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

VLA ELECTRONICS MEMORANDUM NO. 178

FURTHER OBSERVATIONS OF THE NAVSTAR I SATELLITE

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1.0 INTRODUCTION

In VLA Electronics Memorandum No. 174, preliminary measurements of the flux density of the NAVSTAR I[1] satellite of the Global Positioning System are described. The purpose of these measurements was to determine the signal strengths in the vicinity of the 1420-1427 MHz radio astronony band and the OH lines near 1612, 1665 and 1720 MHz, for comparison with the levels harmful to radio astronomy as specified by CCIR Report No. 224-3[2]. The accuracy of the above measurements was limited mainly by the inability to track the satellite continuously, and it was observed during brief transits of the beam of a stationary antenna. Since that time a tracking program has been developed, and this memorandum describes improved measurements that have now been made, again using antennas of the VLA radio telescope.

2.0 EQUIPMENT AND PROCEDURE

The new observations were made using either two or three of the VLA antennas, and the signals were processed by the standard equipment and software used for astronomical observations. A receiving bandwidth of 12 MHz was used and the center frequency was set at five different frequencies between 1380 and 1730 MHz using the tuning capability of the 2-4 GHz Synthesizer (L6) Modules at the antennas. The beamwidth of the 25 m-diameter antennas is approximately 30 arcminutes at the frequencies concerned.

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[1]Object 10684 in the numbering system of the Norad Space Defense Center.

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

The VLA signal processing follows the usual procedures for synthesis arrays. Data from all pairs of antennas are cross correlated to determine the amplitude and phase of the output fringe pattern. These data are integrated for 10 second periods and then recorded on tape by the computer. The flux density of the satellite signals was determined by comparing the recorded amplitudes with those from standard radio sources observed immediately preceding and following the satellite observations.

To track the satellite, a feature of the on-line software was used that is intended for observations of planets and other bodies with slowly varying celestial coordinates. As input it requires the right ascension and declination of the object at a given time, and the first derivative of these coordinates with time. To follow a fast moving object like a NAVSTAR satellite the positions and rates must be updated every few minutes. A program was therefore written to obtain the required positions and rates, using the orbital elements of the satellite as input data; see Appendix I. This program runs in the off-line (DEC-10) computer and produces an output file in the card-image format required by·the on-line computer (four Modcomp units). The program is run a few hours before the observations are made, the output is transferred to the Modcomps via the fixed head disk through which the computers communicate. Further observing data for the calibration sources are added through the usual observing preparation program in the Modcomps.

Even with the above procedure, the tracking of the satellite remains the main limitation on the overall measurement accuracy. Tracking errors result from two effects. First, the planetary tracking facility of the on-line software only allows approximate tracking of a fast moving object. The coordinates of the object are interpolated from the rates every 10 seconds, and the antennas set to the corresponding positions. In the intervening times the antennas track at the sidereal rate, i.e., they follow the last celestial position to which they were set. During 10 seconds the satellite motion can result in a tracking error as large as 11 arcminutes, for which the antenna response drops by about 2 dB. An additional inconvenience is that the error flagging feature generated by the monitor system and the computer cannot be used, since the large position correction to be applied every 10 seconds causes all data to be flagged as bad. Fortunately the calculation of the fringe phases uses continuous interpolation of the coordinates.

The second limitation on tracking accuracy results from the accuracy of the orbital elements used, which depends strongly upon the age of these data. To investigate this effect four sets of elements for NAVSTAR 1 were used to predict positions on the epoch day of the latest set. Assuming that the positions obtained using the current elements were correct, ages of 5, 22 and 30 days in the elements resulted in position errors of 4 to 11, 2·5 to 10, and 18 to 28 arcminutes respectively, the errors varying over the path of the satellite across the sky. Evidently the rate at which errors increase with time depends on the particular element values, presumably because of perturbations in the orbit or varying accuracy in the element derivation. With the half-power beamwidth of 30 arcminutes, errors of several dB can be expected when the elements are more than a few days old. For the present measurements the elements were never more than four days old and were obtained through the GEODSS optical tracking facility.[3]

3.0 OBSERVATIONS AND DATA REDUCTION

Observations of the satellite were made on 1978 September 29 from 0047 to 0405 U.T. and on 1978 October 6, 2306 to October 7, 0127 U.T. On the first occasion three antennas were used; serial numbers 1, 3 and 11 at stations DW8, DE1 and DE8 respectively. Satellite coordinates and their rates of change were calculated for times at 10-minute intervals. A subsequent check showed that linear interpolation of positions over this interval resulted in errors ranging from two to seven arcminutes during the observations. Because of

[3]Operated by Lincoln Laboratories for the U.S. Air Force and located on White Sands Missile Range.

the resulting effect on the signal phases, the data were reduced by scalar averaging of the 10-second records. For the second set of observations the position data were calculated for three-minute time intervals which reduced the interpolation errors to less than one arcminute, and vector averaging of the 10-second data was used. Only two antennas, numbers 3 and 11 were available, spaced 0·45 km apart. The second set of data was judged to be considerably more reliable than the first and was used to derive the final results which are given in Table I.

To obtain an observational check on the tracking accuracy, offsets were applied to the positions calculated from the orbital elements. The satellite signal could thus be recorded with offsets of ±12 arcminutes in both right ascension and declination. The offsets were used only at 1480 and 1680 MHz where the signal was fairly strong. The results did not provide precise corrections for tracking errors because they were not always interpretable in terms of a well-defined position error, and in any case such errors would be expected to vary during the course of an observing period. However the offsets produced a drop in signal amplitude in all cases, which indicates that with no offset the satellite was generally within 2 dB of the maximum beam response.

In reducing the data the values for horizontal and vertical linear polarization were averaged. Since the satellite transmits circularly polarized radiation, and the calibration sources are randomly polarized, a linearly polarized antenna responds to half the power in either case, and the ratio of the flux densities is equal to that of the received signals. The calibration sources were recorded using the same frequencies and bandwidths as for the satellite. The sources were 3C286, 2005+403 and 2134+004, for which flux density values of 14·4, 3·23 and 4·01 Janskys[4] respectively were assumed. Correction for the small variation in flux density from 1380 to 1730 MHz was ignored. A correction was applied for an estimated 2 dB loss in signal strength resulting from

[4] 1 Jansky = -260 dB $Wm^{-2}Hz^{-1}$.

all tracking errors, and as a final step the results were reduced to a satellite range of 20,100 km, so as to be directly comparable to those reported in the earlier memorandum.

The flux density values represent mean power levels received over 12 minutes, which is the length of time for which the satellite was observed at each frequency without position offsets. The estimated errors are ±4 dB of which ±1 dB is attributable calibration uncertainties and ±3 dB to the tracking. The sensitivity limit set by instrumental noise is about -277 dB $Wm^{-2}Hz^{-1}$.

One further observation was made which was an attempt to detect the third harmonic of the satellite frequency at 4725 MHz, which falls within the tuning range of 6 cm wavelength band of the VLA. A bandwidth of 12 MHz and center frequency of 4730 MHz were used from 0040 to 0200 U.T. on October 6. No signal was detected above an equivalent flux density limit of -260 dB $Wm^{-2}Hz^{-1}$. Because the beamwidth is 8 arcminutes at this frequency tracking errors would have serious effects, and no quantitative conclusion should be drawn.

4.0 DISCUSSION

In Figure 1 the flux density values from Table I are plotted as a function of frequency, together with the earlier measurements from VLA Electronics Memorandum No. 174. The CCIR levels harmful to radio astronomy are also shown. Around 1700 MHz, where the signal was detected in both sets of measurements, the present values are 7 to 8 dB lower than would be expected from the earlier result. An examination of the data at 1680 and 1730 MHz shows a considerable fluctuation in amplitude from minute-to-minute during the 12 minutes for which the signal was recorded at each frequency. At 1680 MHz the highest signal strength was 6 dB greater than the value in Table I and persisted for about one minute. The data at 1380 to 1480 MHz do not show such variations and were recorded earlier in the observing period. Variations in signal strength could account for the apparent discrepancy between the June and October measurements, since in the earlier ones the highest observed recorded values were used, the lower ones being attributed to pointing errors. Alternatively there may have been a decrease in the transmitter power of the satellite during the time between the measurements.

Because of the above uncertainties some caution should be exercised in drawing conclusions from the measurements in Table I. It is safe to say that the measured flux density levels fall within the CCIR limits at 1400-1427 and 1665 MHz, but the margin by which they do so is not well determined.

ACKNOWLEDGEMENTS

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FREQUENCY	SATELLITE RANGE	FLUX DENSITY CORRECTED TO 20,100 km RANGE
	10^3 km	dB $Wm^{-2}Hz^{-1}$
1380 MHz	20·67	−269±4
1430 MHz	20·65	−265±4
1480 MHz	20·87	−252±4
1680 MHz	20·73	−258±4
1730 MHz	20·68	−259±4

TABLE I: RESULTS OF THE OBSERVATIONS

APPENDIX I. THE PROGRAM FOR PREDICTING SATELLITE POSITIONS

The program for predicting the satellite positions is written in Fortran and run on the DEC-10 at the VLA site by means of the SOS program editor. The file name used for it is SATPOS.FOR. The program is based in part on a program named SER developed at Haystack Observatory. The program calculates the topocentric positions of the satellite in right ascension and declination at a specified time interval, and determines the mean rates of change of position. The output consists of a series of card images in the format of the source card, planetary motion card and local oscillator card required by the on-line observing program. One each of the three card images is generated for each calculated position. The output is written on a file which can be transferred to the on-line computer, and a copy is also produced on the line printer. Inputs to the program are made through the SOS editor. The required orbital elements are:

epoch of the elements
inclination of the orbit
right ascension of the ascending node
eccentricity
argument of perigee
mean anomaly
mean motion.

In addition, the first and second derivatives of the mean motion, and a time offset if the satellite is early or late, can be inserted if known. The time for the first position calculation and the number of times the position is to be calculated must also be given. Lists of the required observing frequencies for each position, and position offsets, if required, are inserted through data statements.

The program was checked by comparing its output with that from a program used at the GEODSS tracking station. The outputs agreed within a few arcseconds.

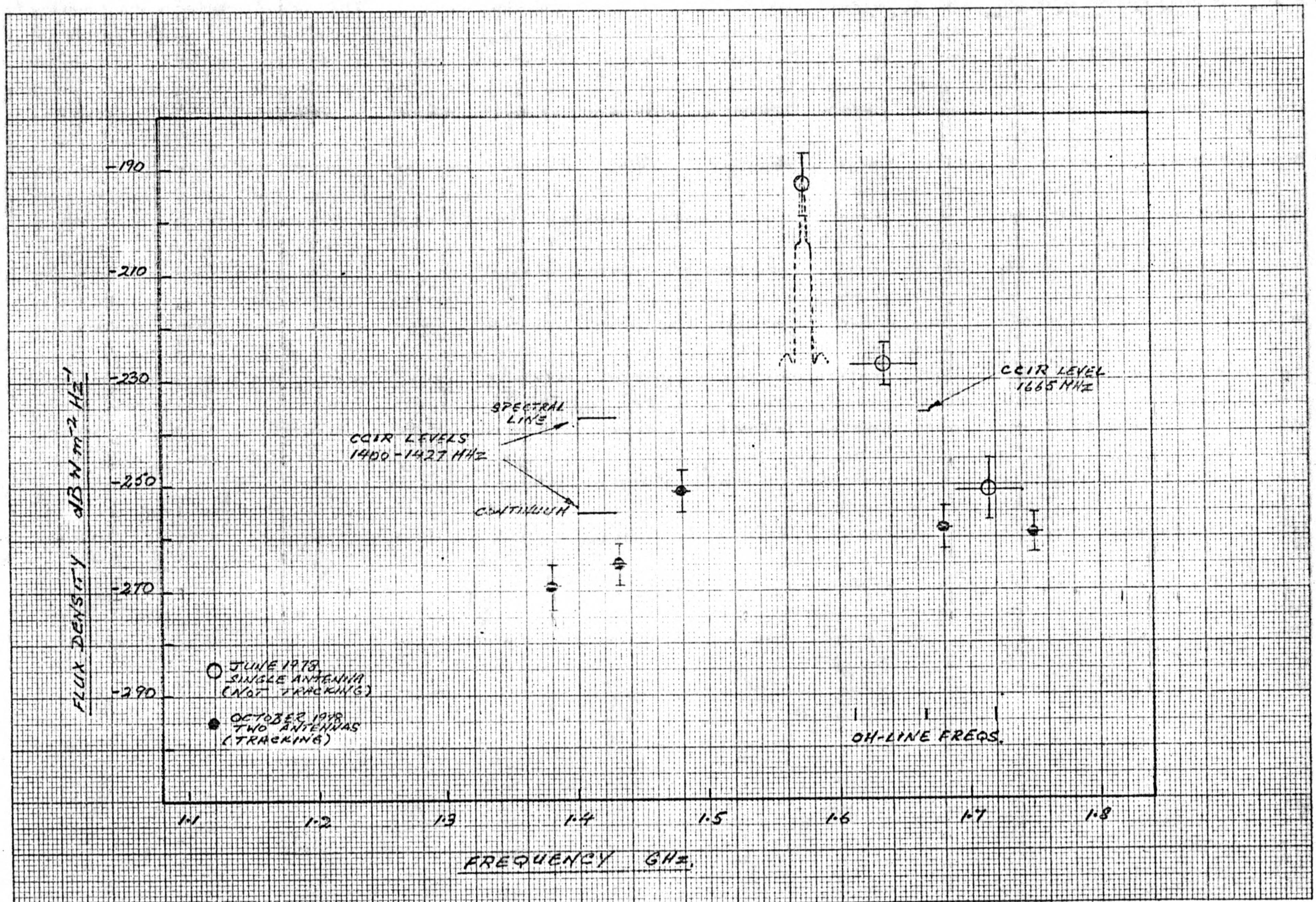

Figure 1: The observed spectrum of NAVSTAR I reduced to a range of 20,100 km. The broken curve near 1575 MHz is based on a spectrum analyzer photograph of the received signal.

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