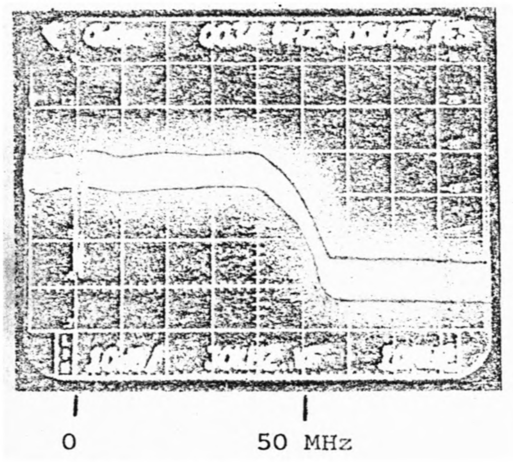


Figure 2: Spectrum of the signal from the satellite observed on June 7, 1978 at 0844 U.T. The spectrum analyzer bandwidth was 300 kHz, the sweep speed was 2 ms per division and the video filter cutoff was 30 kHz. The signal frequencies at the antenna can be obtained by adding 1540 MHz to the indicated baseband frequencies. The vertical scale is 10 dB per large division.



(a) 06·55 U.T.



(b) 07·08 U.T.

Figure 3: Spectrum analyzer records of the band 1590-1640 MHz obtained on June 10, with the satellite in the antenna beam (a), and 10° away from the beam center (b). The spectrum analyzer was used in the long persistence mode with a bandwidth of 300 kHz, a video filter cutoff of 30 kHz and a sweep speed of 50 ms per division. The signal frequencies at the antenna can be obtained by adding 1590 MHz to the indicated baseband frequencies. The vertical scale is 10 dB per large division.

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18 X 25 CM. MADE IN U.S.A.
KEUFFEL & ESSER CO.

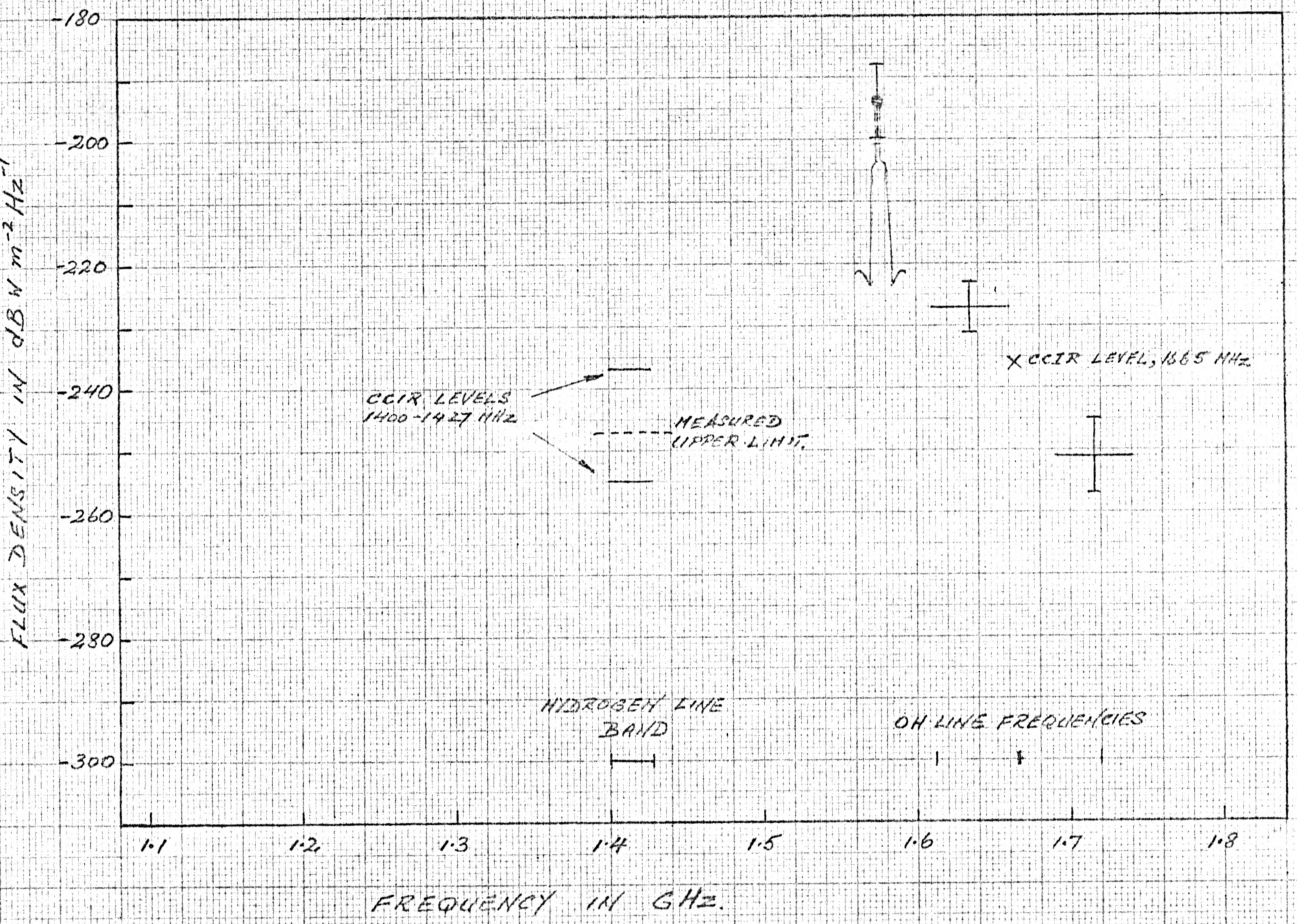

Figure 4: The observed satellite spectrum reduced to a range of 20100 km.

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