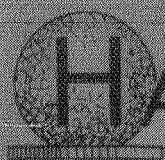


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Quarterly Report of the

HAYSTACK OBSERVATORY

MASSACHUSETTS INSTITUTE OF TECHNOLOGY

15 JANUARY 1971

CASE FILE
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Prepared for

NORTHEAST RADIO OBSERVATORY CORPORATION

ERRATA SHEET
for
Quarterly Report of the Haystack Observatory
15 January 1971

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22 March 1971

QUARTERLY REPORT
OF THE
HAYSTACK OBSERVATORY

MASSACHUSETTS INSTITUTE OF TECHNOLOGY

15 JANUARY 1971

Prepared for
NORTHEAST RADIO OBSERVATORY CORPORATION

The programs in radio astronomy are conducted with support from the National Science Foundation under Grants GP-16918 and GP-25865.

The planetary radar investigations are supported under Grant NGR 22-174-003 from the National Aeronautics and Space Administration.

Radar studies of the moon are conducted under Contract NAS 9-7830 with NASA Manned Spacecraft Center, Houston, Texas.

ABSTRACT

Because this is the first Quarterly Report of the MIT Haystack Observatory since it was separated from Lincoln Laboratory on 1 July 1970, some references are made to work done prior to this quarter. Since that date, the antenna and radiometer systems have been used for radio astronomy observations some 2118 hours, largely under programs proposed by visiting investigators from institutions of the Northeast Radio Observatory Corporation (NEROC) consortium. Additionally, the Planetary Radar system has operated for 421 hours in support of radar investigations of the moon and nearer planets, primarily under the direction of members of the Observatory staff.

Of particular interest are several Very Long Baseline Interferometer (VLBI) experiments in conjunction with other observatories, such as National Radio Astronomy Observatory (NRAO), Kitt Peak, Owens Valley, and the 210-foot Goldstone (JPL) antenna. The Goldstone-Haystack interferometer, for example, the most sensitive VLBI combination yet utilized, provided the basis of an apparent new confirmation of the gravitational bending predictions of the theory of general relativity. The technique is also being developed into a powerful tool for geodetic measurements and for the high-resolution analysis of complex radio sources.

Spectral line observations have received added impetus by the completion of a new high-speed 100-channel digital correlator which affords a 20-MHz "window" at maximum clock rate.

An X-band radar interferometer using Haystack and a 60-foot reflector of MIT Lincoln Laboratory located 4000 feet away has been used to demonstrate the measurement of lunar topography with an error of a few hundred meters.

Improvements in signal processing methods and computer analysis of planetary radar data are making possible improved estimates for the over-all geometric shape of the equatorial regions on Mercury and Venus; indeed, resolution of relatively small topographical features is proving possible in the case of Venus.

Plans for an April-December radar observing period for Mars centered on the 1971 opposition are being completed. A new hardware signal decoder has been completed and this, together with higher radar performance and a closer planetary approach, should yield an excellent body of topographic and reflectivity data.

FOREWORD

This is the first regular Quarterly Report of the Haystack Observatory, a former Lincoln Laboratory research facility provided by the U.S. Air Force, which has been operated since 1 July 1970 by Massachusetts Institute of Technology for the Northeast Radio Observatory Corporation (NEROC), a nonprofit corporation of thirteen educational and research institutions.

It is intended through this one series not only to report on Haystack activities to the member institutions of NEROC, but also to provide current information to the National Science Foundation and the National Aeronautics and Space Administration which, through grants to NEROC, provide primary support for the programs in radio and radar astronomy at Haystack.

It is intended also to cover planning activities and engineering developments which would not ordinarily be published in the scientific journals.

NORTHEAST RADIO OBSERVATORY CORPORATION

A nonprofit corporation of educational and research institutions formed in June 1967 to continue the planning initiated by the Cambridge Radio Observatory Committee for an advanced radio and radar research facility. In March 1969, by agreement with MIT and Lincoln Laboratory, its interest was extended to the existing Haystack Research Facility to seek means of increasing its availability for research. Since July 1970, NEROC has directed the research at Haystack and has had the primary role in arranging for support.

NEROC Institutions

Boston University
Brandeis University
Brown University
Dartmouth College
Harvard University
Massachusetts Institute of Technology
Polytechnic Institute of Brooklyn
Smithsonian Astrophysical Observatory
State University of New York at Buffalo
State University of New York at Stony Brook
University of Massachusetts
University of New Hampshire
Yale University

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Haystack Observatory Office

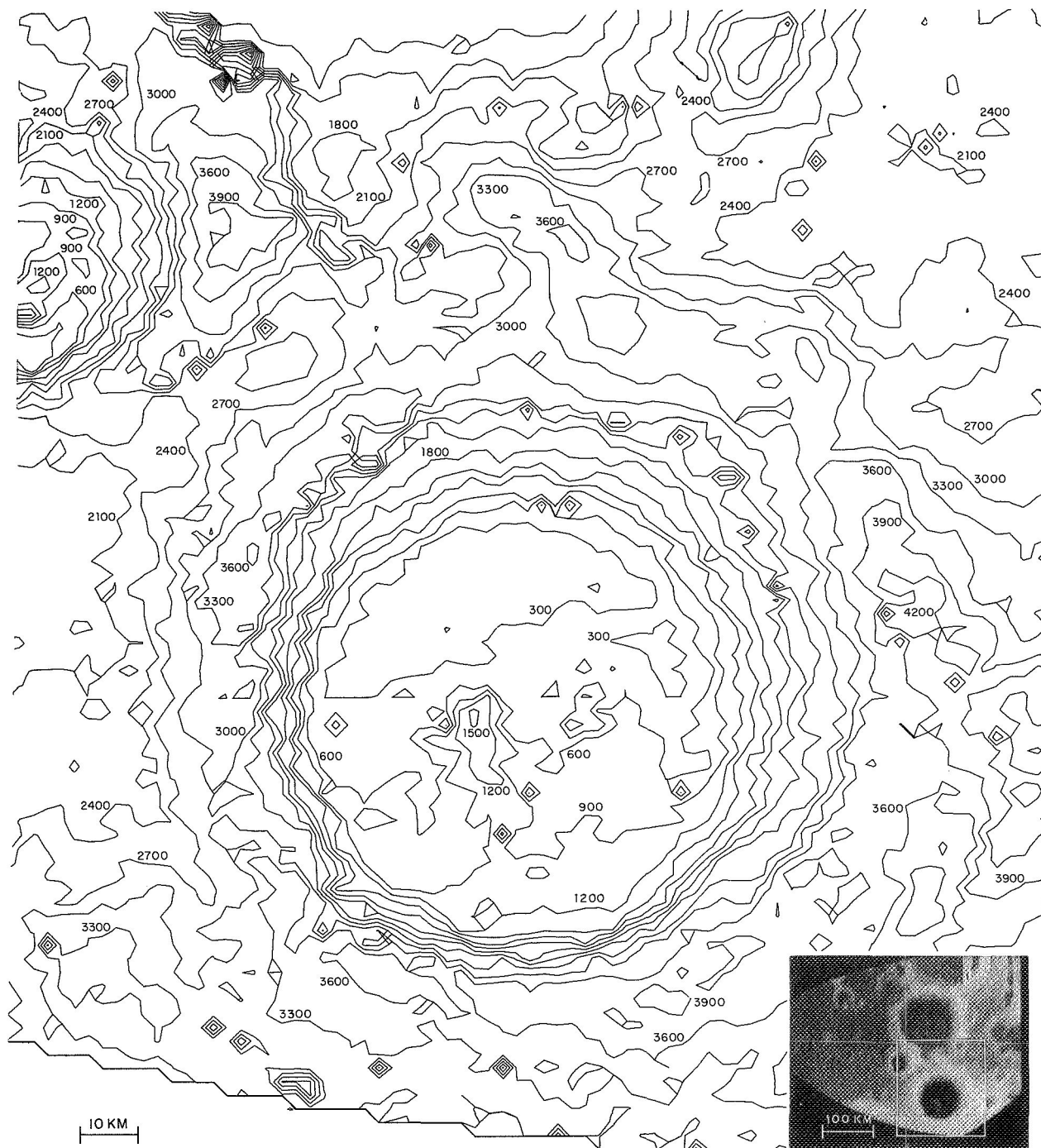
* Alan H. Barrett, MIT
* William A. Dent, University of Massachusetts
† William M. Irvine, University of Massachusetts
† * Edward Lilley, Harvard University
Frank H. McGrory, MIT
* M. Littleton Meeks, MIT, Sec'y, Scientific Committee
† Joel Orlen, MIT
† * Paul B. Sebring, MIT, Chairman
* Irwin I. Shapiro, MIT
McAllister Hull, State University of New York at Buffalo

* Scientific Committee

† Executive Committee

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Contour diagram of area containing Crater Arzachel. Lat. 18°S , Long. 2°W . Contour interval: 300 meters. North at top; East at right. The grey-scale insert shows a larger area in the same region using an alternate display of elevation in which the lighter shading represents the higher regions.

HAYSTACK OBSERVATORY

I. INTRODUCTION

The facilities of the present Haystack Observatory, originally provided by the Air Force for space communications and other microwave research, constitute an unusual national scientific resource. Prior to 1 July 1970, Haystack was operated by MIT Lincoln Laboratory, primarily with support from the Air Force, although auxiliary funding for radar and radio astronomy activities had been provided by both the National Aeronautics and Space Administration and the National Science Foundation in recent years. The major research efforts have for some time been devoted to planetary radar and radio astronomy, partly as a result of trends in satellite communications toward systems not requiring powerful ground terminals such as Haystack.

On 26 February 1970, Dr. Grant L. Hanson, Assistant Secretary of the Air Force for Research and Development, notified Lincoln Laboratory that support for Haystack would be withdrawn by 1 July 1970, and simultaneously wrote to the Director of NSF and the Administrator of NASA, stating in part, "The key factors that led to the DoD decision to discontinue support for Haystack were the need for higher priority DoD efforts at Lincoln Laboratory and the constraints imposed by Section 203 of the Fiscal Year 1970 Military Procurement Authorization Act." The letter offered cooperation to "... any other government agency which ... can commit resources for the operation of Haystack."

Following this, the Northeast Radio Observatory Corporation (NEROC) and Lincoln Laboratory representatives held discussions with both NSF and NASA at which it was learned that neither agency could then assume full responsibility for Haystack. Both, however, indicated that some support could be provided for research programs at Haystack were Haystack a university-owned and operated observatory.

At subsequent NEROC-MIT-Lincoln Laboratory meetings, it was decided that ownership of the Observatory by MIT would be appropriate, and that MIT should propose to operate it under NEROC direction. NEROC would submit the research proposals and administer any resulting grants through sub-grant arrangements with MIT. The Air Force subsequently concurred in the transfer of the Haystack facilities to MIT.

In response to proposals subsequently submitted, the National Science Foundation has provided support for one year for programs in radio astronomy, while the National Aeronautics and Space Administration has provided funds covering a similar period for radar studies of Mercury, Venus and Mars. NASA Manned Spacecraft Center also funded a one-year extension of a previously existing contract with MIT for radar measurements of lunar topography.

Under the present level of support the Observatory has, since 1 July 1970, been utilized for scientific purposes an average of about 100 observing hours per week, while 15 to 20 hours per week have been devoted to maintenance and/or system improvements.

Haystack is one of the better radio telescopes available for work in the wavelength regions between 6 cm and 8 mm. For example, its large size gives it a larger effective aperture and a finer mapping resolution at 8 mm than most other millimeter wave instruments. It is an excellent instrument at H_2O vapor wavelengths (1.4 cm). The computer complex also makes possible considerable data processing on-site, including the generation of intensity and contour maps, spectral plots, etc.

The Planetary Radar system constitutes one of only three radars extant (Goldstone, Arecibo, and Haystack) which can support studies of the surfaces, motions, and topography of the moon, Venus, Mercury, and Mars. These systems are complementary rather than competitive for many experimental purposes because of their differing wavelengths: 70 cm for Arecibo, 12.5 cm for Goldstone (which has only limited time available for astronomy), and 3.8 cm for Haystack.

As of early November, there were sixteen active radio observing programs and four active planetary radar programs being conducted by students, faculty, and staff from nine educational and research institutions.

With the present dearth of starts on badly needed new instruments, the preservation of the relatively advanced capability afforded by the Haystack antenna and its associated electronics, precision pointing system, and computers is of considerable importance to radio and radar astronomy in the United States.

II. RADIO ASTRONOMY

A. Summary of Programs

During 1970, Haystack received 39 proposals for research programs using the radiometric facilities. These included 23 for spectral-line observations, 9 for continuum observations, and 7 for very long baseline interferometer (VLBI) experiments. All of these programs are listed in Table I, which includes the names of investigators, their respective institutions, the cumulative amount of observing time used in 1970, and the amount of observing time requested. Table I is divided into Continuing Programs and Completed Programs.

B. Sketches of Selected Visitor Programs

We have chosen a few representative programs from the Table of Programs (Table I) to present a somewhat more detailed description of some of the kinds of observing programs conducted at Haystack Observatory during the last quarter. These sketches, edited from the experimenters' notes, are organized under the following headings: Spectral-Line Programs, Continuum Programs, and VLBI Programs.

1. Spectral-Line Programs

Diego Cesarsky
Harvard College Observatory

Observations of 66α Recombination Lines at 22.364 GHz

HII regions must be assumed to be out of thermodynamic equilibrium in order to explain the observed variation of recombination-line intensity with frequency. The very-high-frequency recombination lines appear, on the basis of measurements by Churchwell, *et al.*, to reflect non-equilibrium effects even though these effects are expected to be small. This discrepancy, if confirmed, will necessitate a re-evaluation of the current models of HII regions. In this investigation, the $H66\alpha$ transition in Orion A and in M17 are being measured with a higher signal-to-noise ratio than previously achieved. These measurements are in progress with the radiometric system used primarily for water-vapor observations which gives a single-sideband noise temperature of 1600°K. Measurements thus far have achieved the expected sensitivity, but observations and data reduction are not yet complete.

Dale F. Dickinson
Smithsonian Astrophysical Observatory

A Search for Extragalactic Water-Vapor-Emission Sources

The galaxy M33 contains three large HII regions – NGC 604, 595, and 588 – the first region listed being one of the largest such regions observed optically. At the 630-kpc distance of this galaxy we would expect an antenna temperature of about 1°K from a water-vapor source as powerful as the source in W49 within our own galaxy. Although no 22,235-GHz water-vapor emission was detected, it was possible to set upper limits somewhat below this estimate. For NGC 602 and 588, the upper limits obtained thus far are 0.4°K and for NGC 595 the limit is 0.8°K. Water-vapor emission is the most intense of the molecular linars observed thus far, and a successful detection would establish the exact radial velocity of the region and make feasible a search for other extragalactic linars. The search will continue.

David H. Staelin and John Rudzki
Massachusetts Institute of Technology

A Search for the 101-GHz Mesospheric Emission Line of Ozone

Photochemical theories of the upper atmosphere make it possible to predict a diurnal variation of the ozone concentration in the mesosphere, which should be detectable radiometrically from the ground. The presence of an ozone layer, with number densities of approximately 10^{12} cm^{-3} at elevations of about 25 km is well established from in situ measurements. At 70 km, the ozone concentration is predicted to vary diurnally from about 10^8 to 10^{10} cm^{-3} with the maximum density at night. The ozone transition at 101.737 GHz on the basis of theory should produce a signal with a maximum amplitude of 16°K.

The experimenters provided a horn antenna and a radiometer which was connected to the autocorrelation spectrometer at Haystack, and they made an extensive search, primarily at night, for ozone emission. Only mesospheric ozone could have been detected because pressure broadening at lower elevations would produce emission with a bandwidth very much wider than that of the spectrometer. The experiment thus far has failed to detect the expected nighttime maximum indicating that the mesospheric ozone concentration does not vary as widely as predicted.

2. Continuum Programs

Hugh M. Johnson
Lockheed Missiles and Space Company, Palo Alto, California

Radio Frequency Observations of Symmetric Nebulae Around Wolf-Rayet Stars and of an Of Star

Symmetric nebulae are observed optically around the Wolf-Rayet stars HD 50896 and HD 192163 and around the Of star BD+60°2522. The continuum flux of these objects was measured at 7.795 GHz. The latter object, NGC 7635, has a nonthermal microwave spectrum, but it is distinguished from supernova remnants by the presence of the star. Nine more Wolf-Rayet stars were scanned at 7.795 GHz, and emission was detected from one of them, HD 211853. A negative correlation between the mass of a nebula around a Wolf-Rayet star and its distance from the galactic plane is suggested by these observations.

TABLE I
1970 RADIOMETRIC OBSERVING PROGRAMS*
HAYSTACK OBSERVATORY

Continuing Programs as of 31 Dec 70	Investigators	Institutions	Observing Time Used Through 31 Dec 70 (hours)	Hours Requested	Designation
Search for Spectral Lines Around 18.4 and 20.1 GHz	C. A. Gottlieb, H. Penfield A. Penzias	Harvard College Observatory Bell Telephone Laboratories	0	120	GOTT LIEB-4
22-GHz Mapping of Galactic Center Region	M. L. Meeks Shelley Rogers†	Haystack Observatory MIT Physics Department	0	72	MEEKS-3
7.8-GHz Recombination Line Studies (94α) of the Follow- ing Sources: Tau A, Ori A, NGC 2024, Sgr A, W49 & Diffuse Background	E. J. Chaisson	Harvard College Observatory	0	216	CHAISSON-4
7.84-GHz Measurements w/240-ft Goldstone Antenna to Determine the Structure and Spectra of Extra- Galactic Sources	M. H. Cohen D. Jauncey K. I. Kellerman	California Institute of Technology Cornell University National Radio Astronomy Observatory	0	48 VLBI, 24 continuum flux measurement	VLBI-7
7796-MHz Helium Recom- bination Lines (94α), M17 Observations	D. Cesarsky†	Harvard College Observatory	9	32	CESARSKY-3
4830-MHz Formaldehyde Mapping	P. C. Myers† A. H. Barrett	Massachusetts Institute of Technology	82	60	MYERS-1
7792-MHz Recombination Lines, Search of Planetary Nebulae	L. E. Goad†	Harvard College Observatory	12	72	GOAD-1
22.234-GHz VLBI w/NRL, NPAO, & Soviet Union (Crimea)	B. F. Burke, C. Papa, P. R. Schwartz† J. M. Moran S. H. Knowles W. T. Sullivan	Massachusetts Institute of Technology " " " Smithsonian Astrophysical Observatory Naval Research Laboratory University of Maryland and unspecified USSR astronomers	31	216	VLBI-6

* Prepared by M. L. Meeks, 6 Jan 71.

† Graduate student.

TABLE I (Continued)

Continuing Programs as of 31 Dec 70	Investigators	Institutions	Observing Time Used Through 31 Dec 70 (hours)	Hours Requested	Designation
15-GHz Mapping of Westerhout Sources ($\delta < 0^\circ$)	M. A. Gordon J. A. Ball, E. J. Chaisson [†]	National Radio Astronomy Observatory Harvard College Observatory	179	200	GORDON-1
3.8-cm Mapping of Active Solar Regions	J. Aarons, R. M. Straka, D. W. Richards	AF Cambridge Research Laboratory	36	400	AFCRL-2
8- & 15-GHz Monitoring of Quasars & Peculiar Galaxies	W. A. Dent	University of Massachusetts/Amherst	843	50/month	DENT-1
23-GHz Ammonia Transitions, A Search for Jupiter	J. R. Dickel M. L. Meeks	University of Illinois Observatory Haystack Observatory	32	64	DICKEL-1
23-GHz Ammonia Transitions, A Search for Galactic Sources	M. L. Meeks J. R. Dickel	Haystack Observatory University of Illinois Observatory	32	64	MEEKS-2
8.0-GHz Recombination Line Measurements (94 α), A Survey	E. J. Chaisson, [†] J. A. Ball, A. E. Lilley	Harvard College Observatory "	225	225	CHAISSON-1
101-GHz Ozone Emission from the Atmosphere, A Search	J. Rudzki [†] J. W. Waters [†] D. H. Staelin	Massachusetts Institute of Technology	262	275	STAEIN-1
22.36-GHz Recombination Line Measurements (66 α)	D. Cesarsky [†]	Harvard College Observatory	150	56	CESARSKY-2
8.0-GHz Recombination Line Measurements (94 α) in the Cygnus X Region	E. J. Chaisson [†]	Harvard College Observatory	38	120	CHAISSON-3

[†] Graduate student.

TABLE I (Continued)

Completed Programs	Investigators	Institutions*	Total Observing Time (hours)
VLBI Measurements of Excited OH Emission at 6 GHz (Telescopes: Haystack, NRAO 140-foot and Onsala, Sweden, 85-foot)	J. A. Ball T. Clark M. L. Meeks, J. M. Moran P. Palmer O. E. H. Rydbeck J. L. Yen B. Zuckerman	Harvard College Observatory NASA/Goddard Lincoln Laboratory University of Chicago Chalmers University of Technology (Sweden) University of Toronto University of Maryland	48
VLBI Measurement of Relative Positions of OH Emission Features at 1665 and 1667 MHz	J. A. Ball M. L. Meeks, J. M. Moran O. E. H. Rydbeck	Harvard College Observatory Lincoln Laboratory Chalmers University of Technology (Sweden)	48
22-GHz Water Vapor Sources, Monitoring of Time Variations	M. L. Meeks	Haystack Observatory	290
Search for the 9.9 GHz Lamb-Shift Transition in Galactic Sources	P. C. Myers, A. H. Barrett	MIT Physics Department	288
22-GHz VLBI Observations, In- volving NRL 85-ft, NRAO 140-ft, and NRAO 36-ft (Kitt Peak) Antennas	B. F. Burke, C. Papa, P. R. Schwartz,† G. D. Papadopoulos† J. M. Moran M. L. Meeks S. H. Knowles W. T. Sullivan J. Welch	Massachusetts Institute of Technology " " " Lincoln Laboratory Haystack Observatory Naval Research Laboratory University of Maryland University of California/Berkeley	128
Search for Emission from Various Excited States of OH around 6, 8, and 23 GHz	J. A. Ball, C. A. Gottlieb, A. E. Lilley D. F. Dickinson, H. E. Radford J. W. Waters†	Harvard College Observatory " " " Smithsonian Astrophysical Observatory MIT EE Department	50 28
Search for Stratospheric Water Vapor Absorption Against the Sun	C. A. Gottlieb, A. E. Lilley H. E. Radford	Harvard College Observatory Smithsonian Astrophysical Observatory	56
Search for 8-GHz Emission from X-ray Sources	A. H. Barrett	MIT Physics Department	24
Observations of Solar Brightness Oscillations at 23 GHz	M. Simon, P. Burger†	State University of New York at Stony Brook, Long Island	38

* Affiliations at the time of the program.

† Graduate student.

TABLE I (Continued)

Completed Programs	Investigators	Institutions	Total Observing Time (hours)
35-GHz Solar Maps	P. Kalaghan [†] E. Altshuler, F. H. Cleveland, L. E. Telford	Harvard College Observatory AF Cambridge Research Laboratory " " "	56
Mapping of 7.8-GHz Recombi- nation Lines in the Orion Nebula	J. A. Ball, A. K. Dupree L. Goldberg, A. E. Lilley	Harvard College Observatory	71
Mapping of 23-GHz Recombi- nation Lines in the Orion Nebula	J. A. Ball, A. K. Dupree L. Goldberg, A. E. Lilley	Harvard College Observatory	10
Observations of the Solar Eclipse (7 March 70)	M. Simon, P. Burger [†]	State University of New York at Stony Brook, Long Island	8
22-23-GHz Search for H ₂ O and NH ₃ on Jupiter	A. E. Lilley M. L. Meeks	Harvard College Observatory Haystack Observatory	16
VLBI Measurements of Solar Gravitational Deflection (w/Goldstone 210-ft Antenna)	B. F. Burke, I. I. Shapiro R. M. Goldstein T. A. Clark A. E. E. Rogers	Massachusetts Institute of Technology NASA & Jet Propulsion Laboratory NASA/Goddard & University of Maryland Haystack Observatory	81
Search for SO Transitions Around 30GHz	A. H. Barrett	Massachusetts Institute of Technology	98
VLBI Equipment Checkout	S. Criswell, R. Michelini	Smithsonian Astrophysical Observatory	12
7.9-GHz Observations of Star- Like Objects	H. M. Johnson	Lockheed Palo Alto Research Laboratory	36
22-GHz Water Vapor Transition, A Search for Extragalactic Sources	D. F. Dickinson	Smithsonian Astrophysical Observatory	108
22-GHz Water Vapor Transition, A Search of Infrared Sources	P. R. Schwartz, [†] A. H. Barrett	Massachusetts Institute of Technology	255
Search for Two Molecular Transitions Around 22 GHz	D. F. Dickinson A. E. Lilley	Smithsonian Astrophysical Observatory Harvard College Observatory	66

† Graduate student.

Mark A. Gordon, John A. Ball,* and Eric J. Chaisson*
National Radio Astronomy Observatory, *Harvard College Observatory

Mapping of Westerhout Sources of Negative Declination

Haystack is a good instrument for reliably mapping negative-declination sources in the Westerhout catalog at 7.8 and 15.5 GHz, since the reflector tolerance and pointing remain good at low elevation angles. System parameters used in this program are as follows:

	<u>7.8 GHz</u>	<u>15.5 GHz</u>
Beamwidth	4.4 arc min	2.2 arc min
System Temperature	80° K (including ferrite switch)	900° K (TDA)
Bandwidth	15 MHz	1 GHz

A series of repeated drift scans is made over these source regions, and the data are processed into maps by means of the automated mapping program and display system on the CDC 3300. Thus far, the investigators have mapped a region nearly 2 degrees square in the vicinity of W41 at 7.8 GHz and additional selected sources at 15.5 GHz.

3. Very Long Baseline Interferometry (VLBI)†

Haystack Observatory, MIT, and Goddard Space Flight Center

Geodetic Applications

Interferometry observations between Haystack and the 140-foot-diameter NRAO antenna at Green Bank, West Virginia have been used to demonstrate the capabilities of VLBI for precision geodetic measurements. The MIT-developed frequency-switching technique was used at L-band in January 1969 and at X-band in October 1969 to determine the vector separation of the two sites. The results obtained from study of these data during this year are presented in Table II and are compared with the best available results from conventional geodetic survey data. Both from the internal consistency and from the comparison with the survey, it appears that the VLBI results are in error by only a few meters. The baseline declination is the most poorly determined of the components, primarily because of the paucity of observations of high-declination sources in those experiments.

The precision of these VLBI baseline measurements can be improved, perhaps by several orders of magnitude, by eliminating the fringe ambiguity. This can be accomplished by a small improvement in the frequency-switching technique and by simultaneous observation at two widely separated frequency bands. The latter is required to deduce the plasma effect; the former can then be used to eliminate the fringe ambiguity. The accuracy of the resultant baseline determinations will depend on the degree of success in deducing the (nondispersive) effects of the neutral atmosphere.

This VLBI technique will be applicable to intercontinental geodesy where conventional techniques are far less accurate.

Haystack Observatory, MIT, Goddard Space Flight Center,
Jet Propulsion Laboratory, and University of Maryland

Gravitational Deflection of Radio Waves

In early October 1970, Haystack and the 210-foot-diameter JPL antenna at Goldstone were combined to form an extremely sensitive X-band radio interferometer. The "Goldstack"

†Names of individual experimenters are omitted because of the large number involved.

TABLE II
HAYSTACK – GREEN BANK BASELINE PARAMETERS*

	Length (km)	Hour Angle (hr)	Declination (deg)
Geodetic Survey	845.130	4.736 035	-24.670 29
VLBI 1	845.133	4.736 010	-24.670 64
VLBI 2	845.132	4.736 004	-24.670 65
VLBI 3	845.133	4.736 004	-24.671 01
VLBI 4	845.129	4.736 004	-24.669 83
VLBI 5	845.129	4.736 004	-24.669 84
VLBI 6	845.133	4.736 030	-24.670 20
VLBI 7	845.132	4.736 009	-24.670 13
VLBI 2 – Survey	0.002 (≈ 2 m)	-0.000 031 (≈ -6 m)	-0.000 36 (≈ -5 m)
VLBI 1	From January 1969 experiment without atmospheric and ionospheric corrections		
VLBI 2	From January 1969 experiment with atmospheric and ionospheric corrections		
VLBI 3	Same as above except <u>a priori</u> uncertainties in source coordinates were included		
VLBI 4	Same as 1 except using data from October 1969		
VLBI 5 VLBI 6	From October 1969, using 2 disjoint sets of sources, source positions fixed		
VLBI 7	From October 1969, solving for 3 clock parameters, 3 baseline components, and 7 sources		

* The baseline vector points from Haystack to Green Bank.

NOTE: 10^{-5} hr ≈ 2 m and 10^{-4} deg ≈ 1.5 m for this baseline.

interferometer arrangement was possible because of the prior rerigging by JPL of the Goldstone low-noise X-band maser receiver to make it compatible with the Haystack 7840-MHz radar transmitter frequency for bistatic planetary radar experiments. The goal of the October 1970 experiment was to detect the relative gravitational deflection by the sun of radio waves from the quasars 3C279 and 3C273. The former is occulted by the sun each October 8th.

Fringe rate and fringe phase were measured but only in a narrow band; frequency switching was not employed. Two recorders were employed at each site, and observations were made for about 5 hours on each of 12 days that surrounded the occultation. The observations were made in five-minute cycles: approximately two minutes "on" 3C279, one minute to move antennas, one minute "on" 3C273, and one minute to move antennas back to 3C279. Over 700 miles of magnetic tape were obtained with well over 90 percent of the tapes yielding fringes.

To obtain the highest precision in the measurement of the solar gravitational deflection, it is necessary to interpolate fringe phase between successive observations without introducing any 2π ambiguities. It is not yet clear whether the short-term variations in fringe phase introduced by the solar corona will present a serious problem in the interpolation process.

In any event, preliminary results have already been obtained for the fringe-rate data. These, although intrinsically far less accurate for the purposes of the deflection experiment, do not suffer

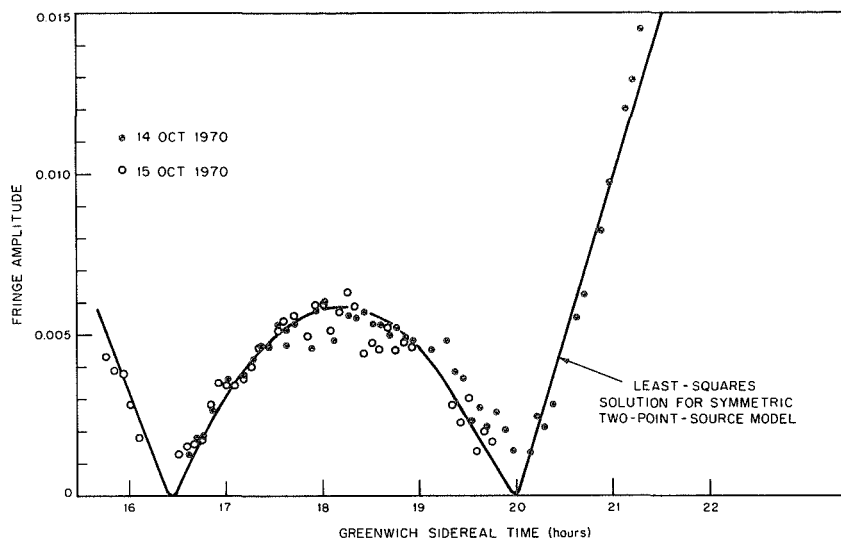


Fig.1. Fringe amplitudes obtained on Quasar 3C279 with Goldstone-Haystack VLBI, 14 and 15 October 1970. (15 October data adjusted to UT scale for 14 October.)

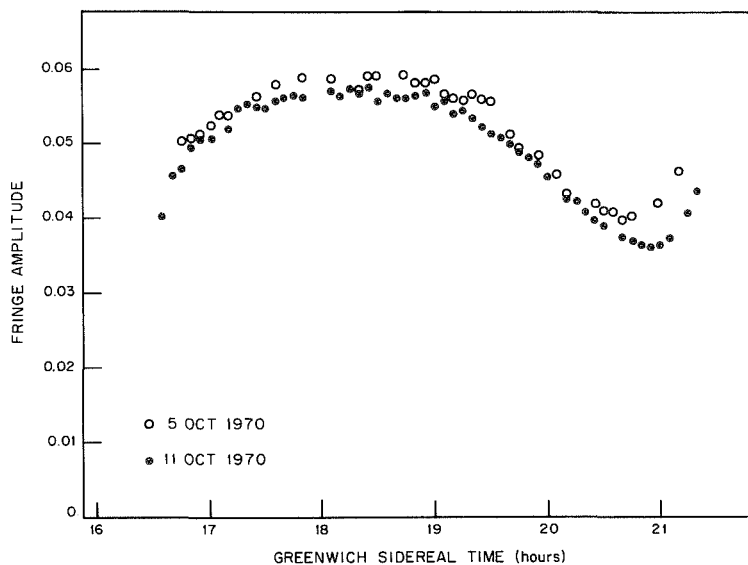


Fig.2. Fringe amplitudes obtained on Quasar 3C273 with Goldstone-Haystack VLBI, 5 and 11 October 1970. (Corrected for atmospheric absorption and emission.)

appreciably from ambiguity problems. We find that the data are in agreement with the gravitational deflection predicted by general relativity, but that the uncertainty is about 15 percent.

We expect to improve this figure somewhat with further analysis of the fringe-rate data. Results from the fringe-phase analysis will probably not be available for several more months.

Haystack Observatory, MIT, Goddard Space Flight Center,
Jet Propulsion Laboratory, and University of Maryland

Quasar Structure at the Millisecond-of-arc Level

The October 1970 "Goldstack" experiment described above also yielded very precise determinations of fringe amplitude for both 3C279 and 3C273. The variations in the amplitudes with sidereal time, repeatable with high accuracy from day to day, show that both sources were at least partially resolved with this interferometer. After these data were corrected for the known effect of atmospheric absorption and emission, it was found that the fringe amplitudes shown in Fig. 1 for 3C279 were well represented by a source-structure model that consists of two point sources of equal strength separated by $0''.00272 \pm 0''.00002$ in right ascension and $0''.0037 \pm 0''.0001$ in declination (formal standard errors). A model with two point sources of unequal strength appears to fit the fringe amplitude curve of 3C273 shown in Fig. 2.

It must be emphasized that, although these are the simplest models that represent the data well, they are not unique; other more complicated brightness distributions may yield equally good representations.

These remarkable results on quasar fine structure provide tantalizing clues to the physical makeup of these objects. The precision with which the separation of the various parts can be determined implies that proper motions would be observable in a few years if the parts were moving transverse to the line of sight with speeds a reasonable fraction of the speed of light. If such motions are detected, they may allow a useful upper limit to be placed on the distances to these quasars.

MIT, Naval Research Laboratory, Smithsonian Astrophysical Observatory,
and University of California, Berkeley

Observations of Water Vapor Sources in W49

A map of the water vapor radiation from the HII region W49 has been constructed from VLBI observations made in June 1970 by visiting investigators from the Naval Research Laboratory and the Smithsonian Astrophysical Observatory. The source is found to be composed of individual features less than $0''.0005$ in apparent size. The map shown in Fig. 3(a) was made using the 120-foot Haystack antenna, the 140-foot Green Bank antenna, and the 36-foot antenna at Kitt Peak, Arizona. The longest baseline, from Haystack to Kitt Peak, which was 2.7×10^8 wavelengths, was still insufficient to resolve the strongest emission feature (at -1.8 km sec^{-1}), implying an angular size of less than $0''.0003$ for this feature.

This map was obtained from the fringe rates of the features relative to the -1.8 km sec^{-1} feature for 24 pairs of tapes made on 21 June 1970. An example of the interference spectrum from one pair of tapes is shown in Fig. 3(b). The centroid of these water-vapor emission features is found to be within $2''$ in right ascension and $8''$ in declination of the OH emission features.

C. Radiometric Instrumentation

This section discusses progress in the development of proposed radiometers; the evaluation, calibration, and improvement of existing systems; and the development of new computer software for the digital control systems and for data processing.

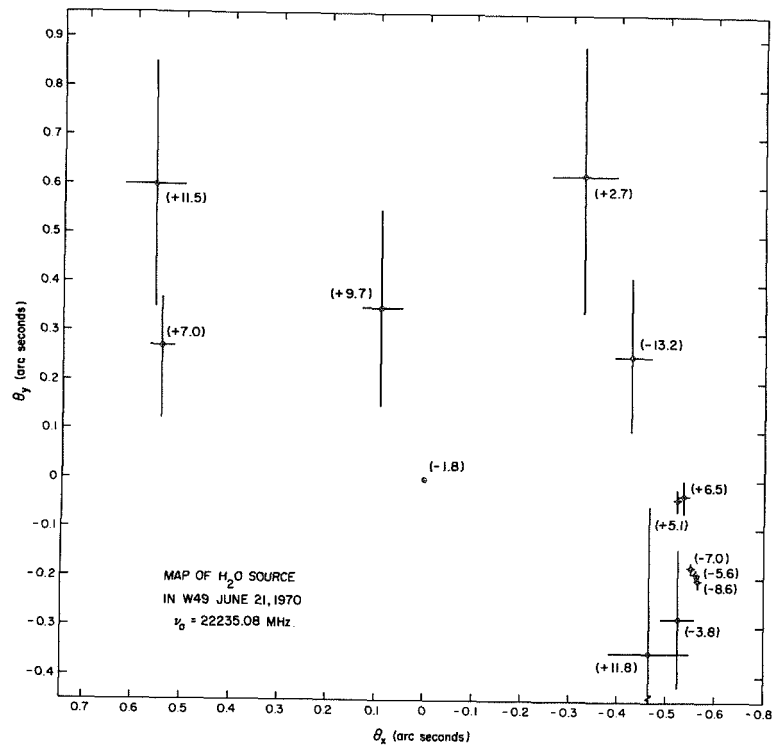


Fig. 3(a). Map of relative positions of features in water-vapor spectrum of W49.

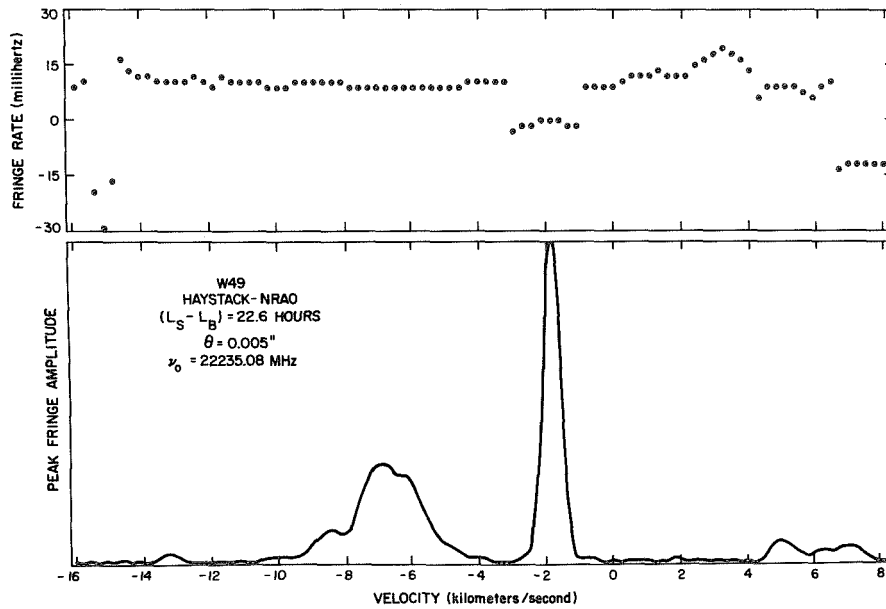


Fig. 3(b). Example of interference spectrum of W49 water-vapor source taken with fringe spacing of 0.005".

1. Proposals Under Consideration

The University of Massachusetts plans to assist in providing a new 15.5-GHz tunnel diode amplifier to combine with the present TDA system in the Radiometer Box to form a dual-channel continuum radiometer system. The two amplifiers would be synchronously switched, 180° out of phase, between the signal and comparison feeds, and the outputs combined after synchronous detection into a single radiometer output. Sensitivity will be improved since the signal feed will be connected to an amplifier at all times in the switching cycle.

During the summer, two 22- to 24-GHz mixer and IF preamplifier units were acquired from Aerojet General, and these were installed in the Radiometer and Planetary Radar Boxes in August. With their 900°K double-sideband noise temperature, these units have proved valuable for water-vapor spectral-line observation. We plan to combine these two units to form a continuum radiometer with 200-MHz bandwidth to complement the pointing precision and 1.5 arc-minute beamwidth of the telescope in this frequency range. If the tests planned for early 1971 confirm the gain stability of this unit, we will construct a dual-channel radiometer system similar to the 15.5-GHz system described above.

Haystack has not had a digital VLBI data recording terminal similar to those developed by NRAO and called "Mark I." The CDC 3300 computer has been programmed to format and record VLBI data on magnetic tape. This task, which makes trivial use of the computer's capability but yet prevents other programs' using it for long periods, is more properly done by a special-purpose formatter and control unit working with a standard high-performance tape drive. With support from MIT, it may be possible to assemble such a unit, thus freeing considerable amounts of 3300 time.

Considerable 3300 time has also gone into the correlation of tapes from cooperating VLBI telescopes to derive fringe amplitudes, rates, etc. This process could be greatly accelerated if the correlation itself were done in a special-purpose device between the tape playbacks and the computer. This is a project of modest size and it may be possible to accomplish it in the next few months.

Despite the impending advent of the Mk II VLBI system (see below), low operating costs, simplicity, and adequate capability for many experiments will probably keep the Mk I technique useful for a long time.

2. Mark II VLBI Recording Terminal

The National Radio Astronomy Observatory developed a concept for recording much wider bandwidths during VLBI experiments. The higher data rate affords the possibility of more precise baseline determinations, better positions on the objects observed, etc. Along with a number of other observatories and under NRAO coordination, Haystack has arranged, with MIT and Harvard support, to procure one of the so-called "Mk II" terminals built under this concept by Leach Corporation to NRAO specification. Currently, NRAO is coordinating certain final changes to all the units prior to delivery.

3. 22- to 24-GHz Maser Amplifier Development

With the cooperation of Prof. Sigfrid Yngvesson of the University of Massachusetts/Amherst, a project has been undertaken to construct a maser amplifier operating at the frequencies of the ammonia and water-vapor transitions. The maser design follows that developed by Prof. Yngvesson while he was at the University of California/Berkeley with Prof. Charles Townes.

The first step involved converting hand sketches to working drawings. The magnet-circuit component drawings have been completed, and several sets of parts have already been machined. Other parts, for which the components are either on hand or readily available, are now being fabricated.

The second area of attack, a more complex and critical portion, is the support for the ruby and microstrip transmission lines. The support must be made of molybdenum, and the task of forming and plating this difficult-to-machine material will be undertaken by an outside shop. Vendors have been located for components not available on-site, such as pump tubes, associated waveguide components, dewars, etc. Drafting and design modification are also continuing.

4. Evaluation and Improvement of Existing Systems

The two Aerojet General low-noise receivers for the range 22 to 24 GHz have been installed – one each – in the Radiometer and Planetary Radar Boxes, providing an observing capability in this frequency range whichever box is installed at the focus of the antenna.

Increased use of the Planetary Radar Box for spectral-line observations at a variety of frequencies has led to providing the local oscillator system with three phase-locked klystrons: one for the radar, one for 4-cm radiometry, and one for 1.5-cm radiometry. As a result, most system changeovers between different wavelengths can be accomplished from the control room by the observer.

The 4.8-GHz system installed in the Radiometer Box for formaldehyde observations incorporated a parametric amplifier borrowed from the Harvard group. This system gave a disappointingly high system temperature (about 350°K), and we hope to supplement it with a lower-noise parametric amplifier borrowed from the National Radio Astronomy Observatory.

At the end of the summer, a new digital correlator providing spectrometer bandwidths as wide as 20 MHz was installed. A new frequency converter for this correlator was installed early in December 1970. Although its performance has been generally good, some baseline stability problems at 20-MHz bandwidth became apparent. Baseline stability is often a problem with wide-band spectral-line radiometers, usually as a result of instabilities in the RF or IF sections of the receiver. In this case, the new converter appears partly at fault, and we are in the process of correcting it.

The radiometric schedule involves frequent changes in equipment setup. In order to facilitate these changeovers and to avoid blunders in interconnecting various components, we have installed a new IF distribution system and are placing block diagrams on control panels to clarify the various IF configurations. A new large sectionalized block diagram of the radiometer setup is also being constructed on a free-standing frame to be located conveniently in the control room.

5. Software Development

a. Univac 490 Pointing System

At the request of visiting investigators, the master control program for the pointing system was modified to provide two additional scan options for frequently used observing procedures: (1) for a sequence of ON-OFF observations, a scan option is now available to cycle the antenna beam between two pointing positions with the time interval and number of iterations specified by the observer; (2) for source mapping with a grid of drift scans, a multiple drift-scan option is now available which permits the scan intervals, declination offsets, and the number of scans to be specified by the observer.

b. Very Long Baseline Interferometer (VLBI) Programs

Some additions to the VLBI recording programs FORHANS written by J. A. Ball (Harvard) have been made by Alan Whitney (MIT). These additions include a time identification word written from the Haystack real-time clock at the beginning of each record and the ability to split up a tape into several runs starting and stopping at prescribed times. This new version of FORHANS was used during the October 1970 relativity experiment to make tapes containing one 3C273 and one 3C279 run.

Several VLBI processing programs now exist for the CDC 3300 computer which process spectral-line VLBI data (written by J. M. Moran of SAO) and frequency-switched continuum VLBI data (written by C. A. Knight and A. Whitney of MIT). These programs are becoming more general and better documented, and they should be generally usable by VLBI experimenters in the near future. Plans to interface a digital correlator with the CDC 3300 computer show promise of speeding up VLBI data processing by about a factor of fifty. This development will require standardization of a VLBI correlation program.

III. RADAR ASTRONOMY

A. Lunar Topography

1. Introduction

In accord with the requirement of Contract NAS 9-7830 with NASA Manned Spacecraft Center, Houston, this section reports progress in the Haystack program for the earth-based measurement of lunar topography by interferometric radar techniques. In this method, interferometer phase, radar range, and differential Doppler shift constitute the three dimensions required for topographic determinations. Formerly, this work was reported in a Lincoln Laboratory Quarterly Progress Report series entitled "Radar Studies of the Moon." The most recent of these reports, dated 15 September 1970, outlined the results of the preceding experimental and paper study effort which had demonstrated the feasibility of topographic measurements using the Haystack antenna and the 60-foot antenna of the Westford Communications Terminal (located about 4000 feet from Haystack) as an interferometer* to receive the echoes from the Haystack transmitted signals.

The central portion of the surface visible from earth is presently being mapped. Despite some limitations imposed by the geometry and other factors, it is expected that all of the central 50° cap will be measured with an elevation precision of about 500 meters and a precision of position on the face of the moon of 0.5 to 2 km.

2. Mapping Procedure

Planning of the observations is based on the same system of ZAC (Zenith-Azimuth Coordinates) areas used in the recently completed background mapping of the entire earthside hemisphere.† Because of the improved surface resolution desired for the topography charts, most of the ZAC areas beyond 20° from the mean subearth joint are being measured in two parts, the near and far halves, in order that the higher range resolution can be achieved with only minor changes to existing equipment and data processing programs.

* A. E. E. Rogers and R. P. Ingalls, Radio Science 5, 425-433 (1970).

† Final Report, "Radar Studies of the Moon, Vol. 1" and "Radar Atlas of the Moon, Vol. 2," Contract NAS 9-7830 (28 February 1970).

Calibration of the instrumental phase of the interferometer is accomplished by observing one of two calibration spots (small radar-bright areas on a dark mare background) after each pair of half-ZAC map measurements. The time-dependence of the instrumental phase is then known on the scale of an hour, which is sufficient under most conditions for the interpolation of the phase value during the ZAC measurement.

3. Progress to Date

Aside from observing periods in December and early January, most of the quarter has been utilized for building, upgrading and speeding up the various computer processing programs. In the following paragraphs there is a description of the mapping procedures, showing the changes and current status of the various steps in the chain.

a. Real-Time Program

The function of this program is basically to absorb and record the radar time samples and to provide a rough printed monitor of the quality of the data. This program is essentially unchanged from the earliest work, except for minor features of convenience.

b. Fourier Transform Program

This program accepts the time samples, reorders them in separated strings for each range-resolved cell, and performs a Fourier transform on each of the range cells to provide resolution in the frequency direction. Because of the earth's rotation, the Westford signal is offset in frequency from the Haystack signal by as much as 2 Hz, which is 10 to 20 frequency-resolution elements. In order to bring the range-Doppler cells of the two signals into coincidence on the lunar surface, the phase of the Westford time signal is rotated at a rate which exactly removes this fringe frequency.

This program has been altered to apply the true motion of the moon in hour angle and declination rather than the fixed sidereal rate which was the approximation originally utilized. This should improve the correlation of the present topography data by 5 to 10 percent, but more importantly should also improve the predicted correlation of the planned higher frequency resolution reprocessing of the same data by about an order of magnitude.

c. Cross-Correlation Program

This program forms the complex cross-product of the signals in the individual range-Doppler resolved cells of the Haystack and Westford signals. The phase-angle of the result depends on the topography referred to an image plane; this program then proceeds to remove the phase component due to an assumed spherical moon, and leaves in the result only the effects of the topography above a 1734.6-km-radius reference sphere.

This program has been completely rewritten in an attempt both to speed it up and to take into account more of the details in the timing of the observations and the best current lunar ephemeris. In addition, the major part of the "mapping" program (see below) has been incorporated into it. The present program processes one half-ZAC map in about 90 minutes, or about $\frac{1}{4}$ the time of the programs it replaces.

d. Mapping Program

This program superimposes the 80-odd individual range-Doppler resolved matrices into one summed map, while removing the effects of the moon's motions during the observation from

matrix to matrix (about 10 seconds per matrix). The original program projected the summed map onto a conventional cartographic projection, which trimmed away in many cases the corners and edges of the measured data. The present program, which is actually a part of the cross-correlation program described above, retains a quasi-range-Doppler projection for the summed map, and a simple auxiliary program will suffice to project this format onto other more familiar coordinate systems.

e. Elevation-Calculating Program

This program is newly written and performs two functions: it removes from the maps of phase data the 360° ambiguity in phase, which is unavoidable in interferometer measurements but false and confusing for interpretation of topography data; it then converts the unambiguous phase values into point-by-point values of elevation. Our first true contour drawings, of which Fig. 4 is an example, have recently been obtained through use of this new program.

While in Fig. 4 the phase ambiguities and nonlinearizing effects of the interferometer geometry have been removed, the map was produced from a June 1970 observation, before certain difficulties with the working ephemeris were fully understood. Thus, the strong slope on the mare floor may be an artifact of the old ephemeris. This area is to be reobserved in January 1971 with a new corrected ephemeris and the results will be compared.

f. Ephemeris Programming

Precise ephemeris generation is a vital function and has received considerable effort during this quarter. We have succeeded in converting all lunar planning and observation programs to use a new lunar ephemeris, integrated by Martin Slade of MIT Earth Sciences Department from the multi-body equations of motion fitted to a large fraction of the available lunar observations of the last century.

From a preliminary look at the data, this new ephemeris appears to be good to much better than 150 m in range. It is expected to be better than 2 mm/sec in range-rate also, which will give the absolute accuracy desired for the present work (2 mm/sec = 0.05 Hz at Haystack's 7.840-MHz frequency, or about 600 m in the "frequency" direction on the lunar surface). This ephemeris accuracy provides a check on the absolute topography generated independently by fitting together overlapping ZAC maps.

4. Observations

About half of the central 50° of the moon will have been observed by 31 January 1971. This represents about 100 half-ZAC areas and a processing load of about 500 hours of required computer time. An additional 300 hours more or less will be required for the phase-calibration areas.

The immediate output from the Lunar Topography program is a series of topographic contour maps on the LAC chart format. Two charts, for LAC's 41 and 58, are planned for the end of the next reporting period; four more ZAC areas are needed at this writing to complete the observations for these, and computer time has been requested for the entire processing job. Observations are continuing meanwhile with the data stored for future processing as time is available on the CDC 3300 computer.

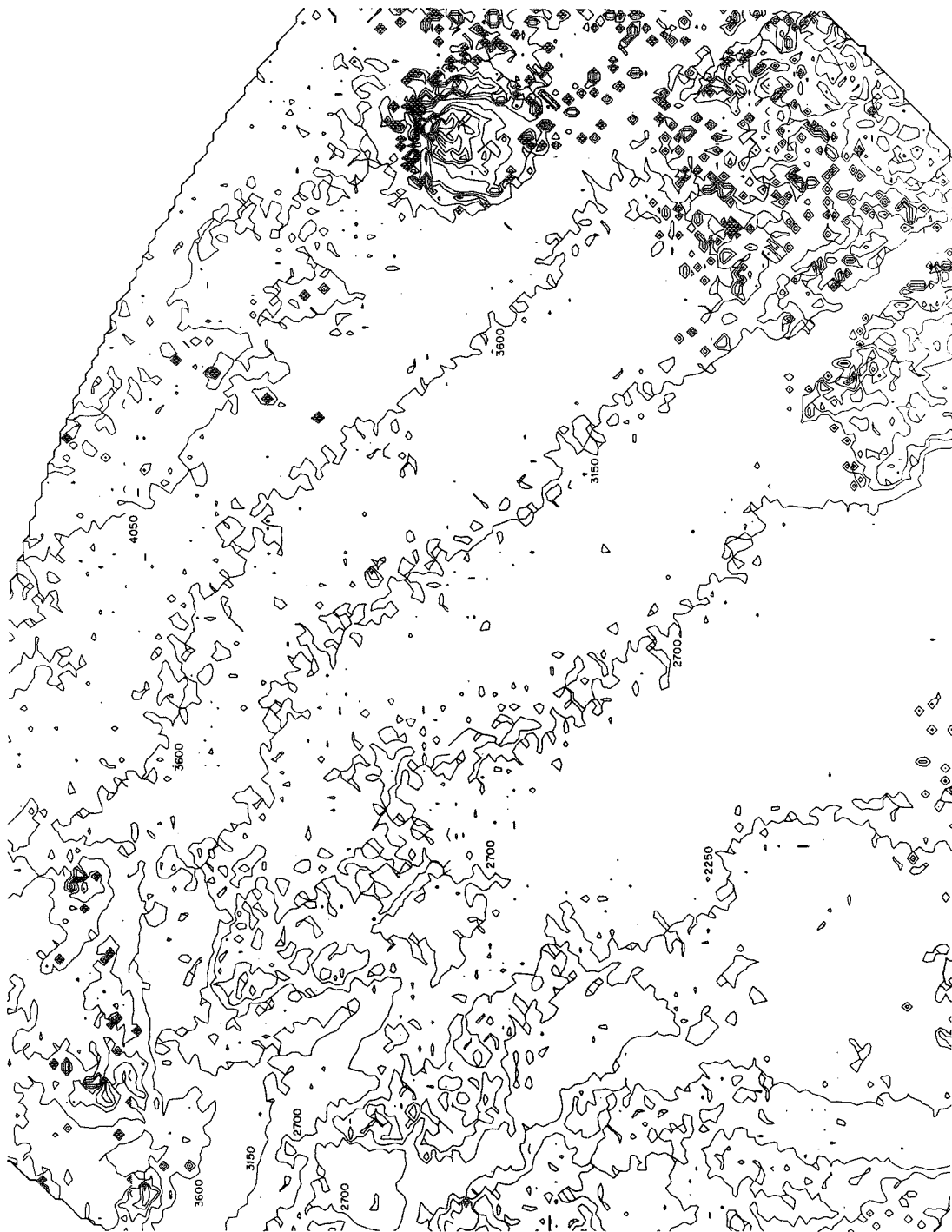


Fig. 4. Early contour map of 400-km-square region of Mare Vaporum with Crater Manilius at the right. Contour interval: 450 meters.

B. Venus and Mercury

1. Observations

Planetary radar observing during this quarter emphasized Venus which was in inferior conjunction on 10 November 1970. Range delay observations were conducted from 28 September 1970 to 20 November 1970 and from 7 December 1970 to 15 January 1971. Mercury delay observations were suspended in September and resumed in December so that more observing time would be available for Venus. Because of the limited transmitter power of 200 kW and the unfavorably distant planet, Mercury coverage was not undertaken during this superior conjunction period. Extensive Venus coverage for precise range delay and equatorial topography measurements was obtained using both standard and new short pulse range delay-frequency processing modes.

For the first time during this period a new generation planetary ranging system has been used that permitted range delay-frequency measurements with a 10- μ sec pulse width resolution. Previous observations of Venus were made with modes that used the CDC 3300 alone for real-time digital processing and were limited to 24- μ sec pulse resolution. The new ranging system uses a real-time hardware decoder and new software as described in Section III-D. The new planetary mode was used with 10- μ sec pulse resolution for extensive topography observations several times per week to provide overlapping longitude coverage. Observations using 24 μ sec in 1967 and 1969 were limited in such overlap.

2. Fourth Test of General Relativity

New results have been obtained for the Fourth Test of General Relativity. Combining all the Mercury and Venus radar echo time-delay data obtained at Haystack and Arecibo yields a value for parameter λ of 1.02 ± 0.03 (formal standard error), where λ would have the value unity were general relativity correct and 0.93 were the Brans-Dicke scalar-tensor theory correct with the arbitrary parameter s set equal to 0.07 in accord with Dicke's interpretation of the Princeton solar-oblateness experiment. Because the investigators have not yet accounted accurately enough in the above data reduction for the surface-height and radar scattering law variations on Mercury and Venus, they feel that $\lambda = 1.02 \pm 0.05$ is a more reliable statement of the result and its "one-sigma" uncertainty. Figure 5 is a graph of some of the Venus time-delay residuals for a period centered at the superior conjunction of 25 January 1970 and containing data from the surrounding inferior conjunctions. Note the dramatic improvement in accuracy in the recent measurements (errors no greater than 1 μ sec) which is attributable to the use of a shorter, 10- μ sec baud made possible by the new decoder described in Section III-D-1.

3. Gravitational Constant

The accumulated radar echo time-delay data allow for the first time a very stringent bound to be placed on the possible time variation of the gravitational constant G . A recent publication (4 January 1971) in Physical Review Letters* presents results based on data through early 1970; in particular, it was found that the magnitude of the fractional rate of change in G was less than 4 parts in 10^{10} per year. No comparable experimental bound has ever been obtained. Inclusion of all the 1970 radar data, much of it at a higher accuracy level, allows the bound to be reduced

* I. I. Shapiro, et al., Phys. Rev. Letters 26, 27 (1971)

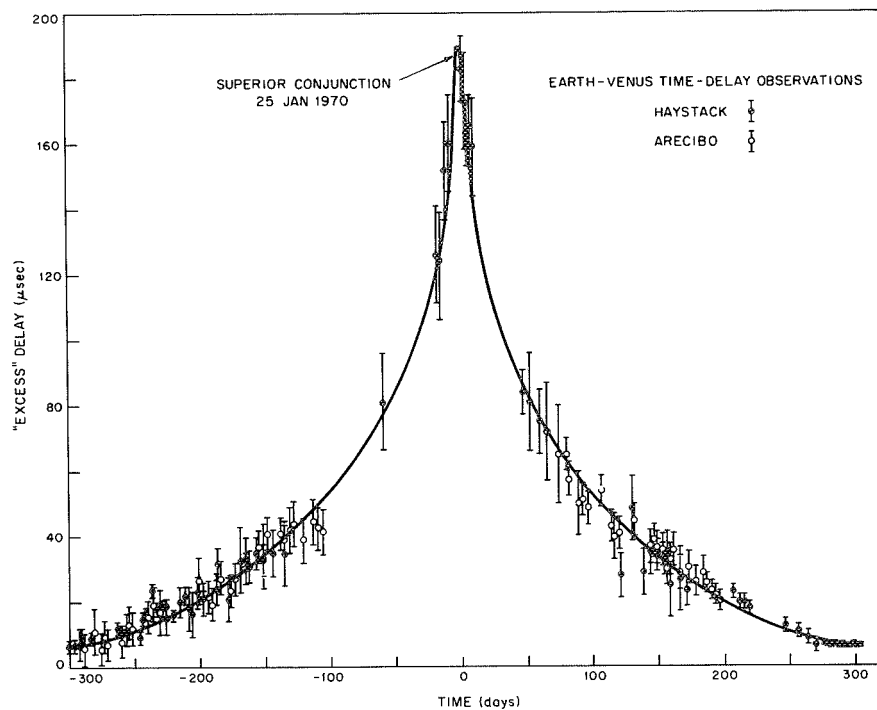


Fig. 5. Sample of time delay residuals from radar data centered on 25 January 1970 superior conjunction.

by almost a factor of two. Several more years of data will be required to reduce the bound to a level of several parts in 10^{11} per year, a value close to that predicted for the rate of change of G by some theorists.

4. Surface-Height Variations

To deduce large horizontal-scale surface-height variations on Mercury and Venus from an analysis of the echo-delay data, the Planetary Ephemeris Program (PEP) has been augmented by a capability to estimate the coefficients of a spherical-harmonic representation of the height variations. These coefficients can be estimated from the data simultaneously with all the other parameters to which the data are sensitive. With this representation, it should be possible to obtain improved estimates for the over-all geometric shape of the equatorial regions on Mercury and Venus that are spanned by the subradar point. The required analyses are in progress but no results are yet available.

5. Small-Scale Venus Topography

Pulse-coded range delay observations of Venus (as reported in Section III-B-2) for purposes of establishing orbit and large horizontal scale topography have been conducted regularly since late 1966. For these observations, the received signals are decoded and sampled at intervals equal to half the pulse width, and signal power spectra are obtained for each processed delay to generate a delay-frequency map of the signal. The over-all delay to the planet is determined by cross correlating the received signal array with a signal model based on known scattering characteristics of the planet. That frequency and delay producing the greatest correlation is taken to be the measured delay and frequency relative to a trial ephemeris used to control radar system process timing. If the orbital component of this delay is known, the deviations from the orbit

as the planet rotates can be interpreted as a measure of mean topography over a relatively large horizontal scale. Since each such delay measurement weights a region typically extending some 5 degrees beyond the subradar point, a different measurement technique is used to investigate smaller-scale topography along the rotation equator.

This "height profile" technique is performed by obtaining an estimate for the delay at each frequency slice within the measured delay-frequency map and comparing this delay with geometrically predicted values. In earlier topography analyses of 1967 and 1969 observations, this delay estimate was accomplished by establishing the point where the echo power rose out of the noise level. The line of maximum leading edge slope through the data samples was extrapolated to the established noise baseline to establish relative delay.

A new algorithm has been developed that uses a least-squares fit to a model of the range delay response of each frequency slice in place of the simple slope fit to estimate leading edge delay.

If the delay estimate (by either method) is done for a number of frequency slices, one obtains a curve of delay vs frequency that is the outline of the nearest portion of the surface along the apparent rotation equator. Since the radius of the planet is known, the predicted delays for a spherical model of the planet may be removed and the residual delays interpreted as a height contour for a strip along the apparent rotation equator. The frequency of each delay point may be geometrically related to longitude on the planet.

This analysis is currently being performed on the measurements obtained from Venus near the November 1970 inferior conjunction for a period covering several months. The least-squares scattering model fitting method is superior for low signal-to-noise ratios as might be expected, but produces difficulties in interpretation if there are anomalous signal returns from areas lying behind the leading edge at latitudes away from the apparent rotation equator. A modification to weigh only the immediate first return is indicated, which situation is already true for the original slope fit algorithm.

Figure 6 illustrates a representative topographic profile measurement on Venus. The curves were obtained using the least-squares model fitting method and the triangles were from the slope

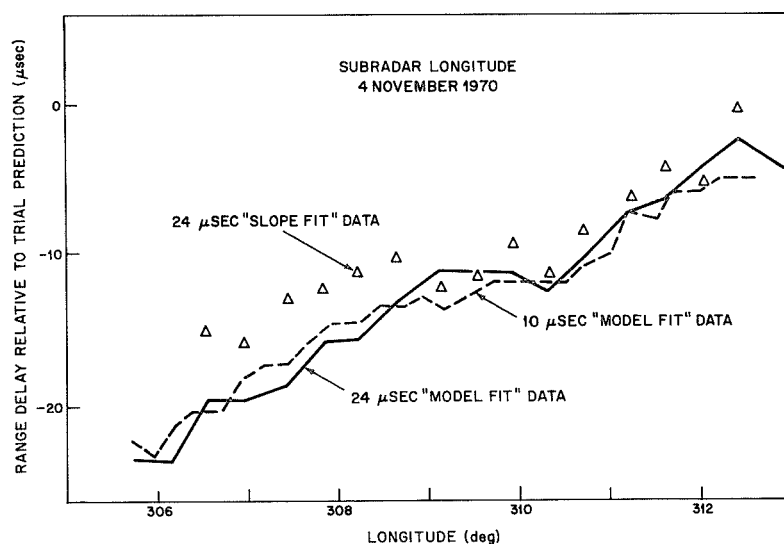


Fig. 6. "Topography profiles" for Venus from radar data taken 4 November 1970 using 10- and 24- μ sec effective pulse width. (The over-all slope is an instrumental effect.)

method. Similar small-scale features are discernible in the two independent measurements. Differences between the model fit and slope algorithms are also quite obvious for the 24- μ sec data. The longitude region observed here was quite regular in scattering characteristics. The over-all positive "slope" of the plots results from a small (-0.3 Hz) frequency difference between the signal and system frequency tracking and not from an actual slope on the planet. It is not presently clear whether the source of this error lies in the radar system or ephemeris. It was present in Venus data taken near inferior conjunction but appears to not be obvious in observations made at other times (admittedly at poorer signal-to-noise ratio and hence with poorer frequency measurement accuracy). An investigation of this phenomenon is currently in progress.

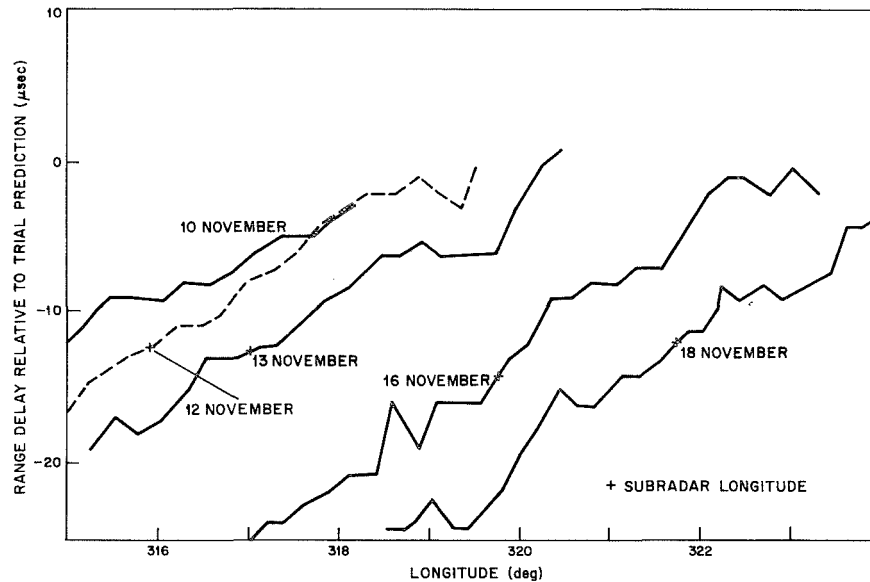


Fig. 7. Venus "topography profiles" from November 1970 radar observations with 10- μ sec effective pulse width. Least-mean-squares model fit. (Correction of frequency error, when done, will remove over-all slopes and align the separate days' observations.)

Integration of the measured series of topography observations will utilize a post-run PEP ephemeris as described in Section III-B-4 above that is more accurate than the observational trial ephemeris. If the relative delay of each observation is correct, the effect of frequency error can be resolved by "rotating" each delay profile with a frequency correction deduced from the data. Several days' overlapping observations (that are as yet uncorrected) are shown in Fig. 7. Small-scale "features" are discernible in the several curves. These observations were taken during a period when the scattering behavior at the subradar longitude was well behaved and a relative (corrected) precision of the order of a few microseconds within each observation is approached. Meanwhile, analysis of the complete set of topographic data is in progress.

C. Plans for Mars in 1971

1. Introduction

Radar observations of Mars have already determined the topography of the planet from the equator to 22° North with good precision.* Observations planned for the 1971 opposition should

* See "Radar Studies of Mars," Final Report, 15 January 1970.

yield yet more precise topography measurements from 10°S to 24°S . An improved radar system, having a higher transmitter power (above 300 kW) and faster signal processing, together with a closer planetary approach this year, should give almost an order of magnitude improvement in delay resolution as compared to 1967 and 1969.

2. Observing Schedule

In order to cover a greater area on Mars and to provide more data for orbit determination, it is desirable to make observations over the widest possible range of dates. Observations made in 1969 show that useful ranging measurements are possible at distances up to at least 1 a.u. Thus, observations in 1971 are planned from April 19 to December 9. Owing to the low declination of Mars in 1971, the range of subradar longitude observable in any single night is only about 75° . Since the subradar longitude at transit decreases by about 10° a day, it is necessary to observe at least once a week to cover all longitudes. However, to cover longitudes missed during the transmit portion of the radar cycle, one has to observe at least two days a week to get

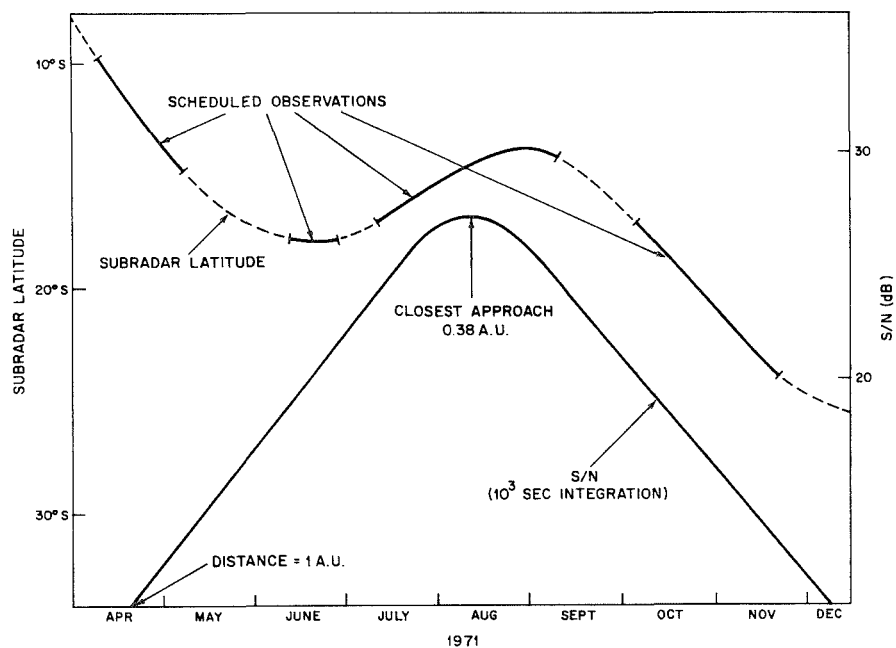


Fig. 8. Planned schedule for Mars radar observations centered on the August 1971 opposition. Subradar latitude and signal-to-noise ratio are shown vs time.

continuous coverage. It would be desirable to observe three days a week both to allow some margin of safety and so that confidence in the measurements may be continuously assured by repeatability checks. However, other demands upon Haystack must be met, and the best compromise is that where possible these will be scheduled when Mars measurements would be redundant, allowing some overlap for closure (see Fig. 8).

3. Signal-to-Noise Ratios, Detectability, and Topographic (Ranging) Precision

The signal-to-noise ratio in units of noise standard deviations is given by

TABLE III
COMPARISON OF 1967 AND 1969 MARS MEASUREMENTS WITH THOSE ANTICIPATED IN 1971

	<u>1967</u>	<u>1969</u>	<u>1971</u>
Distance of closest approach	0.61 a.u.	0.48 a.u.	0.38 a.u.
Dates when Mars is within 4 a.u.	Feb 12 → July 14	Mar 14 → Oct 3	April 19 → Dec 9
Range of latitude covered by subradar point	17.5°N → 23.9°N	2.6°N → 12.0°N	12.0°S → 25.5°S
Relative signal strength at opposition	0.39	1	2.4
Resolution in latitude (coded measurements)	~3° (~180 km)	~3° (~180 km)	~1° (~60 km)
Resolution in longitude	~2° limited by planet's rotation during the signal integration period (which was made equal to the round-trip flight time)	~2°	~2° but could be substantially improved close to opposition as the high signal strength should allow integration period to be shortened
Mean 1 sigma error in a single observation of height	~4 km	~4 km	~150 meters should be possible in smooth areas
Coding scheme	15-element with 60-μsec baud; sampled during receive every 30 μsec; decoding only 6 out of 30 range samples in 1967, 8 samples in 1969		A 255-element code with 6-μsec baud, decoding 30 range samples, is proposed

$$\frac{S}{N} = \frac{GP_T A \sigma \sqrt{T}}{K(4\pi R^2)^2 T_S \sqrt{\Delta f}} \quad ,$$

where G is the antenna gain (66 dB), P_T is the power transmitted (300 kW), A is the receiving aperture (+26.7 dB vs 1 m^2), K is Boltzmann's constant, T_S is the system temperature ($\sim 50^\circ \text{K}$), R is the distance to Mars, T is the total integration period, and Δf is the frequency resolution (the inverse of the coherent integration period) interval. σ is the cross section of the planet limited by the resolution $\Delta \tau$ in delay and Δf in frequency, i.e.,

$$\sigma = \int_{\Delta \tau, \Delta f} S(\Theta) da \quad ,$$

where $S(\Theta)$ is the scattering law and da an element of area. At $R = 1 \text{ a.u.}$, the S/N ratio is (typically) 10 dB, for $\sigma = 3$ percent of the geometric area of Mars, with typical values of $\Delta f = 1 \text{ KHz}$, $T = 10^3 \text{ sec}$. Reducing the delay resolution, $\Delta \tau$, does not affect the integrated cross section, σ , significantly until the half-power point of the delay scattering law is reached. This occurs at $\Delta \tau \approx 6 \mu\text{sec}$ for the smoother regions, or $\approx 30 \mu\text{sec}$ for the rougher regions on Mars.

With the new "hardware" decoder at Haystack, it will be possible to improve the delay resolution to match the scattering law in the smoother areas. Based on the association observed in 1967 and 1969 between dark visible surface markings and regions of higher-than-average radar cross section and smoothness, one may expect in 1971, where the visibly dark south tropical latitudes predominate, that the improved resolution will be usable most of the time. In general, if the echo can be reliably detected at all, the ranging precision achievable is at least as fine as the "matched" baud length, $\Delta \tau$, and may be a small fraction of this if the signal is strong. The repeatability of our measurements made in 1969 with a $60\text{-}\mu\text{sec}$ baud length was better than $1 \mu\text{sec}$ (150 meters) in strong signal cases. Although planetary surface structure will certainly prevent proportionate splitting of much shorter baud lengths, some subdivision (interpolation) will still remain possible.

In sum, the ranging precision attainable is determined largely by the surface scattering law. The limiting precision for smooth-surface areas is about $1 \mu\text{sec}$ (limit probably set by topography) for ranges to 1 a.u.; for rough areas the precision is expected to be about $3 \mu\text{sec}$ at opposition (0.38 a.u.) and perhaps degrading to $15 \mu\text{sec}$ when the signal is very weak ($\gtrsim 1 \text{ a.u.}$). Table III summarizes the resolution and ranging accuracy of radar measurements of Mars made in 1967 and 1969, together with the resolution and accuracy expected using Haystack in 1971.

Our over-all signal-strength calculations have been confirmed by results of other observers, as detailed by Pettengill, et al. (1969).^{*} The detectability of Mars by Haystack at 1.3 a.u. has also been demonstrated (see Fig. 9).

4. Depolarized Echoes

So far, no attempt to detect depolarized echoes from Mars has been made at Haystack. Measurements of depolarized echoes from smooth areas of Venus and measurements of the diffuse component of the (polarized) echo from Mars suggest that the Martian depolarized echo will be about 25 dB (300 times) weaker than the polarized leading-edge echo. Therefore, measurements of the depolarized component will probably be limited to the period between July and September when the echoes are strongest.

^{*} G. H. Pettengill, et al., *Astron. J.* **74**, 461 (1969).

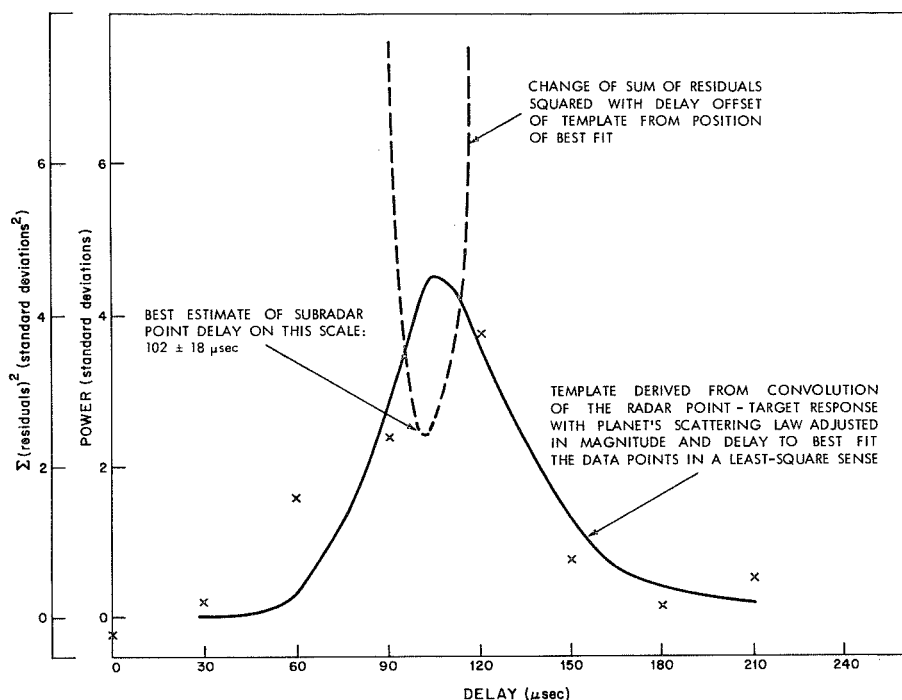


Fig. 9. Example of radar echo from Mars at 1.3 a.u., 25 November 1969, 23h27m. Subradar point: Lat. 19°S; Long. 309°.

D. Radar Instrumentation

1. Hardware Development

a. Haystack Real-Time Decoder

Haystack radar system is equipped with a digital "Real-Time Decoder" that removes phase reversal modulation from the received radar signals. Up to October 1970, this decoder was limited to Barker codes and pseudo-random shift register codes of up to a limit of 31 elements in length. All possible range delays were demodulated, and the CDC 3300 data processing computer was used to record data or perform simple processing for real-time display. The primary advantage of the decoder is to free the CDC 3300 from the task of demodulation so as to allow shorter pulse widths.

The decoder has been modified to accommodate a "partial decode" mode that shares the demodulation task between the decoder and CDC 3300. This mode allows us to decode up to 31 range delays of much longer codes, which minimizes problems of range-delay ambiguity. The decoding can be accomplished for one channel (sampled at either one or two samples per pulse width) or for two channels. Various coding options are listed in Table IV. Currently, software has been written for the 8-6-5-4-0 code to be used with planetary ranging. Pulse widths of 10 μsec were used on Venus, a considerable advance over the 24-μsec mode previously available with the CDC 3300 alone. The 13-element Barker code is used in lunar pulse operations for two radar channels.

Two additional decoder stages were added to the control unit in order to continuously check the output values. These stages are supplied with the data samples and a serial version of the code in use. If all units function properly, the test decoder output should equal the full decoder

TABLE IV
CODING OPTIONS FOR HAYSTACK DECODER

<u>Code</u>	<u>Code Length</u>	<u>Complex Signal Channels</u>	<u>Lags Decoded</u>	<u>Subsums to Accumulate</u>
4-3-0	15	2	15	1 per lag
5-3-0	31	1	31	1 per lag
8-6-5-4-0	255	2	15	17 per lag
10-7-0	1,023	1	31	33 per lag
12-11-8-6-0	4,095	2	15	273 per lag
15-14-0	32,767	1	31	1057 per lag
Barker	13	2	13	1
Others as required	1 to 15	2	1 to 15	1
	1 to 31	1	1 to 31	1

output once every 15 data cycles. A discrepancy will activate the existing radar sequencer alarm system.

b. PR Box Stalo System

The Planetary Radar Box stalo system was modified during this quarter to accomplish greater flexibility, primarily for radio astronomy operations. Operating procedures were written for accomplishing local oscillator setups with less difficulty and change of error. There are now four klystron stalo systems which time-share two synchronizing equipments:

- (1) Planetary Radar: X-band klystron at 7710 MHz synchronized to Station standard.
- (2) K-Band Radiometer: X-band klystron tripled in 22-GHz radiometer. This may also be used at X-band. Synchronized by synthesizer.
- (3) X-Band Radiometer: X-band klystron synchronized by synthesizer. This is completely independent of the radar stalo.
- (4) Simulator: X-band klystron used in generation of test signals synchronized by independent standard.

Stalo changeover procedures have been automated to eliminate many of the problems that were previously encountered during system changeovers. Additional status and fault monitoring circuits have been installed to provide better operational knowledge of system status. Waveguide connections to the K-band radiometer were permanently installed with rigid waveguide so that adequate X-band power is available to triple to 22 GHz.

c. Transmitter Tubes

During this quarter, two upgraded transmitter klystrons were constructed and tested at Varian Associates/Palo Alto. These VA-949BM units in tests at the Varian plant performed extremely well. During acceptance tests, the first klystron, S/N 22, produced 250 kilowatts without showing any of the problems such as arcing that were typical with the VA-949AM model. Pulse performance was equally as promising. These klystrons are scheduled for installation and testing at Haystack during the last week of January 1971.

Meanwhile back at Haystack, transmitter power available with VA-949AM units, S/N 1 and S/N 13, has dropped to 200 kW total. S/N 1, which has been in service a good part of the time since October 1966, is obviously reaching the end of its useful life, having accumulated 4000 filament hours.

2. Computer Programs

a. Planetary Radar Programs

During this period, several real-time and post-run data processing programs have been put into production status. A new post-real-time planetary "correlation" program was put into use. This processing program cross correlates the planetary signal return in delay and frequency with a model based on known scattering characteristics to determine the range delay and frequency of the signal as indicated by maximum correlation. The features of this program version which distinguish it from the original program are:

- (1) The program is generalized to process data generated by many operating modes (including data collected in the bistatic Goldstack experiment with JPL).
- (2) The scattering law used to generate the template model is internally generated upon specification of limb-to-limb Doppler and a single scattering parameter C for the Hagfors* scattering model.
- (3) The template generated now includes the effect of radar system processing in causing smoothing in delay and frequency.
- (4) The program cycles automatically for each set of input data to produce both "fine" and "coarse" correlations.
- (5) The program may be operated in an automatic mode to process many sets of input data recorded on tape.

A new real-time planetary ranging program (PDPR) has been written and used to process data with the hardware decoder operating in the "partial decode" mode. This program will function for a large variety of pulse width and frequency coverage modes and is particularly suited for short pulse width ranging measurements such as those planned for upcoming Mars observations in 1971. The new program may be operated with double-sampled pulse widths down to 10 μ sec. Modes using 10, 20, and 60 μ sec are operational. The pseudo-random code used has 225 elements which, with the pulse width used, specifies the basic sampling period for a given range box. Code intervals may be summed coherently as specified to reduce the sampling rate of the data entering Fourier analysis. Spectral analysis is performed for 128 points. For the partial decode mode, the CDC 3300 takes partial sums developed in the hardware decoder and sums them to complete the demodulation of the pseudo-random coding.

The new ranging system is operational, but there remain a few problems to be resolved before operation with low signal-to-noise ratios. Problems with number truncation have introduced a bias and excess of "sampling noise," but this will be resolved. The parameters of the operational modes are summarized in Table V. Note that the identification summarizes sample, baud, and codes summed.

Several specialized programs for reducing the data collected in the June-July 1970 bistatic Goldstack experiment were used during this period, primarily for reformat purposes on data obtained from JPL and from Haystack lunar modes.

* T. Hagfors, J. Geophys. Res. 71, 379 (1966).

TABLE V
CHARACTERISTICS OF NEW RANGING MODES

<u>All Modes</u>			
Program Title	PDPR		
Decoder Mode	Partial Decode		
Code – Shift Register	8 – 6 – 5 – 4 – 0		
Elements in Code	255		
Range Boxes Processed	30, double sampled in range		
Frequency Boxes	128		
.			
<u>Operational Modes</u>	<u>5/10/12</u>	<u>10/20/4</u>	<u>30/60/1</u>
Baud (μsec)	10	20	60
Sample Interval (μsec)	5	10	30
Code Length (μsec)	2550	5100	15,300
Codes Summed	12	4	1
Frequency Coverage (Hz)	32.7	49.0	65.3
Resolution (Hz)	0.255	0.383	0.510
Depth Coverage (μsec)	150	300	900

A new Venus topography program was written for the purpose of measuring small-scale height variations on Venus. This program differs from a previous version in that it uses a least-squares model fitting technique to estimate leading edge delay as a function of frequency in place of a simple slope extrapolation method. It accommodates input data from several modes of planetary ranging data. The program is functional, but improvements are desirable to make the delay measurement algorithm sensitive only to effects at the leading edge and not biased by later delay return anomalies.

b. Lunar Topography Programs

During this period, considerable effort has been expended in the modification, upgrading, and provision of new software in support of lunar topography measurements. The functions of these programs are described in Section III-A. These topography processing programs are by no means final; as processing of the lunar data progresses, improvements in the methods of processing will be made as the need becomes evident.

c. Ephemeris and Pointing System

The so-called "Mason* Ephemeris Program" and its companion "Preliminary Program" were converted (from IBM 360) to run on the CDC 3300 and thus provide us with the in-house capability of generating planetary ephemerides. This program is absolutely essential as the trial ephemeris for planetary operations. The "transmit" ephemeris is used for flight time settings in the radar timer and the companion "receive" ephemeris is used (through the U-490 pointing

* For W. C. Mason, who prepared the original version.

computer and other equipment) to tune the radar receiver and to produce a range rate offset clock signal for sampling received signals. The printed ephemerides are used also for a number of vital system cross checks during radar operations.

Continued efforts were made to obtain better agreement between the values of Doppler shift and range delay (radar site to lunar center of mass) computed by the Haystack Moon Libration program (MLIB-3) and those computed by the Slade* version of the Planetary Ephemeris Program (PEP). Tolerances of 0.05 Hz in frequency and 0.5 μ sec in range delay are desired. This agreement is required as both PEP and MLIB-3 are used in all phases of lunar topography analysis.

The constants in MLIB-3 have been updated and the linear interpolation procedure used in determining right ascension, declination, distance, and their time derivatives has been changed to a Bessel formula. The agreement in delay and frequency has improved as a result.

Since the basic input predictions use a coordinate system with origin at the geocenter, it is necessary to rotate and translate the coordinate system so that its origin is at the radar site. An ellipsoidal earth is taken as the model; however, the original earth model in MLIB-3 neglected to account for height of the site above sea level in the computation of geocentric latitude and the components of the site vector (geocenter to site). A completely new routine has been written to reflect a new earth model incorporating the height of the site.

Currently, there exist sinusoidal differences in both delay and Doppler frequency between PEP and MLIB-3 with a peak difference of 0.15 Hz and 0.4 μ sec for Doppler and delay, respectively.

In anticipation of using MLIB-3 to generate Doppler frequency steering with the Univac 490, a new mode has been added to MLIB-3 which computes the Doppler frequency value, fits a polynomial to the value, converts the coefficients to U-490 integer format, and writes the Doppler steering tape. This will eliminate the requirement of obtaining a Doppler tape from PEP.

* For Martin Slade, summer staff member.

APPENDIX
PAPERS OF 1970

- Radar Mapping of Venus with Interferometric Resolution of the Range-Doppler Ambiguity
A. E. E. Rogers, R. P. Ingalls
Radio Science 5 (February 1970)
- Very Long Baseline Interferometry as a Means of Worldwide Time Synchronization
A. E. E. Rogers, J. M. Moran
MIT Lincoln Laboratory Technical Report 478 (17 February 1970)
- Search for an Effect of the Sun on the Frequency of 18-cm Radiation
J. A. Ball, D. F. Dickinson, A. E. Lilley, H. Penfield, I. I. Shapiro
Science 167, No. 3926 (27 March 1970)
- Radio Observations of the Distribution of Chromospheric Brightness Temperature
M. Simon, D. Buhl, J. R. Cogdell, F. I. Shimabukuro, C. Zapata
NATURE 226 (20 June 70)
- The 3.8-cm Spectrum of OH: Laboratory Measurement and Low-Noise Search in W3 (OH)
J. A. Ball, D. F. Dickinson, C. A. Gottlieb, H. E. Radford
The Astronomical Journal 75, No. 7 (September 70)
- Very Long Baseline Interferometry with Large Effective Bandwidth for Phase-Delay Measurements
A. E. E. Rogers
Radio Science 5, No. 10 (October 70)
- Very Long Baseline Interferometry of Galactic OH Sources
B. O. Ronnang, O. E. H. Rydbeck, J. M. Moran
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W. B. Smith, R. P. Ingalls, I. I. Shapiro, M. E. Ash
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- Very Long Baseline Interferometer Studies of H₂O Sources
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- Recombination Line Radio Spectroscopy
A. E. Lilley
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- Recent Advances in the Study of Radio Emission from Galactic H₂O Sources
J. M. Moran
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- Observations of the March 7, 1970 Eclipse and of the Solar Oscillatory Component at 1.35 cm
M. Simon, P. Berger, C. Zapata
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- High-Accuracy Topographic Measurements of the Moon by Earth-Based Radar
S. H. Zisk, A. E. E. Rogers
NEREM-70 Record 12 (1970)