III. RADIO ASTRONOMY*

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A. VERY LONG BASELINE INTERFEROMETRY

Very long baseline interferometry (VLBI) techniques (using independent atomic clocks as local oscillators and separate recording of the video signals at the participating radio telescopes) have been extended to extremely accurate measurement of time delay. From such delay measurements both source positions and baseline coordinates, including relative time, can be determined several orders of magnitude more accurately than with any other existing technique. The scientific applications of such measurements are numerous, including such diverse effects as the gravitational bending test of relativity, continental drift, and possibly proper motions of quasars. The basic modification in VLBI methods, which have been used primarily for size and structure measurements for which the inherently small recordable fractional bandwidth and hence very large delay ambiguity was of no serious consequence, was to provide for coherent multifrequency switching of the receivers over a wide band. If the frequency spacings are properly chosen and adequate phase calibration is performed, the phase may be unambiguously extrapolated from one sampled frequency to the next throughout a range of receiving frequencies so that for the purpose of the delay measurement a large effective bandwidth is obtained.

The first significant attempt to use a long baseline delay interferometer (LBDI) was made early in October 1968 at the time of the close approach of the sun to the strong quasar source 3C279. The Haystack 120-ft – NRAO 140-ft interferometer was successfully operated at both X- and L-bands. Fringes have been observed for both bands in the last three days of the experiment at least. The X-band VLB represents the shortest wavelength, thus far, at which successful measurements have been made. The X-band

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receivers had been modified and bench-tested to allow frequency switching over 900 MHz, but a flaw in one paramplifier limited the range of receivable frequencies. An adequate phase calibrator for the large frequency steps had also not yet been developed. Both X- and L-band receivers were switched over approximately 10 MHz in the second local oscillator and should yield delay resolutions of the order of 10-100 nsec. Evaluation of the effects of bending in the sun's gravitational field and of refraction by the solar corona must await reductions that are now in progress. Instrumental problems occurred during the first half of the October experiment, but a substantial quantity of good data were obtained during the second half of the program.

We decided to try a simpler experiment in January 1969, operating only at L-band. Preparation for this experiment included additions to the NRAO and Haystack receivers to allow them to be synchronously returned over approximately 150 MHz, the development of a phase calibrator for the larger frequency steps, additions to and modifications of the video conversion scheme, and a mock switched interferometer system check in which coherent noise was fed into both the Haystack and NRAO front ends at Haystack. Eight of the strongest quasar sources at L-band were chosen to be looked at repeatedly (approximately every hour) while they were at relatively high elevations. Roughly 50 pairs of tapes switched over 150 MHz were taken on each of two days. A preliminary analysis of some of these data shows that a range of frequencies from 1600 MHz to 1710 MHz could be covered consistently. Fringes have been obtained on the weaker, as well as stronger, sources. We have every reason to believe that delay resolution of 1-10 nsec was achieved on most of these data. Reduction program improvements and modifications are being implemented, at present, to allow more consistent and efficient reduction of the data, rapid fringe notation, and combination of the multifrequency results into a best estimate of the delay for a given run. A postprocessing program to take the various delay measurements and convert them to source and baseline coordinates, synchronization, and instrumental delay errors is being developed. Another try at the gravitational bending experiment (October 1968) is being planned, probably with a transcontinental baseline.

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[Professor Irwin I. Shapiro is in the Department of Geology and Geophysics, M.I.T.]

B. PULSAR STUDIES

A search for new pulsars and a program of study of known pulsed sources was started by Professor D. H. Staelin (now on leave) and Dr. E. C. Reifenstein III of the National Radio Astronomy Observatory (NRAO) during 1968. This search led to the discovery of two pulsars in the vicinity of the Crab Nebula.[1,2] Subsequent studies by other groups have shown two new properties of one of these pulsating sources: the pulsar located in the direction of the optical center of the Crab Nebula is slowing down, that is, its period is increasing approximately 40 nsec per day; this same pulsar has been found to have an optical counterpart, also pulsating with the same period.

An enlarged M.I.T.-NRAO effort is now under way to study the properties of those pulsars that are observable with the 300-ft transit telescope at the National Radio Astronomy Observatory. These studies are being carried out by using a 50-channel receiver to obtain frequency resolution, and sampling at rates up to 200 times per second (each 5 msec). Observing frequencies have included a 5-MHz band centered at 112, 234, and 405 MHz. All data are recorded on magnetic tape and are being sorted to enable us to study individual pulses and the time variation of the amplitude of the pulses as a function of time.

D. H. Staelin, R. M. Price, R. F. Burke,
M. S. Ewing, E. C. Reifenstein III

[Dr. E. C. Reifenstein III is at the National Radio Astronomy Observatory.]

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C. PULSAR FACILITY

The components of the feeds for the sixteen 50-ft dishes of the pulsar facility are completed. Assembly of 4 antennas is completed and the remaining feeds will be assembled and mounted as soon as weather permits.

Installation of the open wire transmission lines is essentially completed. A small shed has been built at the center of the array for the transmission lines to feed into. Electronics apparatus of the receiver front end will be housed at that point.

One feed has been erected and tests have been carried out, using the 10-channel receiver, which has also been completed. Further tests will be carried out, as soon as weather permits, to determine the operating frequency necessary to minimize RFI.

B. F. Burke, R. M. Price, M. S. Ewing

D. KU-BAND INTERFEROMETER

The interconnections among the constituent blocks of the interferometer have been completed.

During the months of January and part of February, 1969, several system checks were carried out. To calibrate the index positions of the two dishes, we scanned the sun in declination and hour angle. Preliminary calculations indicate an antenna efficiency of approximately 40%. This efficiency will probably improve when we further adjust the focusing of the radiometer.

G. Papadopoulos, B. F. Burke

E. OBSERVATIONS OF OH EMISSION ASSOCIATED WITH INFRARED STARS

During the past year we have discovered and studied a new class of OH emission sources associated with infrared (IR) stars. These OH sources are characterized by having their strongest emission at the OH satellite line frequency of 1612 MHz, with much weaker emission (if present at all) at the main line frequencies (1665, 1667 MHz) and no emission at the other satellite line frequency 1720 MHz. The strong 1612 MHz emission is largely unpolarized, while the main line emission has a large percentage of polarization (circular and linear).

In July 1968, we made observations of twenty IR stars, using the 140-ft radio telescope of the National Radio Astronomy Observatory (NRAO), searching for OH emission. We found that four of the IR stars had OH emission associated with them (see Wilson and Barrett[1]). Among the four OH sources detected, the IR star NML Cygni is the strongest OH source with a peak flux of 600 flux units (S_o). A spectrum of NML Cygni OH emission is shown in Fig. III-1.

NML Cygni was discovered in 1965 by Neugebauer, Martz, and Leighton,[2] during

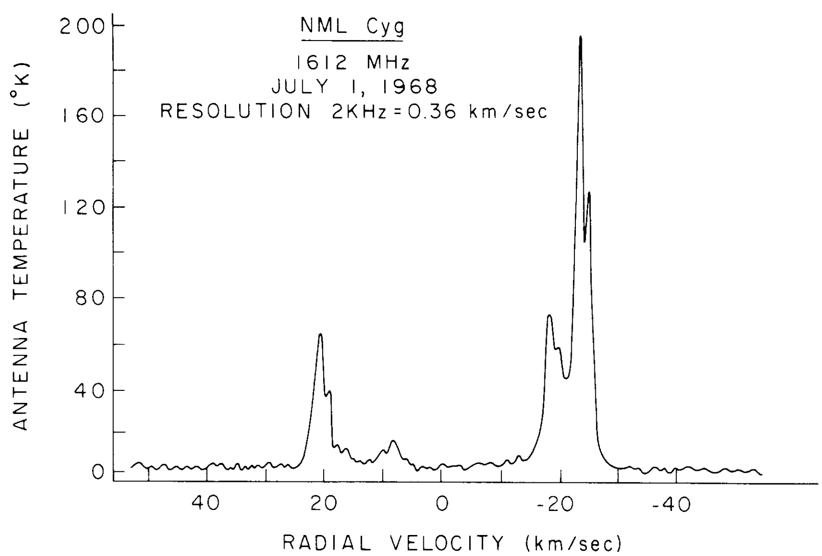

Fig. III-1. The 1612-MHz spectrum of the infrared (IR) star NML Cygni. Antenna polarization was left circular, and integration time was 12 min.

an infrared survey of the sky. It is one of the strongest IR stars known, and has an effective black-body temperature of approximately 700°K. The angular size of the IR emission from NML Cygni was computed by Johnson, Low, and Steinmetz[3] to be 0.2 second of arc. There have been some suggestions that it could be a protostar.

To gain further information on the size of NML Cygni, we made a series of very long baseline interferometer measurements in October 1968. These measurements were made in cooperation with Dr. James M. Moran of Lincoln Laboratory, M.I.T. The two antennas used in the interferometer measurements were the NRAO 140-ft antenna, in Greenbank, West Virginia, and the 120-ft Haystack antenna, at Lincoln Laboratory, M.I.T. The baseline of this interferometer is approximately 5×10^6 wavelengths. The OH features of NML Cygni were detected, and their angular size was measured to be ~0.1 second of arc. (At a distance of 100 parsecs, this corresponds to a diameter of 10 astronomical units.) We found that the NML Cygni source is very complex, with many emission features coming from different locations within a region of radius of 1 second of arc. This could correspond to a region of space containing dense clouds of OH molecules and moving with respect to one another.

In addition to the July 1968 infrared star observations, we made a further survey of 46 infrared sources, in October 1968. In these observations, using the 140-ft antenna of NRAO at a frequency of 1612 MHz, we found 4 more OH emission sources. In December 1968, we again used the NRAO 140-ft antenna to make detailed measurements of the properties of the IR stars previously detected. We are now in the final stages of the reduction of these data. It is possible, however, to summarize some of the preliminary results.

1. Sixty-six IR stars have been observed at 1612-MHz frequency. Eight of these IR stars have detectable OH emission.

2. The strongest OH emission is at 1612 MHz, and is mainly unpolarized — within 10%. Line emission at 1665 or 1667 MHz is much weaker; there is no detectable 1720-MHz emission. The fact of 1612-MHz emission and no 1720-MHz emission can be explained by recent theories of near IR pumping of the OH maser, as proposed by Litvak.[4]

3. The OH sources associated with IR stars have two separate emission velocities, thereby suggesting a contracting or expanding model for the OH cloud.

Further research plans in this field include measurement of the properties of the sources thus detected, looking for time variations in these properties, and extending this OH survey to many additional IR stars to obtain an idea of the statistics involved in this kind of emission.

W. J. Wilson, A. H. Barrett

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F. OBSERVATIONS OF RADIO EMISSION FROM GALACTIC H_2O

The Haystack Research Facility of Lincoln Laboratory, M.I.T., has been used to observe interstellar sources of 1.35-cm microwave emission from the $6_{16} \rightarrow 5_{23}$ rotational transition of water vapor, following the recent discovery of such emission.[1] H_2O emission was observed from the sources NGC 6334(N), Orion A, W3 (two sources), W24 (Sgr B2), W49, W51, W75(S), and VY Canis Majoris. Spectra, uncorrected for atmospheric absorption, taken with the Haystack correlator are shown in Fig. III-2. With the exception of NGC 6334(N), H_2O emission has been previously observed in these sources.[2] VY Canis Majoris is an infrared nebula, while the other sources are H II regions. All except one of the W3 sources are associated with 18-cm OH emission. The range of Doppler velocities in which H_2O emission is observed generally coincides with that for OH emission from a given source, although there are exceptions.

The antenna temperature on Haystack, because of the largest feature in the W49 spectrum, is greater than 1500°K, which makes this line by far the strongest of any observed in radio astronomy before the discovery of interstellar H_2O. In addition to the complex spectrum centered around 0.0 km/sec, spectral features not shown in Fig. III-2 were found in W49 at Doppler velocities of −130, −98, and +140 km/sec. OH emission at these velocities has not yet been observed. Significant time variation in the W49 spectrum over a period of a few weeks has also been reported.[2] Our observations have not been fully analyzed for time variations but the high-velocity line at +140 km/sec in W49 seems to have disappeared between 23 February and 9 March, 1969.

The sources were not spatially resolved with the Haystack antenna beamwidth of 0.025° and an upper limit of approximately 0.01° is placed on the angular extent of the H_2O emitting regions. In Orion A, two emission regions separated by approximately 0.005° were found. The polarization of the H_2O emission does not appear to be appreciable, in contrast to the OH emission. Some of the spectral features in the Orion spectrum may be strongly polarized, however, and more careful analysis of our data is required.

The H_2O emission provides new puzzles for radio astronomers. The molecular transition giving rise to this emission is between two excited levels 445 cm^{-1} above the ground state. Any theory of the emission mechanism must explain the population of these levels and the intense signals received. The upper limit of 0.010° on the size of W49 gives a lower limit of 30,000°K to the brightness temperature of this source. A maser type of amplification is suggested because H_2O would dissociate at this temperature. The occurrence of H_2O emission in regions where no OH emission has been observed and vice versa defies a simple explanation of the chemical relations

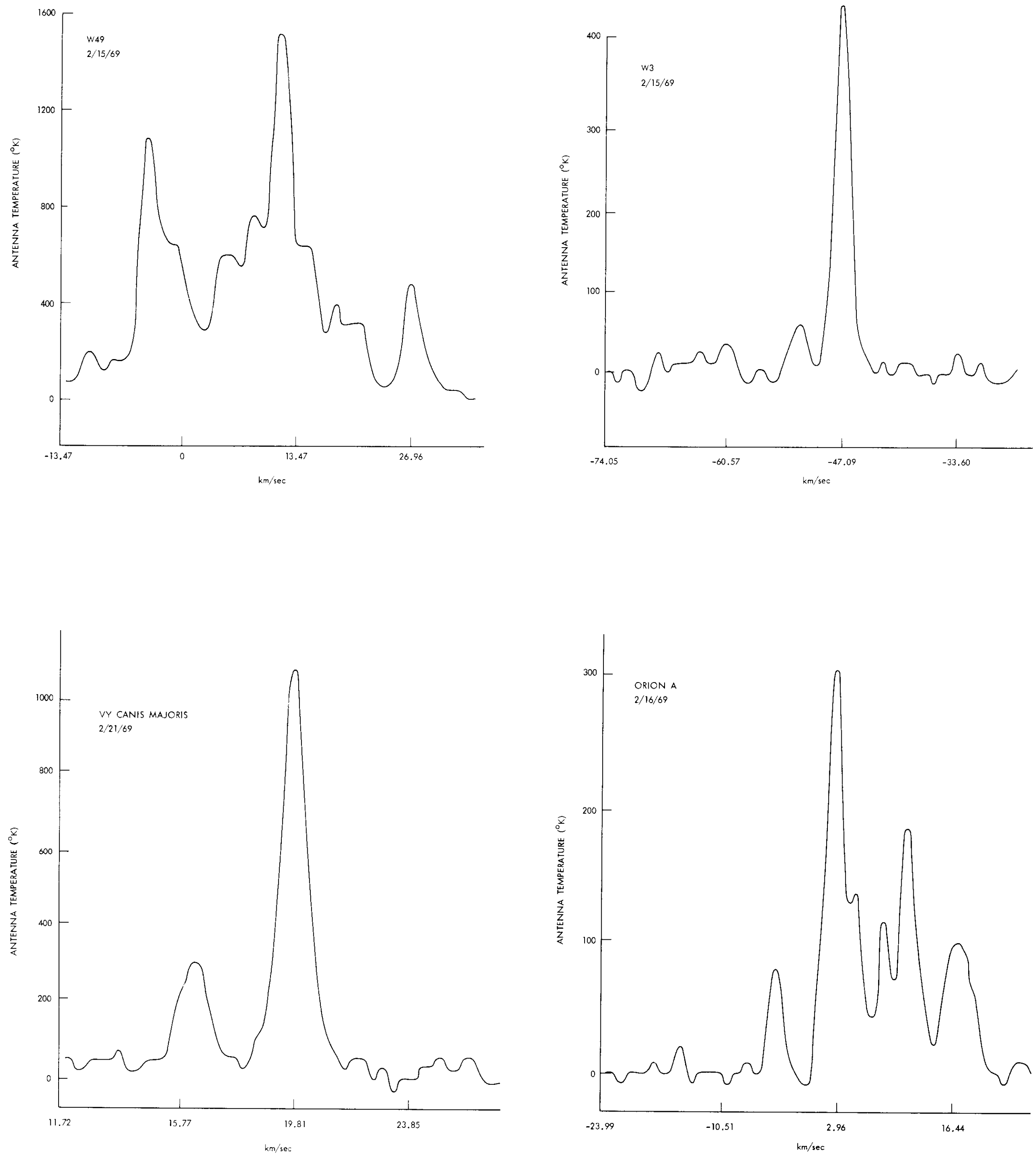

Fig. III-2. Interstellar H_2O Spectra. Antenna temperatures are uncorrected for atmospheric absorption and velocities are with respect to the local standard of rest.

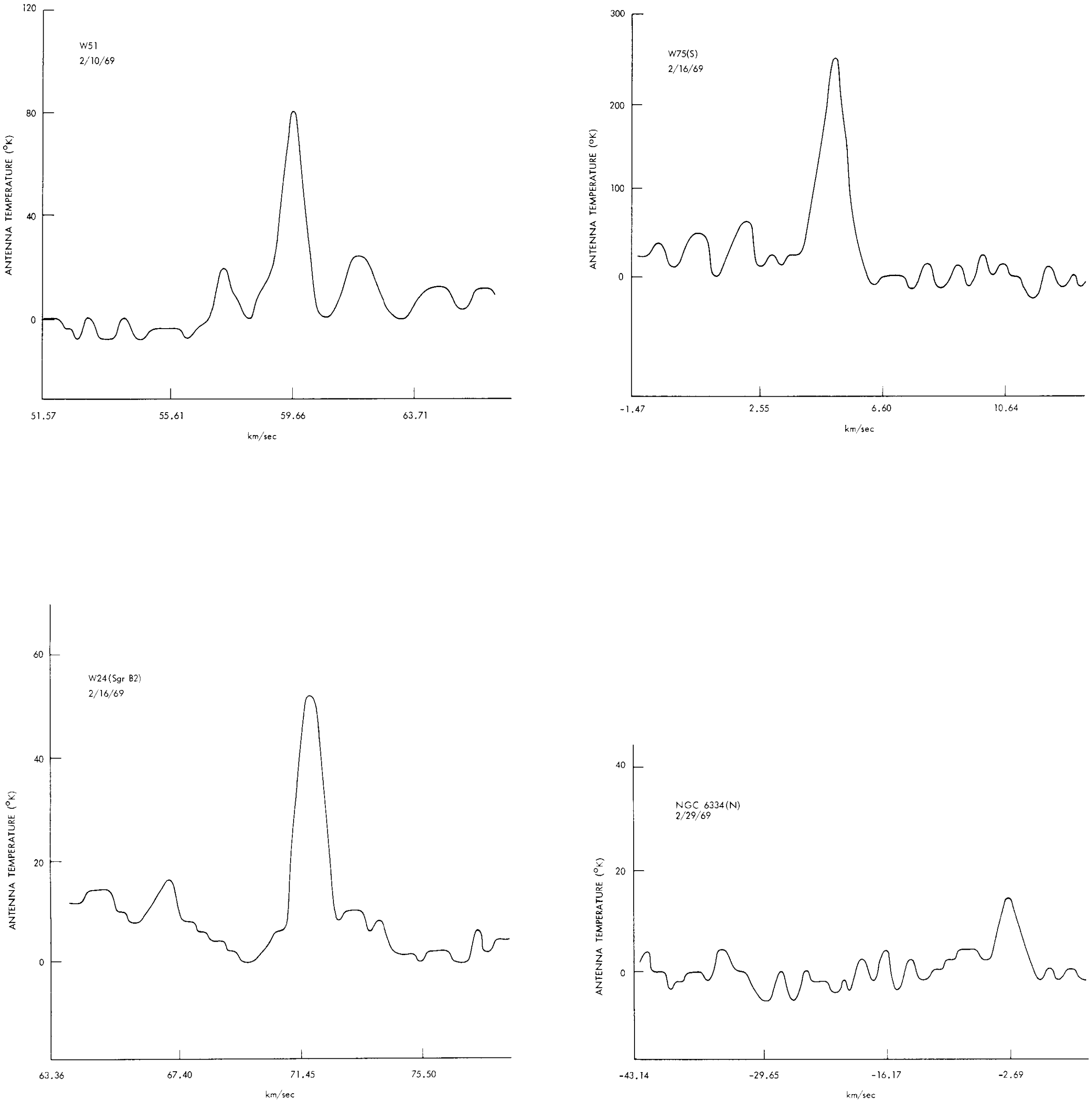

Fig. III-2. (concluded).

between interstellar OH and H_2O. The apparent difference in the polarization properties of the H_2O and OH radiation suggests that different emission mechanisms may be operating in the two cases.

These observations were made jointly with M. L. Meeks and J. C. Carter, of Lincoln Laboratory, M. I. T., and W. E. Brown III, of NASA Electronics Research Center.

A. H. Barrett, P. Rosenkranz, P. R. Schwartz,
J. W. Waters, W. J. Wilson, C. A. Zapata

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G. 20-CHANNEL DIGITAL SYNCHRONOUS DETECTOR

A set of 20 filters with 500-kHz bandwidth covering the frequency range 25-35 MHz were constructed for the 20-channel synchronous detector described in a previous report.[1] This system was taken to Haystack and operated in parallel with the correlator during the interstellar observations described in Section III-F. Although its output agreed qualitatively with that of the correlator, the noise in the 20-channel system was an order of magnitude larger because two command signals were asynchronous. This problem has since been solved.

J. W. Waters

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