II. RADIO ASTRONOMY*

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A. PULSAR OBSERVATIONS WITH A SWEPT-FREQUENCY LOCAL OSCILLATOR

On August 14 and 15, 1969, pulsar observations were made using the National Radio Astronomy Observatory 300-ft antenna and a swept-frequency local oscillator in combination with various 50-channel spectrum analyzers. The swept-frequency local oscillator was swept linearly so as to track dispersed pulsar pulses over bands of widths from 2 to 20 MHz, depending upon the natural pulsar sweep rate.

Below are presented some of our preliminary results from observations of pulses from NP 0532 in the Crab Nebula.[1] In Fig. II-1a is shown a series of spectra obtained at approximately 55-msec intervals from one isolated pulse from NP 0532. The center frequency of the receiver passband was swept from 161.5 MHz to 153.5 MHz at 8.5 MHz/sec. The filter widths were 30 kHz.

The effect of the swept-frequency local oscillator is to change the meaning of the time and frequency axes of Fig. II-1. That is, we could alternatively dimension Fig. II-1a in terms of time and frequency referenced to the original pulse, rather than to the receiver output parameters. Output signals received later in time actually correspond to the pulse received at lower frequencies. Conversely, signals received at different output frequencies actually correspond to the undispersed pulse shape at different points in time. The pulse shown in Fig. II-1b corresponds to the average of those spectra received during the interval from 0.3 sec to 0.5 sec. The abscissa corresponds to time referenced to the original pulse. Single pulses from NP 0532 appear very much like the step response of a single pole RC highpass filter. The possible existence of a separate low-energy impulse at the origin can not yet be excluded.

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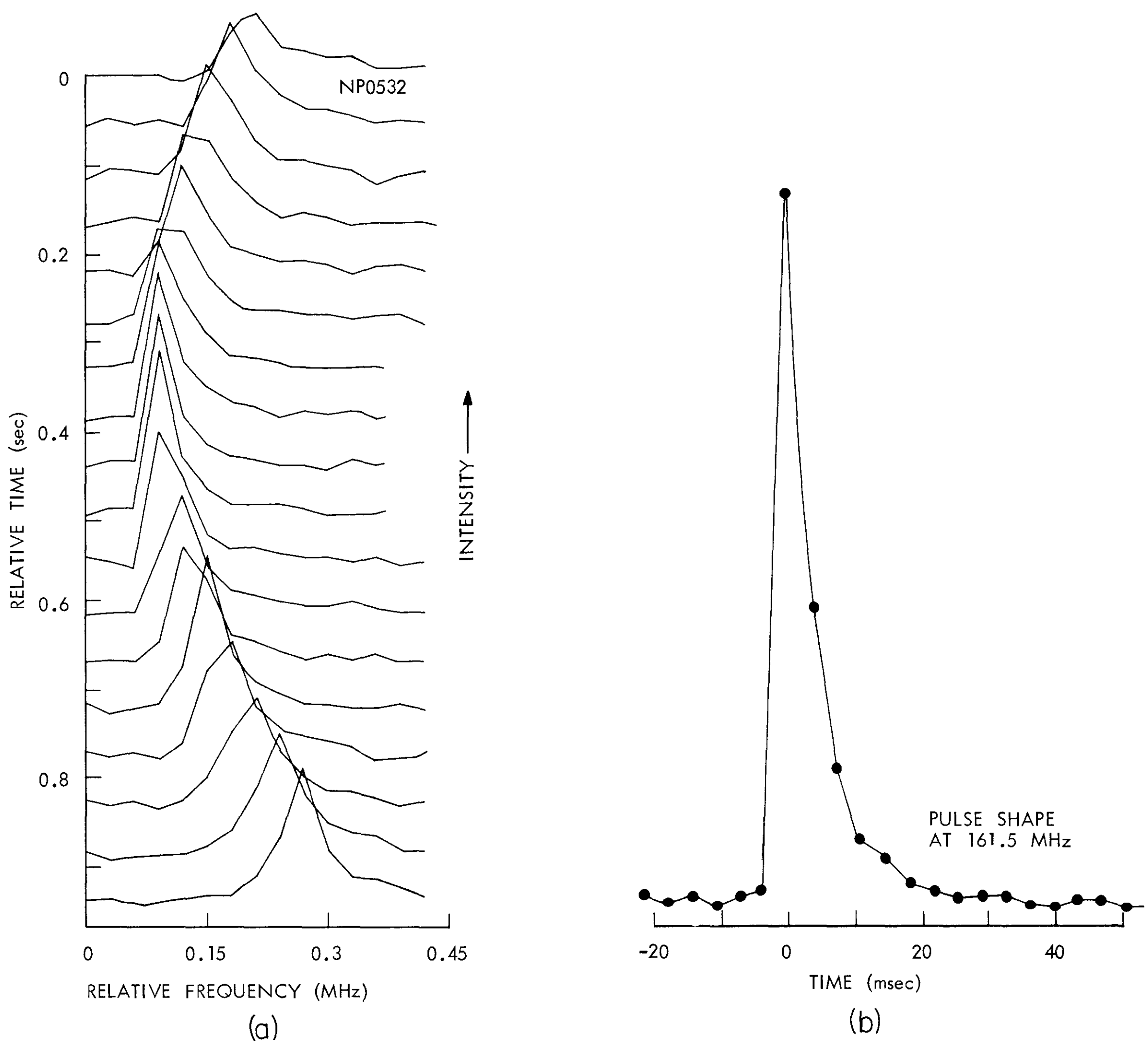

Fig. II-1. Single pulse from NP 0532 (a) as produced directly by the swept-frequency receiver, and (b) as averaged over the center of the data set and displayed as a function of time with reference to the pulsar.

The decay time of these pulses is a strong function of wavelength. This is evident in Fig. II-2, where typical pulses are shown, some centered at 115 MHz, and the others centered at 157.5 MHz.

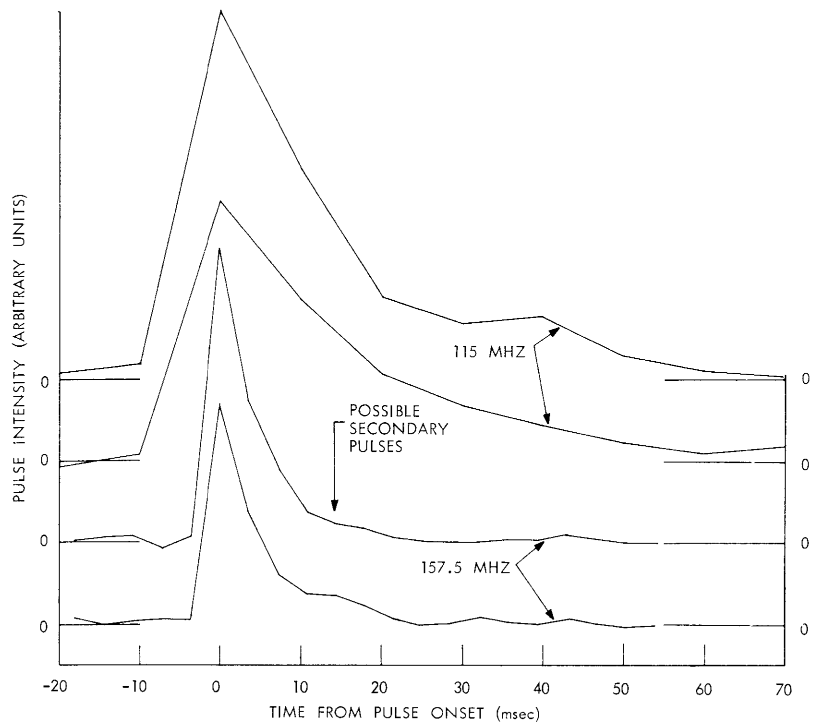

Fig. II-2. Single pulses from NP 0532 received near 115 MHz and 157.5 MHz. The effective time resolutions at these two frequencies are 10 msec and 3.6 msec, respectively.

The decay time constants at 115 MHz and 157.5 MHz are approximately 12.9 msec and 3.8 msec, respectively. Thus the decay time appears to be approximately proportional to λ^4. No obvious simple mechanism could produce this behavior, and thus these measurements and extensions of them to other wavelengths and to higher resolutions may place important constraints upon the emission mechanism or upon the plasma cloud believed to surround the pulsar. Related pulse averages over many minutes have recently been obtained at Arecibo[2].

These data also indicate that strong pulses from NP 0532 normally appear singly, although there are traces of both the secondary pulse 14 msec after the primary pulse, and perhaps the succeeding primary 32 msec after.

D. H. Staelin, J. Sutton, M. S. Ewing

(Dr. J. Sutton is with the National Radio Astronomy Observatory.)

References

1. D. H. Staelin and E. C. Reifenstein III, "Pulsating Radio Sources near the Crab Nebula," Science, Vol. 162, pp. 1481-1483, 1968.

2. F. D. Drake, Personal communication.

B. SEARCH FOR THE 1.35-cm STRATOSPHERIC H_2O LINE

Measurements to detect the 22.235 GHz spike in the thermal emission spectrum of the atmosphere which is due to stratospheric water vapor[1] were performed during June and July, 1969. The measurements were made with facilities of the National Radio Astronomy Observatory in Green Bank, West Virginia. The receiver consisted of a standard-gain microwave horn with 15° full beamwidth at half-power points connected to a 300-MHz bandwidth mixer radiometer. The IF output of the radiometer was followed by a 40-channel band of filters and synchronous detectors for spectral analysis of the signal. The radiometer contained two Gunn-effect solid-state local oscillators which were switched at a rate of 10 Hz to alternately center the line in two filter channels. Two filter banks with 1-MHz and 5-MHz resolution, respectively, were used during the series of experiments. The double-sideband receiver noise temperature was 1200°K.

The experimental procedure included a 5-min observation of the sky spectrum with the microwave horn, followed by another 5-min observation of the sky spectrum in the same manner, but with thermal noise of 55°K added to the signal during one half of the frequency switching cycle. This second 5-min run was used to measure the receiver gain. The thermal noise was obtained from a 10,000°K gas discharge tube with measured attenuation inserted. Finally, another 5-min comparison observation was made by switching the radiometer input to a matched waveguide termination load. The spectrum from the waveguide load is flat, so that our frequency-switching procedure of observation should give zero output in each of the channels. A nonzero output in the comparison mode was interpreted as a spectral feature of the receiver. The comparison spectrum was subtracted from the sky spectrum in the data analysis.

The sequence of three 5-min runs was repeated consecutively, and the spectrum obtained from each was averaged to reduce noise. Measurements were performed at several elevation angles and with different local-oscillator frequencies to separate receiver spectral effects. The major limitation in the experiment was the inability to obtain a flat frequency baseline for various settings of local-oscillator frequency. The nonflat baseline was due to interference among multiple reflections in the waveguide circuit.

No spike at 22.235 GHz was evident in our observations, although some data analysis remains to be done. Our most noise-free spectrum is shown in Fig. II-3. This spectrum is the average of eight spectra taken in the early morning of July 18, 1969. The horn was pointed at 20° elevation and there were no clouds. Local-oscillator frequencies were set for the 22.235 GHz line positive in channel 30 and negative in channel 20 of the 5-MHz resolution filter bank. Also shown in Fig. II-3 is the computed spectrum at 20° elevation for a stratospheric water-vapor mass mixing ratio of 2×10^{-6} gm/gm extending to 60-km altitude. The effects of frequency switching and image sidebands were included in the computation, but reflections in the receiver were not included.

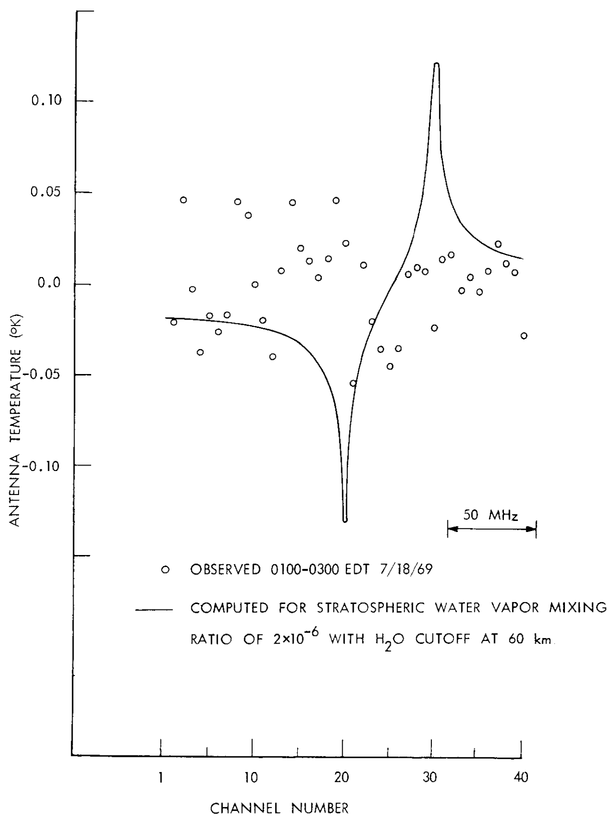

Fig. II-3. Observed and theoretical spectra of stratospheric H_2O.

Balloon[2] and airborne infrared spectrometer[3] measurements of water vapor in the lower stratosphere indicate an average mixing ratio of approximately 2×10^{-6}. Our present measurements and analysis imply that the water-vapor mixing ratio is less than this in the middle and upper stratosphere during the time when the measurements were performed. These measurements do not confirm earlier measurements[4] made from the M. I. T. campus which suggested a mixing ratio of 1.4×10^{-5} in August 1967.

The measurements described here were performed with Mr. D. L. Thacker of NRAO who built the microwave receiver.

Solar absorption experiments to detect stratospheric water are now being performed with the Haystack antenna. These will be described in a later report.

J. W. Waters, D. H. Staelin

References

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2. H. J. Mastenbrook, "Water Vapor Distribution in the Stratosphere and High Troposphere," J. Atmos. Sci. 25, 299 (March 1968).
3. P. M. Kuhn, M. S. Lojko, and E. W. Petersen, "Infrared Measurements of Variations in Stratospheric Water Vapor," Nature 223, 462 (August 2, 1969).
4. Sara W. Law, R. Neal, and D. H. Staelin, "K-band Observations of Stratospheric Water Vapor," Quarterly Progress Report No. 89, Research Laboratory of Electronics, M.I.T., April 15, 1969, p. 23.

C. PULSAR OBSERVATIONS

Several weeks of pulsar observations have been carried out at the 300-ft transit telescope of the National Radio Astronomy Observatory, Green Bank, West Virginia, during the spring and summer of 1969.

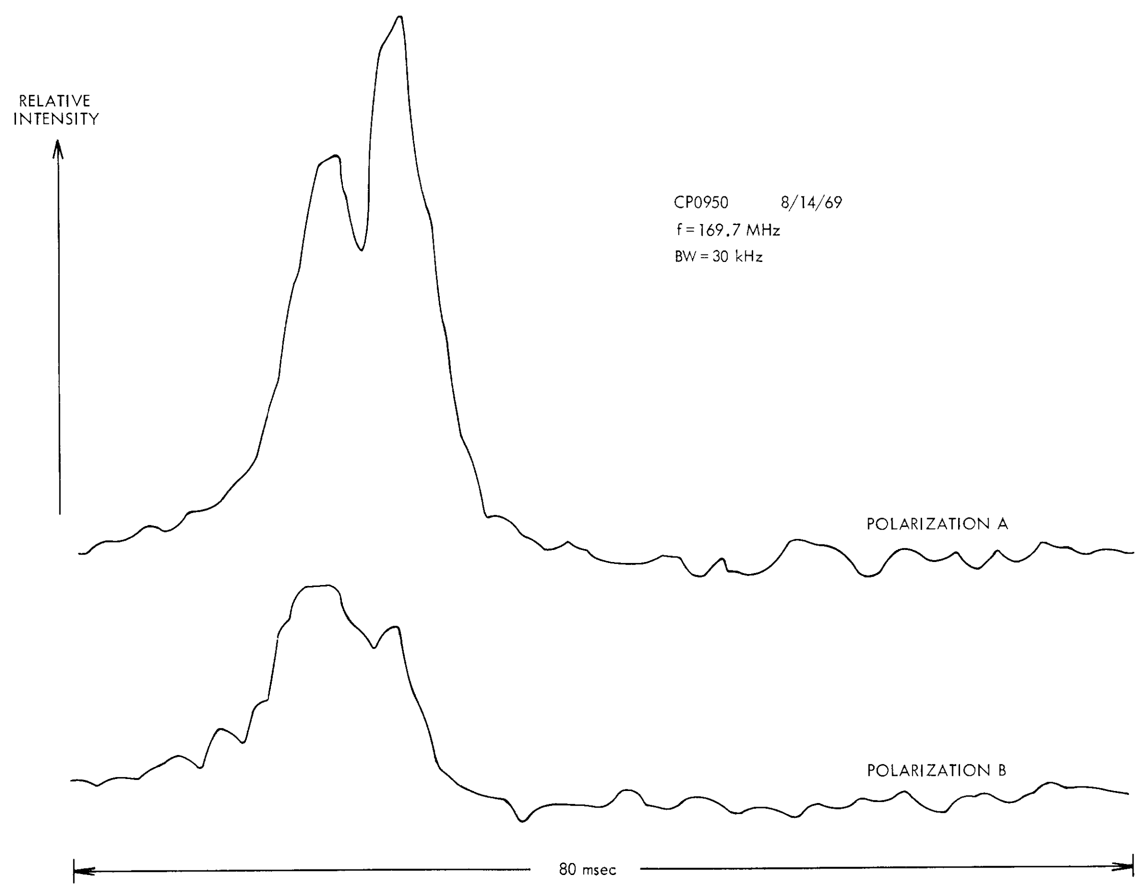

Fig. II-4. High time resolution display of pulse of CP 0950. The two traces represent orthogonal linear polarization.

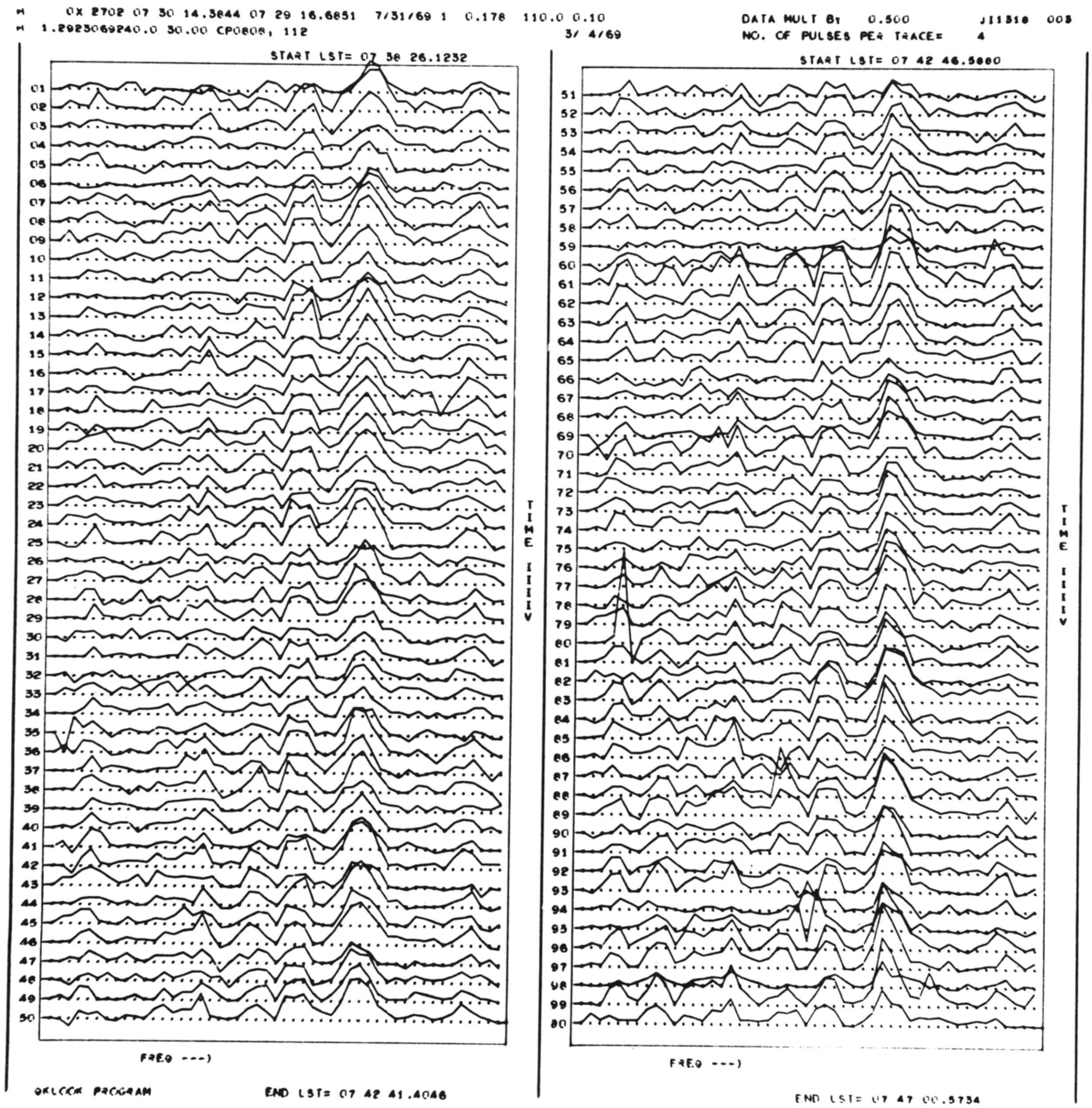

Fig. II-5. Spectra of pulses from CP 0808. Four pulses are averaged in each trace.

Several observing techniques were tested during these sessions. One of these, a travelling feed system, consisted of a remotely controlled carriage and an octave bandwidth antenna. The feed was shown capable of tracking radio sources up to about five beamwidths off the telescope meridian. Antenna efficiency was reduced to approximately 70 per cent of the on-axis value in the frequency range 100-200 MHz. This feed arrangement has allowed a substantial increase in the available observation time for pulsars. The sources may be tracked for about one hour at the celestial equator and for greater periods at higher declinations. For only three hours a day is there no known pulsar within reach of the telescope.

High time resolution was provided by a P. A. R. "Waveform Eductor" (a waveform averaging device), which could analyze two independent inputs simultaneously. This instrument was used to resolve a 5 msec doublet pulse in the source CP 0950. Waveforms were obtained for both vertical and horizontal polarizations at several frequencies near 170 MHz (see Fig. II-4); the pulse components are seen to be highly polarized in different orientations.

Medium time resolution data has been taken with both 100 and 30 KHz resolution in the 50-channel system. The spectra were obtained at center frequencies near 110, 140, and 170 MHz for most pulsars north of declination -20° (the telescope limit). For the first time a systematic pulsed calibration scheme was used during August.

Work has continued on a computer program to analyze the large number (30 to 50) of telescope data tapes. The program is designed to extract energy spectra for individual pulses, correcting for dispersion and baseline effects. Relatively simple correlation and display of the pulse spectra will give new information on characteristics of the frequency and time fluctuations in pulsar signals.

A representative display of the spectra of 400 pulses of the source CP 0808 averaged in groups of 4 is shown in Fig. II-5. The data was taken March 4, 1969 at 110 MHz, 100 KHz resolution. Some evolution of the spectral features is evident but the features are relatively long-lived. Analysis of the data is still in progress.

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D. Ku-BAND INTERFEROMETER

The Ku-band interferometer on the roof of Building 6 at M. I. T. has been operated as a complete system and fringes have been obtained from the Crab Nebula.

1. System Description

a. Computer Control

A small computer, PDP-8, has been incorporated in the system. The sequence of operations performed by the computer during an observation is presented in Fig. II-6.

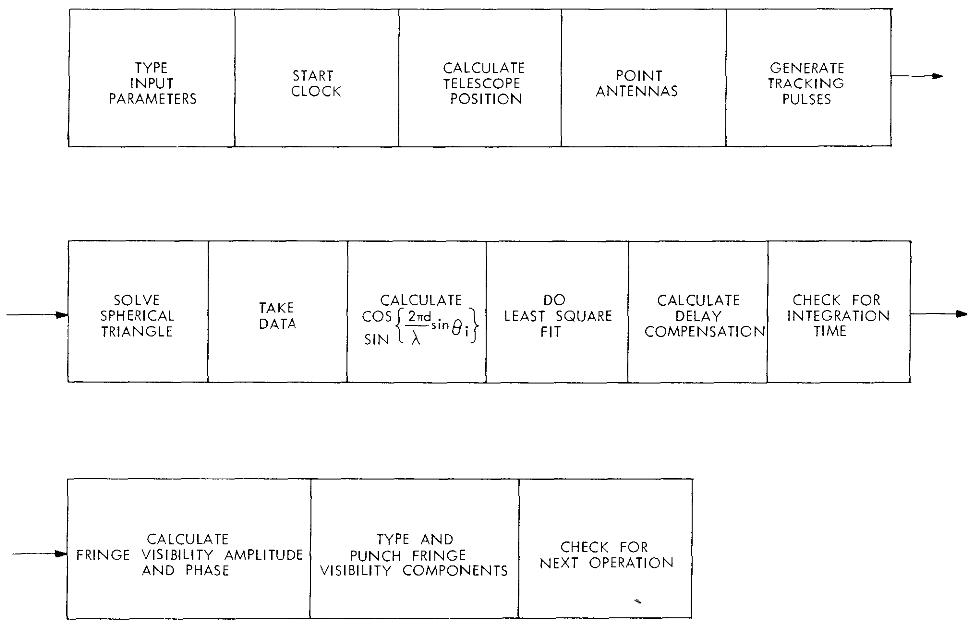

Fig. II-6. Sequence of operations.

In Fig. II-7, the over-all system block diagram is shown. In series with the antenna signal a small amount of noise is injected through a Dicke switch; this noise is used for concurrent gain monitoring. The A-D converter converts the interferometer output as well as the calibration signals into 10-bit digital numbers which are fed into the computer for further processing. The other functions of the computer are to drive the dishes and to control the compensation delays which are in series with the IF strip.

b. Interferometer Back End

Figure II-8 shows the interferometer back end. The 60-MHz IF signals that come from the antenna sites go through a set of delays which are controlled digitally by the computer. The function of the delays is to compensate for the RF signal delay so that the fringes are not wiped out by the system bandpass; these fringes are called white. The condition for the white fringes in the case of a DSB receiver is:

$$2f_{IF}\Delta\tau \ll 1.$$

Since $f_{IF} = 60$ MHz we obtain $\Delta\tau = 1.25$ ns. This number, then, serves as our basic delay unit.

The IF amplifier outputs are multiplied to give the interferometer output, while from the detector outputs of the IF amplifiers the calibration noise is extracted.

c. Phase-Lock System

The two local oscillators must be phase-locked to a common stable frequency in order to preserve the coherence of the input RF signals. Figure II-9 shows the

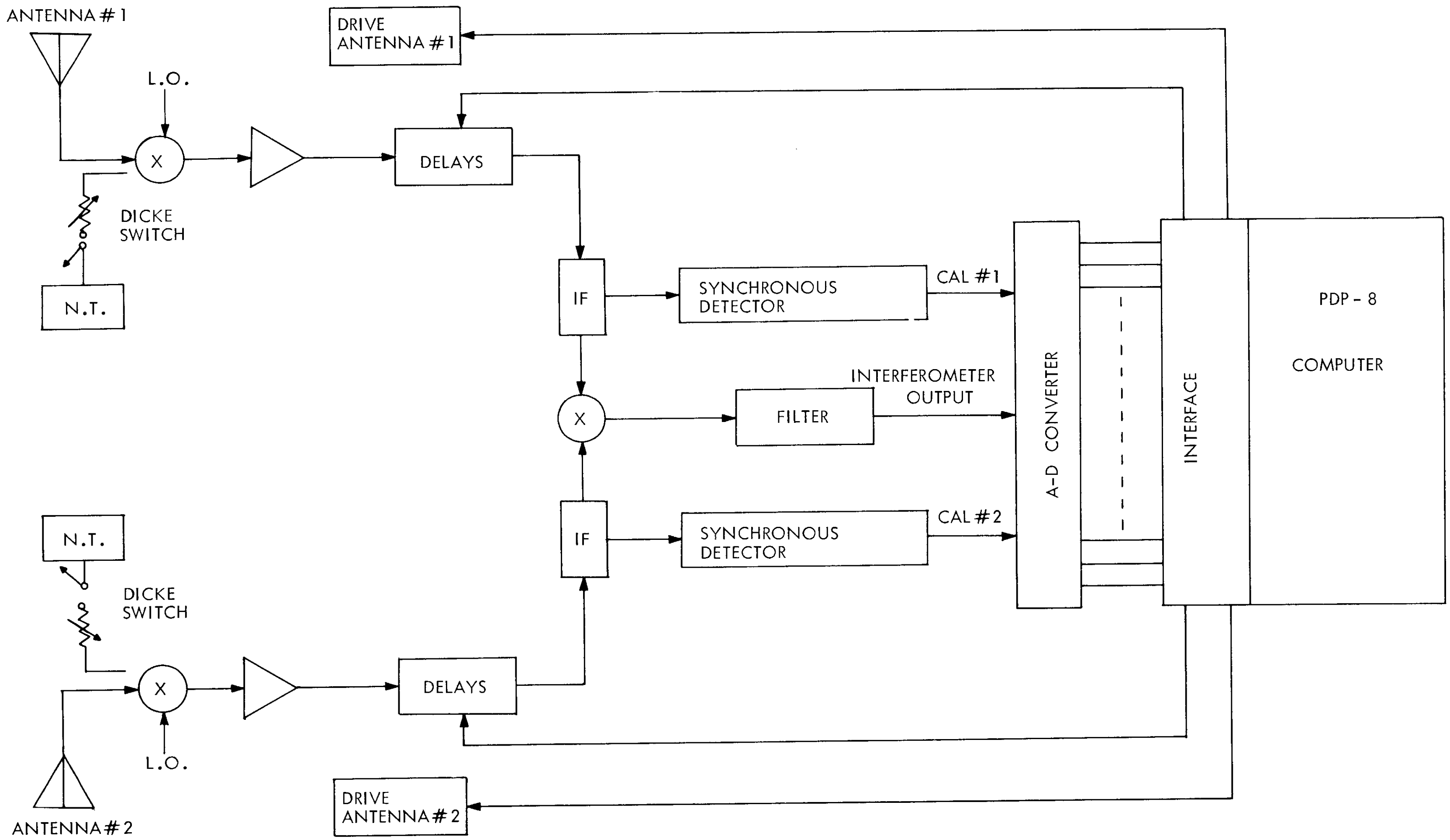

Fig. II-7. Over-all system.

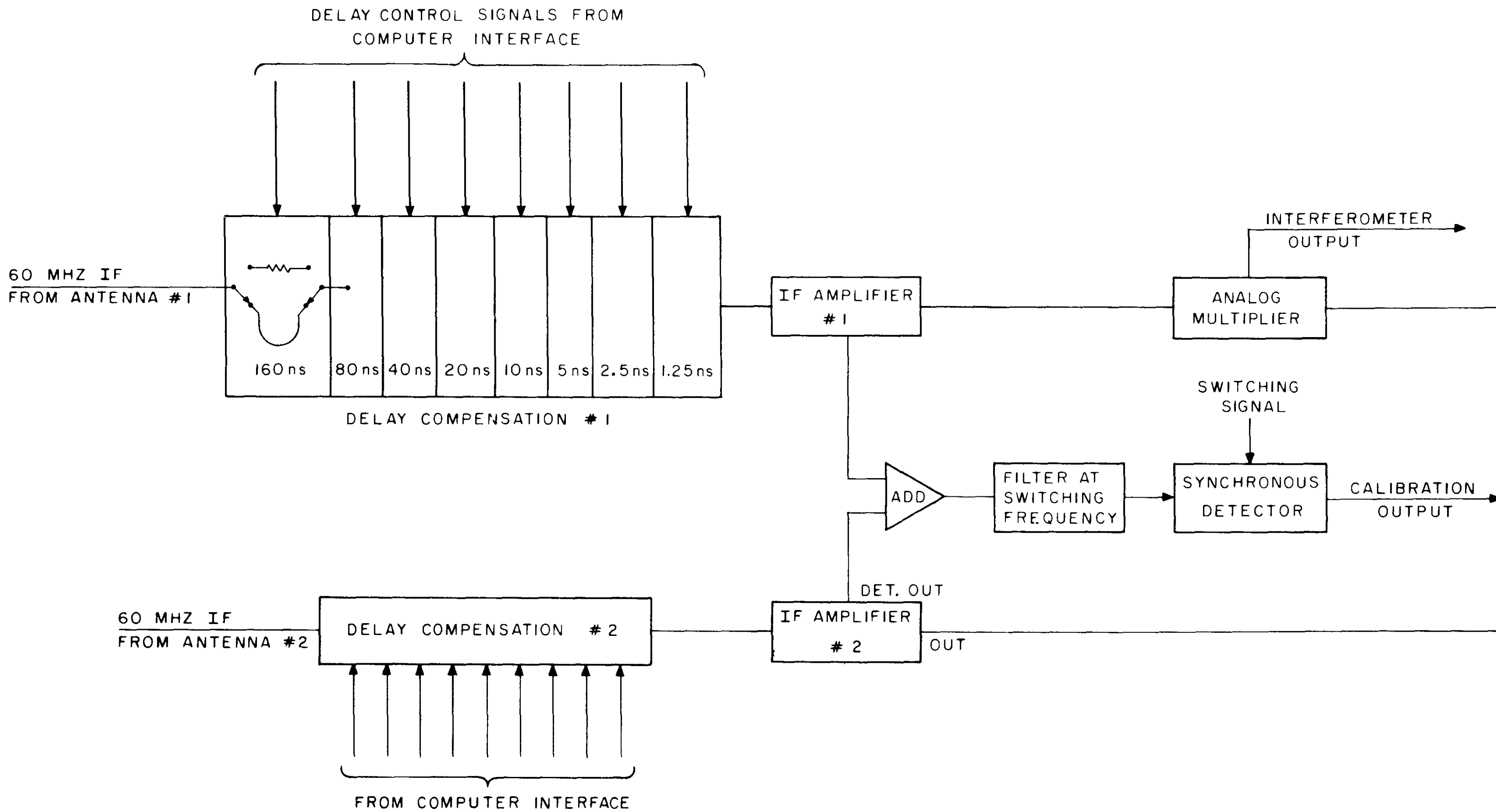

Fig. II-8. Interferometer back end.

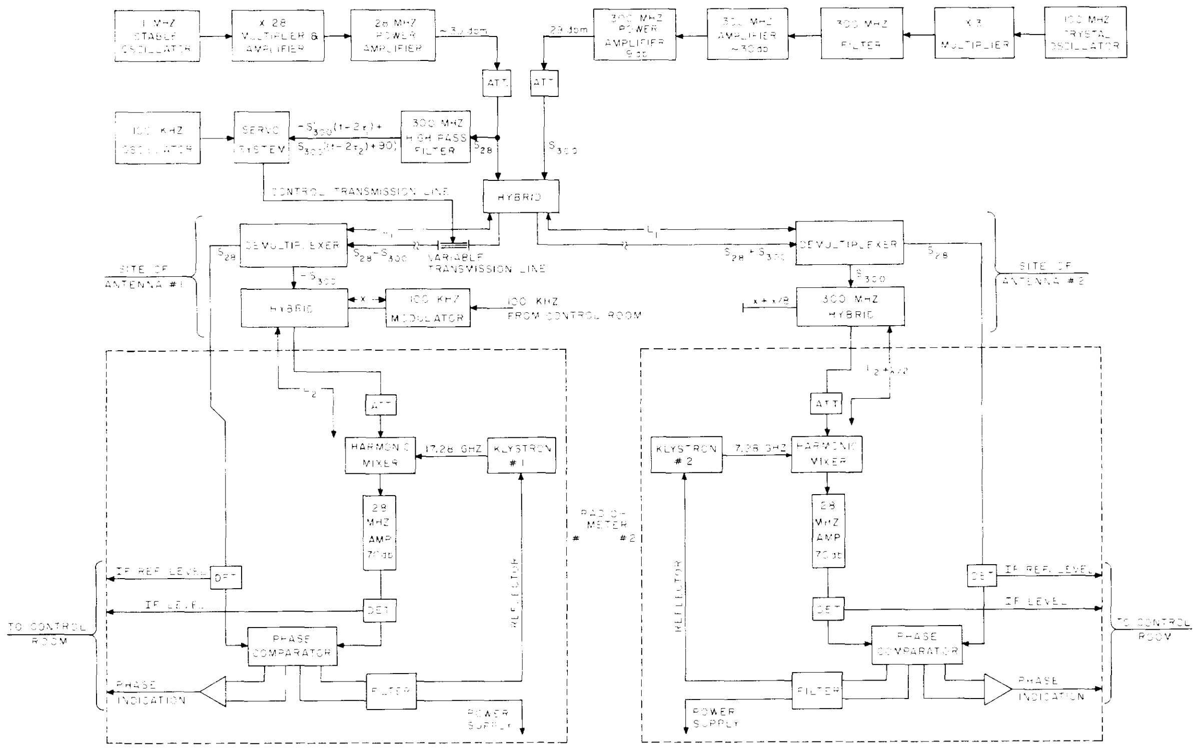

Fig. II-9. Phase-lock system.

phase-lock system used in our interferometer. The two synchronizing frequencies used are 28 MHz generated from a 1-MHz stable oscillator and 300 MHz generated from a 100-MHz crystal oscillator. The servo system is used to keep equal the lengths of the two lines that bring the synchronizing signals to the antenna sites.

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E. EXTENDED BANDWIDTH LONG BASELINE INTERFEROMETRY

The basic technique of extended bandwidth long baseline interferometry, namely that the delay resolution of a wideband interferometer can be equalled by one in which narrow sample bands spaced roughly in geometric series across the "extended bandwidth" are coherently received, has been verified, by using data from the frequency-switched L-band VLBI experiment conducted January 11, 12, and 13, 1969 between the Haystack 120 ft and NRAO 140 ft antennas.

The January 1969 experiment successfully used four "phase-calibrated" sample bands at 1600, 1660, 1670 and 1710 MHz, which yielded an extended bandwidth of 110 MHz. The RF phase-calibration signal consisted in a frequency comb with a tooth separation of 10 MHz, generated by a step recovery diode driven from the station standard. Two "uncalibrated" sample bands at 1659.5 and 1662.5 MHz, obtained by switching the second L.O. synthesizer gave difference frequencies of 0.5 MHz and 2.5 MHz, which covered the gap between the 300-kHz instantaneous recorded bandwidth of each sample band and the minimum phase-calibrated frequency step of 10 MHz.

Another set of one calibrated and two uncalibrated bands at 1750, 1749.5, and 1752.5 MHz, respectively, did not yield any source fringes with amplitude greater than the noise for any run. The correlated amplitude of the very strong phase-calibrated signal, injected for the first few seconds of each run, was observed for the 1750-MHz band to be about one-tenth the value obtained for the other bands. This makes the probable cause of the failure at 1750 MHz improper tuning of the parametric amplifiers at that frequency at one or both stations.

The experiment comprised repeated observations of the strongest known unresolved L-band sources. The geometric delay, which comprises ideally a constant plus a diurnally sinusoidal component for each source, was thus sampled over as large a fraction of the day as possible. As a fail-safe measure each fully switched, that is, nine-frequency, run was paired with one in which the first local oscillator and the parametric amplifier tuning was not switched. Unfortunately, the fixed first L.O. frequency corresponded to the 1750-MHz band which was not functioning.

All of the fully switched runs have undergone preliminary processing with a somewhat nonoptimum reduction program, in that only an "eyeball" estimate has been made for the best common residual fringe rate to the nearest 0.002 Hz; that is, for that fringe rate at which fringe amplitude is maximized. The treatment was nonoptimum because fringes from each band were "detected" separately in the original reduction program. Also the phase of each band was simply taken to be the phase of the central point of a seven-point spectrum produced by Fourier inversion of the crosscorrelation function. The noise in the fringe-rate measurement would decrease if the data from the various bands were summed together coherently. If all the information contained in the cross-spectral function for each band were utilized, the noise in the band-phase measurement would also decrease.

An optimum delay-fringe-rate estimation routine will be ready soon which performs two-dimensional Fourier inversion of the complex correlation data samples in the time-frequency domain for each delay. The absolute maximum of the amplitudes of these transforms yields an estimate of the residual delay and residual fringe rate to the nearest sample in both dimensions. Harmonic interpolation then yields an optimum correction to both the a priori delay and the a priori fringe rate without significant round-off error.

The nonoptimum reduction of the data that has been performed thus far included a simple transform of the single "eyeballed" complex number found for each phase-calibrated band. The coordinate corresponding to the maximum amplitude in the transform, which we call the delay resolution function, is taken to be the residual delay. Since the minimum frequency separation of the calibrated bands was 10 MHz, ambiguities at multiples of 100 nsec exist if no other data are taken into account. These ambiguities are removed, however, by subtracting the differential phase corresponding to the assumed residual delay from the phase of the uncalibrated difference band and checking that the remainder is constant within the noise for all runs.

When theoretical curves of the form $A + B \cos \Omega t + C \sin \Omega t + Dt$ (Ω scales the rotation of the Earth; the last term accounts for a relative rate error between the atomic clocks at the two sites) are least-mean-square fitted to the delay residual measurements on the sources 3C273, 3C279, 3C345, maximum errors of ~2 nsec result. We take this result to be experimental verification of the delay sensitivity of the technique. The clock-rate offset term in the expression above can only be estimated with confidence by comparing residuals measured on the same source at the same sidereal time on different days. All corresponding measurements on these sources yield day-to-day differences identical to each other within 2 nsec.

Some of the measurements on the first day of observations of the sources 3C454.3 and CTA 102 show internal inconsistencies, however. For a period of a few hours an apparent phase reversal (~180° change) in the 2.5-MHz uncalibrated band difference phase was observed, for which we have still no explanation. Whereas each day's data on these two sources can be fitted with a smooth curve of the type described above without much greater error than for the other sources, the day-to-day delay differences derived cluster around a value that is ~23 nsec different from the value derived from the first-mentioned sources. These day-to-day delay differences also have a much larger spread of ~10 nsec. Attempts have been made to relate these systematic discrepancies to the ionosphere and/or dispersionlike changes in the phase-calibrated signal with time. Thus far, no satisfactory explanation has been found.

A least-mean-square fitting program has been written, but is still undergoing corrections, which takes the results of all the observations and solves for all the unknown parameters: source positions, baseline vectors, and clock-offset terms. It puts in a priori corrections for all known delay-influencing phenomena, and can be set up to solve for unknown parameters in more complex models of such phenomena.

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