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OBSERVATIONS OF THE SMS-1 SATELLITE WITH THE 140-FOOT TELESCOPE

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ABSTRACT

The first of a series of meteorological satellites (SMS-1), known to be a source of potentially harmful interference in the radio astronomy band 1660 to 1670 MHz, was launched by NASA in 1974 May. SMS-1 was observed with the NRAO 140-foot telescope in 1974 August, and the radiated spectrum was analyzed over the interval 1660 to 1695 MHz. Within the radio astronomy band, the interfering signals have a mean strength of -236.6 dB W/m^2Hz. This level is 12.4 dB above the level specified by the CCIR as harmful interference for continuum work. For spectral-line work, the interference prevents even crude astronomical observations within 2.5 degrees of the satellite, and may well prevent very sensitive observations anywhere on the sky.

I. INTRODUCTION

The SMS-1 satellite was launched by NASA on May 24, 1974, and parked in a geostationary orbit at latitude ∿0°, longitude ∿45° west. It is a meteorological satellite which takes raster-scan pictures of the earth in both visible and IR, taking 18^m to scan an 1800-line picture. This data is sent to Wallops Island receiving base in real time in a so-called "fast-data" mode, at a rate of 28 Mb/s which, using 4-phase PSK, modulates a fast-data carrier at 1681.6 MHz with a sin x/x envelope. This envelope spills over into the radio astronomy band at 1660-1670 MHz, and is the one we are primarily concerned with here. The satellite spin period is 600 ms, of which 30 ms is used to transmit this fast (VISSR) signal. Simultaneous with the VISSR data transmission is the telemetry, whose carrier is at 1694.0 MHz, and the DCP reports at 1694.5 MHz. The modulation envelope for these carriers is expected to be narrow, although high order (5th or 7th) intermodulation products of this carrier with other signals can produce birdies far away, possibly in the radio astronomy band. During the remaining 570 ms of each spin period, a "stretched-VISSR" signal is sent at a slower digital rate, 1.75 Mb/s, for use by smaller antennas and less sophisticated receivers. Its carrier is at 1687.1 MHz. It contains the same earth-scan information as the fast-data signal, but because of the slower rate, the associated sin x/x modulation envelope should be much narrower, and should not spill over into the radio astronomy band. Note that the VISSR and stretched-VISSR signals are not on at the same instant.

When the satellite signals are shut down, as can be effected by command from earth via a 2029 MHz signal, the SMS-1 still continues to transmit a "noise pedestal" which is 8.2 MHz wide, centered at 1687.1 MHz. It is transmitted 570 ms out of the 600 ms period, and is expected to have a spectrum characteristic of gaussian noise.

The NASA-calculated power flux density in the radio astronomy band, arising from the fast-data VISSR signal has a maximum of 236 dB W/m^2 Hz, when account is taken of an effective duty cycle of 30 ms/600 ms. It is arranged that the sin x/x envelope have a null at 1667 MHz and a maximum at 1660 MHz. This estimate does not include the possible contamination of the radio astronomy band by intermodulation products, but does include the broad sin x/x envelope arising from the 3rd order intermodulation product of the telemetry carrier. This latter tends to fill in the null at 1667 MHz. Figure 1 shows the expected spectrum as given by NASA.

After an 18^m picture is scanned and transmitted, there is a 2^m "rewind" period, followed by a 10^m picture-off period. During this picture-off period the satellite looks at dark sky above the pole of the earth, but this "null" picture is still transmitted at a 28 Mb/s rate, so that the broad sin x/x envelope still persists although the details of its spectrum differ from those of the picture-on mode.

All SMS-1 signals are transmitted by a beam whose total width is about 20° to 3 dB points, just enough to cover the earth. We found the signals to be linearly polarized with E-plane E-W. The satellite position describes a figure-8 on the sky, oriented N-S, of size 2° by 8° and period 24 hours.

II. MEASUREMENTS

On August 2, 3, 4 and 5, 1974, we made measurements of SMS-1 from ∿1400 UT to ∿2000 UT, in accordance with a NASA schedule in which a picture-on mode was started every 30^m on the hour or half-hour. (We received any deviations from this schedule, including shut-downs, either by direct telephone from NASA, or by telex at the end of the day in question.)

The 140-foot telescope, whose full beam width to 3 dB points is 18' at 18-cm wavelength, was equipped with a dual-channel parametric amplifier receiver ($T_R \approx 60K$), an autocorrelation receiver which was operated as two independent spectrometers of 192 channels each, and an HP 8552A spectrum analyzer. This analyzer has a wider bandwidth and greater dynamic range than the autocorrelator, as well as a highly variable sweep rate and high-persistence CRT which were essential for recording (via polaroid film) the spectral envelope of the fast-data sin x/x envelope.

Calibration of traces on the HP spectrum analyzer is not direct. The scale is in dB, in terms of a reference point at its input, which can be related to the power input at the antenna only if all gains and attenuations ahead of the HP are known. Since this cannot be determined very accurately, we calibrated HP traces in terms of the receiver noise, by inserting a 20 MHz filter in the (150 MHz) IF line. The receiver noise in turn was calibrated in terms of noise tubes whose sizes were 3 K and 18.5 K. The noise tubes were determined in terms of the radio source Virgo A.

Nominal positions of the satellite were provided by NASA in an ephemeris for every half-hour. Positions were in azimuth and elevation. We found a constant offset of 0.1 deg in both az and el, which did not vary over our 6^h observing period, nor from day to day. (NASA does not claim an accuracy better than this.)

From time to time we found the total output power of SMS-1 to be highly variable. On several occasions it suddenly dropped 15 dB from its nominal value, as indicated both on a strip-chart output and on the HP analyzer. All carriers and envelopes decreased by this amount. The recovery to nominal power was sudden in some instances; gradual (as long as 30^m) in others. Pointing and spectrum studies were obviously very difficult during these periods, which occurred in both picture-on and picture-off modes, or transcending both modes. NASA has no explanation for this behavior and seemed unaware of its existence. A combination of drift of the satellite relative to our beam, and of attendant change in polarization angle, could account in principle for only $\sim$1 dB over the 6^h observing period; we eliminated these effects completely by frequent pointing and peaking up in polarization angle.

The problem of saturation of our receivers by the strong SMS-1 signals was checked by noting whether the receiver noise pedestal (with 20 MHz filter) changed in amplitude on the HP analyzer when the paramps were respectively on and off. It was found that both paramps could be left on in channel A, which monitored the radio astronomy band (1660 to 1670 MHz) ($T_R \approx 60$ K), while in channel B (monitoring either the band 1670-1680 MHz or the band 1680-1690 MHz) the paramps were shut off ($T_R \approx 1550$ K). These conditions apply to the HP analyzer traces shown in the figures.

HP Analyzer Results

In order to capture the fast and slow data signals from SMS-1 in a single coherent picture, a very slow sweep rate (1 MHz/s) was utilized, which required 50 s to traverse the 50 MHz wide spectrum shown in the figures. A single sweep, requiring a 50 s time exposure was used. (If a fast sweep rate, say 10 MHz/s, is used, then the 30 ms VISSR pulses are caught at random instants during successive sweeps in a single exposure, and a picket-fence of pulses is seen, as in Figure 2. This appears to be the type of display used by Jodrell Bank. It is not very useful, because one cannot define the frequency of the 30 ms pulses.)

In the following pairs of figures, (a) is with a 20-MHz filter in the IF, to define the receiver noise, while (b) is without the 20-MHz filter, to show the satellite signals more clearly. Band center is 1665 MHz, and scale is 5 MHz per division unless otherwise noted.

Figures 3(a) and (b) are with both paramps off ($T_R \approx 1550$ K). The satellite is in picture-off mode. Because of the large T_R the sensitivity of this display is relatively low, although it can be seen that the VISSR envelope (the series of "pips") is as much as 5 dB above the level $T_R = 1500$ K in the radio astronomy band. Note the generally ragged appearance of the VISSR envelope when the picture is off. The expected nulls and maxima do not in this case fall where predicted. The maximum of the VISSR envelope is at 1675 MHz, not at the expected 1681.6 MHz. The solid appearing line is the stretched-VISSR signal, on for 570 of the 600 ms spin period. Its maximum occurs near 1687.1 MHz, as expected, although here it appears at 1686.0 MHz; its sin x/x modulation envelope can be seen to either side (solid-line maxima at 1681.5, 1683.2, and 1688.2 MHz). The spike at 1678.8 MHz is a 3rd order IM product of the telemetry carrier at 1694 MHz.

Figures 4(a) and (b) are the same as Figure 3 except that SMS-1 is now in picture-on mode. Note the stretched-VISSR and telemetry-produced IM product have not changed, but the VISSR envelope is now much smoother, has a minimum at ∿1667 MHz, and a maximum near the expected 1681.6 MHz carrier. Because of the saturated modulation on SMS-1, the carriers themselves are suppressed and only the modulation envelopes show and are flattened on top. Across the radio astronomy band the VISSR power level appears to be quite uniform, and typically 3 dB above the T_R = 1550 K level.

Figures 5(a) and (b) are centered at 1675 MHz and are both without the 20 MHz filters but on the same scale as the previous displays; (a) is with SMS-1 picture on, (b) with picture off. Note the telemetry carrier at 1695.5 (not at 1694.0 MHz as expected; we could be seeing the 400-kHz wide envelope of the DCP reports signal, expected at 1694.5 MHz and associated with the telemetry signal, but this was not established). Note also in (b) that the center of the stretched-VISSR envelope is at 1685.9 MHz (not 1687.1 MHz) and the center of the VISSR envelope is at 1680.0 MHz (not 1681.6 MHz). The pips passing through the lower portions of the stretched-VISSR envelope arise because this signal is off for 30 ms out of every 600 ms.

Figure 6, centered at 1675 MHz, shows the SMS-1 spectrum when the S-band carriers were shut down, August 4, UT 1620-1630, as occurred when NASA performed a power switch-over because of impending thunderstorm. The stretched-VISSR modulation has disappeared and is replaced with a "noise pedestal" centered at 1686 MHz and ∿ 8 MHz wide. The width is as NASA predicted. The VISSR signal is that of the usual picture-off mode and is still contaminating the radio-astronomy band.

To achieve more sensitivity for measurement of SMS-1 signals in the radio astronomy band, both paramps in channel A were turned on, and checks made to determine that there was no overloading. The following figures are all centered at 1665 MHz, and the calibrated receiver temperature off the satellite is $T_R = \sim 62$ K.

Figures 7(a) and (b) show the receiver spectral response with (a) and without (b) the 20 MHz filter. Pointing was 14.4 deg north in elevation of SMS-1, at an expected null in the telescope antenna pattern.

Figures 8(a) and (b) are for a picture-on mode. Note the increased structure now visible in the envelopes of both VISSR and stretched-VISSR signals. Note also a new phenomenon, not properly visible before. The 570 ms stretched-VISSR signal itself actually consists of two signals; one is the 1.75 Mb/s bi-phase, which is on for 480 ms and transmits the visible meteorological data. The other is 0.524 Mb/s stretched signal, on for 90 ms, which transmits the IR meteorological data. The pips lying below the solid stretched-VISSR trace are the 90 ms, 0.524 Mb/s IR signal. Since the bit rate is least for the IR signal, its sinx/x envelope should be narrowest, and therefore its envelope should lie below that of the 1.75 Mb/s signal. Note, however, that even the 0.524 Mb/s envelope lies higher, by ∿1 dB, than the baseline level defined in Figure 7. This is a real effect, not gain suppression, as is verified by noting how these levels behave as we attenuate the signal either by pointing off the satellite or by rotating the polarization. For calibration purposes, therefore, we apply the baseline level of Figure 7 to Figure 8. At 1665 MHz, where the VISSR power is typical of that across the radio astronomy band, the VISSR power is then 15.9 dB above $T_R = 62$ K, or produces an antenna temperature of 2400° K.

Figures 9(a) and (b) are the same as Figure 8 except that the SMS-1 mode is picture-off.

All of the above pictures were taken when SMS-1 exhibited its "nominal" power levels, as opposed to those periods when the level fell by as much as 15 dB. During the 4-day study, the spectra of SMS-1 never changed by any measurable amount, for a given operation mode.

Autocorrelator Results

For all autocorrelator results, checks were performed to verify that the signals arise from SMS-1 and not from overloading of any of the electronics used in the observations. In particular all autocorrelator signals are verified to shift in 1:1 correspondence with changes in L.O. setting, and to have amplitudes which decrease linearly with decreasing SMS-1 signal when the antenna is pointed off or the polarization is rotated. As a final check, all signals in the RA band were verified to be the same with the paramps in channel A on, and off, respectively. Test signals, injected by a sweep generator, indicated that spurious effects occur for signals some 20 dB above the SMS-1 signal levels, although since these test signals are monochromatic, they cannot provide an unambiguous test of saturation levels for SMS-1 signals, which are not monochromatic.

The autocorrelator was used with 10 MHz bandwidth and was arranged so that channel A was centered at 1665 MHz, the center of the radio astronomy band, while channel B was centered at 1685 MHz (and included the 1687.1 MHz stretched-VISSR signal).

The autocorrelator produces spectra for the slow stretched-VISSR that qualitatively agree well with those produced by the HP analyzer. This is not the case for the fast VISSR signals. The reason is not clear, there being no fundamental reason why 30 ms wide pulses cannot be properly time-averaged over intervals of $\gtrsim 1^m$ to reproduce accurately the spectral information. Since the VISSR is transmitted at a 28 Mb/s rate, one expects spectral features at intervals of 28 MHz from the carrier at 1681.6 MHz. These do not correspond to what is shown below, but additional spectral features may arise by beating of these features with other carriers or IM products.

In the following figures, which show autocorrelator spectra, channel A is centered at 1665 MHz and channel B at 1685 MHz. The largest signal produced in the radio astronomy band, A, is a birdie at $\sim$1664.15 MHz and a broader signal some 2 MHz lower. Both of these signals may arise from the slow stretched-VISSR or telemetry signals. The birdie appears to be a high order (7th) IM product of the 1687 and 1694 MHz carriers. (If the order is 3rd, 7th, 11th, ..., the modulation gets folded back in, resulting in a birdie-type signal, whereas this is not the case for 5th, 9th, ..., order products, for which a broad signal, such as that at $\sim$1662 MHz, could occur).

There is no definite indication whether the fast VISSR signal is seen at all by the autocorrelator, in either channel. Even if it is not, such signals would affect continuum observations directly.

Calibration of the autocorrelator signal in channel B is a problem when the telescope is pointed directly at the satellite and the polarization is aligned, because the system temperature exceeds the digitizing capability of the on-line computer program. In these cases (Figs. 13, 18, 19), a system temperature was chosen which made the stretched-VISSR intensity in channel B equal to its intensity derived from the HP analyzer traces. This gives a result consistent with that derived from observations of the same signal when the antenna is pointed away from the satellite.

When both telescope pointing and polarization are aligned with the satellite, the strength of the birdie at 1664.15 MHz is typically 550 K or 2×10^{-23} W/m^2 Hz, while the broad signal at 1662 MHz is ∿40 K or 1.5×10^{-24} W/m^2 Hz in the picture-off and rewind modes (Figs. 10 and 11) and ∿100 K or 3.6×10^{-24} W/m^2 Hz in the picture-on mode (Fig. 12). In Figures 10 to 12, the linearly polarized receiving feed is aligned with the satellite signal in channel A, and is orthogonal in channel B. Orthogonality is not sufficient to prevent a fairly strong signal in channel B (∿ 100 K or 3.6×10^{-24} W/m^2 Hz). In Figure 12 the channel A band center has been shifted 2 MHz.

Figure 13 shows spectra taken during shutdown of the SMS-1 (see above). Polarization in this case is aligned for channel B; orthogonal for channel A. This explains the weak signal in A.

Figures 14 and 15, taken with the telescope pointed 18' north of SMS-1, show the magnitude of variations that apparently can occur in SMS-1 signals. Figure 14 is during a picture-off mode; Figure 15 is a picture-on mode. However, similar changes were noted at other times and are *not* always associated with the on/off picture mode. Polarization is aligned for channel A.

Figures 16 and 17 are with the same polarization, and the telescope pointed 1° north of the satellite. The picture is off, and on, respectively.

Figures 18 to 20 have polarization aligned in channel B. Figures 18 and 19 are with telescope pointed at the satellite, picture off, and on, respectively. Figure 20 is with the telescope pointed $1\overset{\circ}{.}5$ north of the satellite, picture-on.

Area of Influence

The above scans taken with the autocorrelator involve a reference scan of 15^m integration and typical on-scan integration of 2^m. Channel A paramps are on when the telescope is pointed off the satellite; off when pointed at the satellite. Channel B paramps are off throughout. Under these conditions, in which for channel A the peak-to-peak noise is 0.25 K (0.9×10^{-26} W/m^2 Hz) for a spectral resolution of 50 kHz, we can detect the signal in channel A (the radio astronomy band) to a distance of $2\overset{\circ}{.}5$ from the satellite, in all directions. Longer integrations at larger distances were not attempted, but it may be surmised that at levels that characterize very sensitive astronomical observations (10^{-28} W/m^2 Hz or better) the SMS-1 satellite will probably cause interference over most of the sky.

III. DERIVED INTERFERENCE LEVELS IN THE RADIO ASTRONOMY BAND

A. Continuum Work

We adopt the value $T_A = 2400$ K for the 30 ms pulses, as is typical across the radio astronomy band.

--- antenna temperature 2400 K. At λ 18 cm on the 140-ft antenna, 1 K = 3.64 flux units (1 f.u. = 1×10^{-26} W/m Hz).

--- for 1 polarization mode and 2400 K:

$$2400\ \mathrm{K}\ \frac{\frac{3.64}{2} \times 10^{-26}\ \mathrm{W}}{\mathrm{m}^2\ \mathrm{Hz\ K}} \rightarrow 4.36 \times 10^{-23}\ \mathrm{W/m^2\ Hz} = -223.6\ \mathrm{dB\ W/m^2\ Hz}$$

--- 30 ms/600 ms duty cycle	-13 dB
net	-236.6 dB W/m^2 Hz

Alternatively:

--- antenna temperature 2400 K	+33.8 dB K
--- 140-ft antenna gain at λ 18 cm	-54.7 dB
gives effective isotropic antenna temperature, T_e (or 8.13×10^{-3} K)	-20.9 dB K
--- 30 ms/600 ms duty cycle	-13 dB
--- Boltzmann constant	-228.6 dB W/K Hz
--- power in 1 polarization mode = k T_e:	-262.5 dB W/Hz
--- effective area of isotropic antenna at λ 18 cm	+25.9 dB/m^2
net power	-236.6 dB W/m^2 Hz

This result is 12.4 dB above the CCIR level of -249 dB W/m^2 Hz, or a factor of 17.4.

B. Spectral-Line Work

The strongest signals actually recorded by the autocorrelator spectrometer in the radio astronomy band, when the telescope was pointed at SMS-1 and the polarization aligned, correspond to T_A = 600 K, or -242.6 dB W/m^2 Hz. This is below the CCIR limit of -236 dB W/m^2 Hz. However, it must be stressed that we do not clearly understand the autocorrelator signals in the radio astronomy band, and that it is possible that much stronger spectral features would be produced in other types of spectrometers, such as filter banks.

IV. CONCLUSIONS

In the radio astronomy band (1660-1670 MHz) the SMS-1 power levels exceed the CCIR limit by 12.4 dB for continuum work, but do not exceed the CCIR specified harmful levels for line work.

It must be pointed out that the CCIR specified harmful levels for line work do <u>not</u> adequately reflect the limits of sensitivity commonly attained today. Although the bandwidths (typically 10 kHz) are much narrower for line work than for continuum work, this difference is totally compensated by the much longer integration times attainable nowadays in line work (10^5 s as compared with 2 x 10^3 s for the CCIR specified continuum integration time). These factors make an appropriate CCIR limit for line work <u>no larger than that specified for continuum work</u>.

As an example of this point, the molecule HCOOH (formic acid) produced a 140-foot antenna temperature of only 0.04 K in the λ18-cm lines arising from Sgr B2, the strongest source, and therefore needed a sensitivity limit of 0.008 K to be reliably detected. Owing to spillover and to ground reflections of the satellite signal, it is possible that the SMS-1 interference would exceed a level of 0.008 K over the entire sky.

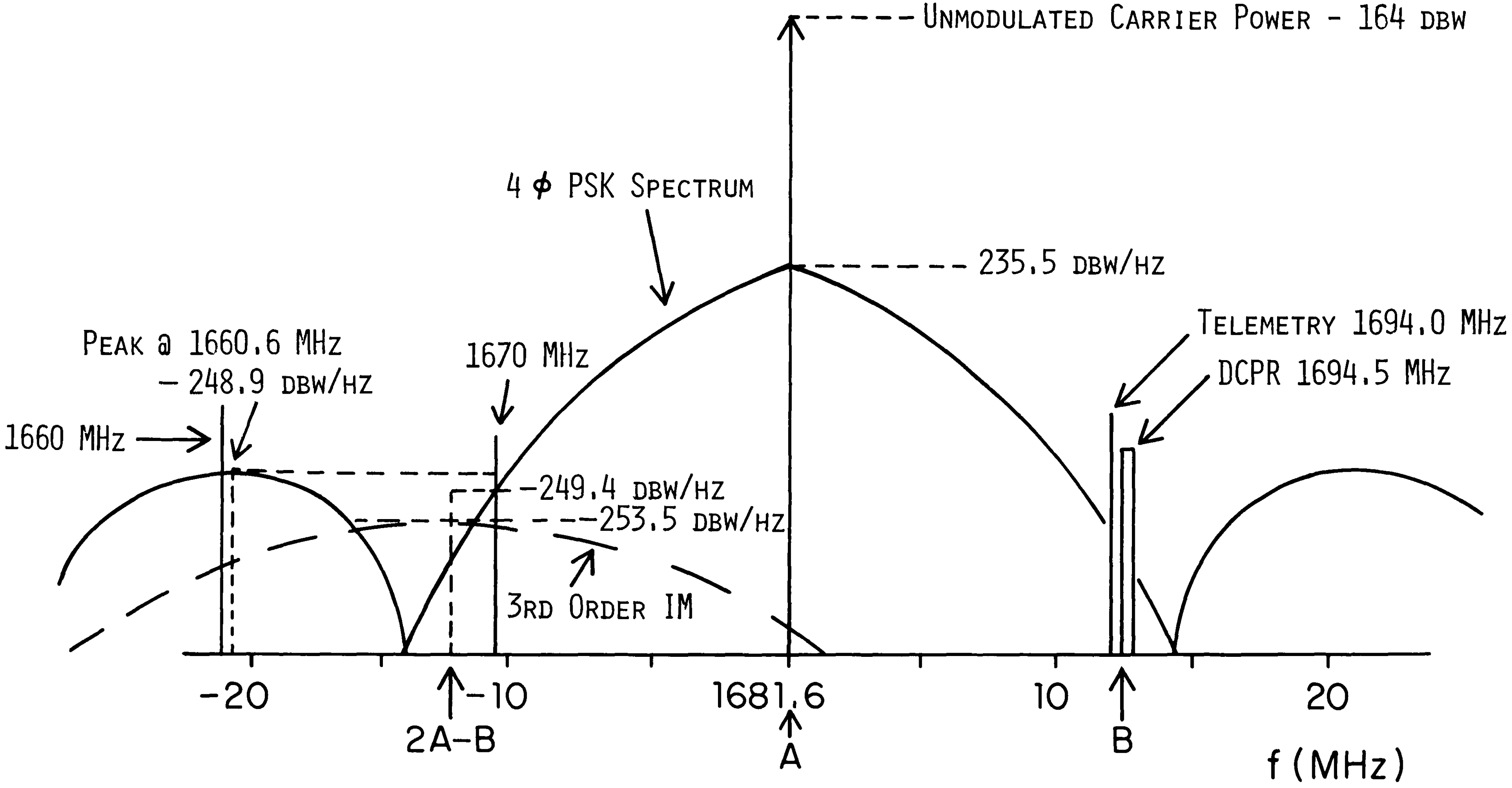


FIGURE 1 SPECTRAL DENSITY PLOT SHOWING THE ADDITIVE INTERFERENCE TERMS (TELEMETRY + DCPR) PRODUCED BY THE SATURATING AMPLIFIER.

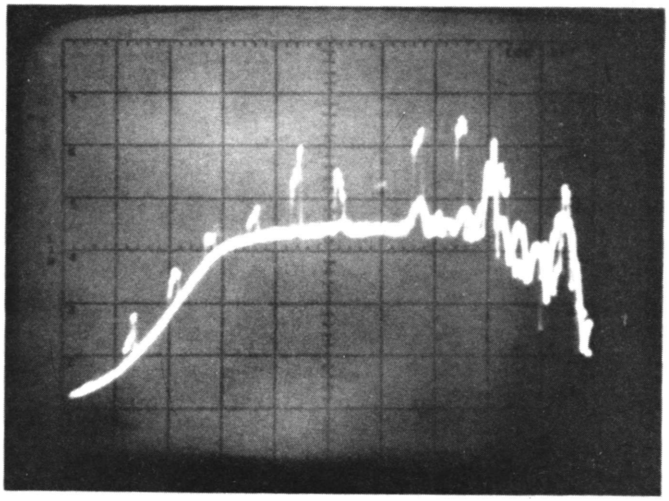


FIG. 2

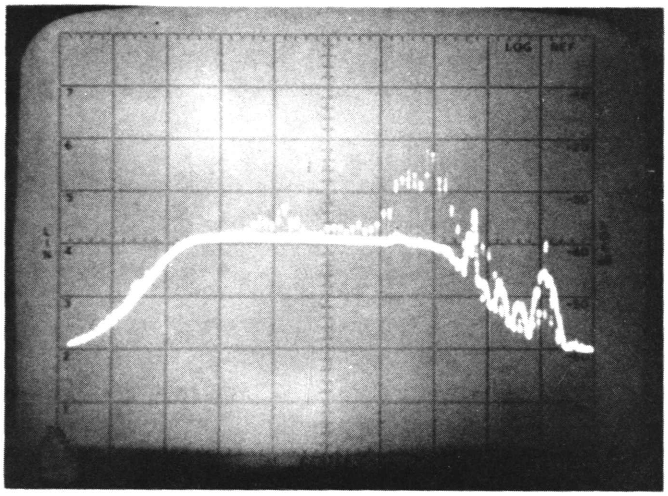


FIG. 3(A)

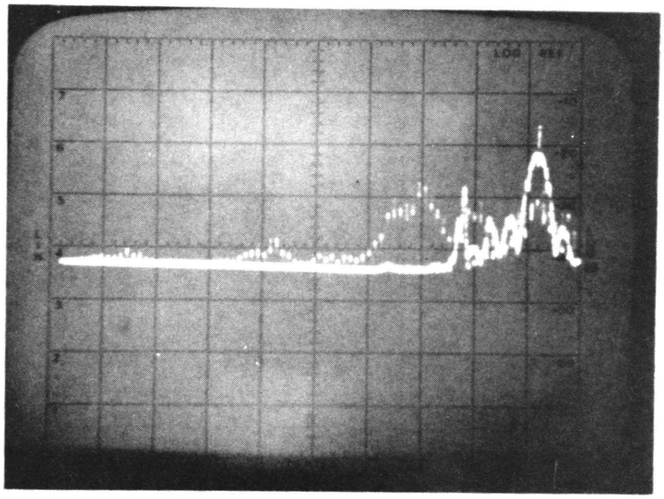


FIG. 3(B)

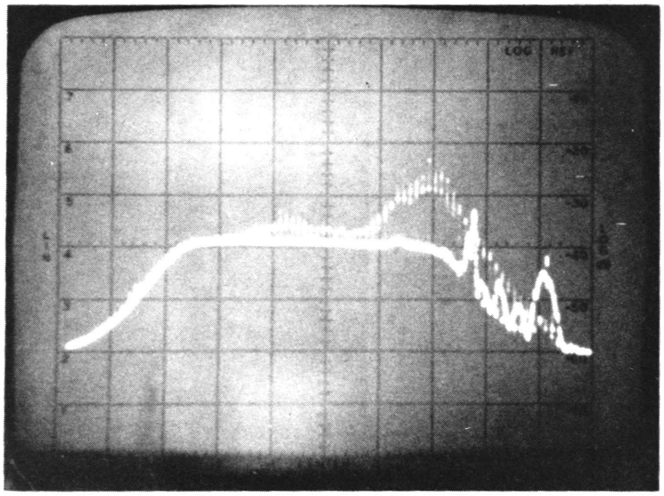


FIG. 4(A)

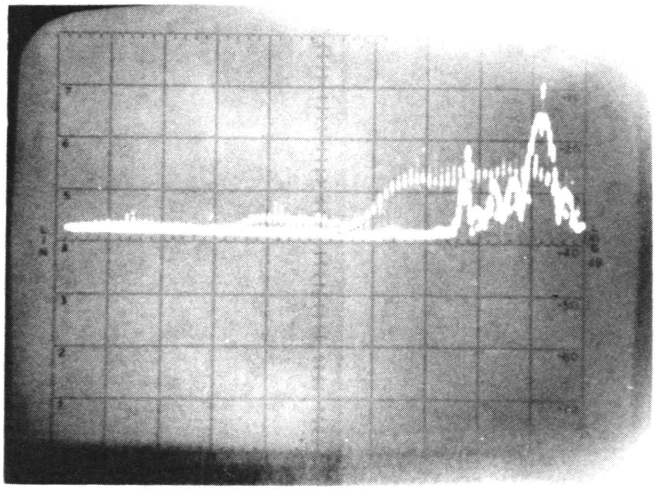


FIG. 4(B)

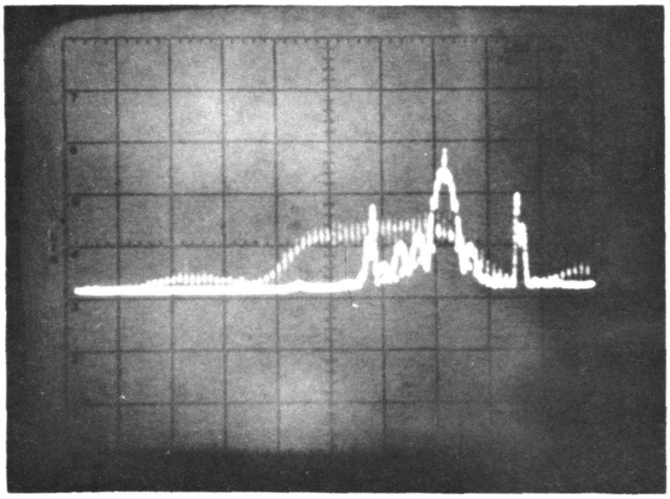


FIG. 5(A)

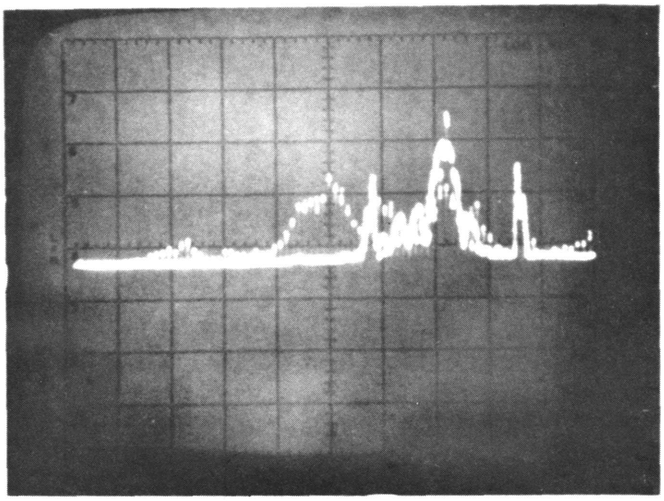


FIG. 5(B)

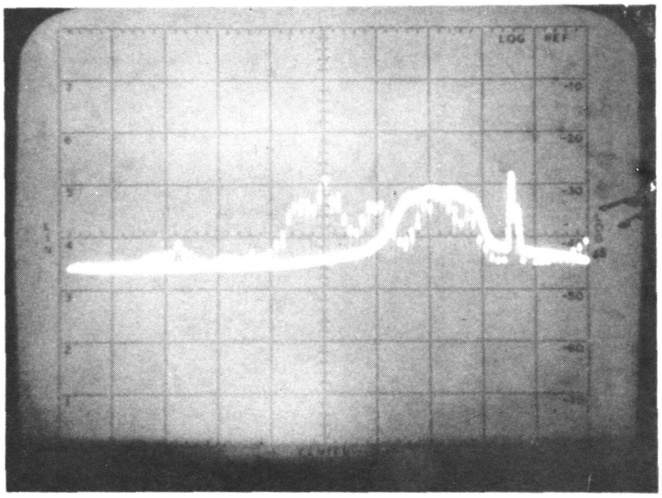


FIG. 6

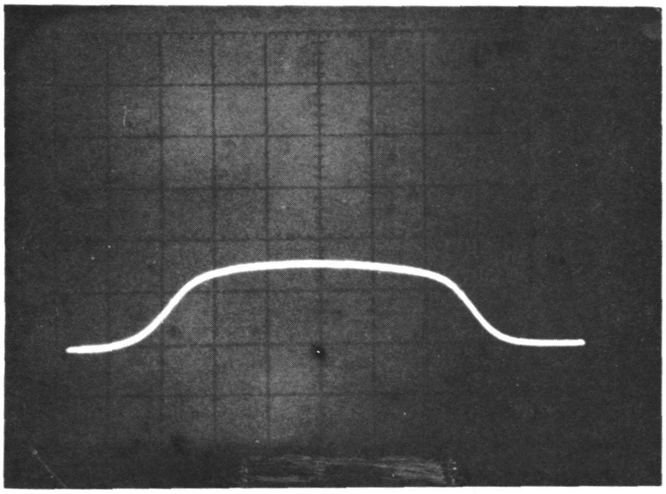


FIG. 7(A)

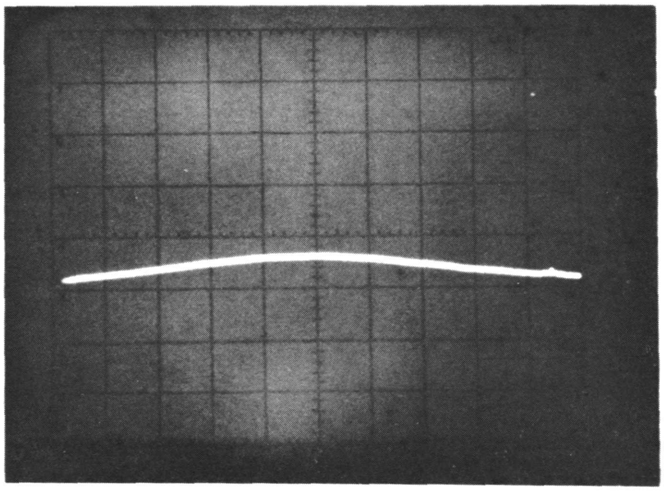


FIG. 7(B)

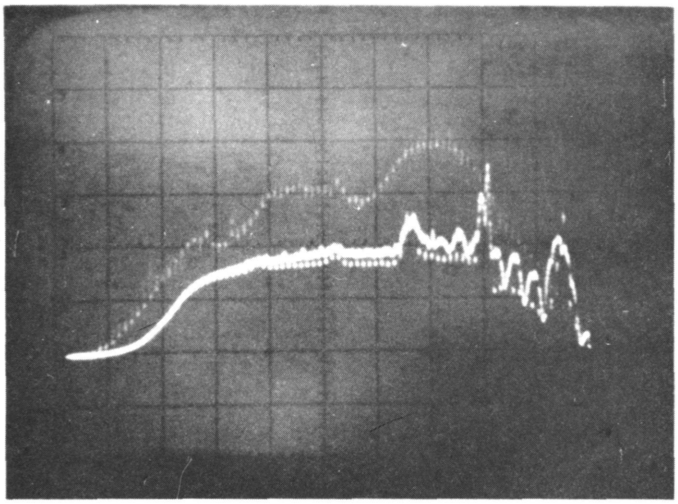


FIG. 8(A)

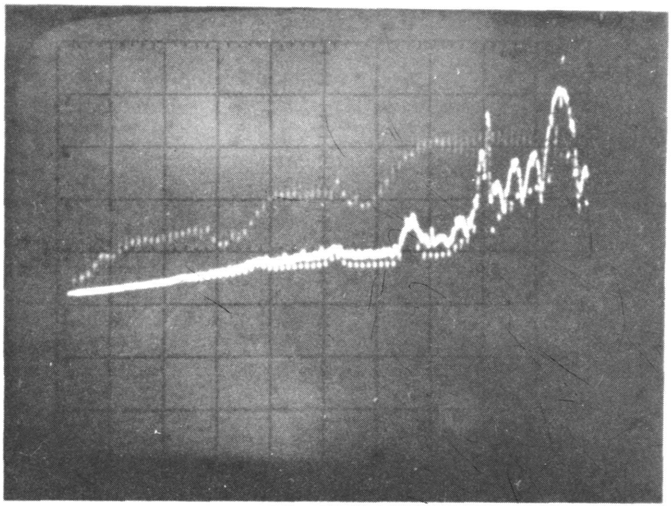


FIG. 8(B)

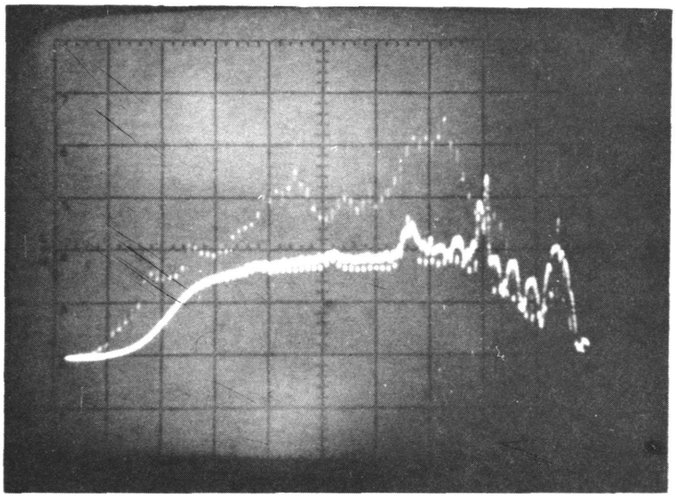


FIG. 9(A)

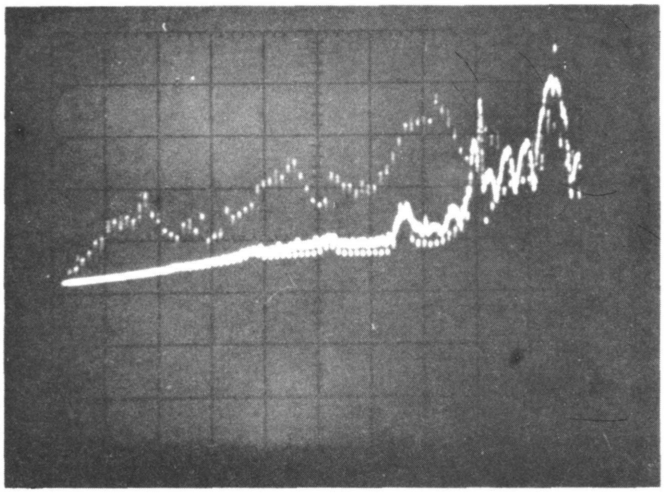


FIG. 9(B)

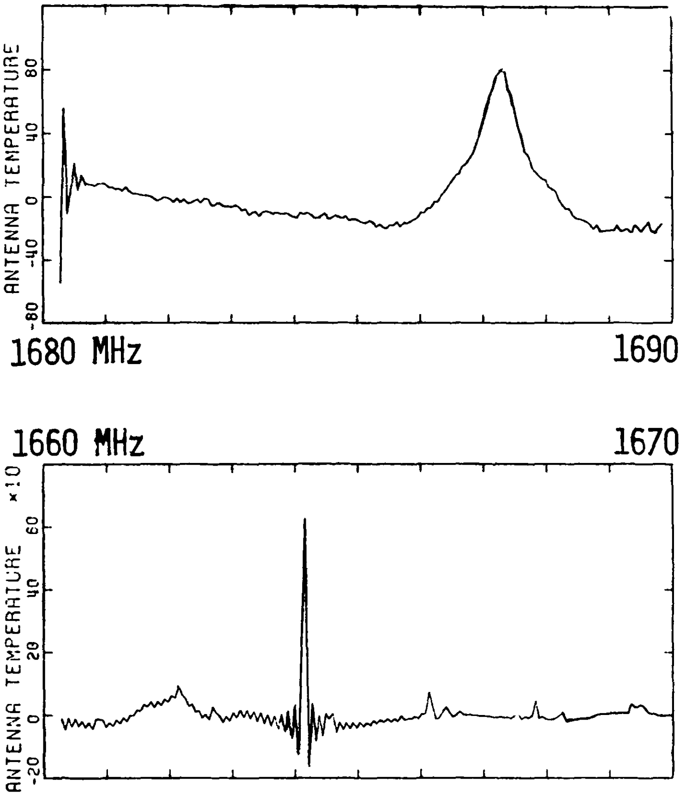


FIG 10

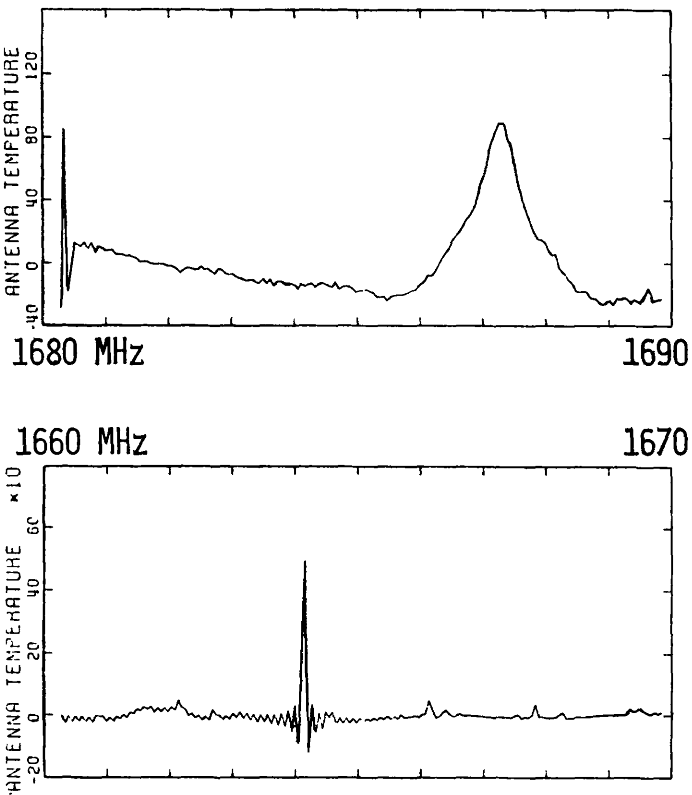


FIG 11

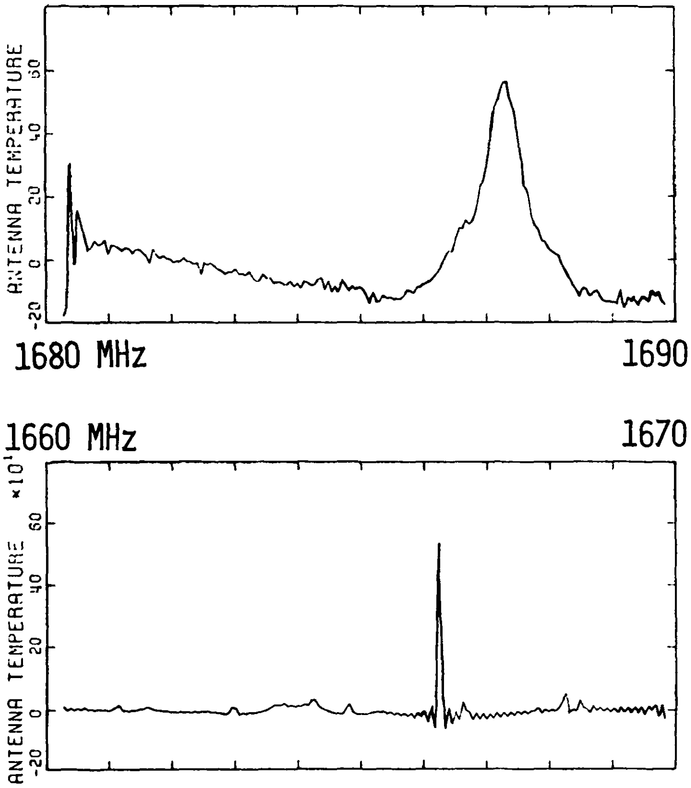


FIG 12

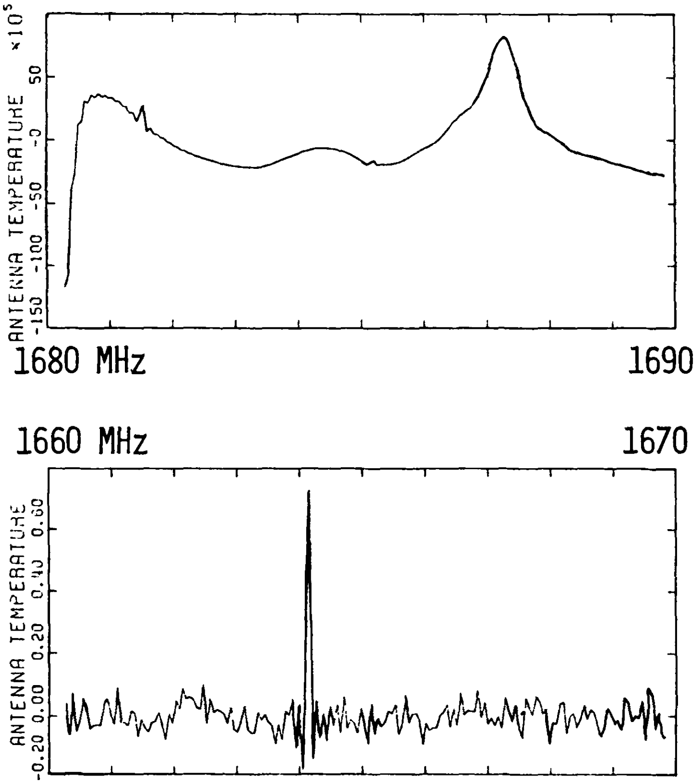
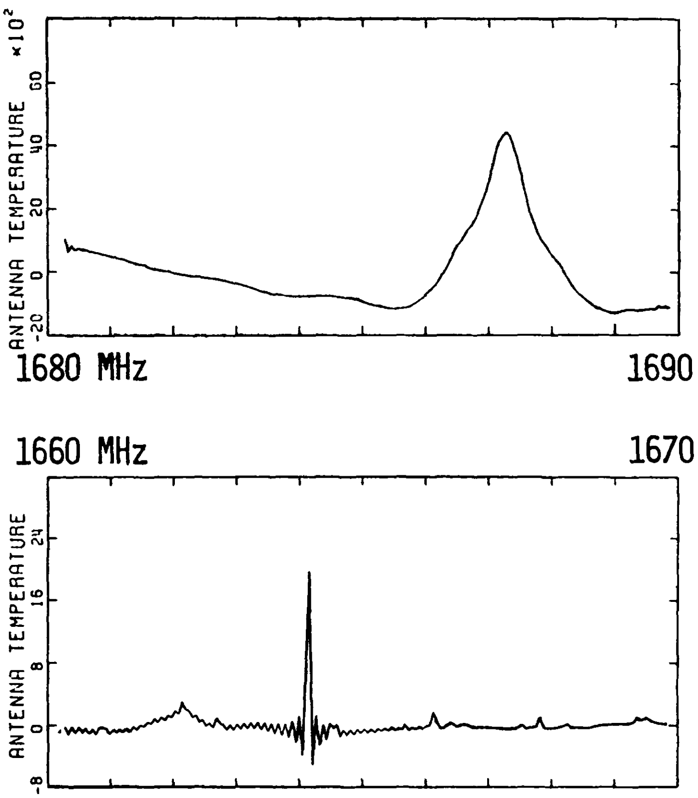


FIG 13



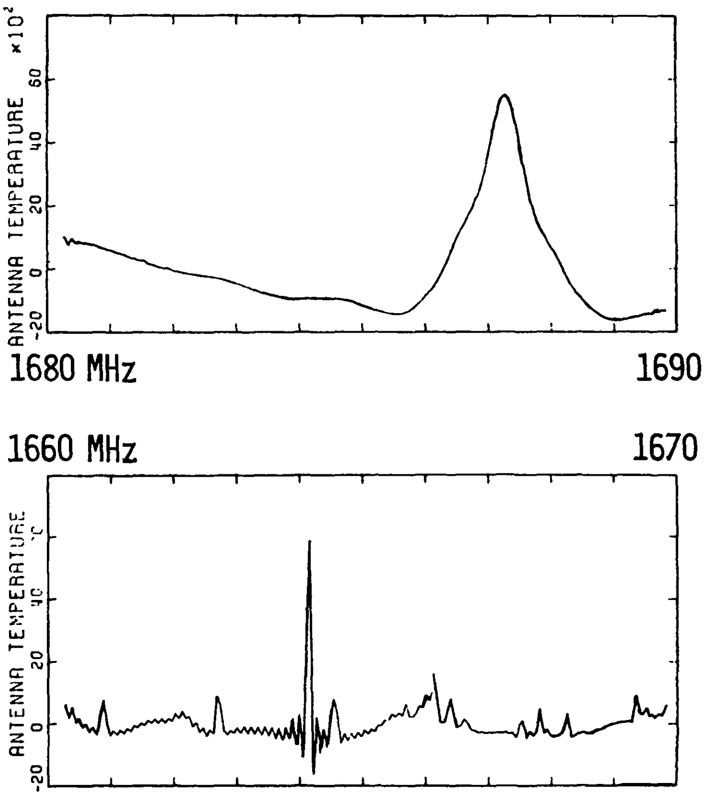
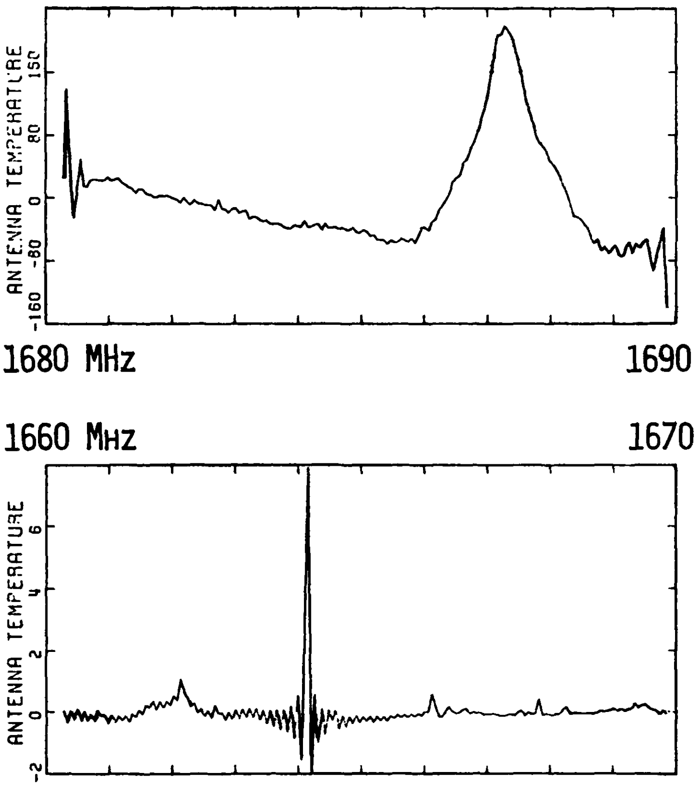


Fig 14

Fig 15



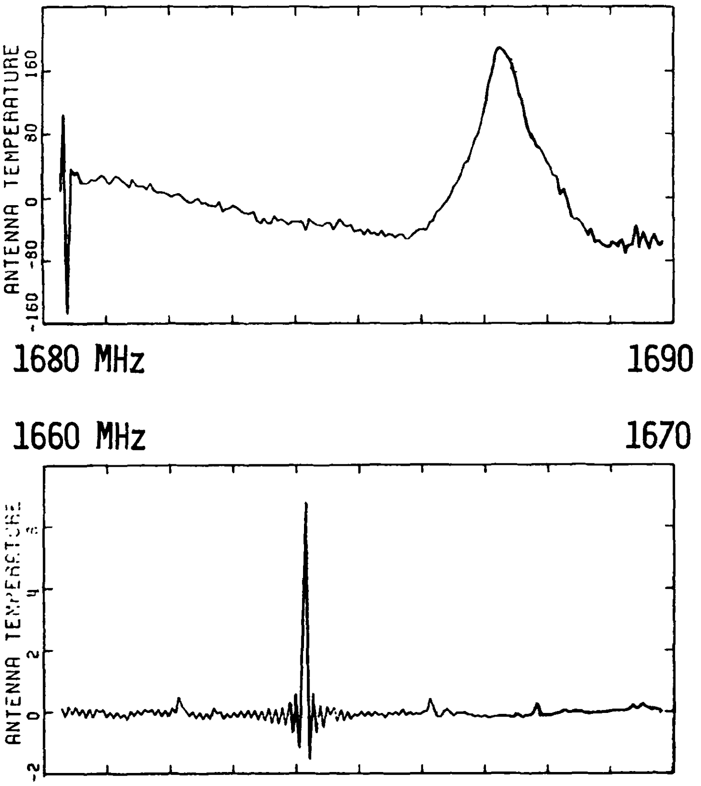


Fig 16

Fig 17

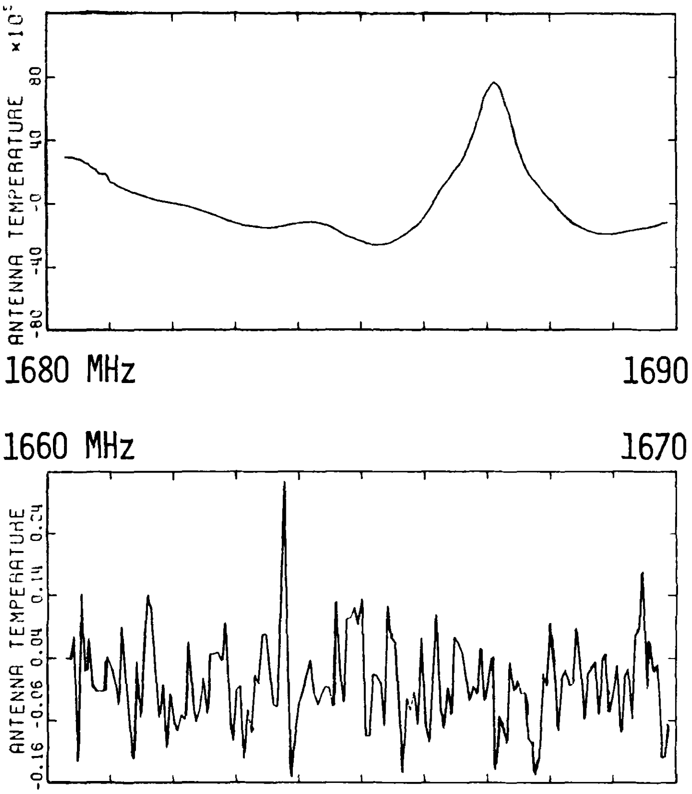


Fig 18

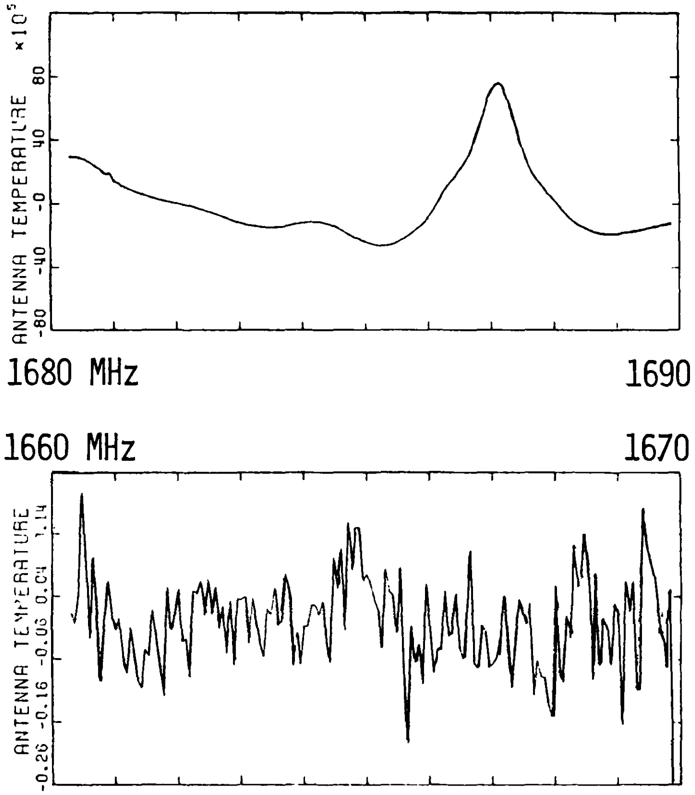


Fig 19

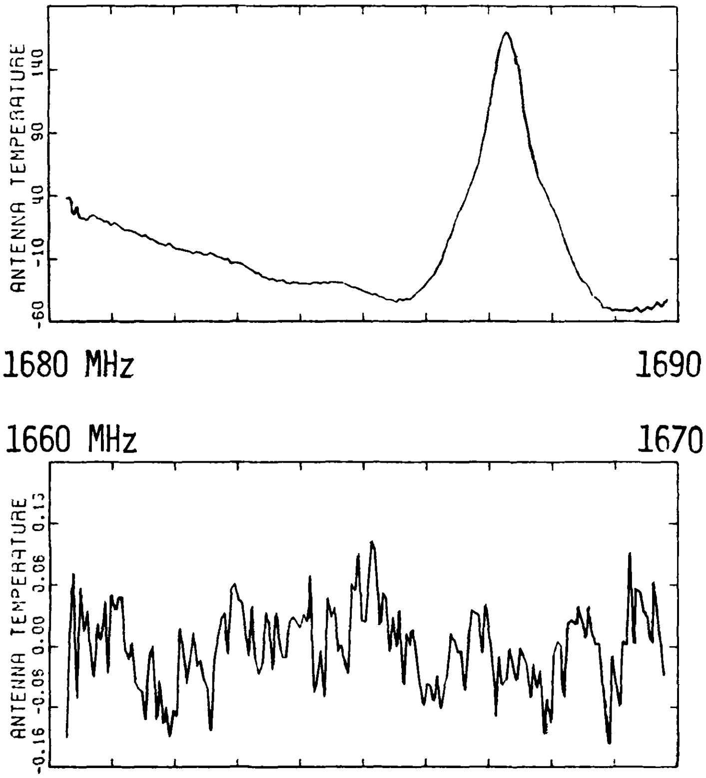


Fig 20