III. RADIO ASTRONOMY[*]

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A. OBSERVATIONS OF INTERSTELLAR $O^{18}H$

This spring, we made a series of radio astronomical observations using the 140-ft radio telescope of the National Radio Astronomy Observatory in a search for the emission and absorption lines of interstellar $O^{18}H$ molecules. (The majority of OH studies have been on the most abundant isotopic species $O^{16}H$.)

Observations of the galactic center (Sagittarius A) were made in March and April 1968. In March a wideband 50-channel filter receiver (filter bandwidth, 100 kHz) was used to observe both the 1639-MHz and the 1637-MHz $O^{18}H$ lines simultaneously. (These lines correspond to the 1667-MHz and the 1665-MHz lines of $O^{16}H$, respectively.) Two nights (6 hours on the source) were spent with the 50-channel receiver. Also in March and then in April, further observations of the galactic center were made with the 100-channel autocorrelation receiver, which had an effective resolution bandwidth of 30 kHz. The 1639-MHz line was observed on 4 nights (14 hours on the source), and the 1637-MHz line on 2 nights (7 hours on the source). Only one line could be observed at a time, since the correlator bandwidth was 2 MHz. In these observations both frequency switching and the OFF/ON technique were used to reduce baseline nonlinearities.

Both of the $O^{18}H$ lines were detected in absorption in the galactic center with absorption strengths of 0.33°K at 1639 MHz, and 0.24°K at 1637 MHz. With rest frequencies 1639.46 MHz and 1637.46 MHz, as calculated by Barrett and Rogers,[1] the velocity of absorption (+40 km/s) agrees very well with the $O^{16}H$ absorption velocity, which implies that the absorption is occurring in the same cloud. The ratio of the line strengths of $O^{18}H$ to those of $O^{16}H$ is approximately 1/100 (measured directly with the 140-ft telescope in March and April). If an abundance ratio of 1/500 for $O^{18}H$ to $O^{16}H$ is assumed (the abundance ratio on Earth of O^{18}/O^{16} is 1/490), a large optical depth of the order

of $\tau = 10$ may be predicted for these OH clouds. This is a surprising result, since it was believed previously that the optical depth was of the order of unity. Further observations of the galactic center will be made this summer to better define the line strengths and shapes.

In March, at the National Radio Astronomy Observatory, a search for $O^{18}H$ emission at 1637 MHz in the source W3 was performed. (W3 is one of the strongest $O^{16}H$ emission sources at 1665 MHz.) W3 was observed for 26 hours with an effective resolution bandwidth of 3 kHz. The rms noise was measured to be $0.04°K$, with all spectrum points less than $0.08°K$. (Linear polarization was used on this equatorially mounted radio telescope.) The peak temperature measured on W3 with linear polarization at 1665 MHz was $65°K$; therefore, this measurement sets an upper limit for $O^{18}H$ emission from W3 of 1/800 as strong as the $O^{16}H$ emission.

W. J. Wilson, A. H. Barrett

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1. A. H. Barrett and A. E. E. Rogers, Nature 204, 62 (1964).

B. LONG BASELINE STELLAR INTERFEROMETER

In 1921, Michelson and Pease, using an optical interferometer developed by Michelson,[1] made the first measurement of a stellar diameter. This original system, with a 20-ft baseline, was later superseded by a 50-ft system described by Pease.[2] More recently, Hanbury-Brown measured the diameters of several more bright stars, using an optical intensity correlation interferometer capable of baseline lengths up to 600 ft.[3] All of these stellar measurements were limited instrumentally to stars brighter than magnitude 2.5. Furthermore, the intensity-correlation system requires 1 month of observation per star. The limitations of stellar magnitude and baseline are significant because many stars are neither bright nor of large diameter.

A different type of interferometer system incorporating photomultiplier tubes has been analyzed theoretically, and found to enable observation of stars of magnitude 6 with a signal-to-noise ratio of 10 for 100-sec integration.[4] The system should be capable of operating over long baselines without the great expense entailed with even the 50-ft system of Pease. At the ends of the baseline the analyzed system incorporated two 4-in. mirrors each of which directed the incident starlight into a signal-combiner system located between the mirrors. This system combined the two plane waves and focused them upon the face of a photomultiplier tube. One of the two interferometer arms contained a mirror that oscillated at a frequency of a few kHz, and the photomultiplier tube output was filtered at this frequency.

The primary difficulties encountered in such a system are the angle of arrival and

path-length fluctuations that affect the two light beams. The atmospheric effects have been modeled on the basis of stellar measurements and theoretical considerations. The angular fluctuations were assumed to be 0.4 second of arc rms, and the differential path-length fluctuations to be 20λ rms, which is believed appropriate for a 20-ft baseline. For longer baselines it might be necessary to integrate longer in order to obtain the 20-ft baseline performance.

P. L. Kebabian, D. H. Staelin

References

1. A. A. Michelson and F. G. Pease, "Measurement of the Diameter of a Orionis with the Interferometer," Astrophys. J. 53, 249 (1921).

2. F. G. Pease, "The New Fifty-ft Stellar Interferometer," Sci. American 143, 290 (1930).

3. R. Hanbury-Brown, "Stellar Interferometer at Narrabio Observatory," Nature 218, 637 (May 18, 1968).

4. P. L. Kebabian, "Analysis of a Long Baseline Stellar Interferometer System," S.M. Thesis, Department of Electrical Engineering, Massachusetts Institute of Technology, May 1968.

C. RESULTS OF INFERRING ATMOSPHERIC TEMPERATURE FROM SIMULATED MICROWAVE MEASUREMENTS

This report describes results of inferring atmospheric temperature profiles from simulated microwave radiometric measurements. The measurements are simulations of those that would be obtained by a satellite-borne microwave radiometer operating in the 60-GHz molecular oxygen resonance band. The statistical inversion technique used in obtaining the results presented here has been described in a previous report.[1]

Figure III-1 shows the results of inversions performed on simulated data computed from 100 U.S. Weather Bureau radiosonde records. The radiosonde records were made at Huntington, West Virginia, and included 50 summer and 50 winter soundings. The simulated experiment was that of a radiometer looking down at nadir from an altitude of 20 km. Brightness temperatures of the radiation received by the radiometer were computed at 3 frequencies in the oxygen band, and were used as data in the inversion technique. Inversion results are shown for noise-free data and for data to which 1°K noise was added. The dashed lines in Fig. III-1 give the standard deviation in the errors of the 100 inversions, and represent the accuracy of inferring the temperature profile from the radiometric measurements. The average error was zero for all altitudes. For comparison, the standard deviation of the actual temperature profile for the 100 records is also shown. The results shown in Fig. III-1 supersede those presented in Fig. III-5 of our previous report.[1] These results incorporate the method of inverting nearly singular matrices that was described, but not used, in our earlier report.
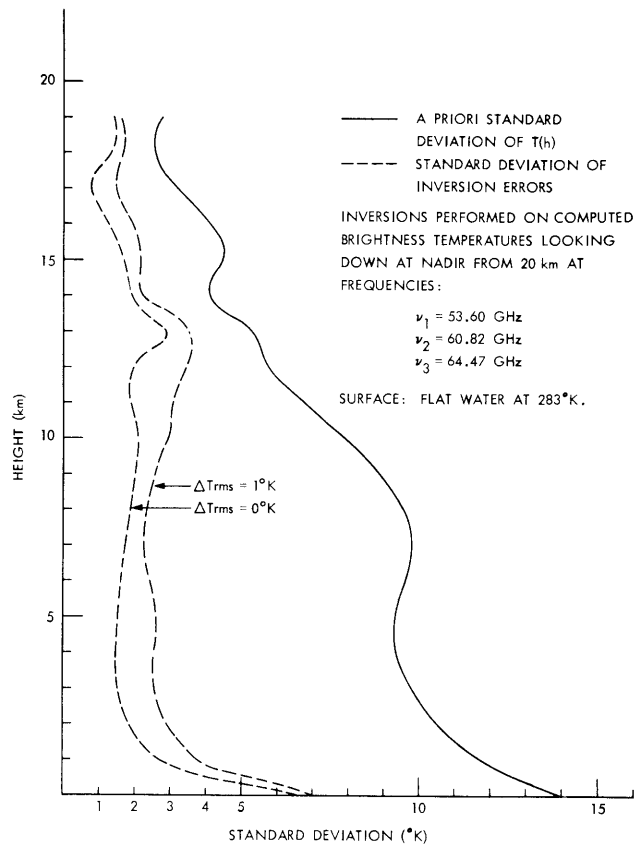
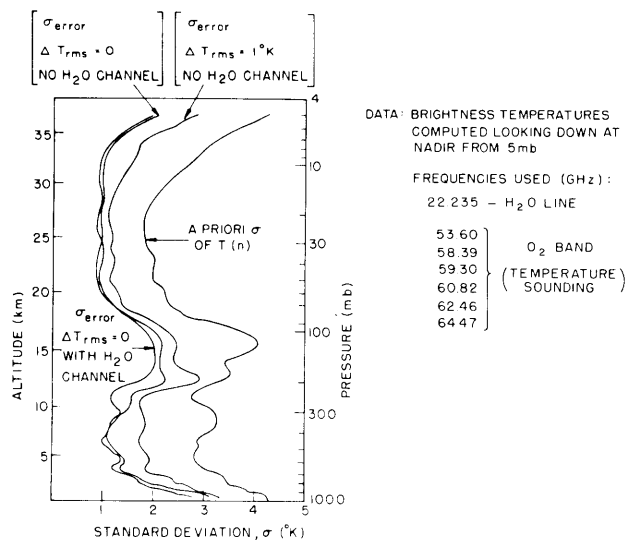**Fig. III-1.** Inversions performed on computed brightness temperatures looking down at nadir from 20 km.

Fig. III-2. Inversion accuracy; only summer statistics used.

Figure III-2 shows inversion results based only on summer radiosonde records. The soundings used are from Peoria, Illinois, for the months of June through September. Only soundings that reached a pressure altitude of 5 mb (approximately 37 km) were included. Data consisted of computed brightness temperatures looking at nadir from the 5-mb level. Six frequencies in the oxygen band were used. These frequencies gave temperature weighting functions at 6 separate atmospheric levels below 30 km. Also shown in Fig. III-2 is the effect of including a measurement at the 22.235-GHz water-vapor resonance.

By considering only summer records, the a priori standard deviation is greatly reduced from that of Fig. III-1, which included both summer and winter data. In this case, the simulated microwave measurements increase the accuracy of inferring the temperature profile by one or two degrees over that which could be obtained from a priori statistical information alone. This is compared with the 5-10° improvement shown in Fig. III-1. The value of the microwave measurement is thus strongly dependent on the statistical information that we have concerning the atmosphere.

For the results given in Figs. III-1 and III-2, the atmosphere was stratified into layers of approximately 0.5-km thickness. In other words, a height resolution of 0.5 km
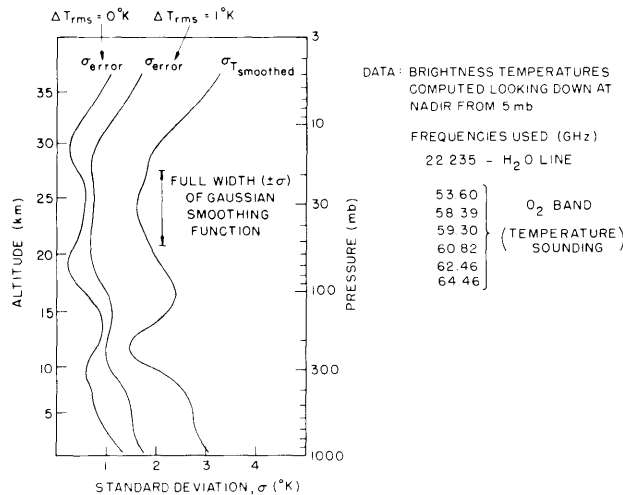

Fig. III-3. Inversion accuracy for 8-km height resolution
and summer statistics.

was asked of the inversion scheme. If one is satisfied with the temperature averaged over a thicker vertical layer, the accuracy will be improved. Figure III-3 shows inversion results for the temperature profile which has been smoothed by a Gaussian function with a full width of 8 km. For 8-km smoothing, the atmospheric

temperature can be inferred to an accuracy of better than 2°K, if the brightness temperature of the upwelling radiation is measured to an accuracy of 1°K at each of the frequencies. Such accuracy of measurement is within the limits of present radiometric systems that could be carried on a satellite.

J. W. Waters, D. H. Staelin

References

1. J. W. Waters and D. H. Staelin, "Statistical Inversion of Radiometric Data," Quarterly Progress Report No. 89, Research Laboratory of Electronics, M.I.T., January 15, 1968, pp. 25-28.

D. DIGITAL SYNCHRONOUS DETECTOR

An improved 20-channel version of the 5-channel digital synchronous detector and data control system[1] has been designed, and a 1-channel prototype has been tested.[2] Each digital synchronous detector consists of a voltage-to-pulse frequency converter and an 18-bit up-down counter, of which the 12 high-order bits are read out at periodic intervals. The system permits integration times as long as 15 minutes, with almost negligible rms error, and a DC offset that is less than 1% of the dynamic range. For integration times less than 1 minute the 12-bit output is essentially error-free. The use of integrated circuits and printed circuits has reduced the approximate cost per additional channel to $100.

The wired program unit permits the radiometer to operate automatically in nonrepeating sequences as long as 9 hours.

L. P. A. Henckels, D. H. Staelin

References

1. D. H. Staelin, "Microwave Spectrum of Venus," Sc.D. Thesis, Department of Electrical Engineering, M.I.T., January 1965.
2. L. P. A. Henckels, "Digital Output Unit for a Multichannel Radiometer," S.M. Thesis, Department of Electrical Engineering, M.I.T., May 1968.

E. RADIOMETER WITH A 23.8-GHz PARAMETRIC AMPLIFIER

A degenerate parametric amplifier, designed by D. H. Steinbrecher, has been constructed, tested in several ways, and installed in front of the K-band 20-channel radiometer.[1,2] Noise figure and loss measurements of the components and the system have yielded the noise and loss budget shown in Table III-1.

Table III-1. System losses and noise temperature.

Component	Loss (dB)	Noise Figure (dB)	Noise Temperature (°K)
Input Isolator	0.6		
Directional Coupler	0.5		
Dicke Switch	0.8		
Second Isolator	0.6		
Circulator	0.6		
Parametric Amplifier		1.6	
System		4.7	560
Contribution from radiometer back end with 15-dB parametric amplifier gain			120
Total System Temperature			680

The system performance was evaluated by means of a noise tube and a noise figure meter. The 3-dB system bandwidth during these tests was approximately 100 MHz, and the system gain fluctuation was observed over a period of 5 minutes to be approximately 0.5% rms for an average gain of 15 dB.

P. W. Rosenkranz, D. H. Staelin

References

1. P. W. Rosenkranz, "A Low-Noise K-Band Radiometer for the Measurement of Narrow Spectral Lines," S.M. Thesis, Department of Electrical Engineering, M.I.T., May 1968.
2. D. H. Staelin, R. M. Weigand, and J. W. Waters, "20-Channel Microwave Spectrometer," Quarterly Progress Report No. 86, Research Laboratory of Electronics, M.I.T., July 15, 1967, pp. 25-26.

F. POSSIBLE MICROWAVE EXPERIMENT FOR
A PLANETARY PROBE TO VENUS

The recent Mariner V and Venera IV planetary probes to Venus[1] indicate that the planetary surface is hotter than 500°K, and the surface pressure is many atmospheres. The microwave spectrum between 0.3-cm and 30-cm wavelengths is therefore presumably dominated by high surface brightness temperatures attenuated at wavelengths

shorter than ~3 cm by nonresonant atmospheric absorption. Nonresonant absorption could occur in CO_2, other gases at high pressures, clouds, or some combination of these sources. If the absorption is dominated by atmospheric gases with a nearly constant mixing ratio, then the temperature structure of the atmosphere might reasonably be monitored by a planetary orbiter similar to those proposed for terrestrial studies (see Sec. III-C). That is, the brightness temperature observed from space as a function of frequency, $T_B(\nu)$, would be

$$T_B(\nu) = \int_0^\infty T(h)\, W(h, \nu)\, dh, \tag{1}$$

where $T(h)$ is the desired temperature profile, and $W(h, \nu)$ is the weighting function. Typical weighting functions are shown in Fig. III-4 for a 90% CO_2 atmosphere. Thus
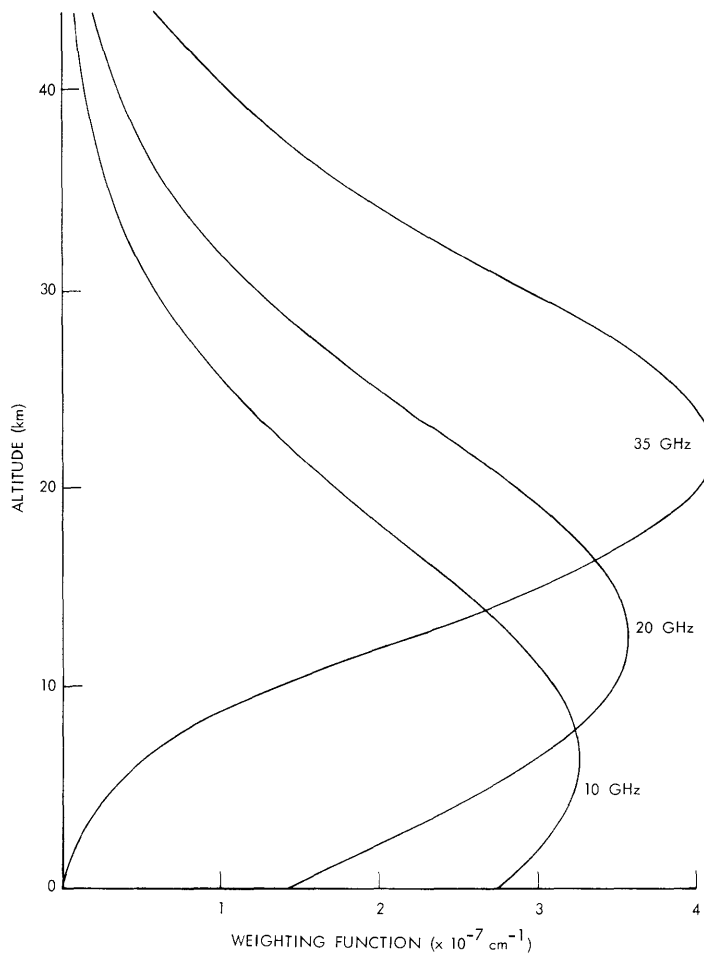

Fig. III-4. Venus temperature functions at nadir.

the temperature profile may be determined with a resolution of 25 km.

Whether such an experiment might ever enable monitoring meteorological phenomena on Venus with a space probe in orbit about Venus depends upon the stability of the atmospheric absorption coefficient. If clouds are not negligible absorbers near the frequencies of interest, then such observations could be severely hampered by variations in cloud cover.

An instrument package that could land on the planetary surface would establish the validity of such an orbiting meteorological experiment. Not only could such an instrument measure composition, temperature, and pressure profiles on the way to the surface, but it could also measure the microwave properties of the clouds. Cloud opacities at various frequencies could be determined by a microwave radiometer viewing space as it descends through the atmosphere. A thin cloud would be evident because of the resulting discontinuity in the apparent brightness temperature as a function of altitude, $T_B(h)$, and a thick cloud would be evident because of the resulting discrepancy between theoretical and experimental $T_B(h)$. The sensitivity of such an attempt to detect cloud absorption would be limited by receiver sensitivity in the upper regions of the atmosphere, and by the accuracy of the a priori expression for $\tau(\nu)$ in the lower regions.

If it is assumed that a zenith-looking radiometer mounted on a landing vehicle would yield brightness temperatures with an accuracy (3σ) of 6°K, and that the simultaneous composition measurements would permit opacity calculations accurate to ~10% (3σ), then the presence of clouds or other constituents could be detected with an accuracy (3σ) of $\Delta\tau$, where $\Delta\tau$ is presented in Table III-2 for 2 frequencies and 3 altitudes. The model atmosphere used in the preparation of this table is consistent with the recent planetary probes.[1] The altitudes are presented in terms of equivalent pressures and temperatures because pressure and temperatures are more relevant to cloud composition than altitude.

Table III-2. Minimum detectable cloud opacity $\Delta\tau$.

Pressure (mm Hg)	Temperature (°K)	10 GHz	40 GHz
266	245	0.01	0.014
667	300	0.01	0.014
2494	400	0.01	0.040
6944	500	0.02	0.085

Table III-2 indicates that such an instrument landing on the surace would be quite sensitive to clouds, and certainly should be capable of validating a temperature-sounding experiment mounted in a planetary orbiter.

Sara E. Law, D. H. Staelin

References

1. A. Kliore, G. S. Levy, D. L. Cain, G. Fjeldbo, and S. I. Rasool, "Atmosphere and Ionosphere of Venus from the Mariner V S-band Radio Occultation Measurement," Science 158, 1683-1688 (1967).