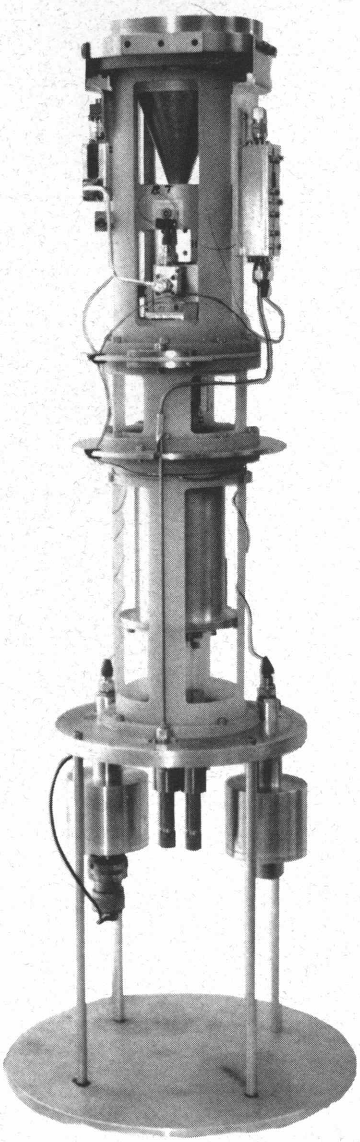

NEW TECHNOLOGY FOSTERED BY RADIO ASTRONOMY

Compiled by the Staff
of the
National Radio Astronomy Observatory

July 1990

National Radio Astronomy Observatory is operated by Associated Universities, Inc., under Cooperative Agreement with the National Science Foundation.

Cover Illustration: One of several receiver inserts that are part of a new modular receiver system currently under construction for the NRAO Twelve-Meter Telescope. The receiver system will operate at millimeter wavelengths; the insert shown here is designed for 3-mm operation (90 to 116 GHz). Each insert contains lens, feed horn, local oscillator injection coupler, mixer, isolator, and amplifier. The mixer uses a superconductor-insulator-superconductor (SIS) junction and the amplifier uses high-electron-mobility transistors (HEMTs), so that this assembly incorporates in a single module the technology developed at NRAO in photon-assisted tunneling mixers, transistor amplifiers, and associated components (see pp. 4–6).

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OVERVIEW

Radio astronomy is a science whose progress 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 when driven by the war effort. It was evident then, and it is ever so clear today, that in order for a radio astronomer to work at the forefront of the discipline, the instruments that are employed must be at the forefronts of the associated technologies.

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 largest collecting area, 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, applications outside of radio astronomy have been discovered later on. In other cases, a more symbiotic relation between the needs of radio astronomy and those of other sciences, or of industry, has 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.

OVERVIEW

Engineering and software innovations developed principally for radio astronomy have contributed most significantly to the six specific areas of technology listed 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;*
- *Computer languages.*

We present here a compilation of brief summaries of technological developments in radio astronomy that have made contributions in these areas.

I. SENSITIVE MICROWAVE RECEIVING SYSTEMS

A. Antennas of Large Collecting Area

Radio astronomers strive to design and construct antennas of the largest possible size and the greatest achievable precision because signals of celestial origin are extremely weak. Astronomers' stringent requirements have led to several major new technological developments that are just beginning to find commercial applications.

The Homology Principle. One of the major difficulties in the construction of large steerable antennas with precise reflecting surfaces is the detrimental effect of gravitational deformations that change as an antenna is moved from one sky position to another. In 1967 S. von Hoerner published an explication of his *homology principle* in a paper addressed to astronomers[1] and in another addressed to structural engineers[2]. While an antenna designed according to the homology principle does deform, perhaps considerably, under changing gravitational stress, it has the property that it deforms into another paraboloid—albeit one with a different focal position and different focal length. By keeping track of the focal position the effect of the gravitational deflection is minimized, and thus very large, accurate antennas are possible. In the strictest sense, only in radio telescope design has full use been made of the homology principle, but nowadays the designs of all large reflector antennas take advantage of homology at least to some degree. As the commercial antenna industry moves to ever higher frequencies, homologous design will become even more important.

Holographic Antenna Metrology. Formerly, 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 exploits the Fourier Transform relationship between the aperture illumination pattern and the diffraction pattern of an antenna. Scott and Ryle[3] first used this technique to evaluate the antennas of the Cambridge five-kilometer array, following a suggestion of

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[1] S. von Hoerner, "Design of large steerable antennas", *The Astronomical Journal*, **72** (1967) p. 35.

[2] S. von Hoerner, "Homologous deformations of tiltable telescopes", *Proceedings of the American Society of Structural Engineers—Journal of the Structural Division*, **93** (1967) p. 461.

[3] P. F. Scott and M. Ryle, "A rapid method for measuring the figure of a radio telescope reflector", *Monthly Notices of the Royal Astronomical Society*, **178** (1977) p. 539.

R. Hills. Bennett *et al.*[4] were the first to publish a description of the technique. The radio astronomy group of the University of California at Berkeley 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 testing and acceptance programs of most new radio telescopes and large communications antennas.

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

Carbon-Fiber Epoxy Antennas. Modern short-wavelength radio telescopes are among the first applications of carbon-fiber epoxy (CFE) technology to ground-based antennas. Examples include the fifteen-meter antennas of the millimeter-wavelength interferometric array at the Institut de Radio Astronomie Millimétrique (IRAM) in France, which combine CFE and steel members, and the Max-Planck-Institut für Radioastronomie (MPIfR) and University of Arizona ten-meter submillimeter-wavelength telescope, which has CFE panels and structural members. CFE is now the material of choice to break through the performance limits imposed by thermal effects on steel structured antennas.

Correcting Subreflectors. The ability to accurately measure the irregularities of an antenna's primary reflecting surface provides the motivation for finding means to compensate for those distortions. In 1976 S. von Hoerner[5] published work on a method of correcting for such errors by utilization of 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 adjusting the surface of a small subreflector rather than that of the large primary reflector. The first application was the deformable subreflector on the NRAO 140-Foot Telescope; this system compensated for gravitational deflection of the primary surface by bending the subreflector.[6] More recent applications utilize specially fabricated

[4] J. C. Bennett, A. P. Anderson, P. A. McInnes, and A. J. T. Whitaker, "Microwave holographic metrology of large reflector antennas", *IEEE Transactions on Antennas and Propagation*, **AP-24** (1976) p. 295.

[5] S. von Hoerner, "The design of correcting secondary reflectors", *IEEE Transactions on Antennas and Propagation*, **AP-24** (1976) p. 336.

[6] S. von Hoerner and W.-Y. Wong, "Improved efficiency with a mechanically deformable subreflector", *IEEE Transactions on Antennas and Propagation*, **AP-27** (1979) p. 720.

optical devices to correct for specific surface errors revealed by holographically produced maps. The radio astronomy group of the University of California at Berkeley recently reported improvements to one of their millimeter-wave antennas achieved by use of an error-correcting lens.[7] The University of Texas millimeter-wavelength astronomy group have made dramatic improvements in the high-frequency performance of their five-meter telescope using error-correcting mirrors.[8,9] They have also constructed an error-correcting secondary mirror for the NRAO Twelve-Meter Telescope. High-performance telescopes of the future may well incorporate error-correcting optics routinely, in order to meet required specifications.

Shaping of the Reflector Surface. The Jet Propulsion Laboratory (JPL) antenna design group were the first to suggest use of unconventional Ritchey–Chrétien optics to achieve high (on-axis) efficiency. The antennas of the NRAO's Very Large Array (VLA) and its Very Long Baseline Array (VLBA) represent the first implementation of this concept. The refurbished antennas of the DSN also incorporate surface shaping.

Feeds for Spherical Primary Reflectors. The National Astronomy and Ionosphere Center (NAIC) has led in the development of line feeds for use on telescopes with spherical primary reflectors, such the 1000-foot Arecibo telescope, in Puerto Rico. More recently NAIC engineers have developed a Gregorian feed system, with shaped secondary and tertiary reflecting surfaces, that provides wideband, high-efficiency performance for the Arecibo telescope.

Highly Efficient Antenna Feeds. In the 1960s, driven by the needs of radio astronomy, engineers and astronomers in the U.S. and Australia independently developed feed horns able to very 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 recently been documented by Thomas.[10] Such horns are manufactured by many companies, including Rantec, Inc., TIW, Inc., and ERA Technologies, Ltd.

Innovations from the Green Bank Telescope (GBT) Project. Several modern radio telescopes incorporate active control of the shapes of their primary reflecting surfaces (the Nobeyama Observatory's 43-Meter Telescope, the

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

[8] H. Foltz, "Dual subreflector feeds", Technical Report No. 85–3, Electrical Engineering Research Laboratory, The University of Texas at Austin, 1985.

[9] C. E. Mayer, "Texas 5-m antenna efficiency doubled at 230–290 GHz with error-correcting optics", abstract, URSI (National Radio Science Meeting), January 1986, Boulder, CO.

[10] B. MacA. Thomas, "A review of the early developments of circular-aperture hybrid-mode corrugated horns", *IEEE Transactions on Antennas and Propagation*, **AP-34** (1986) p. 930.

IRAM Interferometer's 15-meter antennas, and the James Clerk Maxwell 15-Meter, for example). The new 100-meter class, fully steerable antenna being designed for construction in Green Bank, West Virginia represents the largest application of active optics in any antenna. The computer-controlled adjustment of the telescope's surface panels will extend its frequency coverage well beyond the limits of other antennas of this size. The GBT is also the largest example of an offset-feed, clear-aperture design. Earlier examples in radio astronomy include the AT&T Bell Laboratories' eleven-meter millimeter-wave antenna and their horn antennas.

B. Low-Noise Receivers

Maser Amplifiers. Maser amplifiers were first used in the 1950s, both by the communications industry and by radio astronomers, for reception of weak signals. Early communications satellites transmitted at comparatively low power levels due to the scarcity of on-board electrical power. (This is less of a problem today, following the advent of high-performance solar cells.) The interchange between developers of techniques employed for radio astronomy equipment and for military and commercial equipment was especially noteworthy in the realm of maser development. Following the pioneering work of C. H. Townes at Columbia University, and others, Airborne Instruments Laboratory (AIL) built a number of maser systems for a wide range of applications. The construction of each new unit advanced the understanding of this new technology; none was simply a copy of any previous one. Radio astronomy requirements were as significant a motivating factor as the pressure for improved satellite communications. Maser systems 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, NASA is continuing to support maser development (at JPL) to enable better reception of weak signals from deep-space probes and also for use by the radio astronomy community in the 20 to 50 GHz frequency range.

Parametric Amplifiers. Strongly supported by radio astronomy, companies including AIL developed parametric amplifiers in the late 1950s. Specifically, the radio astronomy community provided a major part of the driving force for higher sensitivity, wider bandwidth, and higher frequency capabilities. The satellite communications industry, both commercial and military, benefited in the 1960s and 1970s from this earlier work. In fact, a series of companies were formed on Long Island around that time to meet this need for high-performance satellite communications systems. The entrepreneurs who started some of these companies (LNR, Comtech, etc.) had actually been in-

[11] R. Reinhard, "The Giotto encounter with Comet Halley", *Nature*, **321** (1986) p. 313.

volved at the workbench level in building parametric amplifiers for the radio astronomy community.

GaAs FET Amplifiers. The first impetus to develop gallium-arsenide field-effect transistor (GaAs FET) amplifiers arose primarily within the communications industry. These have replaced parametric amplifiers as the most commonly used low-noise amplifiers for reception of satellite transmissions. However, the radio astronomy community (viz., NRAO and the University of California at Berkeley) has pioneered the development of cryogenically cooled GaAs FET amplifiers for high-sensitivity receiving systems. The Berkshire Technologies company was formed by former radio astronomers to meet NASA's and industry's requirements for cryogenic GaAs FETs.

HEMT Amplifiers. High-electron-mobility transistors (HEMTs) are recently developed semiconductor devices that have already found their way into both the computer and the communications fields. The radio astronomy community (NRAO) with help from NASA (JPL) has supported the development of HEMT devices by the General Electric Company and Cornell University for use in cryogenically cooled amplifiers. Since these developments are relatively recent, their full impact is not yet clear; however, NASA/JPL is evaluating the use of these amplifiers on the Deep Space Network to replace maser amplifiers, which are difficult to maintain in the field. HEMT amplifiers were installed on the VLA, and used with great success, in order to obtain higher sensitivity for the reception of signals from Voyager 2 during the Neptune encounter of August 1989.

Schottky-Diode Mixers. Cooling is known to reduce the inherent noise of many types of solid-state devices. Weinreb and Kerr[12] pioneered the application of cryogenic cooling of GaAs Schottky-diode mixers in order to improve their performance in radio-astronomical applications. Although the cooling of mixers, *per se*, has not found wide commercial use, the engineering techniques developed for fabrication of cooled mixers have done so. 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 on microwave and millimeter-wave mixers.[13,14] Millitech, Inc. 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

[12] S. Weinreb and A. R. Kerr, "Cryogenic cooling of mixers for millimeter and centimeter wavelengths", *IEEE Journal of Solid-State Circuits*, **SC-8** (1973) p. 58.

[13] A. R. Kerr and D. Held, "Conversion-loss and noise of microwave and millimeter-wave mixers: I—Theory", *IEEE Transactions on Microwave Theory and Techniques*, **MTT-26** (1978) p. 49.

[14] A. R. Kerr and D. Held, "Conversion-loss and noise of microwave and millimeter-wave mixers: II—Experiment", *IEEE Transactions on Microwave Theory and Techniques*, **MTT-26** (1978) p. 55.

industry needs moved up to the millimeter-wavelength range (for battlefield radar systems, etc.).

Superconductor-Insulator-Superconductor (SIS) Mixers. SIS millimeter-wave receivers represent one of the very few practical applications of superconductors. The SIS mixer was initially developed by radio astronomers about ten years ago.[15,16] Most major radio astronomy observatories with facilities for millimeter-wavelength observations are currently developing SIS mixers for low-noise receivers. Several observatories have succeeded in using these devices for astronomical observations. Despite the few years that these devices have been in use, there is already a technology interchange in progress between NRAO and several commercial organizations (Hypress, IBM, etc.).

Solid-State Oscillators and Multipliers. Ten years ago, phase-locked millimeter-wave sources for use as broadly tunable local oscillators for radio astronomy were not readily available commercially. Consequently, the radio astronomy community has pioneered the development of varactor multipliers[17] and widely tunable Gunn oscillators[18]. 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: 15 degrees Kelvin and 4 degrees Kelvin are commonly used temperatures. The closed-cycle refrigerators used are usually Gifford–McMahon refrigerators built by Cryogenics Technology, Inc. (CTI). The 4-K 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 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 components of low-temperature vacuum pumping units.

[15] G. J. Dolan, T. G. Phillips, and D. P. Woody, "Low-noise 115 GHz mixing in superconducting oxide-barrier tunnel junctions", *Applied Physics Letters*, **34** (1979) p. 347.

[16] P. L. Richards, T. M. Shen, R. E. Harris, and F. L. Lloyd, "Quasiparticle heterodyne mixing in SIS tunnel junctions", *Applied Physics Letters*, **34** (1979) p. 345.

[17] J. W. Archer, "An efficient 200–290 GHz frequency tripler incorporating a novel stripline structure", *IEEE Transactions on Microwave Theory and Techniques*, **32** (1984) p. 416.

[18] J. E. Carlstrom, R. L. Plambeck, and D. D. Thornton, "A continuously tunable 65–115 GHz Gunn oscillator", *IEEE Transactions on Microwave Theory and Techniques*, **MTT-33** (1985) p. 610.

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 the observation of an atomic or a molecular spectral line. The frequency bandwidths that the astronomer needs to analyze, typically 10 to 1000 MHz, are extremely large to be accommodated by traditional techniques such as analog filtering. Instead, radio astronomers have developed digital techniques involving coarse quantization (one to three bits) and autocorrelation of wideband signals. The advantages of digital correlation are greater flexibility, reliability, and stability, achieved with inexpensive components. The seminal work on one-bit digital techniques for application to radio-astronomical spectral analysis was done by Weinreb[1] and Cooper[2].

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.*[3]

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 were to be performed with floating-point numbers in a large computer, the power of 100 CRAY supercomputers would be needed. Instead, a special-purpose digital correlator employing three-level arithmetic was built for this task at a cost of only two million dollars.

B. Innovative Cross-Correlators

Japanese radio astronomers were the first to construct a synthesis telescope signal correlator that Fourier transforms the signals *before* cross-correlating. The cost and flexibility advantages of this innovation have made it the choice for the VLBA correlator.

[1] S. Weinreb, "A digital spectral analysis technique and its application to radio astronomy", MIT Research Laboratory of Electronics, Technical Report No. 412, 1963.

[2] B. F. C. Cooper, "Autocorrelation spectrometers", in *Methods of Experimental Physics*, Volume 12B, M. L. Meeks, Ed., Academic Press, New York, 1976, p 280.

[3] W. L. Urry, D. D. Thornton, and J. A. Hudson, "Hat Creek millimeter-wave hybrid spectrometer for interferometry", *Publications of the Astronomical Society of the Pacific*, **97** (1985) p. 745.

C. 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 tape.[4] The technique for doing so has attracted commercial interest.

D. Archival Mass Storage

The enormous data storage requirements of radio-astronomical observations make 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 for archival data storage. 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 $2\frac{1}{2}$ gigabytes 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 $2\frac{1}{2}$ gigabytes of data on a four-dollar cassette tape, in an essentially error-free environment, makes such a recorder attractive in widely varied applications. 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 lifelong royalty-free license to the U.S. 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 manufacture the recorder. The company has further developed the recorder, devising a double-density version, and is now marketing several models.

[4] K. I. Kellermann and A. R. Thompson, "The Very Long Baseline Array", *Science*, **229** (1985) p. 123.

III. IMAGE RESTORATION ALGORITHMS

A. Aperture-Synthesis Techniques

The angular resolution of a radio telescope is proportional to its linear size (e.g., its diameter, assuming it to be dish-shaped). Larger telescopes can more easily see fine-scale details in cosmic sources. But there is a limit to the size of an individual antenna that can be built. 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 wavefront at many widely separated locations and then uses the Fourier transform of these data to simulate 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 in 1974 for the conception and demonstration of this technique.

The principles of imaging techniques developed in radio astronomy have been directly incorporated in many non-astronomical image construction endeavors and have played a role in their development. Examples are synthetic-aperture radar and X-ray tomography of human tissue.[1,2]

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 aperture-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 array telescopes in order to circumvent these effects and sharpen the radio images.[3] This technique, suitably refined and known as self-calibration, is now routinely employed in radio astronomy to yield images with angular resolution better than one one-thousandth of a second of arc.[4]

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[1] R. N. Bracewell and A. C. Riddle, "Inversion of fan-beam scans in radio astronomy", *The Astrophysical Journal,* **150** (1967) p. 427.

[2] R. N. Bracewell, "Correction for collimator width (restoration) in reconstructive X-ray tomography", *Journal of Computer Assisted Tomography,* **1** (1977) p. 6.

[3] R. C. Jennison, "Fourier transforms of spatial brightness distributions of small angular extent", *Monthly Notices of the Royal Astronomical Society,* **118** (1958) p. 276.

[4] F. R. Schwab, "Adaptive calibration of radio interferometer data", *Proceedings of the Society of Photo-Optical Instrumentation Engineers,* **231** (1980) p. 18.

With an optical telescope—and even in naked-eye observations—the effect of the atmosphere is easily seen: in the twinkling of stars, for example. Atmospheric turbulence generates an irregular distortion of the wavefront across the telescope aperture. If it is possible to distort the shape of the telescope mirror in a reciprocal manner, then one can cancel the atmospheric distortion and sharpen the image. This is precisely what is sometimes done. With an articulating mirror driven by pistons, the shape of the mirror is continuously deformed in real-time until the image sharpens. Such instrumentation for optical telescopes is generally referred to as "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.[5]

C. The Maximum-Entropy Algorithm

Aperture-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.[6]

So successful has been this improvement that the data-processing 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, such as Maximum Entropy Data Consultants Ltd., now market computer software based upon maximum-entropy algorithms for myriad applications.

D. The Astronomical Image Processing System (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 mini-computers to supercomputers; it is routinely used in non-astronomical image-analysis applications. Several hardware vendors advertise and promote the suitability of their equipment for AIPS support. Among these are Convex Computer Corporation, Inc., and International Imaging Systems, Inc.

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[5] R. Muller and A. Buffington, "Real-time correction of atmospherically degraded telescope images through image sharpening", *Journal of the Optical Society of America*, **64** (1974) p. 1200.

[6] S. Gull and G. Daniell, "Image reconstruction from incomplete and noisy data", *Nature*, **272** (1978) p. 686.

IV. TIME AND FREQUENCY STANDARDS

A. Hydrogen-Maser Frequency Standards

The technique of very-long-baseline interferometry (VLBI), in which tape-recorded data taken by antennas thousands of miles apart are brought together and cross correlated, requires that the equipment at each antenna 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.[1]

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 National Bureau of Standards. Prior to the time that their use became necessary in VLBI work, there was no commercial source 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 provide 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 defense 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 might 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. The rate of this rotation is not constant. Not all earth days are of the same duration, owing to subtle wobbles in the earth's axis of rotation.

The U.S. Naval Observatory (USNO) relies heavily on the radio-astronomical data for their daily determination of the earth's rotation period. Using a worldwide network of optical telescopes augmented by radio-astronomical observations from the NRAO interferometer in Green Bank, WV,

[1] A. Rogers and J. Moran, "Coherence limits for very-long-baseline interferometry", *IEEE Transactions on Instrumentation and Measurement*, IM-30 (1981) p. 283.

the USNO until 1989 monitored the rotation of the earth relative to an astrometric network of very stationary radio sources (quasars). Unlike the optical observations, the radio-astronomical observations can be 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 are discussed by Winkler[2] and Matsakis *et al.*[3] Since 1989 the USNO has used a VLBI network to measure earth rotation.

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

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[2] G. Winkler, "Time keeping and its applications", *Advances in Electronics and Electron Physics*, **44** (1977) p. 33.

[3] D. Matsakis *et al.*, "The Green Bank interferometer as a tool for the measurement of earth orientation parameters", *The Astronomical Journal*, **91** (1986) p. 1463.

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 temperatures 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 in microwave scans of the human body.

Radio astronomers have adapted their measurement techniques to noninvasive measurement of the temperature of subcutaneous human tissue.[1] Although microwave radiometry has coarser spatial resolution than infrared thermography, it has a greater sensitivity to the temperature of deep tissue. 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.[2] Moreover, microwave thermography does not expose patients to harmful radiation. Radiophysics, Inc., markets microwave thermography systems.

B. Monitoring of Atmospheric Ozone

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 ultraviolet radiation on the surface of the earth will result from a diminished O_3 concentration. For several years scientists have known that chlorine monoxide (ClO) is a key participant in the stratospheric ozone-depletion cycle arising from natural and man-made injection of chlorine-containing compounds, particularly halocarbons, into the atmosphere. The reactions

$$O_3 + Cl \rightarrow ClO + O_2$$

$$\text{and} \quad ClO + O \rightarrow Cl + O_2$$

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

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[1] A. H. Barrett and P. Myers, "Subcutaneous temperatures: a method of noninvasive sensing", *Science*, **190** (1975) p. 669.

[2] A. H. Barrett, P. C. Myers, and N. L. Sadowsky, "Microwave thermography of normal and cancerous breast tissue", in *Proceedings of the Third International Symposium on Detection and Prevention of Cancer*, Marcel Dekker, New York, 1978.

Radio telescopes can directly measure and monitor the stratospheric abundance of ClO, as well as diurnal and long-term abundance variations. Radio astronomers demonstrated the efficacy of this technique by means of observations of the $J = 11/2 \rightarrow 9/2$ and $J = 15/2 \rightarrow 13/2$ 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.[3]

C. Remote-Sensing Satellites

One of the most economically significant applications of radio-astronomical 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, 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 National Oceanographic and Atmospheric Administration (NOAA) and Department of Defense 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.

We cite several references describing these applications.[4,5,6,7,8]

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[3] 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*, **224** (1984) p. 1210.

[4] D. Staelin *et al.*, "Microwave spectroscopic imagery of the earth", *Science*, **197** (1977) p. 991.

[5] D. Staelin, "Passive microwave techniques for geophysical sensing of the earth from satellites", *IEEE Transactions on Antennas and Propagation*, **AP-29** (1981) p. 683.

[6] D. H. Staelin and P. W. Rosenkranz, Eds., *High-Resolution Passive Microwave Satellites*, Final Report of the Applications Review Panel, Contract NAS5–23677, Research Laboratory of Electronics, MIT, April 1978; available from the National Technical Information Service via NASA Accession No. N81–71117.

[7] P. Gloersen *et al.*, "A summary of results from the first NIMBUS 7 SMMR observations", *Journal of Geophysical Research*, **89** (1984) p. 5335.

[8] R. N. Colwell, Ed., *Manual of Remote Sensing*, Vol. 1, Second Edition, American Society of Photogrammetry, Falls Church, Virginia, 1983.

D. Earth-Satellite Positions and Tracking

To determine the precise positions of artificial earth satellites, one needs not only a means of measuring the positions but also a fixed reference frame to which one can refer those positions. An astrometric network of cosmic radio sources distributed over the whole sky, and carefully studied 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

The most accurate means of navigating interplanetary spacecraft relies heavily on the radio-astronomical VLBI technique. This measurement technique allows the angular position and the velocity of a spacecraft to be determined relative to an extragalactic reference frame composed of active galactic nuclei.[9] The validity and the potential of this method were first demonstrated during the early portion of the Voyager mission,[10] and it is now an integral part of the navigation of all planetary spacecraft. In order to make optimal use of the measurements of spacecraft position and velocity in the VLBI reference frame it is necessary to tie the motion of planets to this frame. This has been accomplished through VLBI observations of spacecraft in orbit about planets, which positions the spacecraft (and hence the planets) in the VLBI frame.[11] NASA also employs VLBI observations of the sources in the VLBI reference frame to determine the relative locations of NASA tracking stations and (see Section F) to monitor the rotational irregularities of the earth—both are important components in accurate spacecraft tracking. In addition to the VLBI contributions to planetary spacecraft navigation, observations of planets and celestial radio sources are routinely used by NASA's Deep Space Network to

[9] A. E. Wehrle, D. D. Morabito, and R. A. Preston, "Very long baseline observations of 257 extragalactic radio sources in the ecliptic region", *The Astronomical Journal*, 89 (1984), p. 336.

[10] J. S. Border, F. F. Donivan, S. G. Finley, C. E. Hildebrand, B. Moultrie, and L. S. Skjerve, "Determining spacecraft angular position with Delta VLBI: the Voyager demonstration", AIAA Paper 82–1471, *American Institute of Aeronautics and Astronautics/American Academy of Sciences Astrodynamics Conference*, August 1982, San Diego, CA.

[11] X X Newhall, R. A. Preston, and P. B. Esposito, "Relating the JPL VLBI reference frame and the planetary ephemerides", in *Astrometric Techniques*, H. K. Eichhorn and R. J. Leacock, Eds., International Astronomical Symposium No. 109, D. Reidel, Dordrecht, 1986, p. 789.

determine the performance of the antennas used for spacecraft tracking (e.g., to measure their gain, sidelobes, surface accuracy, and pointing precision).

Earth-based radio interferometry has been used as a navigational aid:

- To monitor the position of the Apollo astronauts on the moon during their explorations aboard the Lunar Rover;[12]
- To precisely locate sounding balloons released into the atmosphere of Venus by the Soviet VEGA spacecraft mission;[13]
- To establish the relative position of the VEGA pathfinder, during its 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 approach to the nucleus of the comet);[14]
- To establish reference frames for navigation of planetary probes (e.g., Voyager and Galileo), as described above.
- In addition, Interferometrics, Inc., is building a radio interferometer that will be used to track satellites in NASA's Tracking and Data Relay Satellite System (TDRSS).

F. Geodetic Studies and Crustal Dynamics

Radio-astronomical VLBI observations have become a valuable tool for geophysicists in their studies of the motions of the poles of the earth and changes in the earth's rotation. These phenomena reveal much about the nature of the earth's core.

Geophysical studies of the earth's crustal dynamics depend on high-precision measurements spread over several years. Radio-astronomical VLBI observations are used to monitor the separations between geodetic radio telescopes to accuracies better than one centimeter. Regional terrestrial deformations and global plate motions are thus measurable in cases where two or more of the telescopes span known fault lines and tectonic plates. This technique allows geophysicists to study pre- and post-earthquake seismic activity, with the aim of earthquake prediction and to gain a basic understanding of worldwide tectonic motions.[15]

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[12] C. C. Counselman, III, H. F. Hinteregger, and I. I. Shapiro, "Astronomical applications of differential interferometry", *Science*, **178** (1972) p. 607.

[13] R. Z. Sagdeev, V. M. Linkin, J. E. Blamont, and R. A. Preston, "The VEGA Venus balloon experiment", *Science*, **231** (1986) p. 1407.

[14] R. E. Münch, R. Z. Sagdeev, and J. F. Jordan, "Pathfinder: accuracy improvement of comet Halley trajectory for Giotto navigation", *Nature*, **321** (1986) p. 318.

[15] A. E. E. Rogers *et al.*, "Very-long-baseline radio interferometry: the Mark III system for geodesy, astrometry, and aperture synthesis", *Science*, **219** (1983) p. 51.

VI. COMPUTER LANGUAGES

A. FORTH

One of the most visible spin-offs from radio-astronomical research is FORTH, a high-performance computer programming language and operating system. Developed at the NRAO in the early 1970s, FORTH is widely used today in industrial process control, robotics, vision systems, and microprocessor-based instruments. About fifty books have been published on FORTH. There is a FORTH users' group with about 5,000 members, and an American National Standards Institute (ANSI) language standard is being prepared for FORTH. There are approximately twenty vendors of FORTH-based products, supplying systems tailored to applications on small hand-held computers, as well as on VAX mainframes. There are also a number of computers which execute FORTH directly; that is, in these cases the central processor's basic instruction set consists of FORTH commands.

FORTH was invented by Charles Moore. Frustrated with existing languages and operating systems, he devised his own interactive system. His first application for FORTH was a control and data-processing system for NRAO's 36-foot millimeter-wave telescope on Kitt Peak, near Tucson, Arizona. The performance of the system was exceptional for that time, which inspired many astronomers all over the world to have the system installed on their own telescopes, both radio and optical. FORTH soon spread to industry. Moore and his associates left the NRAO in 1974 and formed FORTH, Inc., to develop the language further and exploit its commercial potential. Some examples of FORTH applications today include:

- The hand-held computers carried by Federal Express delivery agents (50,000 units in the field);
- A high-accuracy densitometer used by Eastman Kodak for quality-control of their film-manufacturing process;
- The environmental-control system for a large airport in Saudi Arabia;
- An adaptive-optics simulation program able to provide mainframe-like performance in an IBM PC;
- A rule-based (or "expert system") automotive engine analyzer manufactured by Allen Test Products for use at service stations (over 20,000 units worldwide, used in five languages).