TECHNOLOGICAL DEVELOPMENTS FOSTERED BY RADIO ASTRONOMY

National Radio Astronomy Observatory

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OVERVIEW

Radio astronomy is a science that is driven by the pace of technological improvements to its research instrumentation. Although the pioneering work in radio astronomy was conducted prior to 1940, the infant science did not fully blossom until after World War II. Major advances in the science came in the post-war era primarily due to the availability of the superb radar instrumentation developed during the war and also because of the interest of brilliant technologists who had excelled as radar and radio engineers driven by the war effort. It was clearly evident then, as it is today, that in order for a radio astronomer to work at the forefront of the discipline, his instruments needed to be at the forefront of the associated technology.

The communications industry has instrumental needs that are in many respects similar to those of radio astronomy, with the major exception that radio astronomers have no control over the natural radio signal transmitters that they struggle to detect. Consequently, radio astronomers have always been forced to develop antennas of the highest gain, receivers of the highest sensitivity, and in general instrumentation that defines the state of the art in signal reception and analysis. In many cases the required instrumentation was not available in other scientific disciplines or in industry and had to be developed specifically for radio astronomy. Oftentimes non-radio astronomy applications were discovered later. In other cases, a more symbiotic relation between the needs of radio astronomy and those of other sciences or of industry led to the development of instrumentation of value for each discipline. However, in all these circumstances the technical requirements of radio astronomy have directly or indirectly fostered technological innovations of wide applicability.

Engineering and software developments done principally for radio astronomy have contributed most to the five specific areas of technology that are described below:

- Sensitive microwave receiving systems, including
    - high gain antennas
    - low noise receivers
    - solid state oscillators and frequency multipliers
    - cryogenics
- Data correlation and recording technology
- Image restoration techniques
- Time and frequency standards
- Remote sensing, navigation, and geodesy

I. SENSITIVE MICROWAVE RECEIVING SYSTEMS

A. High Gain Antennas

Radio astronomers design and build antennas of the largest possible size and quality because celestial signals are extremely weak. This requirement has led to several major new technological developments that are just beginning to find commercial applications.

Homology Principle

One of the major limitations to the construction of large steerable antennas with precise reflecting surfaces is the gravitational deformations that change as the antenna is moved from one sky position to another. In 1967, S. von Hoerner published his Homology Principle in a paper addressed to astronomers[1] and in another to structural engineers[2]. An antenna with a design that incorporates homology will deform under changing gravitational stress--but it will deform into another paraboloid, albeit one with a different focal position and focal length. By tracking the focus the effect of the gravitational deflection is minimized and very large, accurate antennas are possible. In the strictest sense only radio telescopes have made full use of the homology principle, but nowadays all designs of large reflector antennas take advantage of homology at least to some degree. As the commercial antenna industry moves to ever higher frequencies, homology will become even more important. The Very Long Baseline Array (VLBA) antennas are examples of a modern design that has replaced an old 25-m antenna design providing a factor of four improvement in rigidity.

Holographic Antenna Metrology

Until recently the only techniques available for verifying the surface accuracy of an antenna were mechanical. Although radio astronomers helped develop these mechanical techniques, their greatest contribution to antenna metrology is the recent development of an electrical technique. This so-called "holographic method" uses the Fourier Transform relationship between the aperture illumination and

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[1] S. von Hoerner, "Design of Large Steerable Antennas," Astron. J., vol. 72, p. 35, 1967.

[2] S. von Hoerner, "Homologous Deformations of Tiltable Telescopes," Proc. ASCE - J. Struc. Div., vol. 93, p. 461, 1976.

the diffraction pattern of an antenna. Scott and Ryle[3] first used this technique to evaluate the antennas of the Cambridge 5-km array, following a suggestion of R. Hills. Bennett et al.[4] were the first to publish a discussion of the technique. The University of California, Berkeley radio astronomy group were the first to reset the surface panels of an antenna using this technique. It has been applied to the evaluation of virtually all major radio telescopes, and it is now part of the routine test and acceptance program of most new telescopes.

Holography is a valuable new method for measuring the amplitude and phase of the electric field in the aperture of an antenna and, as antenna standards are tightened, the antenna industry is expected to make increasing use of this technique. Two firms evaluate antennas holographically as a commercial service: a group in Sheffield, England, and Interferometrics, Inc., of Vienna, Virginia. NASA has adopted the technique as the standard for evaluating the quality of the antennas used in the Deep Space Network.

Correcting Subreflectors

An improved knowledge of the irregularities of the primary reflector has suggested methods for their compensation. In 1976, S. von Hoerner[5] published a procedure to correct for such errors by constructing a subreflector with compensating errors. Most radio telescopes employ multiple reflecting surfaces to bring radiation to the receiver system and Von Hoerner's idea was to improve telescope performance by dealing with a small subreflector rather than the large primary surface. The first application was the deformable subreflector on the NRAO 140-ft telescope which compensated for gravitational deflection of the primary surface by bending the subreflector.[6] More recent applications have fabricated optics to correct for specific surface errors revealed by holographically produced maps. The California, Berkeley radio astronomy group recently reported improvements to one of their millimeter-wave telescopes by use of an

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[3] P. F. Scott and M. Ryle, "A Rapid Method for Measuring the Figure of a Radio Telescope Reflector," Mon. Not. Roy. Astr. Soc., vol. 178, p. 539, 1977.

[4] J. C. Bennett, A. P. Anderson,. P. A. McInnes, A. J. T. Whitaker, "Microwave Holographic Metrology of Large Reflector Antennas," IEEE Trans. Ant. & Prop., vol. AP-24, p. 295, 1976.

[5] S. von Hoerner, "The Design of Correcting Secondary Reflectors," IEEE Trans. Ant. & Prop., vol. AP-24, p. 336, 1976.

[6] S. von Hoerner and W-Y. Wong, "Improved Efficiency with a Mechanically Deformable Subreflector," IEEE Trans. Ant. & Prop., vol. AP-27, p. 720, 1979.

error-correcting lens.[7] The University of Texas millimeter astronomy group has made dramatic improvements in the high-frequency performance of their 5-m telescope with error-correcting mirrors.[8,9] High performance telescopes of the future may well incorporate error-correcting optics as a standard technique for meeting specifications.

High Efficiency Antenna Feeds

In the 1960's, driven by the needs of radio astronomy, engineers and astronomers in the U.S. and Australia independently developed feeds which efficiently illuminate the main reflector. These circular-aperture hybrid-mode corrugated feed horns are widely used now in the communications industry and are essential to the operation of communications satellites. The history of this development has been documented recently by Thomas[10]. These horns are manufactured by many companies, including Rantec, Inc., TIW, and ERA Technologies, Ltd.

B. Low-Noise Receivers

Masers

Maser amplifiers were first used in the 1950's by the communications industry and radio astronomers for the reception of weak signals. Early communication satellites transmitted at a comparatively low power level due to the scarcity of on-board electrical power. (This is less of a problem these days since the advent of higher performance solar cells.) The interchange between techniques developed for radio astronomy equipment and for military/commercial equipment was especially true in the area of maser development. Following the pioneering work of Townes at Columbia University and others, AIL (Airborne Instruments Laboratory) built a number of maser systems for a wide range of applications. Each one advanced the understanding of this new technique; none were simply copies of previous units. Radio astronomy instrumentation was as much of a motivating factor as the pressure for improved satellite communications. Maser systems

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[7] J. Hudson, abstract, URSI (National Radio Science Meeting), June 1985 Vancouver meeting.

[8] H. Foltz, "Dual Subreflector Feeds," Technical Report No. 85-3, Elec. Engr. Res. Lab., Univ. of Texas at Austin, 1985.

[9] C. E. Mayer, "Texas 5-m Antenna Efficiency Doubled at 230-290 GHz with Error Correcting Secondary Optics," abstract, URSI (National Radio Science Meeting), January 1986 Boulder meeting.

[10] B. MacA. Thomas, "A Review of the Early Developments of Circular-Aperture Hybrid-Mode Corrugated Horns," IEEE Trans. Ant. & Prop., vol. AP-34, p. 930, 1986.

installed on the Parkes Radio Observatory antenna in Australia received data from the Giotto satellite during its closest approach with Comet Halley[11]. Although maser amplifiers have been largely superseded at lower frequencies, development is being continued by NASA/JPL for reception of weak signals from deep space probes and also by the radio astronomy community for use in the 20-50 GHz frequency range.

Parametric Amplifiers

Strongly supported by radio astronomy, companies like AIL (Airborne Instruments Laboratory) developed parametric amplifiers in the late 1950's. Specifically, the radio astronomy community provided a major part of the driving force for higher sensitivity and wider bandwidth at higher frequencies. The satellite communications industry, both commercial and military, benefited in the 1960's and 1970's from this earlier work. In fact, a series of companies were formed on Long Island about this time to meet this need for high performance satellite communication systems. The entrepreneurs who started some of these companies (LNR, Comtech, etc.) had been actually involved at the bench level in building parametric amplifiers for the radio astronomy community.

GaAs FET

The push to develop GaAs FET (gallium-arsenide field effect-transistor) amplifiers came largely from the communications industry. These have replaced parametric amplifiers as the most commonly used low-noise amplifier for the reception of satellite transmissions. However, the radio astronomy community (NRAO and the University of California - Berkeley) have pioneered the development of cryogenically-cooled GaAs FET amplifiers for high sensitivity receiving systems. Berkshire Technologies was formed by former radio astronomers to meet NASA and industry requirements for cryogenic GaAs FETs.

HEMT

HEMT's (high-electron-mobility transistors) are recently developed semiconductor devices that have already found their way into both the computer and communication fields. Again, the radio astronomy community (NRAO) with help from NASA (JPL) has supported the development of HEMT devices by GE and Cornell University for use in cryogenically-cooled amplifiers. Since these developments are relatively recent, the full impact is not clear yet; however, the NASA/JPL DSN (Deep Space Network) is evaluating the use of these amplifiers to replace masers which are difficult to maintain in the

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[11] R. Reinhard, "The Giotto Encounter with Comet Halley," Nature, vol. 321, p. 313, 1986.

field. There are also early indications that there is interest by a company involved in defense work in a technology transfer from NRAO. These amplifiers are currently being installed on the Very Large Array (VLA) in order to obtain higher sensitivity for the reception of signals from Voyager II during the Neptune encounter during August 1989.

Schottky Mixers

Cooling reduces the noise of solid-state amplifiers. Weinreb and Kerr[12] pioneered the application of cryogenic cooling of GaAs Schottky mixers in order to improve their performance for radio astronomy. Although the cooling of mixers has not found wide commercial use, the engineering that has gone into the fabrication of cooled mixers has. The IEEE papers of Kerr and Archer have attracted world-wide interest from commercial and defense organizations. Kerr and Held were awarded the IEEE Microwave Prize for their papers covering conversion-loss and noise of microwave and millimeter-wave mixers[13,14]. Millitech was formed by a few talented radio astronomers and is now a major support firm for millimeter and submillimeter wave technology. The success of this company comes from having the right background at a time when the defense industry needs moved up into the millimeter range (battlefield radar systems, etc.).

Superconducting-Insulating-Superconducting (SIS) Mixers

Most major radio astronomy observatories making millimeter-wave observations are currently developing SIS mixers for low-noise receivers. Several observatories are successfully using these devices in receivers. Despite the few years that these devices have been in use, there is already a technology interchange in progress between NRAO and several commercial and government organizations (Hypress, NRL, NSA, etc.).

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[12] S. Weinreb and A. R. Kerr, "Cryogenic Cooling of Mixers for Millimeter and Centimeter Wavelengths," IEEE Journal of Solid-State Circuits, vol. SC-8, February 1983.

[13] A. R. Kerr and D. Held, "Conversion-Loss and Noise of Microwave and Millimeter-Wave Mixers: I - Theory," IEEE Trans. on Microwave Theory and Tech., vol. MTT-26, p. 49, 1978.

[14] A. R. Kerr and D. Held, "Conversion-Loss and Noise of Microwave and Millimeter-Wave Mixers: II - Experiment," IEEE Trans. on Microwave Theory and Tech., vol. MTT-26, p. 55, 1978.

Solid-State Oscillators and Multipliers

Phase-locked, millimeter-wave sources for use as broadly tunable local oscillators for radio astronomy are not readily available commercially. Consequently, the radio astronomy community has made substantial progress in the development of varactor multipliers[15] (Archer) and voltage-tunable Gunn oscillators[16] (Carlstrom, Plambeck, and Thornton). There has been considerable commercial interest in these devices and follow-up work at Millitech Inc. has led to their successful marketing.

Cryogenics

The low-noise amplifiers used on radio astronomy antennas are generally operated at cryogenic temperatures - 15K or 4K are commonly used. The closed-cycle refrigerators used are usually Gifford-McMahon refrigerators built by CTI (Cryogenics Technology, Inc.). The 4K system uses the same refrigerator type with an add-on Joule-Thompson circuit. Reliability of these cryogenic systems has always been important to the radio astronomy community, and radio engineers have worked closely with the manufacturer (CTI) to improve system performance and reliability. Some improvements to the compressors that were developed and evaluated by NRAO have been incorporated by the manufacturer. These systems have also had beneficial use in the semiconductor industry as the central component of low temperature vacuum pumping units.

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[15] J. W. Archer, "An Efficient 200-290 GHz Frequency Tripler Incorporating a Novel Stripline Structure," IEEE Trans. on Microwave Theory and Tech., vol. 32, p. 416, 1984.

[16] J. E. Carlstrom, R. L. Plambeck, and D. D. Thornton, "A Continuously Tunable 65-115 GHz Gunn Oscillator," IEEE Trans. on Microwave Theory and Tech., vol. MTT-33, p. 610, 1985.

II. DATA CORRELATION AND RECORDING TECHNOLOGY

A. Digital Correlation Techniques for Spectral Analysis of Broadband Signals

Many radio astronomical observations involve the spectral analysis of a broadband signal, the most common example being observations of an atomic or molecular spectral line. The frequency bandwidths that the astronomer needs to analyze, 10-1000 MHz, are extremely large for traditional techniques such as analog filters. Instead, radio astronomers have developed digital techniques involving coarse quantization (1-3 bits) and autocorrelation of wideband signals. The advantages of digital correlation are greater flexibility, reliability, and stability, with inexpensive components. The seminal work on digital techniques for spectral analysis in radio astronomy is that done by Weinreb[17] and Cooper[18].

Digital correlation is now used extensively in remote sensing applications (from earth satellites), oceanography, and oil exploration.

A contemporary digital spectrometer which provides the flexibility needed in radio astronomy to analyze signals of vastly different bandwidths (from 1.25 to 320 MHz) is described by W. Urry et al.[19]

Digital techniques employing coarsely quantized data also permit one to cross-correlate data rapidly from many separate signals. For example, the VLA radio telescope requires data to be correlated at a rate of 2×10^{12} multiplications per second. If this was to be performed with floating point numbers in a large computer then the power of 100 CRAY supercomputers would be needed. However, by using 3-level arithmetic, a special purpose digital correlator was built for this task at a cost of only 2 million dollars.

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[17] S. Weinreb, "A Digital Spectral Analysis Technique and Its Application to Radio Astronomy," M.I.T. Research Laboratory of Electronics, Tech. Report 412, 1963.

[18] B.F.C. Cooper, "Autocorrelation Spectrometers," Methods of Experimental Physics, vol. 12B, p. 280, 1976.

[19] W. L. Urry, D. D. Thornton, and J. A. Hudson, "Hat Creek Millimeter-wave Hybrid Spectrometer for Interferometry," Publ. Astron. Soc. Pacific, vol. 97, p. 745, 1985.

B. Wideband Tape Recording

The radio astronomical technique of Very Long Baseline Interferometry (VLBI) requires very wideband tape recording. Simultaneous observations are made at radio telescopes separated by tens to thousands of miles, and the tape recorded data are played back and cross-correlated at a latter time at a common location. Initially, radio astronomers used video cassette recorders, readily available in the consumer market at low cost, to record digital data. In addition, instrumentation recorders have been improved by more than an order of magnitude for high VLBI data rates. VLBI observations are recorded at a density of one million bits of information on each square inch of instrumentation tape.[20] The technique for doing so has attracted commercial interest.

C. Archival Mass Storage

The enormous data storage requirements of radio astronomical observations made conventional magnetic storage techniques uneconomical. To meet these requirements, astronomers have developed low-cost instrumentation recorders by using analog recorders to record digital data. One system in operation uses a Video Cassette Recorder for this purpose.

The NRAO has investigated whether the performance of these devices could be improved so that they might also be employed to store archive data. In the process of investigating the feasibility of using such a recorder for VLA archive data, the NRAO developed a prototype recorder suitable for high performance recording.

The new recorder resembles a streaming magnetic tape drive. It has a capacity of 2.5 gigabytes of user data and a data rate of 120 kilobytes per second. It employs read after write, error correction circuitry, and spatial multiplexing to achieve a rate low enough for high-performance recording.

The ability to place 2.5 gigabytes of data on a $4 cassette tape in an essentially error-free environment makes such a recorder very attractive for a number of fields. Disk backup, archiving of both scientific and business data, and medical electronics are but a few.

Ray Escoffier, the inventor and an AUI employee, has applied to patent the recording system and to provide for a life-long royalty free license to the United States Government. The first patent (Serial No. 870,305) is currently pending. Digi Data, an OEM manufacturer of magnetic tape equipment located in Maryland, has been licensed to

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[20] K. I. Kellermann and A. R. Thompson, "The Very Long Baseline Array, Science, vol. 229, p. 123, 1985.

manufacture the recorder. The company has further developed the recorder, taking it from a demonstration of feasibility to a product and plans to market it in late 1986.

III. IMAGE RESTORATION ALGORITHMS

A. Aperture Synthesis Techniques

The angular resolution of a radio telescope is proportional to the diameter of the dish antennas measured in wavelengths. Larger telescopes can more easily see fine scale details in cosmic sources. But, there is a limit to the size of an individual telescope that one can construct. To achieve still higher angular resolution, it is possible to synthesize a single telescope from an array of spatially separate antennas which simultaneously observe a position in the sky. The basic technique of aperture synthesis samples an electromagnetic wave front at many widely separated locations and then uses the Fourier transform of these data to stimulate the response that would have been obtained with a much larger, single antenna. The radio astronomer Sir Martin Ryle received the Nobel Prize in Physics for the conception and demonstration of this technique.

The principles of the aperture synthesis technique are directly incorporated in many non-astronomical image construction endeavors which are widely available commercially, such as the following,

- synthetic aperture radar
- X-ray tomography of human tissue.[21]

B. Self-Calibration Algorithms: Adaptive Optics

Distortion of an image by the atmosphere is a problem common to both radio and optical telescopes. This problem restricts synthesis array radio telescopes such as the VLA. The distortion manifests itself through collimation errors resulting from spatially and temporally varying refractivity of the atmosphere above the array. Years ago the radio astronomer Roger Jennison derived phase closure mathematical relations that could be applied to observations with telescope arrays in order to circumvent these effects and sharpen the radio images.[22] This technique, suitably refined and known as self-calibration, is now routinely employed in radio astronomy.[23]

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[21] R. N. Bracewell and A. C. Riddle, Ap. J., 150, 427, 1967.

[22] R. C. Jennison, "Fourier Transforms of Spatial Brightness Distributions of Small Angular Extent," Mon. Not. Roy. Astr. Soc., vol. 118, p. 276, 1958.

[23] F. R. Schwab, "Adaptive Calibration of Radio Interferometer Data," Proc. Soc. of Photo-Optical Instrumentation Engrs., vol. 231, p. 18, 1980.

To an optical telescope, the effect of the atmosphere is easily seen in, for example, the twinkling of stars. Atmospheric turbulence generates an irregular distortion of the wavefront across the telescope aperture. If it were possible to distort the shape of the telescope mirror in the same way, then one could cancel the atmospheric distortion and sharpen the image. This is precisely what is done. With an articulating mirror driven by pistons, the shape of the mirror is continuously deformed in real-time until the image sharpens. Such a technique for optical telescopes is called "adaptive optics," but it is in all ways analogous to the radio astronomical technique of self-calibration. Adaptive optics is also used in satellite cameras to improve their photographic capabilities.[24]

C. Maximum Entropy Algorithm

Synthesis array telescopes do not fully sample the incoming electromagnetic wavefront, and it is necessary to interpolate from the measured points so as to fill in the "missing" data. Such image processing by means of the maximum entropy algorithm, a technique first developed for the analysis of seismic data, has been greatly refined for application to radio astronomical problems.[25]

So successful has been this improvement that the astronomical software algorithms developed by radio astronomers are now used for problems of blurred photographic images in non-astronomical contexts (e.g., sharpening images for police work). Several commercial firms now market the maximum entropy algorithms for diverse applications. Maximum Entropy Data Consultants Ltd. is one such firm.

D. Astronomical Image Processing Systems (AIPS)

AIPS is an extensive integrated software package for manipulation of multi-dimensional images. Developed by the NRAO, AIPS is distributed without charge for use by hundreds of scientists worldwide. Designed to be machine independent, it runs on all classes and makes of computers, from minicomputers to supercomputers; it is routinely used in nonastronomical image analysis applications. Several hardware vendors advertise and promote the suitability of their equipment for AIPS support. Among these are the following:

CONVEX Computer Corporation, Inc.
International Imaging Systems, Inc.

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[24] R. Muller and A. Buffington, "Real-time Correction of Atmospherically Degraded Telescope Images Through Image Sharpening," J. Optical Soc. of America, vol. 64, p. 1200, 1974.

[25] S. Gull and G. Daniell, "Image Reconstruction from Incomplete and Noisy Data," Nature, vol. 272, p. 686, 1978.

IV. TIME AND FREQUENCY STANDARDS

A. Hydrogen Maser Frequency Standard

The technique of Very Long Baseline Interferometry (VLBI), in which tape-recorded data taken by telescopes thousands of miles apart are brought together and cross correlated, requires that each telescope maintain exceptional frequency stability. Specifically, the frequency at each station must be stable to better than one part in 10^{14} over a period of several hours. At the present time only active hydrogen masers can provide the required stability.[26]

Hydrogen masers, which produce the 1420-MHz hyperfine transition of atomic hydrogen as their fundamental output, were developed as an experimental time standard by the NBS. Prior to the needs of VLBI, there was no commercial maker for this laboratory device. Reliable field-ready hydrogen masers were subsequently developed by the Smithsonian Astrophysical Observatory and at NASA/Johns Hopkins Applied Physics Laboratory in order to supply each individual VLBI antenna with its own hydrogen maser frequency standard. These designs have been developed into a commercial product by Oscilloquartz S. A. in Switzerland and Sigma Tau Standards Corporation in Alabama, among others. The present market for hydrogen maser frequency standards is dominated by space communications and DOD needs. Finally, Hughes Research Laboratories is developing a space-qualified hydrogen maser for use on the NAVSTAR Global Positioning Satellites.

B. Time Standards and Time Transfer

A standard of time may have more than one appropriate definition. For a laboratory experiment a suitable time standard may be an atomic clock. For an astronomical observation, on the other hand, or a determination of the position (orbit) of an earth satellite "time" refers to the rotation of the earth on its axis. This rotation is not constant. Not all earth days are of the same duration owing to subtle wobbles of rotation of the earth.

The USNO relies heavily on the radio astronomical data for their daily determination of the earth's rotation periods. Using a worldwide network of optical telescopes augmented in an important way by radio astronomical observations with the NRAO interferometer in Green Bank, WV, the USNO constantly monitors the rotation of the earth relative to an astrometric grid of very constant radio sources (quasars). Unlike the optical determinations, the radio astronomical observations can be

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[26] A. Rogers and J. Moran, "Coherence Limits for Very Long Baseline Interferometry," IEEE Trans. on Instru. and Measur., vol. IM-30, p. 283, 1981.

made day and night, and they are affected by clouds or the weather to a relatively small degree. The USNO radio technique and its application is discussed by Winkler[27] and Matsakis et al.[28]

In order to transfer a single laboratory reference time to distant clocks with high accuracy, one must develop a synchronization method. The VLBI technique is routinely used in radio astronomy to synchronize telescope clocks to nanosecond accuracy worldwide. This method also has applications for very precise navigation and in other non-astronomical contexts.

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[27]G. Winkler, "Time Keeping and Its Applications," Advances in Elect. and Electron Phys., vol. 44, p. 33, 1977.

[28]D. Matsakis et al. "The Green Bank Interferometer as a Tool for the Measurement of Earth Orientation Parameters," Astron. J., vol. 91, p. 1463, 1986.

V. REMOTE SENSING, NAVIGATION, AND GEODESY

A. Microwave Thermography of the Human Body

Observations of cosmic sources of radio radiation made with a radio telescope are fundamentally measurements of the temperature of those objects. Instead of looking at the sky, one can use the same technique to scan the human body and, in so doing, measure precisely the distribution of temperature across the body. Since malignant tumors and regions of vascular insufficiency are thermally anomalous, these features are readily apparent on microwave scans of the human body.

Radio astronomers have adapted this technique for non-invasive measurement of the temperature of subcutaneous human tissue.[29] Although microwave radiometry has coarser spatial resolution than infrared thermography, it has a greater sensitivity to deep tissue temperature. Flesh is transparent at microwave frequencies. Clinically, in application to the detection of breast cancer, the combination of microwave and infrared thermographic data provides a true-positive detection rate of 96 percent.[30] Microwave thermography does not expose patients to harmful radiation.

B. Atmospheric Ozone Monitoring

The depletion of the protective layer of ozone (O_3) in the stratosphere is a matter of utmost current concern since potentially increased levels of solar UV radiation on the surface of the earth will result from a diminished O_3 concentration. For several years scientists have known that chlorine monoxide ($C\ell O$) is a key tracer of the stratospheric ozone depletion cycle arising from natural and man-made injection of chlorine-containing compounds, particularly halocarbons, into the atmosphere. The reactions

$$O_3 + C\ell \rightarrow C\ell O + O_2$$
$$C\ell O = O \rightarrow C\ell + O_2$$

constitute the catalytic cycle by which chlorine atoms convert ozone to diatomic oxygen.

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[29] A. H. Barrett and P. Myers, "Subcutaneous Temperatures: A Method of Noninvasive Sensing," Science, vol. 190, p. 669, 1975.

[30] A. H. Barrett, P. C. Myers, and N. L. Sadowsky, "Microwave Thermography of Normal and Cancerous Breast Tissue," Proc. 3rd Intern. Symp. on Detection and Prevention of Cancer (Decker: New York), 1978.

Radio telescopes can directly measure and monitor the stratospheric abundance of ClO, and its diurnal and long-term variation. Radio astronomers demonstrated the efficacy of this technique by means of observations of the J = 11/2 - 9/2 and J = 15/2-13/2 rotational transitions of ClO at 204 and 278 GHz, respectively. Such ground-based observations provide a cost-effective way of monitoring potential damage to the ozone layer using existing radio astronomical instruments and techniques.[31]

C. Remote Sensing Satellites

One of the most economically significant applications of radio astronomy techniques has been to remote sensing satellites which carry passive imaging microwave spectrometers operating at wavelengths ranging from several centimeters to a few millimeters. Early successes in mapping atmospheric temperature and humidity fields, polar ice distributions, and other geophysical parameters, even in the presence of clouds, have led to the steady use of passive microwave temperature sounders on the operational NOAA and DOD weather satellites, and the anticipated primary use of a 20-channel imaging microwave spectrometer on operational NOAA satellites beginning in 1990. The following types of investigations are under way:

Operational Weather Monitoring - temperature profiles, water vapor distribution, and rain bands
Atmospheric Research - stratospheric and mesospheric temperature profiles, water vapor profiles, trace constituent profiles, and winds
Polar Ice Studies - ice pack evolution and navigability
Land and Ocean - sea surface temperature, sea surface wind, oil spill observations, soil moisture, and snow cover

Several references describe these applications.[32,33,34,35,36]

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[31] P. M. Solomon, R. de Zafra, A. Parrish, and J. W. Barrett, "Diurnal Variation of Stratospheric Chlorine Monoxide: A Critical Test of Chlorine Chemistry in the Ozone Layer," Science, vol. 224, p. 1210, 1984.

[32] D. Staelin et al., "Microwave Spectroscopic Imagery of the Earth," Science, vol. 197, p. 991, 1977.

[33] D. Staelin, "Passive Microwave Techniques for Geophysical Sensing of the Earth from Satellites," IEEE Trans. Ant. & Prop., AP-29, p. 683, 1981.

[34] Applications, Review Panel Report, "High Resolution Passive Microwave Satellites," D. H. Staelin and P. W. Rosenkranz, eds., Final Report, Contract NAS5-23677, Research Laboratory of Electronics, M.I.T., April 1978. Available from NTIS as NASA Accession No. N81-71117.

D. Earth Satellite Positions and Tracking

To determine the precise positions of artificial earth satellites, one needs not only a means of measuring the position but also a fixed reference frame to which one can refer those positions. The astrometric grid of cosmic radio sources, established over the whole sky by radio astronomers, provides the only truly "fixed" reference system, to which other moving objects may be referred.

The location of those artificial satellites which transmit a radio signal can be established to exceptionally high precision by the radio astronomical technique of Very Long Baseline Interferometry (VLBI). The technique has been verified on the Global Positioning System (GPS) satellites, which are the primary position reference beacons for the next-generation of military, commercial, navigational and geodetic applications.

E. Spacecraft Navigation

Earth-based radio interferometry, precisely as practiced by radio astronomers, has provided a straightforward means of "triangulation" for spacecraft navigation.

- To monitor the position of the Apollo astronauts on the moon during their explorations aboard the Lunar Rover.
- To precisely locate sounding balloons released into the Venusian atmosphere by the Soviet Vega spacecraft mission.
- To establish the relative position of the Vega pathfinder flyby of Comet Halley with respect to the radio astronomical reference system of cosmic radio sources. (Necessary for course corrections during the Giotto spacecraft's close nuclear approach.)

F. Geodetic Studies and Crustal Dynamics

Radio astronomical VLBI observations have become a valuable tool for geophysicists in their study of the motion of the poles of the earth, changes in the rotation of the earth, and the nature of lunar-induced tides in the solid earth.

Geophysical studies of the earth's crustal dynamics depend on high precision measurements spread over several years. The positional

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[35] P. Gloersen et al., "A Summary of Results from the First NIMBUS 7 SMMR Observations," J. Geophys. Res., vol. 89, p. 5335, 1984.

[36] Manual of Remote Sensing, vol. 1, R. N. Coldwell, ed. (2nd ed.), American Society of Programmetry, 1984.

accuracy obtained with radio astronomical VLBI observations is used to monitor the separation between geodetic radio telescopes to a few centimeters. Regional terrestrial deformations and global plate motions are thus measurable where the two telescopes span known fault lines and tectonic plates. The technique allows geophysicists to study pre- and post-earthquake seismic activity with the aim of earthquake prediction and a basic understanding of worldwide tectonic motions.[37]

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[37] A.E.E. Rogers et al., "Very Long Baseline Interferometry: The Mark III System for Geodesy, Astrometry, and Aperture Synthesis," Science, vol. 219, p. 51, 1983.