VIII. RADIO ASTRONOMY

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RESEARCH OBJECTIVES AND SUMMARY OF RESEARCH

1. Atmospheric Measurements with Passive Microwave Techniques

U. S. Air Force – Electronic Systems Division (Contract F19628-73-C-0196)

A. H. Barrett, D. H. Staelin, K-S. Lam

The 118-GHz O_2 resonance can be used for sounding atmospheric temperature profiles to mesospheric altitudes because of its great opacity. The same resonance also provides an opportunity for measuring the water content of clouds. It can be done by comparing either ground or satellite observations of spectral bands having comparable absorption by O_2 near 60 GHz and 118 GHz. In the absence of clouds the two bands appear identical. Since clouds absorb more strongly at 118 GHz, the 60-GHz and 118-GHz intensities differ in proportion to the liquid water content of observed clouds. Such observations at various frequencies should permit the altitude distribution of heavy clouds to be deduced.

A 118-GHz radiometer is being fabricated for this project, but funding limitations have slowed purchase of certain necessary hardware.

It is well known that the theory of microwave absorption is inadequate when applied to overlapping spectral lines, i. e., when the widths of the lines are comparable to their spacing. Detailed theories, which include the effect of overlap, have not been applied to the microwave spectrum of molecular oxygen when broadened by oxygen-nitrogen, oxygen-oxygen, and oxygen-water collisions.

We are attempting to apply these theories to microwave absorption by molecular oxygen in an atmospheric environment. We have made microwave observations of oxygen emission from high-altitude balloons looking downward, and hope to test these theories using these data.

2. Microwave Spectroscopy of the Interstellar Medium

National Science Foundation (Grant 40484X)

A. H. Barrett, P. T. Ho, R. N. Martin, K. P. Bechis, P. C. Myers

Radio spectroscopy of the interstellar medium has revealed that many molecules are present in detectable amounts. In the majority of cases the population distribution

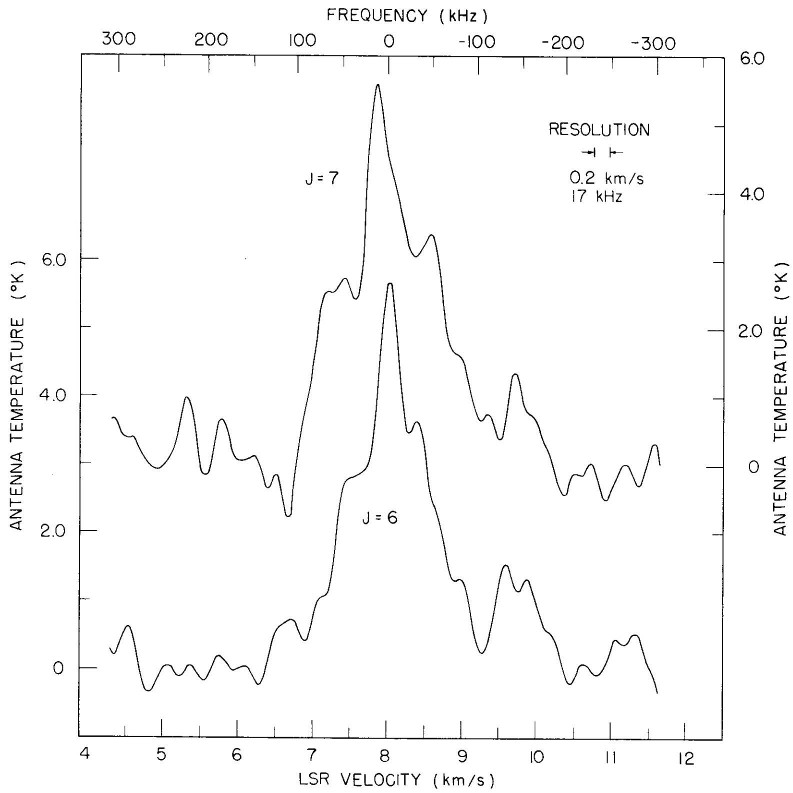

Fig. VIII-1. Sample spectra of the J = 6, J = 7 lines of CH_3OH.

among the molecular energy levels is nonthermal, which makes it difficult to interpret the observational data in terms of physical parameters of the interstellar environment, such as temperature, gas density, radiation density, molecular composition, gas-to-dust ratio, and so forth. Our studies have focused on the emission of OH, H_2O, CH_3OH, and CH_2O in galactic HII regions and in stellar sources that have an infrared excess. Temporal studies of OH and H_2O emission are being conducted in coordination with infrared observations of stellar sources. A program of CO observations has been initiated to study emission from infrared stars and its correlation with the visual output of these stars, and emission in the galactic plane with particular emphasis on the column density of CO in the direction of x-ray sources.

Studies of CH_3OH in the Orion Nebula have indicated detailed structure in the spectral lines when examined with a frequency resolution of 17 kHz. The structure appears to be characteristic of the molecule because it shows a high degree of symmetry about the center of the line and a systematic increase in line width as lines of higher and higher rotational quantum number are measured. The lines appear to be polarized, which, coupled with the symmetrical line structure, is indicative of Zeeman patterns. Figure VIII-1 shows sample spectra of the J = 6 and J = 7 lines of CH_3OH.

3. Sensing of Subsurface Body Tissue Temperatures with Microwave Radiometry

Joint Services Electronics Program (Contract DAAB07-71-C-0300)

National Institutes of Health (Grant 1 RO1 GM20370-01)

A. H. Barrett, P. C. Myers

Introduction

During the past year we have continued to work on a preliminary study of the ability of microwave radiometry to detect localized subsurface temperature elevations in animals and humans. As we have reported previously,[1,2] the rationale behind this work rests on the following factors:

1. All objects emit thermal electromagnetic radiation, whose intensity depends on the temperature of the object and the frequency of observation at microwave frequencies. Thermal radiation is readily detectable from humans with present microwave radiometers.

2. In the 100 MHz-10 GHz band microwave radiation can penetrate, and therefore also escape from, body tissue depths of several centimeters. This behavior is illustrated in Fig. VIII-2. Radiation received from the body in this band can therefore indicate subsurface tissue temperatures. Microwave radiometry of this type is directly analogous to infrared thermography, except that the temperature information pertains to depths of ~1 cm instead of ~0.1 mm.

3. Detection of spatial variations in the body's thermal patterns may provide valuable medical diagnostic information in numerous applications, including early detection of malignant tumors, especially in the breast, detection of cerebrovascular insufficiency – a sign of an impending stroke – and detection of peripheral vascular insufficiency and local inflammation.[3]

Equipment Development

Development of equipment has involved operation of radiometers at 1.3 GHz and 3.3 GHz, and fabrication of antennas of various apertures and spatial resolution. Auxiliary temperature sensing equipment, including recording thermocouples and thermistors, has been developed and employed. Mechanical equipment for precise control of antenna positioning has been designed and built; digital circuitry for signal calibration, averaging, and recording has been constructed and is under test.

Research Results

Radiometric data have been taken at 3.3 GHz, using cats and humans as subjects in order to detect localized temperature elevations under various circumstances. This work has served as a basis for more detailed clinical tests on humans, which will begin next year in collaboration with physicians at local Boston hospitals. The radiometer is a superheterodyne of the Dicke-switched type. A detection sensitivity of ~0.2°K antenna temperature was achieved with an integration time of 3 seconds. The antenna was a straight section of WR-90 rectangular waveguide of 0.4 × 0.9 inch cross section, filled with a low-loss solid of dielectric constant $\epsilon = 11$, in order to propagate the dominant waveguide mode above its cutoff frequency. The antenna aperture was placed flush against the skin, to provide better impedance match and spatial resolution than could be obtained with an intervening air gap. The resultant spatial resolution across the antenna axis is essentially that of the antenna near field, or ~0.4 × 0.9 inch.

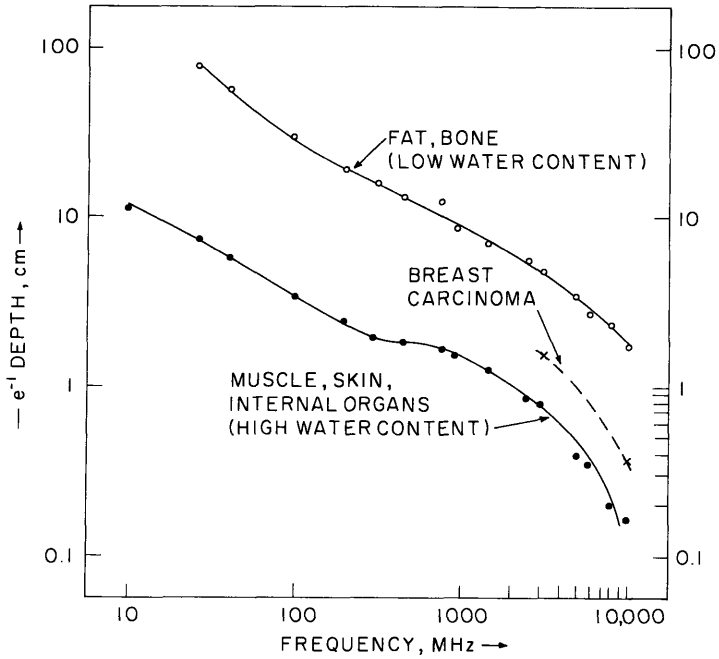

Fig. VIII-2. Microwave penetration depth in human tissue. These data are taken from the literature on dielectric tissue properties.[4-8] The curves show the depth from which microwave radiation of a given frequency will originate, if it is attenuated by e^{-1} or 37% when it reaches the surface. A 1-GHz radiometer can thus see radiation from an e^{-1} depth of ~1.4 cm in muscle, or ~8 cm in fat.

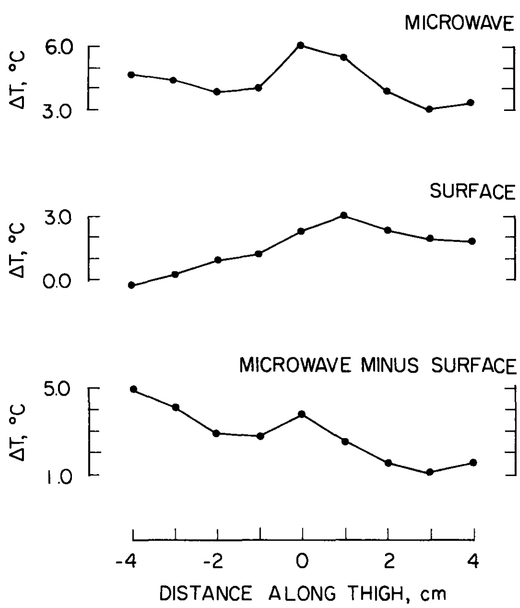

Fig. VIII-3.

Temperature scans of locally heated cat thigh. Data were taken along a line on the surface of the thigh, whose interior was heated ultrasonically by ~3°C within a volume $\lesssim 1$ cm^3. Each scan shows the difference between temperatures measured while heating, and ~30 minutes after heating was ended. The relative microwave temperature increase is greater than the relative surface temperature increase. This indicates microwave ability to sense subsurface temperature elevation more effectively than a device which measures surface temperature. Measurement error: ±0.2°C.

In radiometric studies involving cats we employed focused ultrasound as a source of localized subsurface tissue heating.[9] A dead cat was studied first; these results, obtained in the absence of circulating blood, have been reported previously.[2] Essentially the same techniques of heating, internal thermal sensing, and antenna scanning were used in more recent studies of live anesthetized cats. Results obtained in one such study are shown in Fig. VIII-3. Here the local microwave antenna temperature increase is ~2° C, while the surface temperature increase is ~1° C. The microwave method is thus more capable of detecting subsurface temperature elevations than an instrument that has the same temperature sensitivity but measures surface temperature only (e.g., an infrared thermograph).

A study of a sterile abscess created in the thigh of a cat by injection of gum turpentine indicated a ~1° C subsurface temperature elevation but no surface temperature rise immediately following injection, at the injection site. Subsequent measurements of the same cat during a 14-day period showed a migration of the "hot spot" and its decline at the end of this period.

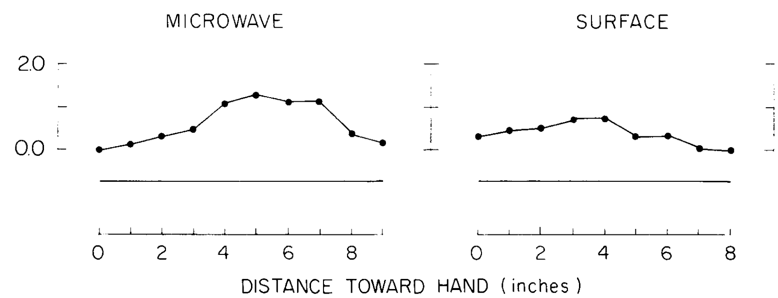

Fig. VIII-4. Temperature scan of forearm heated by muscle contraction. Scans were taken along a line on the forearm, with the palm up. Muscles in the forearm were contracted by repeated clenching of the fist. Each curve is the temperature difference between the contracting and relaxed cases. A local increase is seen in a region including contracting muscles. No corresponding surface temperature increase is evident.

Internal heating of the human forearm by muscular contraction was achieved by repeated clenching of a fist. The microwave and surface temperature response was measured (see Fig. VIII-4). Here each curve shows an average of two difference scans along the arm, where temperatures measured before heating are subtracted from temperatures measured during heating. Again a region of subsurface temperature elevation is seen, while no corresponding surface temperature increase is noted. The region of subsurface heating corresponds to the location of the three forearm muscles employed in clenching the fist. This effect was observed in three subjects; the relative surface temperature increase was detectable in two cases not shown here. In all cases, however, the microwave antenna temperature increase was greater than the surface temperature rise.

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4. Long-Baseline Optical Interferometer

U. S. Air Force – Air Force Systems Command (Contract F33615-72-C-2129)

D. H. Staelin, P. L. Kebabian

A coherent optical interferometer has been designed for measuring angular diameters of very small optical sources such as stars. Baselines up to ~100 ft are feasible. New devices developed include a diffracting beam splitter and chopper system and an efficient 3-level chopper. Upper limits have been placed on the tracking capability and sensitivity of such systems when located on the terrestrial surface.

5. Environmental Sensing with Nimbus Satellite Passive Microwave Spectrometers

California Institute of Technology (Contract 952568)

D. H. Staelin, K. F. Kunzi, P. W. Rosenkranz, J. W. Waters

The Nimbus-5 Earth-observatory satellite was launched in December, 1972, into a nearly circular polar orbit at an altitude of 592 NM. The 5-channel microwave spectrometer (NEMS) views the nadir with half-power 10° beamwidth. Individual channels are located at a weak water-vapor resonance in a spectral window, and at 3 positions on the edge of the oxygen absorption band (5-mm wavelength); the center frequencies are 22.235, 31.4, 53.65, 54.9, and 58.8 GHz.

The passive observations of the thermal microwave radiation in these five bands have yielded both the temperature profile and the vapor and liquid water content of the terrestrial atmosphere over ocean, even under overcast conditions. Information has also been obtained on geophysical parameters that affect the surface emissivity, such as ice type, sea roughness, and snow cover.

In Fig. VIII-5 the rms discrepancies between the NEMS inferred atmospheric temperature profiles and those interpolated in time and space from the National Meteorological Center 0^h and 12^h operational analysis grids are presented. Typical rms errors are 2°K, with larger values near the surface and tropopause, approximately as expected. These data demonstrate the ability of microwave soundings to yield acceptable temperature maps over the entire globe, even in the presence of most clouds, including some clouds that hamper similar infrared observations.

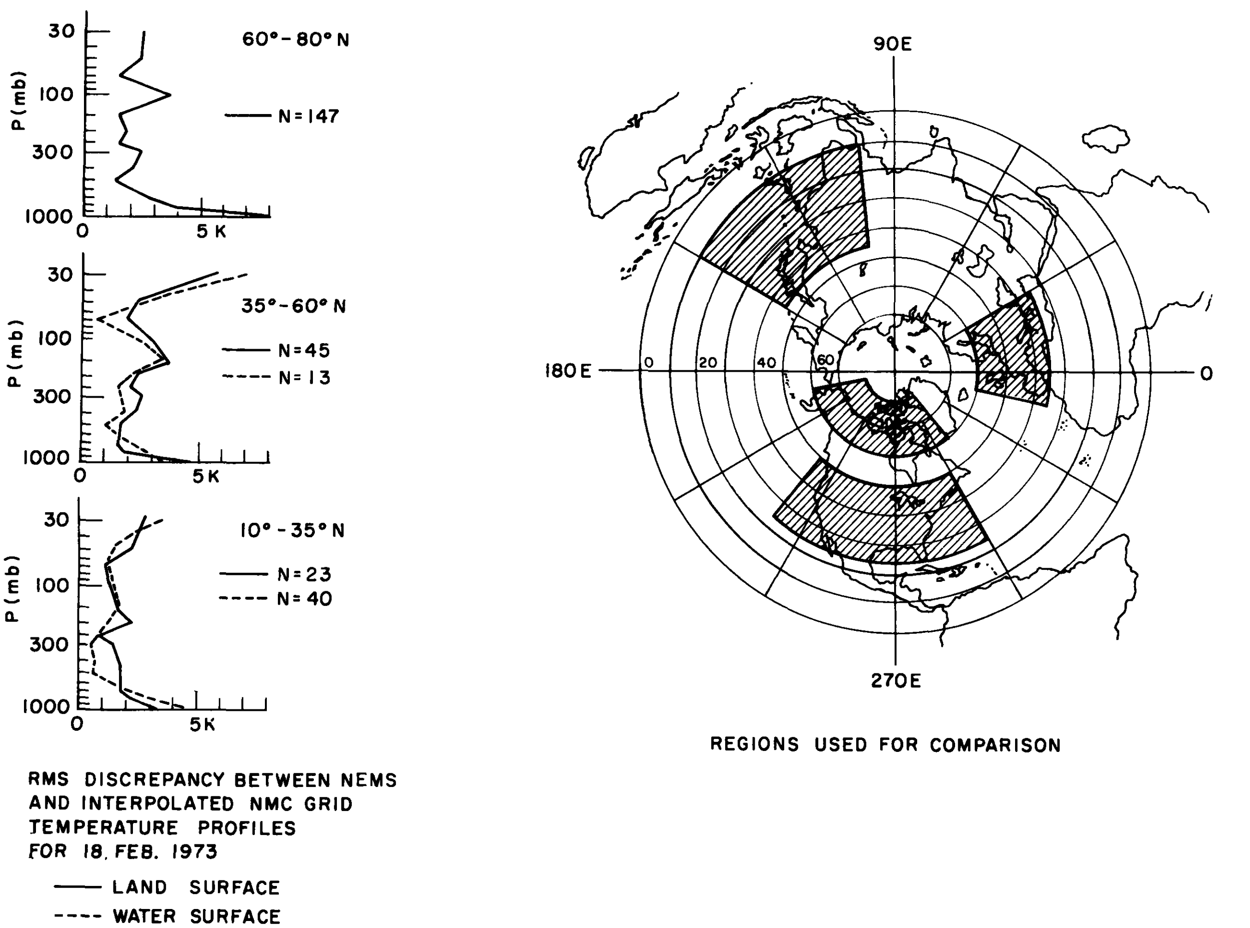

Fig. VIII-5. Temperature profiles.

The ability of microwaves to sense abundances of water vapor and liquid water content over ocean is also unique, and preliminary analyses yield reasonable agreement with operational radiosonde observations of water vapor. Studies of ice and snow, deserts, and other surfaces are also furnishing new and unexpected results.

The Nimbus-6 satellite, which will be launched in 1974, will carry a scanned version of NEMS, and provide two complete global maps with 200-km resolution each day. Preparations for this next experiment are under way.

6. Experiments for Microwave Temperature Sounding of the Mesosphere and Upper Stratosphere

National Aeronautics and Space Administration (Contract NAS1-10693)

P. W. Rosenkranz, D. H. Staelin, J. W. Waters

The extremely opaque O_2 resonances near 60 GHz provide an opportunity for satellite-borne microwave radiometers to measure thermal radiation originating from levels up to 75-km altitude. It appears possible to map on a global scale the atmospheric temperature profile from 0-75 km altitude with a vertical resolution of ~5-20 km and a horizontal resolution of 100-400 km.

To explore the problem further, a 23-channel microwave spectrometer covering a 40-MHz band and tunable over several gigahertz near 53 GHz has been developed. Observations of the strongest lines near 60 GHz will only be made from satellites. This instrument was first used on the ground at various latitudes to observe the 23_-, 25_-, 27_-, 29_-, and 31_- O_2 resonances. The 27_- line was observed more intently during February and March, 1973, using the NASA Convair 990 observatory aircraft (which crashed subsequently). These observations reveal what may be a fairly serious discrepancy between theory and experiment; the lines appeared to be approximately 50% stronger than expected.

Future work will be directed toward resolution of the apparent conflict between theory and experiment and final development of a satellite capability. An engineering model of such an instrument (at 53 GHz) is now being fabricated at the California Institute of Technology Jet Propulsion Laboratory.

7. Radio Structure of Galaxies

National Science Foundation (Grant GP-40485X)

R. M. Price

Investigations under this program include radio astronomical studies of the structure of our Galaxy and extragalactic "normal" spiral galaxies. In the first area continuum observations have been used to study the distribution of nonthermal radio emission regions in our Galaxy. These observations yield information on the distribution of galactic cosmic-ray electrons and the strength and orientation of interstellar magnetic fields.

In the studies of our Galaxy we have included high galactic latitudes, the so-called halo region, low galactic latitudes, the galactic disk, and more recently the region of the galactic center. Recent results of these studies indicate that approximately one-half of the total power emitted from the galactic disk at wavelengths near 1 meter originates in spiral features.

During the coming year, galactic structure studies will be directed toward an interpretation of the radio emission from the region of the galactic center and a further definition of the nonthermal emission regions in the disk. A study of radio emission from mass-loss nebulae associated with Wolf-Rayet stars will also be completed.

In the area of extragalactic studies, a survey of normal spiral galaxies is being carried out (with P. C. Crane) using the three-element interferometer of the National Radio Astronomy Observatory. Preliminary observations at 3 cm and 11 cm have already been completed on a sample of 185 galaxies with angular diameters greater than 4 minutes of arc. Observations of another sample of 200 galaxies are planned for Spring 1974.

This study is designed to yield data on the radio structure of spiral galaxies. Of particular interest are sources of small diameter or source complexes associated with the galactic nuclei, extended emission regions associated with the disks (including spiral features), and sources in the vicinity of galaxies that might have been ejected from a "parent" galaxy. As part of this survey, we are investigating galaxies noted by Sersic as having abnormal optical properties associated with their nuclei.

Preliminary reductions of our observations yield the following results. Sources are detected in the fields of approximately 60% of the galaxies surveyed thus far. Of these, 45 sources (25% of the total sample) have small diameters and their positions indicate they are probably associated with the nuclei of the galaxies, 35 are extended sources (20% of the sample) with less well-determined positions but indicative of structure associated with the galaxies, and 30 sources (15% of the sample) have confused fields that will require further observation.