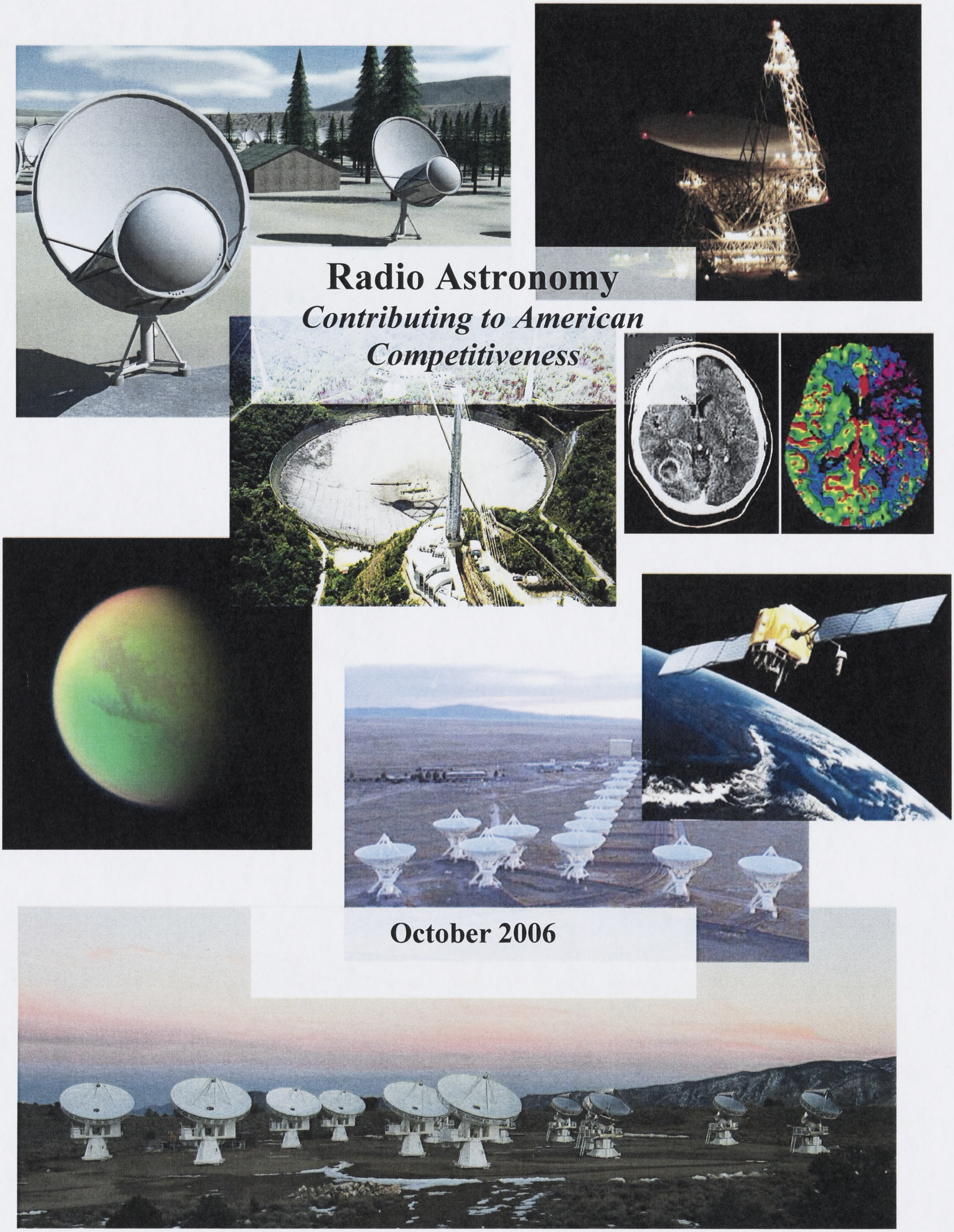

Radio Astronomy

Contributing to American Competitiveness

October 2006

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Compiled by the staff of the National Radio Astronomy Observatory (NRAO).
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CONTENTS

Executive Summary

Radio astronomy is an exemplary national resource that increases American competitiveness in many ways. It contributes uniquely and significantly to our understanding of the universe, and has been a catalyst for enhanced scientific training and basic research in many fields. Extreme distances, weak signals, and vast amounts of astronomical data require instrumentation and processing that pushes the state of the art to its limits. Radio telescopes, facilities, and instruments are developed on a scale that requires collaborative effort and greater funding than a single organization can provide. These technical innovations lead to private sector investment in research and development that translates fundamental discoveries into the production of useful and marketable technologies, processes, and techniques that effect our lives each day.

Technical innovations developed or enhanced for radio astronomy are found in communication antennas, transistor design, cryogenic coolers, medical and scientific imaging, time and frequency standards, atomic clocks and GPS navigation, precision spacecraft navigation, location of cell phone 911 calls, laser rangefinders, and quasi-optical applications. Radio astronomy tracks solar flares that can cause disruption of earth-based communications, damage to orbiting satellites, and destructive surges on power grids. The vast amount of computing capacity required for Searches for Extraterrestrial Intelligence radio signal processing led to a unique grid computing concept that has been expanded to many applications.

Building a highly qualified workforce in the U.S. results in increased American competitiveness. Astronomy is an extremely powerful stimulus for attracting students, and radio astronomy naturally lends itself to educational outreach. The mysteries of the universe and the excitement of space exploration are of great interest to many students who will consider making astronomy a career. Astronomy students also study mathematics, physics, chemistry, and engineering. Even if astronomy is not the final career choice for a student, studying astronomy results in a highly qualified workforce for a large cadre of technical occupations, with flexible skills that can adapt to changes in the labor market, and with abilities at levels where most of the jobs exist. Furthermore, well-funded and publicized astronomy programs in the U.S. attract international students who often remain here to work in technical careers in American companies.

Current radio astronomy projects should result in critical to cutting-edge breakthroughs that can be applied to the engineering sciences and technologies. Recent radio astronomy research has helped reveal the mechanisms by which complex molecules form in the interstellar medium, and may lead to new breakthroughs in medical technologies, materials science, and nanotechnology.

New radio astronomy initiatives have the potential for dramatic increases in American competitiveness in multiple sectors. Radio astronomy is entering a new phase of its development which requires unprecedented increases in the sensitivity of its instruments. Development of low cost components may have direct benefits to several commercial markets, such as the construction of smaller and less costly satellites that require smaller and less expensive rocket boosters. Cryogenic refrigerators required for low noise radio astronomy receivers may have application in the high-performance semiconductor industry. Integration of wideband receivers with data transmission electronics has the potential for expanding the reach of data services to underserved regions of the country and the world.

It is clear that radio astronomy is a valuable national resource that not only increases our fundamental knowledge of the universe, but also contributes significantly to American competitiveness. Only a few endeavors lead to a wide variety of useful and marketable technologies, processes, and techniques, and at the same time, stir the imagination of young and old minds alike. Radio astronomy is one of them.

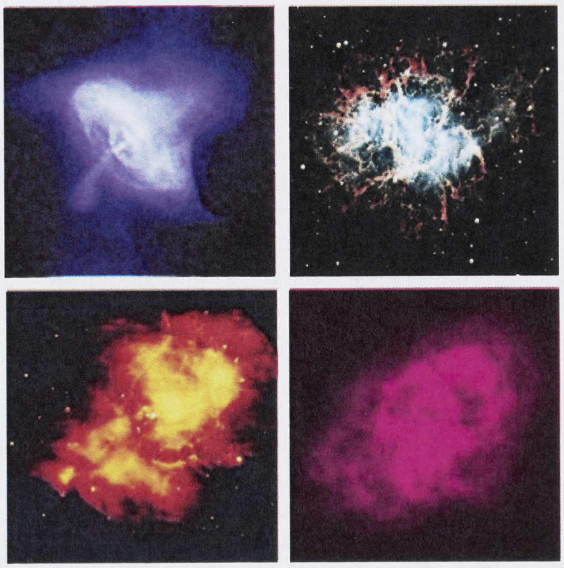
Modern Astronomy

Most of the American public is awed by the splendor of Hubble imagery, fascinated by the explorations of space probes, and proud of the achievements of our astronauts. Furthermore, many people accept that the science behind these programs adds to human knowledge, even though they rarely understand what the results mean. However, only a few outside of a small technical community appreciate how much astronomy affects their daily lives. In reality, the fundamental knowledge gleaned about physical processes in the universe is the impetus for enhanced scientific training and basic research in multiple disciplines, and the technical innovations developed for astronomical research and observations may result in significant advances for our nation's security, and increased competitiveness in the commercial sector.

Multidisciplinary Science

Modern astronomy has changed dramatically over the past half century. It is a multidisciplinary science that includes quantum and high energy physics, general relativity, electrical and mechanical engineering, information technology, chemistry, communications, optics, complex mathematics, materials science, and more. The extreme distances, weak signals, and vast amounts of astronomical data require instrumentation, computational algorithms, and computer software that pushes the state of the art to its limits. The interplay between astronomical requirements and new technical development has far-reaching impact in many other applications from national security to home appliances. Astronomical science tests hypotheses about the creation of energy, the formation of molecules, the nature of sub-atomic particles, and even the building blocks of life in a cosmic laboratory that cannot be replicated here on Earth.

Most matter emits, reflects, and/or absorbs energy across the spectrum from very short wave gamma and x-rays to very long microwave and radio waves. Each portion of this information spectrum is unique and important in understanding the physical processes being observed. Quite often, energy from one portion of the electromagnetic spectrum will be blocked by interstellar matter, interplanetary dust, or atmospheric constituents, while energy from other portions of the spectrum will be transmitted freely to the astronomical equipment.



The Crab Nebula appears quite different at various wavelengths: x-ray (upper left); optical (upper right); infra-red (lower left); radio (lower right). Image source: NASA Remote Sensing Tutorial.

Radio Astronomy

The radio telescope at Green Bank, West Virginia.

Radio astronomers study naturally occurring radio emission from stars, galaxies, and other astronomical objects between wavelengths of about 10 meters and 0.1 millimeters. Since the discovery of extraterrestrial radio waves in 1932 by Karl Jansky at Bell Laboratories, radio astronomy has contributed enormously to our understanding of the universe. For example, in 1963 Maarten Schmidt of the California Institute of Technology discovered quasars as a result of his research on radio galaxies. Subsequent radio observations of quasars led to the discovery of pulsars by Jocelyn Bell and Tony Hewish in 1967. Pulsars are spinning neutron stars that sling lighthouse-like beams of radio waves or light around as they spin. A neutron star is what is left after a massive star explodes at the end of its normal life. With no nuclear fuel left to produce energy to offset the stellar remnant's weight, its material is compressed to extreme densities. Neutron stars are incredible laboratories for learning about the physics of the fundamental particles of nature, and knowledge of these fundamental particles has far reaching impact in basic research for many applications.

Radio telescopes vary widely, but they all have two basic components: (1) a large radio antenna (or arrays of antennas) and (2) a sensitive radiometer or radio receiver. The sensitivity of a radio telescope, the ability to measure weak sources of radio emission, depends on the area and efficiency of the antenna and the sensitivity and bandwidth of the radio receiver used to amplify and detect the signals. Because cosmic radio sources are extremely weak, radio telescopes are usually very large and only the most sensitive radio receivers are used. Moreover, weak cosmic signals can be easily masked by terrestrial radio interference, and great effort is taken to protect radio telescopes from human-generated interference.

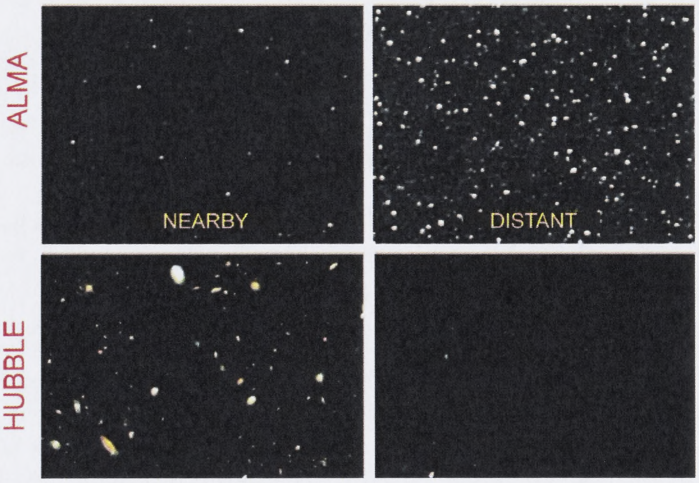
The ability of a radio telescope to distinguish fine detail in the sky depends on the wavelength of observations and the size of the telescope. Because radio telescopes operate at much longer wavelengths than do optical telescopes, radio telescopes must be much larger than optical telescopes to record the same level of detail. At radio wavelengths, the distortions introduced by the atmosphere are less important than at optical wavelengths, and so the theoretical resolution of a radio telescope can be achieved even for the largest dimensions. Radio signals from a single source can be measured over large distances without distortion, and it is possible to build radio telescopes of essentially unlimited dimensions – even larger than Earth’s diameter. This opportunity has led radio astronomers to solve engineering problems related to the construction of very large telescopes, and arrays of smaller telescopes that can exceed the level of detail of a single large instrument by using the principles of interferometry to synthesize a very large effective aperture from a number of smaller radio telescopes.

The Very Long Baseline Array is the world's largest-dimension, full-time, astronomical instrument, consisting of a series of 10 radio antennas spread out across North America from Hawaii to the Virgin Islands. Each antenna is 25 meters in diameter, weighs 240 tons, and is nearly as tall as a 10 story building. The antennas, controlled by the Array Operations Center in Socorro, New Mexico, function together as one instrument with very high resolution and sensitivity.

The Very Large Array

The Very Large Array (VLA) consists of 27, 25-meter telescopes located on the Plains of San Agustin near Socorro, New Mexico. The VLA is the most scientifically productive radio telescope ever built. It is presently being upgraded to the Expanded Very Large Array (EVLA) which will have 10 times the sensitivity and 100 times the spectral capability.

The Atacama Large Millimeter Array (ALMA) is an international radio astronomy facility currently under construction, and will be the largest and most sensitive instrument in the world at millimeter and sub-millimeter wavelengths. ALMA will interconnect 50 or more antennas located in Llano de Chajnantor, Chile, and will provide spatial detail 10 times better than the VLA and the Hubble Space Telescope.



Although the Hubble Space Telescope shows more nearby galaxies than in the simulated ALMA image, ALMA will clearly outperform the Hubble instrument when observing distant galaxies, and may yield significant information about the creation of the early universe. (Imagery sources: ALMA – NRAO; Hubble – SUNY-SB).

The Arecibo Observatory in Puerto Rico is the site of the largest single-dish radio telescope in the world. It operates on a continuous basis and provides observing time, electronics, computer, travel, and logistic support to scientists from all over the world. The observatory is recognized as one of the most important national centers for research in radio astronomy, planetary radar, and terrestrial aeronomy. The huge spherical dish is 305 meters in diameter, 50 meters deep, and covers an area of about 20 acres. A 900 ton platform is suspended from three reinforced concrete towers 140 meters above the reflector. The combined volume of reinforced concrete in all three towers is 9,100 cubic yards. Each tower is back-guyed to ground anchors with seven steel bridge cables. Another system of three pairs of cables runs from each corner of the platform to large concrete blocks under the reflector. They are attached to giant jacks which allow adjustment of the height of each corner with millimeter precision.

The Arecibo radio telescope.

CARMA. Image credit: Andrew West - U.C. Berkeley/Radio Astronomy Lab

The Combined Array for Research in Millimeter-wave Astronomy (CARMA) merges two university-based millimeter-wavelength-capable arrays, the Owens Valley Radio Observatory millimeter array and the Berkeley-Illinois-Maryland Association millimeter array, to form a powerful astronomical tool. At a new high-altitude site in eastern California, CARMA provides unparalleled sensitivity, broad frequency coverage, sub-arcsecond resolution, and wide-field heterogeneous imaging capabilities, along with new innovative technologies and educational opportunities. Water vapor in the lower parts of Earth's atmosphere absorbs and distorts astronomical signals at millimeter wavelengths. Locating the new array approximately 2450 meters above sea level reduces signal loss, and results in an equivalent increase in the collecting area of the array by 50 to 100 percent without building any new antennas.

The Robert C. Byrd Green Bank Telescope (GBT) is the largest fully steerable radio telescope in the world. At nearly 17,000,000 pounds of moving weight, it is believed to be the largest moving structure on land. Despite its enormous size, the telescope can point to better than 2 arcsecond accuracy, which is equivalent to the angular size of a dime viewed at a distance of over a mile. The telescope was designed for observations of radio wavelengths as short as 3 millimeters. To achieve this precision, the telescope surface is composed of 2004 reflecting panels, each of which can be positioned using precise, motorized setting screws. The surface is continuously adjusted to compensate for the effects of gravity on the structure as the dish assumes different poses.

All radio telescopes require sophisticated engineering and technical development. It is not only the knowledge gleaned from radio astronomy observations that has profound effects on human development, but also it is the technology developed for radio astronomy instrumentation and data processing that is transferred to other technical applications. This development and subsequent transfer of the state of the art technology from radio astronomy has helped to create dramatic improvements in American commercial competitiveness.

Technical Innovations from Radio Astronomy

The contribution of radio astronomy to other applications has been more than the basic technology transfer from one discipline to another. In addition to the greater understanding of the physical processes in the universe gleaned from radio astronomy that has been a catalyst for basic and applied research in other fields, the technical requirements driven by the construction of radio astronomy instruments has both driven new technological advances and pushed existing technologies. Sometimes, requirements of radio astronomy for technology that did not exist have been the impetus for basic and applied engineering development. In other cases, new technology developed for other applications had the potential to support radio astronomy, but did not meet the stringent requirements demanded by radio astronomy, and thus the existing technologies were pushed to greater levels of performance. Radio astronomy development projects are usually quite large in scope, and large sources of funds are necessary to support the technical developments that might not have been started without radio astronomy financial support.

Although radio astronomy began prior to 1940, it was the development of superb radar instrumentation during World War II that dramatically changed the science and led to significant technical achievements. There have been three Nobel prizes, the Microwave Application Award from the IEEE MTT Society, and the IEEE Microwave Prize awarded to radio astronomers and engineers. In addition, radio astronomy has contributed significantly to the development of sensitive microwave antennas and receiving systems, data analysis and visualization methods, computer processing technology, time and frequency standards, navigation, and geodesy. Some of the early contributions have been superseded by newer technologies, others are still important today, and many more continue to be the basis for on-going and new technological development.

Radio Location of Cell Phone 911 Calls

The Federal Communications Commission requires that cellular telephone providers be able to specify the location of 911 calls in order to speed the arrival of emergency services. As a spin-off of radio astronomy interferometry techniques, a commercially designed passive system utilizes the difference in arrival times of 911 calls at different cell towers to find locations with an accuracy of 500 feet. Another radio astronomy development is the basis for a commercial system that locates faulty transmitters that interfere with the operation of communication satellites by using the interfering signals received by the satellites themselves to determine the locations of the offending transmitters.

Time and Frequency Standards; Atomic Clocks and GPS Navigation

Radio astronomers developed very long baseline interferometry (VLBI) to achieve resolutions of celestial objects that are more than a hundred times better than the Hubble Space Telescope. VLBI stations require exceptional frequency stability and time synchronization. At the present time, only active hydrogen masers can provide this required long-term stability. Hydrogen masers, which produce the 1420-MHz hyperfine transition of atomic hydrogen as their fundamental output, were developed as an experimental time standard at the National Bureau of Standards. Prior to the time when 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 commercial products that are used today for space communications, satellite navigation, and defense applications.

For thousands of years the rotation of the Earth was the fundamental clock to which all time keeping was synchronized. However, the Earth's rotation rate is quite variable. Since 1950 there has been a gradual migration of time standards to atomic time, as defined by the fundamental oscillation frequencies of atoms, including the simplest one, hydrogen. Precise navigation requires an extremely accurate connection between Earth rotation rate and atomic time, and a key element of this synchronization is VLBI. The most stable reference frame is formed by the positions of extremely distant radio galaxies and quasars. VLBI antennas are fixed to Earth, and thus they can measure Earth's rotation with respect to distant objects with great precision. Using this precision technology, the International VLBI Service (IVS) was established as an international collaboration of organizations that supports geodetic, geophysical, and astrometric research. Some of its products are a terrestrial reference frame, the international celestial reference frame, and Earth orientation parameters. All IVS data and products are archived in data centers and are publicly available for research in related areas of geodesy, geophysics and astrometry.

GPS satellite. Source: NASA.

The GPS satellite system, used by everyone from astronauts and pilots to motorists and hikers, has its time and position system tied to Earth and the cosmos by the IVS. Each GPS satellite has four small atomic clocks that use either rubidium or cesium atoms to send precise time information to GPS navigation systems. The rubidium and cesium atomic clocks are very accurate, but are not as accurate as larger hydrogen maser atomic clocks that are located at ground stations around the earth and are used to reset the satellite clocks when they drift in time.

Communications and Radar Antenna Precision

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 the shape of the antenna as it is moved from one sky position to another. In 1967 at the National Radio Astronomy Observatory, Sebastian von Hoerner developed his homology principle that described how to mitigate these shape changes, and this technology has had direct application to commercial and government communication antenna design and fabrication. Electrical and holographic methods for measuring the antenna deformations have been developed, leading to commercial firms offering such measurement capability as a commercial service. Furthermore, many commercial antenna companies offer a pointing model for large antennas that was developed for radio astronomy. The ability to measure antenna deformations has resulted in the development of sub-reflecting surfaces that can be used to automatically correct the deformations in the large primary surface, and thereby provide better efficiency and performance for large communication antennas.

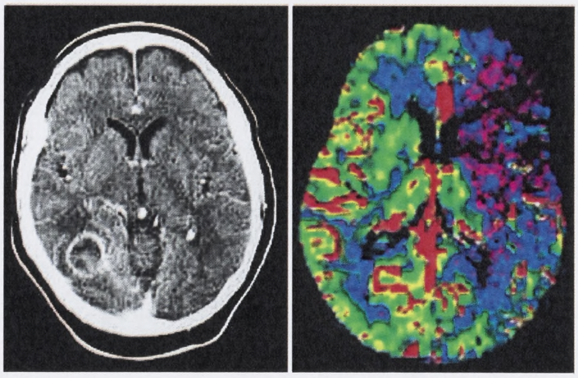
Transistors and Cryogenic Coolers

High-electron-mobility transistors (HEMTs) are semiconductor devices that have already found their way into both the computer and the communications fields. The radio astronomy community, with help from NASA, supported the development of HEMT devices by the General Electric Company and Cornell University for use in cryogenically cooled amplifiers. The "Pospieszalski noise model" for these devices, which is used in the design of both cooled and uncooled amplifiers, is named for its inventor, a radio astronomy engineer. HEMT amplifiers have been installed on nearly all radio astronomy antennas, and were used with great success on the Very Large Array in New Mexico to obtain higher sensitivity for the reception of signals from Voyager-2 during the Neptune encounter of August 1989. All of the HEMT amplifiers for NASA's WMAP satellite, which determined the conditions of the very early universe with great precision, were built and tested in a radio astronomy lab.

The low-noise amplifiers and superconducting devices used on radio astronomy antennas are generally operated at cryogenic temperatures. Reliability of cryogenic cooling systems is important to the radio astronomy community, and radio engineers worked closely with manufacturers to improve system performance and reliability. Improvements to the cryogenic compressors were developed, evaluated, and subsequently incorporated into commercial products. These systems have found beneficial use in the semiconductor industry as the central components of low-temperature vacuum pumping units.

Medical and Scientific Imaging

Image construction, restoration, and enhancement techniques developed in radio astronomy have been directly incorporated into a variety of other applications. For example, construction of visible images from reflected radio signals is the basis for visualization of synthetic aperture radar images of geophysical features. Imaging techniques from radio astronomy have also found their way into medical-imaging tomography of human tissue. Aperture-synthesis radio array telescopes do not fully sample the incoming electromagnetic wave front, 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. 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 context such as sharpening images for police forensic analysis. Several commercial firms now market computer software based upon maximum-entropy algorithms for a myriad of applications.

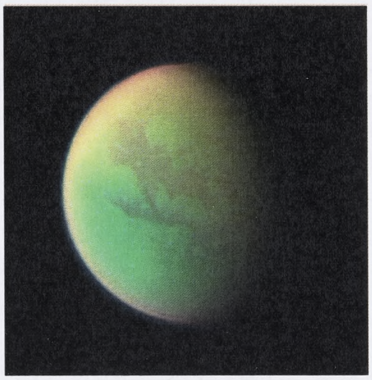


Gray level and color-coded CAT scan of a transaxial section through the human brain. Image source: NASA Remote Sensing Tutorial.

Observations of cosmic sources made with a radio telescope are measurements of the temperatures of those objects. In addition to looking at the sky, these radio astronomy measurement techniques have been adapted to non-invasive measurement of the temperature of subcutaneous human tissue. Malignant tumors are regions of vascular insufficiency that are thermally anomalous, and these features are readily apparent in microwave scans of the human body. Although microwave radiometry has coarser spatial resolution than infrared thermography, it has a greater sensitivity to the temperature of deep tissue. In clinical applications of the detection of breast cancer, the combination of microwave and infrared thermographic data provided a true-positive detection rate of 96 percent, and commercial firms have marketed microwave thermography systems.

Precision Spacecraft Navigation

An 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. The validity and the potential of this method were first demonstrated during the Neptune fly-by portion of the Voyager mission, and it is now a part of the navigation of planetary spacecraft. More recently, this technique was used by NASA's Deep Space Network to precisely track the Cassini spacecraft and its daughter-probe, Huygens, as the latter parachuted through the atmosphere of Titan, Saturn's largest moon. Radio astronomy telescopes were the first antennas on Earth to detect the signal from Huygens after it separated from Cassini, and they provided much of the information necessary to measure the winds on Titan. Atmospheric research on Titan may help us to better understand similar processes here on Earth.



False-color composite was created with images taken during the Cassini spacecraft's closest flyby of Titan on April 16, 2005. Image courtesy of NASA.

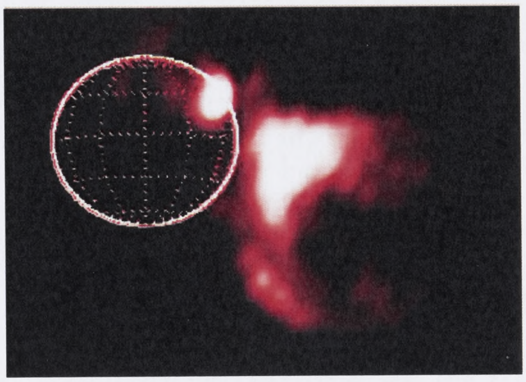
Quasi-optical Technology

Quasi-optical propagation is an analysis technique that combines optics with radio wave technology to extend the limits of electronic systems into the very short radio-wave spectrum. Although quasi-optical propagation of radio waves predates radio astronomy applications, this technology was greatly advanced for radio astronomy by researchers around the world. Radio astronomy has been at the forefront of opening the radio spectrum at shorter and shorter wavelengths for scientific and commercial applications. The link between the radio and optical regime is made with integrated antenna structures with a goal of developing advanced circuits and systems at high frequencies. Quasi-optical technology is multidisciplinary, involving a combination of antenna theory, high frequency circuit design, device physics, optics, communications theory, and computational electromagnetics. Distributed transistor oscillator gratings, amplifier arrays, modulators, switches, tuners, multipliers, and phase shifters have already been developed using this technology, and such devices are being used in applications that include coupled-oscillator systems, gyromagnetic components, imaging radar systems, concealed weapons detection systems, non-invasive medical imaging systems, spacecraft communications, plasma diagnostics, materials processing, automotive collision avoidance systems, indoor wireless and covert battlefield communications, and identification tagging for tracking inventory.

Emerging Technologies

During the past decade, recent technical innovations in radio astronomy have been used as the foundation for emerging technical developments in other applications as well as being integrated into on-going operations of government and commercial systems.

Communications Disruption Warnings and Prevention of Damage from Solar Flares



The first radio telescope image of a powerful coronal mass ejection from the Sun (position shown as a circle). Color enhanced; original image source: Nancay station for radio astronomy radioheliograph taken April 20, 1998.

Tracking solar flares once they leave the sun is extremely important because they can cause disruption of earth-based communications, damage to orbiting satellites, danger to astronauts, and destructive surges on power grids. After solar flares leave the immediate solar region, they can be tracked using radio astronomy instruments. Knowledge of the strength, direction of travel, and expected time of arrival of solar flares provides information that can be used to prepare for them. For example, orbiting satellites can be put in safe-hold mode and oriented to the best possible position during the period of highest damage potential. These informed actions both minimize the amount of lost time in satellite functionality and may prevent total loss of the satellite. In addition, power grid operators can configure their systems to limit the damage from huge currents induced by solar particles raining down on Earth, and electric power customers can be spared loss of service for extended periods. The economic consequences of the loss of a single satellite or power outages over large areas can run into the hundreds of millions, and sometimes billions, of dollars.

Grid Computing Applications

One of the most tantalizing applications of radio astronomy is the observation of radio signals as part of Searches for Extraterrestrial Intelligence (SETI). The first SETI project in the late 1950's used a radio astronomy dish. Some years later the SETI Institute, a privately-funded organization, was formed to pursue more extensive searches using various radio telescopes in the U.S. The SETI Institute is now building its own array, again with private funds but in close collaboration with radio astronomy engineers and researchers at many observatories and universities.

The vast amount of computing capacity required for SETI radio signal processing has led to a unique grid computing concept that has now been expanded to many applications. SETI@home is a scientific experiment that uses Internet-connected computers to download and analyze radio telescope data for the SETI program. A free computer software program harnesses the power of millions of personal computers, and runs in the background using idle computer capacity. More than 5.2 million participants have logged over 2 million years of aggregate computing time.

Grid computing is now being used for other applications that include biology, medicine, earth sciences, physics, astronomy, chemistry, and mathematics. The Berkeley Open Infrastructure for Network Computing (BOINC) is free, open-source software for volunteer computing and desktop grid computing. Running the BOINC platform allows users to divide work among multiple grid computing projects, choosing to give only a percentage of CPU time to each. These projects have tremendous humanitarian and economic potential. For example, the malariacontrol.net project is an application that makes use of network computing for stochastic modeling of the clinical epidemiology and natural history of plasmodium falciparum malaria. Simulation models of the transmission dynamics and health effects of malaria are an important tool for malaria control. They can be used to determine optimal strategies for delivering mosquito nets, chemotherapy, or new vaccines which are currently under development and testing.

Another grid computing application is climateprediction.net which investigates the approximations that have to be made in state-of-the-art climate models by running the models thousands of times to find out how the models respond to minor variations in the approximations. This project may improve the understanding of how climate models are sensitive to small changes in the models, and to changes in carbon dioxide and other atmospheric chemicals. These simulations should improve confidence in climate change predictions that have long term effects on the global economy.

Laser Metrology and Precision Rangefinders

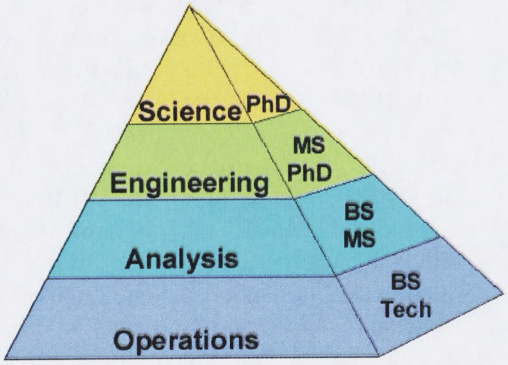
New laser range-finding techniques have been developed by radio astronomy engineers for measuring antenna deformations to accuracies of a few tens of micrometers over distances of several hundred meters. Laser metrology developments have led to precision rangefinders for commercial, military, and scientific applications. One example is precisely locating the position of synthetic aperture radar antennas on the wingtips of aircraft as they flex during flight.

Education, Training, and Workforce Development

Education, training, and workforce development are integrated objectives. Too often, these objectives are addressed as separate issues, resulting in either a large number of highly trained workers with few available jobs, or conversely, open work positions without qualified candidates to fill them. All technical occupations can be viewed as having a trained workforce that is pyramid-shaped in structure.

Workforce Pyramid

At the apex of the pyramid are the scientists and engineers who perform basic and applied research by formulating and testing hypotheses. Almost always, a Ph.D. in a scientific or engineering discipline from a university graduate school is required as the foundation for independent research. The number of workers trained and the number of positions available at this level is quite small. The next level represents the engineers who design and develop processes and instrumentation based on the fundamental work of the scientists. Depending on the complexity of the design work, most workers at this level have an M.S. or Ph.D. degree in a technical discipline. A significantly larger number of people work at this level of the pyramid, but the numbers are still relatively small.



The technical workforce pyramid.

The analysis level of the pyramid includes research and data analysts, computer programmers, and others who use, but do not develop, technical processes and tools. Most of the workers at this level are either at a graduate student assistant level or have a technical college degree. Whether or not an M.S. degree is required depends on the specialization of the technical work. The number of people trained and the number of available workforce positions at this level is much higher. At the base of the pyramid are the operators who run and/or maintain the equipment or processes, use the output of previous analyses as a small part of their job, or support those above them in the pyramid. Quite often, supplementary technical training in a community college or technical school is the only requirement to use a particular technology at this level, and this level comprises the vast majority of the national technical workforce.

The key to a successful education, training, and workforce development program is to attract the appropriate number of people to be trained at levels that match both their abilities and the number of available jobs at those levels. Fortunately, astronomy is an extremely powerful stimulus for attracting students. The mysteries of the universe and the excitement of space exploration are of great interest to many students who will consider making astronomy or space science a career. Because astronomy is a multidisciplinary science, students who have an interest in the space sciences will study mathematics, physics, chemistry, and engineering in addition to astronomy. Thus, even if astronomy is not the final career choice for a student, studying astronomy will serve as a very important catalyst in creating a highly qualified workforce for a large cadre of technical occupations. Furthermore, well-funded and publicized astronomy programs in the U.S. attract international students who often remain here to work in technical careers in American companies.

Educational Outreach

Radio astronomy naturally lends itself to educational outreach. Some of the most interesting aspects of astronomy are studied in the radio portion of the spectrum. Pulsars, neutron stars, black holes, and other phenomena may raise student interest in studying astronomy and related sciences.

To this end, radio astronomers in the U.S., both at local university and national levels, have developed and maintain a wide variety of educational outreach programs for educators. One program is a two-year K-12 teacher enhancement activity sponsored in part by the National Science Foundation (NSF). Another NSF sponsored program gives K-12 teachers research experience by providing summer jobs working alongside a radio astronomer or engineer, and there is a one-week workshop that provides training on the use of astronomy image processing software. Other outreach efforts include an NSF sponsored program consisting of 3-day intensive workshops for undergraduate college faculty and a bi-annual radio astronomy class for teachers.

The radio astronomy community reaches out to students as well. Undergraduate summer student research assistantships are partially funded by the NSF's Research Experiences for Undergraduates (REU) program. Students spend the summer working with a radio astronomy advisor on a research project. Similar graduate level summer student research assistantships are also available. Undergraduate engineering and computing co-op students can spend two or three semesters working in cooperation with their academic institution and the radio astronomy technical staff on a project at the forefront of technology. Graduate students can pursue research in radio astronomy and related fields as an intern. A pre-doctoral research program provides support for Ph.D. students in radio astronomy, engineering, or computer science.

Supporting the American Competitiveness Initiative

Clearly, the student outreach program is designed to train scientists and engineers to work at the upper two levels of the technical workforce pyramid in radio astronomy. The educator outreach program is designed to train teachers so that they can expose students to radio astronomy to better educate the nation as a whole, and to encourage some students to pursue a course of study in science and technology. Although educational outreach in radio astronomy helps to make our country more technically competitive, increased funding for astronomy may yield only a modest increase in the number of jobs in astronomy when compared to some other industries. However, increased funding for radio astronomy can result in dramatic increases in jobs resulting from technical innovations in complex astronomical data processing and highly technical instrumentation design and development that is transferred to other industries. For example, construction of visible images from radio astronomy signals as the basis for medical-imaging tomography of human tissue has resulted in the creation of numerous jobs at all levels of the medical technology workforce pyramid, ranging from medical research and instrument design positions to medical imaging technician jobs.

Much more could be done with increased funding for radio astronomy outreach programs. Technical and community college curricula could be developed to train students using radio astronomy-based processes and equipment in preparation for jobs in multiple technical occupations at the two lower levels of the workforce pyramid. Such broad-based technical education would provide students with training that could be applied to a variety of jobs, with flexible skills that can adapt to changes in the labor market, and with abilities at a level where most of the jobs exist.

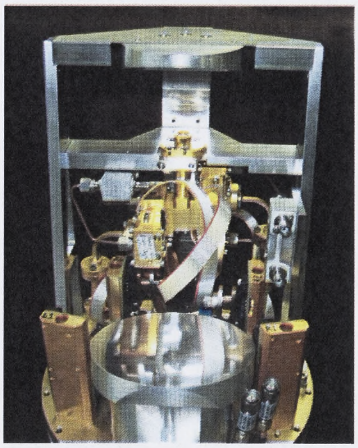
The Future Role of Radio Astronomy in American Competitiveness

Radio astronomy is an exemplary national resource that increases American competitiveness in many ways. Radio telescopes, facilities, and instruments enable discovery and development that is unique, and require collaborative funding and effort that is on a scale beyond the means of a single organization. Educational outreach inspires students and educators, and equips new generations of Americans with the educational foundation for future study and inquiry in technical subjects. Funding for radio astronomy supports institutions of higher education that provide American students access to world-class education and research opportunities in mathematics, science, and engineering. Radio astronomers continue to demonstrate that their research results in fundamental discoveries. There is a great incentive to enter into collaborative research and development agreements with commercial industry to the mutual benefit of both, leading to private sector investment in research and development that enables the translation of fundamental discoveries into the production of useful and marketable technologies, processes, and techniques that effect our lives each day.

Potential Breakthroughs from Currently Funded Programs

Currently funded development of radio astronomy instrumentation and continued observational research should result in a number of critical to cutting-edge breakthroughs that can be applied to engineering sciences and technologies.

Understanding how molecules form in interstellar space contributes to the science of molecule formation in the laboratory, and may lead to new breakthroughs in medical technologies, materials science, and nanotechnology. A team of researchers has used the Green Bank Telescope (GBT) to detect eight complex, pre-biotic molecules in just over two years, an unprecedented pace of discovery in this field. This research has helped reveal the mechanisms by which complex molecules form in the interstellar medium. The Atacama Large Millimeter Array (ALMA) will work together with the GBT to advance this field. ALMA will have the large total bandwidth, high spectral resolution, and sensitivity needed to detect the myriad of lines associated with heavy, pre-biotic molecules such as those which may have been present in the young Solar System. This capability may uncover the chemical composition of the molecular gas surrounding young stars, including establishing the role of the freeze-out of gas-phase species onto grains, the re-release of these species back into the gas phase in the warm inner regions of circumstellar disks, and the subsequent formation of complex organic molecules. ALMA will image the formation of molecules and dust grains in the circumstellar shells and envelopes of evolved stars, novae, and supernovae, and will resolve the crucial isotopic and chemical gradients within these circumstellar shells, which reflect the chronology of the invisible stellar nuclear processing.



One of the 640 ALMA radio telescope receiver cartridges that operates simultaneously in two linear polarizations that are down-converted using a sideband-separating SIS mixer. Image credit: Neil Horner

Virtually all millimeter wave radio astronomy observatories now use Superconductor-Insulator-Superconductor (SIS) mixers for their low noise characteristics. SIS millimeter wave receivers have a sensitivity near the quantum limit. The first SIS mixers were developed by radio astronomers about 25 years ago at the University of California at Berkeley and independently at AT&T. Much of the subsequent development has been accomplished through a series of collaborations between radio astronomers and a variety of industry partners. As military electronics continue to improve, SIS mixers may play a significant role in military systems operating at frequencies greater than 100 gigahertz. Terahertz radar can form high resolution three-dimensional images, and can provide detailed target discrimination information by extracting target composition from spectral data.

Additional Potential Benefits from Enhancements to the Current Program Funding

Several new radio astronomy initiatives now seeking funding have the potential for dramatic increases in American competitiveness in multiple sectors. These programs would involve collaborative development and funding from the radio astronomy community, government entities, and the private sector.

Radio astronomy is entering a new phase of its development which requires unprecedented increases in the sensitivity of its instruments. The newest radio telescopes now or will soon cover nearly all frequencies from 10 megahertz to 1000 gigahertz. Major new advances in the science will require 10 to 100 times more collecting area than is presently available. This requirement will most likely take the form of thousands of antennas in the 6 to 12-meter diameter class with extremely low noise receivers on each antenna. The manufacturing costs of a relatively large number of radio astronomy components will be the primary limit to the observational reach of radio telescopes of the future. Use of new materials may be required to achieve an order of magnitude cost reduction. Increased funding for radio astronomy to support advanced development of low cost components will have direct benefits to consumer and other commercial markets. The successful design, development, and fabrication of new radio astronomy instruments with increased sensitivity and reduced size will lead for example, to the construction of smaller and less costly satellites using lower power transmitters, and thus to smaller and less expensive rocket boosters. Similar advances in other commercial sectors will likely result.

Cryogenic refrigerators required for low noise radio astronomy receivers may have application in the high-performance semiconductor industry as heat dissipation becomes an ever-increasing limit to processor speed. Integration of wideband receivers with data transmission electronics has the potential for expanding the reach of data services to underserved regions of the country and the world.

Concluding Remarks

It is clear that radio astronomy is a valuable national resource that not only increases our fundamental knowledge of the universe, but also contributes significantly to American competitiveness. Radio astronomy programs are unique, and are on a scale that requires collaborative effort and greater funding than a single organization can provide. Only a few endeavors lead to a wide variety of useful and marketable technologies, processes, and techniques, and at the same time, stir the imagination of young and old minds alike. Radio astronomy is one of them.