NATIONAL RADIO ASTRONOMY OBSERVATORY

NRAO

LONG RANGE PLAN 1987 - 1991

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I. INTRODUCTION

The NSF planning period 1987-1991 witnesses the beginning of the fourth decade of continuous operation of the National Radio Astronomy Observatory. It is worth pausing to recognize that the NSF initiative of 1957 which established the NRAO as a federally funded, visitor-oriented radio observatory managed by a private contractor was exceptionally well conceived. Thirty years ago radio astronomy was a maturing science in Europe and Australia, but it was an orphan in the United States. The NSF turned this state of affairs around with a prescient enterprise. Today the NRAO telescopes and instrumentation are the world's forefront radio astronomical facilities and, most important, these facilities are made available to astronomers and scientists with a viable research program irrespective of the individual's institutional affiliation. The NSF began the NRAO, and continues to support and augment the NRAO, in order to further radio astronomy and not for any other purpose.

The furtherance of radio astronomy has many facets. Construction of unique telescopes is one crucial aspect. Each of the new NRAO instruments, being unique in its own right, has provided astronomers with a new view of the universe and each in turn continues to produce startling discoveries. Here it is worthwhile to emphasize that major improvements in any of the critical instrumental parameters leads to qualitative as well as quantitative changes in the science that is produced. Large increases in sensitivity, frequency coverage, and angular resolution provide not simply a clearer picture of familiar objects, although this is by no means to be minimized, but more important they provide an opportunity for entirely new classes of objects to be studied. Major discoveries will be hastened by our determination and ability to foster technological advances and to respond to opportunities for new instruments and new capabilities.

In planning the first half of the fourth decade of NRAO operation, the NSF and the NRAO are presented with the challenge of accommodating two such technological opportunities. First, construction and completion of the Very Long Baseline Array. The VLBA will provide the unprecedented capability of being able to image the radio sky on an angular scale of a milli-arcsecond or less over a frequency range of more than two decades. Second, the application of supercomputing power and resources for the purpose of refining the fidelity of radio images produced by the VLA and the VLBA. Realization of the potential for the contemporary furtherance of radio astronomy afforded by these two opportunities is the principal task facing the NSF and the NRAO in this planning period. Additional opportunities for developing and applying technological advances to radio astronomy abound, and these must be seriously considered as well.

II. PLAN OVERVIEW

The NRAO Long Range Plan places particular emphasis on the two principal new facilities that are the major challenges presented to the NSF and to the NRAO:

- the need to expeditiously complete construction of the VLBA and to bring this new telescope into routine operation;

- the need to provide a dedicated supercomputer facility for interactive reduction, analysis, and display of radio astronomical images.

Second, the Long Range Plan recognizes that the continued operation of the major NRAO observing facilities at Green Bank, WV (the 140-ft and 300-ft telescopes); at Tucson, AZ (the 12-m millimeter-wave telescope); and at Socorro, NM (the VLA) is made increasingly difficult in a time of declining budgets. Most difficult to accommodate are downward budget revisions that must be accomplished with short notice. In these cases significant savings can only be made in such areas as deferred maintenance. Although deferrals constitute a viable option in any one year, maintenance must be restored to normal or higher levels the next. Major maintenance needs cannot be ignored.

Continued operation should not be construed to mean that we operate today as we did yesterday. In such a climate the science will stagnate. Thus, even for the established observing facilities, it is crucial that continual improvements and enhancements be made to the instrumentation and observing techniques. The Research Equipment section of the Long Range Plan addresses this need.

Finally, Section VII is devoted to a discussion of new initiatives and new directions for the NRAO. Radio astronomy is a particularly dynamic science in which development opportunities abound and, in many cases, straightforward exploitation of new technological advances will directly lead to marked advances in observing capabilities. Section VII recognizes these opportunities; a discussion of the scientific need and the technical approach to seven of the most desirable and promising new NRAO initiatives is included in the present plan.

To summarize: The NRAO Long Range Plan 1987-1991 emphasizes the need to bring to fruition two major facilities (the VLBA and the image analysis supercomputer center); it recognizes the operational demands of existing facilities; and it presents opportunities for new initiatives in radio astronomy.

III. VERY LONG BASELINE ARRAY

A. The Instrument and Research Program

The Long Range Plan for the period 1987-1991 calls for the completion of the Very Long Baseline Array, ten precision 25-m diameter antennas located throughout the United States from the Virgin Islands to Hawaii, that will allow images of radio sources to be constructed with an angular resolution better than one thousandth of an arc second. Equipped with radio receiving systems covering assigned radio astronomy bands in the frequency range 327 MHz to 43 GHz, the VLBA will provide an unprecedented opportunity for astronomers to study radio sources over a broad range of resolution and surface brightness. Realization of the scientific potential of the VLBA is the principal challenge of the NRAO in the next half-decade.

VLBI observations made with existing radio telescopes have already given an enticing glimpse into the heart of quasars, galaxies, interstellar masers, and radio stars, but the nature of their central energy source remains a mystery. With the VLBA it will be possible to explore in detail the dynamics of the energy generation process. Of particular interest will be the apparent faster-than-light motions arising from the explosive ejection of relativistic material from quasars and active galactic nuclei.

Even within our own Galaxy there are a variety of very compact radio sources of interplanetary dimensions that will be studied by the VLBA, although they are unresolved by conventional radio telescopes. One of the most important problems in galactic astronomy is to understand the life cycle of stars. Clouds of molecular OH, H_2O, and SiO are often found in regions where stars are formed and in the atmosphere of very old stars. They are excited by the stellar radiation field and may act as interstellar masers. High-resolution radio images made with the VLBA will be able to probe the dynamics and magnetic fields in these regions on a scale of astronomical units and give new clues on the birth and death of stars.

The high resolution of the VLBA will also enable it to extend the range of direct distance measurements by the methods of trigonometric and statistical parallax. This improvement will have major implications for cosmology, because knowledge of the correct scale of the Universe is vital to a better understanding of its mass and energy content, as well as its past and future evolution. Observations of proper motions will be possible both throughout our Galaxy and in other galaxies. This will open up an exciting range of astrometric problems concerning the structure and rotation of the Galaxy.

The VLBA will also be used for a broad range of problems in physics and geophysics, as well as for astronomy and astrophysics.

Because the spacing of the interferometer fringes depends on the vector distance between the antennas, precise analysis of the radio signals received from celestial objects gives the separations with very high accuracy. This has a variety of applications to geodesy and crustal dynamics (plate tectonics), as well as locating the instantaneous position of the Earth's rotation axis and the wandering of the poles. The VLBA will also give a more accurate determination of variation in the rate of the Earth's rotation (time) which has been related to global climatic changes as a result of the shifting angular momentum of the earth's atmosphere-mantle system.

The operation of a radio telescope with elements dispersed over 8000 km presents a number of unique challenges. Each of the ten elements of the VLBA will be controlled via dedicated telephone lines from the Array Operations Center (AOC) located in Socorro, NM. The AOC, which contains the central control computer, the data playback system, the image-forming computers, as well as the resident scientific and technical support staff, will be the heart of the VLBA. The central computer will simultaneously monitor the performance of the antennas and receivers as well as the meteorological conditions at each site. An array control operator will be present at all times at the Array Operations Center (AOC) to intervene when necessary and to carry out various bookkeeping tasks. From time to time brief samples of the received signal at each antenna will be sent to the AOC via the telephone lines and correlated in nearly real-time to check that all components of the array are functioning properly. Normal analysis of the data at the AOC will be done by simultaneously replaying the data tapes recorded at each antenna in a specially built playback processor system capable of operation at 10 Gigabits/sec.

Normally, each antenna will be unattended, but technicians and operators will be available at each site for inspection, routine maintenance, and the simpler unscheduled repairs. The local staff will also update the operating systems at the local control computer, change the data tapes, and ship them to the AOC, and be responsible for security, for emergency intervention, and for routine start-up and shutdown procedures.

The AOC will provide personnel and facilities for major maintenance and repair. However, since it is planned to build much of the electronics in modular units and to replace complete modules in the case of failure, most such replacements can be easily performed by the local site personnel. Defective modules will be returned to the AOC for repair.

B. Funding Schedule

Construction of the VLBA was planned by NRAO and the NSF as a three-year project, to be funded at a rate of $20 M per year. This was revised to four years of construction at $15 M per year, which would have completed the construction in 1988. The funds available for the first year (1985) were only $9 M, for the current year only $8.6 M, and the agency request for 1987 is only $9.4 M. Continued funding at $9.4 M per year until the project is completed would have the following consequences:

- a delay in the scientific impact of the VLBA, and the loss of badly needed research opportunities for the scientific community;
- a delay in full operation until at least 1995 and the need to support operations of the ad hoc VLBI network for a longer period of time;
- an increase in total construction cost from $60 M to nearly $100 M as a result of the inefficiencies of multiple construction contracts, the renegotiation of existing fixed-price contracts, increased cost of personnel and space, and anticipated inflation increases;
- a loss of key project personnel through resignation and retirement with subsequent added costs and inefficiencies of new replacements;
- a disproportionate effort in responding to multiple proposed budget changes, rescheduling interdependent tasks, renegotiating existing contracts, etc., all seriously impacting project morale;
- continued impact on NRAO's other operations and support for ongoing research activities;
- delays in completing and testing key components, such as the correlator system, which will impact the orderly transition from the construction to the operation phase;
- an erosion of U.S. leadership in world-wide VLBI research and technical development;
- reduction in capability to support the planned space VLBI programs;
- conflicts with other initiatives in ground-based astronomy.

If the funding can be significantly increased in 1988 and succeeding years, as outlined in the schedule given by the budget plan attached to this Long Range Plan, construction could be finished by 1991. The savings in construction costs, even after allowance is made for operations costs, are substantial compared with those of a "level of effort" construction plan. In return for the higher rate of funding, the total cost is less, science comes earlier, and the problems listed above are ameliorated.

Besides completing the entire project at lower cost, the stage at which significant interim VLBA science is possible arrives sooner. With the funding plan given in Section X, work can begin earlier and proceed more rapidly in three critical areas to allow operation with 7 antennas and a 7-station playback processor to begin as early as 1989. Additional funds in 1987, beyond the $9.4 M of the NSF request to Congress, would get the process of accelerating work in these areas started even earlier and more smoothly. These key areas are:

- the playback processor (correlator) system;
- the Array Operations Center;
- the recording systems.

Equally important, these facilities are needed early in the program to allow adequate time for testing, evaluation during early operations, and, where necessary, retrofits.

C. Consolidation of VLBA and VLA Operations

The VLBA in many ways is the logical extension of the VLA to still greater telescope spacings (higher angular resolutions). The receiving equipment, data handling, and image formation tasks are very similar in the two instruments, and many scientific problems will require both the VLA and VLBA. As the first VLBA antennas become operational, we wish to add the necessary instrumentation to effectively tie the VLBA and VLA together, to make possible a new range of research activities not possible with either instrument alone.

There are also considerable economies to be realized if the two instruments are operationally consolidated. In particular, shared personnel will allow each operation the access to a larger pool of technical and scientific expertise than would be available to either instrument alone. Maintenance facilities can be shared, and the larger staff can more readily react to unplanned exigencies.

Beneficial economies such as these provide a compelling motivation for the NRAO to merge the VLA and VLBA operations. Since the VLBA Array Operations Center (AOC) will be located on the campus of New Mexico Institute of Mining and Technology in Socorro, NM, we are moving the VLA control from the Plains of San Agustin to Socorro also. Both arrays will be controlled from a common site, eventually even a common console when the VLA telescopes can be connected to the AOC by means of a microwave link. From an operational standpoint such a consolidation is very attractive--problems with either array will be diagnosed and repaired quickly--and from an administrative standpoint consolidation simplifies both operations.

The NRAO 1985 Long Range Plan called for $2 M in 1987 for the construction of the VLA portion of a shared VLA/VLBA operations center, with the VLBA portion to be funded from VLBA construction. Funds are no longer required from the NSF for the VLA part of this building. The 1986 session of the New Mexico State Legislature has appropriated $3 M for this purpose. NSF funds for the VLBA part are, of course, still needed. If made available no later than early in FY 88, the second phase of construction can proceed in an orderly manner, avoiding the added complexities and costs of introducing a gap in the building construction.

IV. RADIO ASTRONOMICAL IMAGING AND IMAGE PROCESSING: ALGORITHM DEVELOPMENT AND OBSERVATORY COMPUTING SYSTEMS

Although we may choose to measure the success of the National Observatory in several ways, to the astronomer there is only one standard, and that is by the quality of the images it produces. Ultimately, the astronomer will extract the scientific content of his observations directly from the image. And here "image" need not refer specifically to a "picture" of the sky: An image can be a time sequence of radio intensity at a particular point in the sky (e.g., pulsar observations) or it may be the intensity of radio emission as a function of frequency at one or more spatial positions (e.g., spectral-line observations). Everything the Observatory does to improve its instrumentation--provide more sensitive receivers, improve the telescope aperture efficiency, increase the spectral bandwidth--is ultimately apparent in the quality of the image. The expectation, of course, is the better the image the better the science (more precise measurements, more far-reaching conclusions).

In recent years, astronomers have made increasing use of synthetic aperture radio telescopes, such as the VLA, to obtain ever higher angular resolution and sensitivity. Since the image-forming optics of such instruments are computers, major improvements can be made even after construction of the telescope hardware is finished. This flexibility has led to a dramatic increase in scientific productivity since both the quality and quantity of the images produced by the VLA now greatly exceed the original goals of the VLA.

The situation is similar for the NRAO single-dish telescopes. New data-taking and data-manipulation techniques, such as the dual-beam restoration methods used to circumvent atmospheric difficulties, provide marked improvements in the depth and breadth of the science. They provide for better images, but they do so at the expense of a greatly increased computational burden.

The dramatic breakthrough in producing high-quality images has come at a time when funding restraints prevented acquisition of computer resources sufficient to take full advantage of these new techniques. At this time only a small fraction of those exciting scientific investigations, which are very computer-intensive, are being pursued.

Because the computing needs are most acute for synthesis instruments, it is useful to give some details for the VLA. When the VLA was originally proposed in 1971, it was expected to produce images in which the ratio between the brightest features and the faintest believable features would be limited by various errors to 100:1 (dynamic range). The two main effects which cause this limited dynamic range in synthesis arrays are: (1) incomplete measurement of the coherence of the wavefront due to the finite number of antennas and limited observing time; and (2) wavefront collimation errors due to the spatially and temporally varying refractivity of the atmosphere above the array (i.e., "bad seeing"). In recent years two new techniques, deconvolution and self-calibration, have been developed which can correct for both of these sources of error. Their use has greatly increased the quality of the best VLA images from the 100:1 dynamic range specified in the VLA proposal to over 10,000:1, but at the cost of greatly increased computation time. The impact of self-calibration has been even greater in VLBI where true imaging of objects, at resolutions up to a thousand times greater than that available with the VLA, is now possible.

In 1984, almost 600 observers from 140 different institutions used the VLA to conduct their research. On the basis of these projects and the demands for other projects which are not feasible with the present inadequate computer resources, the NRAO has estimated future demand for data processing. Similar estimates have been made for the VLBA. From this analysis of present needs, it is concluded that the future computer demands for image formation and enhancement will exceed the present total capacity of the NRAO by more than a factor of 20. Those requirements imply a need for an achieved continuous computer capacity of at least 60 megaflops. This is 100 times greater than the power of one of the current NRAO image-processing (VAX) systems and can be provided by one relatively large supercomputer. The supercomputer needs a very large, fast access memory and the best achievable disk I/O performance in order to facilitate the processing of the large VLA and VLBA images.

As remarked in the Curtis Report to the NSF, lack of access to supercomputers has inhibited activity in certain scientific fields. This situation certainly occurs with synthesis radio telescopes. The best astronomers, conscious of computer limitations, will simply turn to other problems, and the potentially most imaginative and most important problems in radio astronomy may not be studied. For observations which are just feasible with the present resources, the long turn-around time inhibits both experimentation with data analysis methods and investigation of unusual effects. Limited computer resources which act as barriers between the scientist and his observations artificially arrest scientific progress.

The central aspect of NRAO's computing plan is the acquisition of a Class VI computer for the analysis of data from radio synthesis telescopes. In the interim, NRAO is pursuing initiatives designed to allow progress to be made.

- The Astronomical Image Processing System (AIPS) software development at the NRAO for the reduction and analysis of radio astronomical images has been installed on one of the NSF Phase I supercomputer centers (Digital Productions). A limited number of VLA observational programs have been processed at Digital Productions and important scientific results have been obtained from the superb images obtained at this unique facility.

- Progress is being made and work is progressing on the installation of AIPS at one or more of the NSF Phase II supercomputer centers. The utility, efficacy, and convenience of these facilities for radio astronomical image processing remains to be demonstrated, even for resident scientists. Here the basic limitation is that these computing facilities are optimized for general computing and not for image analysis. Current network technology and economics do not allow these facilities to be used for remote interactive image processing. Nevertheless, work toward these ends will continue.

- A CONVEX Computer Corporation mini-supercomputer has been acquired to augment the NRAO's processing capabilities in the interim period. Software written for this vector machine is directly transferrable to the supercomputers and hence work preparatory to, and needed for, the NRAO-operated supercomputer facility can be done now. Moreover, the CONVEX is linked via (slow) telephone lines to all the NRAO sites and experimentation with remote data reduction and analysis has begun. The CONVEX will be a suitable front-end machine for the NRAO supercomputer.

- Several initiatives which involve the NRAO in a shared supercomputer facility optimized for image processing are being investigated. The need for a dedicated supercomputer for radio astronomical image processing will have to be confronted in the present planning period.

- A basic limitation to the use of any supercomputer center by NRAO and its user community is a lack of personnel. Fourteen staff for programming and user assistance are required to address the estimated computing needs.

- The image processing algorithms CLEAN, maximum entropy, and SELF-CAL, which have increased the dynamic range of VLA images by over a factor of 100, are only the first three of a potentially much longer list of such algorithms. Research in image processing must be expanded beyond what is possible with the resources available now.

- Prior to acquisition of supercomputer capability and independent of how that happens (an NRAO machine, use of a nearby center and/or NSF centers), there are serious needs for computing the VLA which must be addressed:

  - replacement of the pipeline;
  - replacement of the DEC-10;
  - installation of a mass storage/common file system.

All of these are needed today and are simply beyond the resources available in the operating budget. All can be used in the supercomputer hardware configuration when NRAO acquires one.

In summary, the Observatory's interim plan for computing envisions the development of new image-processing algorithms and the incorporation of these algorithms in AIPS. The support of AIPS will be continued and expanded on NRAO-operated and user-community computers--VAX's at universities, Convex-class machines at major astronomical centers, and supercomputers where users have access. Until NRAO acquires its own supercomputer, we will continue to use the NSF Access Program and other remote facilities that are available.

V. OPERATING EQUIPMENT AND MAJOR MAINTENANCE

Large investments in capital equipment at all the sites, whether for buildings, telescopes, or computers, impose a maintenance burden which may be (1) frequent and incremental or (2) episodic and appreciable. The former are appropriately included within normal operating budgets. The latter, having a time scale between events longer than a given budget year, need to be planned for individually. Neither, however, can be forgotten.

None of the needs in the latter category are being addressed in 1986 due to a severely restricted budget. The most critical major maintenance items needed, in priority order, for each site are:

VLA

- Major maintenance to the railroad track and track bed ($130 k per year for 3 years = $390 k; $40 k per year thereafter).
- Road repairs, and sealing and paving ($250 k).
- Mobile emergency power generator and supplies for repair of power lines to antenna stations ($50 k).

Green Bank

- Telescope painting ($100 k; $50 k per year thereafter).
- Road repairs and sealing ($50 k).

Tucson

- Replacement fabric dome cover ($250 k).
- Dormitory building on mountain to replace old high-maintenance mobile homes ($90 k).

VI. RESEARCH EQUIPMENT

The major goal of the NRAO over the past years has been to provide the community with radio astronomical instruments having unique capabilities and to make those capabilities available to astronomers from all disciplines. Thus, the task involves not only developing state-of-the-art instrumentation but also making the telescopes straightforward to use and providing suitable data reduction facilities. All aspects of this program are important to the commitment of the Observatory to radio astronomy in this country. In the next five years we hope to maintain, and indeed extend, this commitment. To do so we present, by telescope, the major areas of scientific interest to be addressed and the anticipated instrumentation developments that the coming half-decade will bring.

A. The Very Large Array

By every measure the VLA is the most powerful and the most scientifically productive radio telescope ever built. Many of the VLA users are not traditional radio astronomers, and their overwhelming demand for the instrument has been a strong endorsement of its capabilities in support of today's problem-oriented, multi-wavelength, inter-disciplinary astrophysics. The many capabilities of the VLA have given new impetus to radio studies of every class of object which is detectable in the short wavelength, X-ray, UV, optical, and infrared spectral regimes. Direct comparisons of the spectral properties of individual objects are no longer restricted by resolution incompatibilities, and nearly all branches of astronomy have benefited from VLA observations.

If the trends evident over the past year continue, astronomers will spend increasingly larger blocks of time on the VLA exploiting its ability to survey quickly large regions of sky or large numbers of sources. In so doing, they can obtain a statistically significant sample of the radio properties of a class of object (or part of the sky) in just a few days of telescope time. Current examples of such programs include surveys of the time variations of cataclysmic variables such as DQ Her, or BY Dra variables, and comparisons of the radio emission from starburst galaxies with their infrared properties. Literally thousands of possible gravitational lens candidates have been observed and evaluated on the VLA; this is possible owing to the frequency flexibility of the VLA which readily permits one to assess whether the flux ratio of the putative lens candidates is achromatic.

The high angular resolution available on the VLA is the discriminant of interest for many other research programs. Here, examples include studies of the cosmic ray circulation into and out of the halo of spiral galaxies which are investigated by means of observations of the continuum non-thermal radiation from edge-on spiral galaxies. HI spectral-line observations of precisely the same galaxies can be used to study the disk kinematics in spirals and from this to model the spatial mass distribution of the components of dark matter resident within or around the galaxies.

The combination of high frequency and high angular resolution afforded at 22 GHz on the VLA provides an opportunity for the positions of H_2O maser stars to be determined with a precision equal to or greater than that obtained by optical astrometry. By means of a comparison of the radio and optical positions of these stars, it becomes possible to refer accurately the positions of radio objects to the standard optical astrometric standards. Further, the ability to determine precise positions also enables planetary astronomers to observe and accurately determine the orbits of various satellites, for example, Neptune's moon Triton, even during those times of the year when the planet is a daytime object.

The very large demand for "non-traditional" radio astronomical research with the VLA is evidence not only for the versatility and flexibility of the telescope, but also for its availability and convenience to the astronomical community.

Many modifications to the VLA have already been incorporated during its first few years of operation and have had a significant effect on the scientific productivity of the VLA. Additional improvements are planned during the next five years that will greatly enhance its capabilities to serve the varied requirements of its ever-widening astronomical clientele. These projects will potentially expand the wavelength coverage of the telescope, upgrade its sensitivity and performance at its present operating wavelengths, and provide for improved calibration and data-handling.

- 22 GHz receivers are being upgraded with new GaAsFET amplifiers, eventually to have HEMT first stages. Many important ammonia-line experiments, such as observations of accretion disks, circumstellar material, distant star-forming complexes, and extragalactic ammonia, will benefit from the upgrade in K-band (22-25 GHz) performance. The projected improvement at 24 GHz by a factor of 5-6 means a tremendous boost in speed and sensitivity. Experiments will be 20-30 times faster. Eight-hour experiments will then take only a little over an hour. Instead of one region per u-v track, 20-30 regions can be studied at once. This is a very significant step forward.

- 300-350 MHz receivers are being installed at prime focus on all antennas at the rate of approximately six antennas per year. Scientifically, this additional frequency range provides an opportunity for studies of those sources particularly bright at low frequencies (e.g., pulsars) and for objects as large as 60-90 arc minutes in diameter. Technically, the lower frequency allows us to experiment with restoration algorithms that will be necessary to remove ionospheric effects and the effects of confusing field sources: such algorithms will be indispensible if still lower frequency observations are to be attempted with the VLA.

- A 75-MHz capability for the VLA will be investigated. First, a few and then, pending successful test results, many antennas will be fitted with very simple dipole-type feeds to evaluate the interference environment, ionospheric effects, and the efficacy of the restoration algorithms developed to handle the 327 MHz observations. If such algorithms, suitably modified, prove satisfactory for 75-MHz observations, then the goal is to construct a low-frequency synthesis interferometer on the Plains of San Agustin as described in Section VI.

- Water Vapor Radiometers. At the higher VLA frequencies the array sensitivity to low-level emission in a field that does not contain a bright source (e.g., detection experiments) depends on the phase stability of the atmosphere. As the atmospheric phase errors worsen, the sensitivity is correspondingly diminished. In principle, these errors can be corrected in real-time by means of radiometric measurements of the fluctuating water content in the sky above each antenna. An operational test of these ideas is planned in the following way: two VLA antennas will be equipped with water-vapor radiometers and the data from these instruments will be compared with the phase fluctuations seen by the VLA antennas on the common baseline.

- Ionospheric Measuring Device. The sensitivity of the VLA for linear polarization measurements at 20 cm is significantly, and at longer wavelengths seriously, limited by Faraday rotation in the ionosphere. Current methods of correcting for ionospheric Faraday rotation rely on knowing the electron content of the ionosphere as a function of time. Approximate values for the VLA, calculated from observations of geostationary satellites, are obtained from the World Data Center in Colorado. However, the only way to improve the accuracy of these values for the VLA longitude and latitude is to make appropriate measurements at the VLA.

- VLBA Record Equipment. There will be many VLBA experiments that will request the phased VLA, or a single VLA antenna, as part of the VLBA array. Among the VLBA observations that would benefit by including the VLA are those sensitivity-limited observations as well as those observations made in very complex sources where short spacings are critical. However, to be included in the VLBA on such an ad hoc basis, the VLA will require data formatting and record equipment comparable with that used in the VLBA. The Research Equipment Plan includes one such recording system to be installed very soon, say 1987. Later, it will be desirable to install more--see Section E under New Initiatives and Directions.

B. The 300-ft Telescope

The 300-ft transit telescope operates principally as a survey instrument, accessing many sources per day as each in turn crosses the meridian of the instrument. Sensitivity to faint sources depends on the large collecting area, low-noise receivers, and integration times which may span many meridian crossings. The availability of this telescope over the years has been a powerful resource for innumerable large-scale surveys for galactic and extragalactic sources of varied character. Future surveys for low-luminosity pulsars, low-frequency variable sources, and of the velocities and structures of galaxies, clusters, and super-clusters will depend on continued improvements to the telescope and receiver systems. The wealth of fundamental data that the 300-ft provides in an environment unrestricted by competition from short-term, limited programs, is unparalleled in its contribution to large-scale programs which are otherwise difficult to schedule on other major telescopes in the U.S.

As a survey instrument the 300-ft telescope requires certain performance characteristics that are of lesser importance at the other telescopes. Specifically, the need is to frequently change observational parameters, start and stop observations and do so routinely, reliably and with minimal active intervention by observer or telescope operator. Unfortunately, this need has been ill accommodated by the 20 year-old DDP-116 control computer and manually-controlled Mark III autocorrelation spectrometer. In order to rectify this deficiency, the telescope is in the process of being completely modernized. When finished it will be, in essence, a new telescope. Planned for completion in 1986 are the installation of a new control computer and completion of a 7-feed, 14 receiver, dual-polarization, multi-beam, 5 GHz mapping receiver. The control computer and its attendant software are expected to simplify the interface between telescope and user. Eventually, they may lead to more automated observing.

The remaining components of the telescope modernization program include the following elements of Research Equipment:

- Spectral Processor. A device is under construction which is a combination spectrometer and signal processor, designed to replace the Mark III autocorrelator and the Nicolet signal averager. It will improve on existing instrumentation in two major areas. Spectral-line observations will have greater resistance to interference since spectral estimates are produced once every 10 microseconds instead of once every 10 seconds as in the autocorrelator. This allows spectral estimates contaminated by radio-frequency interference to be excised from the accumulated spectrum. The spectral processor will also increase the number of spectral channels, providing 2048 channels across 40-MHz bandwidth as compared with the present limit of 384 channels across 10-MHz bandwidth available with the Mark III autocorrelator. Secondly, the spectral processor will greatly improve data acquisition capabilities for pulsar observations at the 300-ft. As a pulsar dedisperser, it will allow high time-resolution studies of average waveforms and single pulses with full polarization information. Scintillation studies will be possible that employ a wide range of bandwidths and with spectral windows centered on different pulse components.

- Data Storage and Display. The increased data-taking facilities which are an integral part of the 300-ft telescope modernization will lead to a need for augmentations to the existing data storage and display instrumentation. In the next five years optical disk technology will adequately address the storage problem while a suitable computer workstation connected to the NRAO communications network (Section VI) will provide the 300-ft telescope user with a measure of computer power scaled to the current task or problem.

- L-band (1.3-1.8 GHz) Receiver. One of the principal uses of the 300-ft telescope is for redshift surveys. A cooled FET amplifier for HI and OH observations can be permanently located in the feed cabin, it can easily time-share observations with one of the low-frequency receivers mounted on the traveling feed, and such an arrangement would facilitate unattended telescope operation.

C. The 140-ft Telescope

In recent years a major effort has been directed toward improving the sensitivity and frequency coverage of radiometers on the 140-ft telescope. This has taken two forms: A maser/upconverter receiver has been installed at the Cassegrain focus for observations virtually anywhere in the 5-25 GHz range; at lower frequencies, 1-3-2.0 GHz, an optimized GaAsFET prime focus receiver provides a system temperature of less than 25 K. These receivers have had a major impact on the scientific productivity of the 140-ft telescope. Detections of numerous weak transitions of molecular species have become routine; the first interstellar molecular ring, C_3H_2, has been identified and shown to be ubiquitous in the Galaxy, and even detectable in external galaxies; OH "megamasers" have been seen in exceptionally distant galaxies. The frequency agility, large collecting area, and all-sky coverage of the 140-ft telescope ensure a continuing high demand for this instrument throughout the current planning period.

Future gains in sensitivity at the 140-ft telescope are realizable from additions to the available receivers, computers, and spectrometers as well as from improvements to the telescope structure.

- A second 5-25 GHz maser/upconverter receiver is nearly complete. Once a polarization splitter is installed, the two 5-25 GHz receivers can be used simultaneously to receive opposite polarizations, thereby doubling the sensitivity of the telescope throughout this frequency range.

- Holographic measurements of the telescope surface will be made so as to accurately characterize the telescope's behavior as a function of hour angle, zenith distance, and under variable environmental conditions. The results of these measurements will be used to improve the figure of the surface for better high-frequency performance.

- The control and analysis computers at the 140-ft telescope are rapidly becoming obsolete principally owing to their 16-bit architecture. To achieve needed flexibility and commonality with telescope control systems elsewhere in the Observatory (so that software can be shared) an upgrade to 32-bit architecture machines is desirable.

- A copy of the 300-ft spectral processor/spectrometer will be made for the 140-ft telescope in order to improve interference excision and expand interactive spectral-line observations.

- VLBA record equipment will be installed on the 140-ft in order to allow the telescope to participate in those VLBA observations that would benefit from the addition of this telescope. The 140-ft is expected to play an especially important role during the long construction phase of the VLBA.

D. The 12-m Telescope

The demand for observing time on the NRAO 12-m millimeter-wavelength telescope continues to be high. The improved surface, giving a greater effective collecting area especially at the shorter wavelengths, coupled with a new generation of receivers with greater sensitivity and stability, has enabled millimeter astronomers to undertake more and more challenging observations.

There is at this time heavy emphasis on the gas content of spiral and irregular galaxies. A number of the nearby galaxies have been mapped in detail and, for example, the content in CO density between spiral area regions and inter-area regions has now been measured. A large number of galaxies shown to be bright in the far infrared have been detected in CO, and there is a correlation between the strength of the CO signal and the flux density at a wavelength of 100 micrometers. However, the observational progress is intrinsically slow because the nearby galaxies are very large compared to the size of the beam—the CO in IC 342, for example, covers 400 beam areas at 230 GHz--while the distant galaxies are faint and require long integration times. Both types of observation would benefit from the availability of low-noise receivers, and particularly from multi-beam receivers (Section VI).

The NRAO millimeter effort is best known for the results in galactic astronomy and in astrochemistry, and, indeed, research in both of those fields continues to be vigorous. The search for new molecular species now tends to be concentrated on a few molecules, such as $HCNH^+$, that occupy key positions in one or the other of the proposed schemes by which interstellar molecular chemistry proceeds. The development of a new receiver giving access to the two bands at 280-310 GHz and 330-360 GHz has renewed interest in the search for metal-containing molecules such as the hydrides of sodium and magnesium.

The galactic studies span a wide range of problems. There is at this time intense interest in star-forming regions and molecular studies of certain of the complexes, in conjunction with suitable infrared data, offer, the prospect of measuring the mass function of the clumps of gas that are in the process of forming stars. Many objects that are apparently recently formed stars appear to be blowing away the matter left over in the collapse of the gas cloud which formed the star. The outflow of the residual matter is often not spherically symmetric about the star, but is instead concentrated into two oppositely-directed streams, forming a "bipolar flow." These curious objects have attracted the interest of gas dynamicists as well because the theories of accretion disks and the production of collimated gas streams can be confronted by the observational evidence.

One especially exciting area of galactic research has been the study of circumstellar envelopes of evolved stars. By now more than 100 stars of spectral types M and N have been detected at radio wavelengths. The radio data have been used to estimate the rate at which matter is lost by the stars and to study the chemical composition of the ejected material. These data are also useful in the exploration of the path that may be followed by these supergiant stars as they evolve toward the planetary nebula stage.

Research with the 12-m telescope is dominated by molecular-line studies, but there is also an active continuum effort. The most exciting recent development has been the introduction of the switched-beam mapping technique which enables satisfactory continuum maps to be obtained in less-than-excellent weather.

With each successful program, and particularly with each discovery, the pressure to improve the capability of the 12-m telescope and its associated electronics mounts. For example, the study of the CO in infrared galaxies is leading us to look at galaxies having redshifts in excess of 10,000 km s^{-1}. These galaxies are faint, so that higher sensitivity is required. Often these galaxies are experiencing a burst of star formation in which the interstellar gas is accelerated to large velocities so that broad bandwidth with good baseline stability is required. The program of instrumentation for the period 1987-1991 will address these requirements.

Throughout the planning period, activities will concentrate on the following projects requiring support from Research Equipment:

- A general improvement in the performance of the existing instrumentation, with emphasis on the receiver baseline stability and the telescope pointing accuracy. It appears that a significant saving in the amount of data lost to these two causes can be achieved, although the investigation of these problems will require a heavy investment in engineering research.

- A new control system for the telescope. The existing control system seriously limits the possibility of new equipment because it cannot handle higher data rates. The new system will be able to handle the multifeed systems, the new spectrometer, and new observing techniques.

- A new spectrometer. The existing spectrometer is comprised of a series of filter banks which limit flexibility in the choice of bandwidth and resolution. A new spectrometer using a hybrid filter bank/digital autocorrelation design will be installed. This spectrometer will also be suitable for multifeed systems.

- Increased bandwidth at intermediate frequency. Clearly the coherent continuum receivers would benefit immediately from a larger IF bandwidth. However, the present 500-MHz bandwidth now limits the velocity range at 230 and 345 MHz for certain active galaxies so that line observers are pressing for this improvement as well.

- Broadband Fourier Transform Spectroscopy. There are at least three areas which might benefit from access to an FTS using an SIS detector. These are: spectral lines in planetary atmospheres; broad spectral lines in galaxies; and features in the spectrum of the microwave background. The value of the FTS technique will be evaluated and, if it is appropriate, a device will be built.

VII. NEW INITIATIVES AND DIRECTIONS

A. Sub-Arcsecond Imaging with the VLA

A decade and a half ago the design of the VLA recognized the scientific potential inherent in the comparison of multi-wavelength images. In particular, it was noted that the similarities, to the extent that they existed, between radio and optical images, of radio galaxies, for example, were directly indicative of regions of active particle acceleration. Similarly, a comparison of the radio HI image of a normal galaxy with the optical [OII] or Hβ image can provide information on the circulation of gas into and out of regions of star formation. The radio and optical images together provide much greater insight than either can alone. Since any such comparison must be made with images of the same angular resolution, the VLA was specifically designed to provide an angular resolution equal to that of the best ground-based telescopes, viz., 1". The VLA achieves this resolution.

Today two realizations alter somewhat this perspective and both argue for a sub-arcsecond imaging capability for the VLA. The first is attributable to the success of the VLA: A surprisingly large range of sources have radio structures on an angular scale less than 1". For example, not only are the cores of radio galaxies and quasars less than an arcsecond but so also are the hot spots in the lobes and shock regions in the nuclear jets. Since it is in these latter regions that secondary electrons are accelerated and the effect of the confining circumgalactic gas is manifest, it is vital that, if we are to understand the physics of such regions, we have sufficient resolution to unravel their structure. A more striking example is provided by circumstellar envelopes. With the VLA we find that the gas expelled from the atmospheres of evolving stars nearly always has an angular scale less than 1" and presently cannot be resolved. Sub-arcsecond resolution is needed to explore the kinematics of such phenomena. The second realization that argues for a sub-arcsecond capability at the VLA is simply the Hubble Space Telescope. The angular resolution of this optical/uv telescope is 0".1. Again, if we are to compare optical and radio images, an enhancement of the VLA capability is needed.

The completion of the two VLBA antennas in New Mexico provides an opportunity to achieve sub-arcsecond imaging with the VLA at a very modest expense if these antennas can be provided with a wideband link to the VLA. Here we propose to connect first the Pie Town VLBA antenna and later the Los Alamos antenna to the VLA by means of fiber optics links. This, together with suitable modifications to the VLA's delay, fringe-rotation, and control systems, will more than double the resolving power of the VLA and will provide a true sub-arcsecond radio imaging capability.

B. Development of a Multi-Beam Mapping Capability

Research programs which involve mapping extremely large areas of the sky are an important aspect of the work done on all the NRAO single-dish telescopes. Not only are maps of CO spectral-line emission of molecular clouds or bipolar flows crucial to the understanding of these objects, and very demanding of telescope time, but so also are enormous projects undertaken on the Green Bank telescopes directed towards an understanding of the distribution of radio sources over the whole sky or the extent of an atomic hydrogen emission in the Galaxy. In all these cases, the mapping of a very extended region with a single, small beam is very time consuming. Once the intrinsic receiver noise has been reduced as far as is feasible, the only way to speed the mapping process is to introduce a multi-beam capability on the telescope. This is the thrust of the present initiative; it encompasses several new instruments.

8-Feed, 220-230 GHz Receiver

There is heavy pressure on the 12-m telescope for observations of the J=2-1 lines of CO and the isotopes. The pressure arises in part because of a shortage of good days with favorable atmospheric transparency at 1.3 mm and partly because objects of interest (galaxies, molecular flows) extend over tens to hundreds of telescope beamwidths. To address this pressure an 8-feed receiver is planned. The orientation and separation of the feeds is now being studied. The initial version of the receiver will use Schottky mixers, some of which are already in hand. However, a novel feature of the design is that the dewars will be able to accept either Schottky mixers or SIS junctions. Accordingly, as SIS junctions become available, the Schottky mixers can be easily replaced. The 8-channel output of the receiver will be fed into the hybrid spectrometer, which can accept 8 independent IF's.

Direct-Detection SIS Continuum Receivers

Recent continuum maps from the 12-m have demonstrated the abundant scientific potential of this field of research. Not only is it possible to map the distribution of radiating material in Galactic HII regions and supernova remnants but for the first time at radio frequencies it is also possible to map the thermal dust emission in molecular clouds and circumstellar shells. However, to be successful, all such mapping programs should be done quickly in order to minimize the effect of changing atmospheric conditions. This points both to a need for very sensitive continuum receivers and a multi-beam capability.

In the laboratory, it has been possible to use a SIS mixer as a direct detector (essentially a photo-diode). The enormous instantaneous bandwidth of such a devise, 10 GHz, means that it should be possible to achieve a continuum radiometer that is background limited. If further research and development of this device continues to be successful, the intention is to provide such a multi-beam continuum receiver at both 90 and 230 GHz.

To fully realize the marked increase in mapping speed, both for continuum and spectral-line work, it will be necessary to expand the spectrometer and the continuum processor to handle eight data channels and to make corresponding enhancements to the computing resources. most demanding in this respect is the construction and implementation of the planned hybrid filter-bank/digital autocorrelation spectrometer covering 2.4 GHz bandwidth and separable into eight separate sections each with 256 channels cross 300 MHz bandwidth.

Adaptive Array Receiver

Although the 300-ft telescope has a multi-beam mapping capability at 1.4 and 5.0 GHz, it also has a need for a novel multi-beam receiver at lower frequency which would allow the (meridian transit) telescope to track a single source for longer periods of time. Presently source tracking is limited to 10 or 20 minutes (at 400 MHz) owing to a degradation of the telescope gain off-axis. To rectify this problem, feed array has been designed, which is an array of dipoles. With appropriate combining networks, the antenna beam of the traveling feed mechanism could be scanned over the full 17.4 degrees with minimal loss in gain. This receiver will cover an astrophysically significant frequency range not covered by other receivers and will permit observations of one source for more than an hour.

This receiver offers an opportunity to study very exciting new technology: the signals from the array of dipole feeds can be individually amplified and correlated, much the way the signals from VLA antennas are processed. It is then possible, in principle, to implement the image-processing algorithms used for synthesis telescopes. For example, self-calibration could be used to eliminate errors in the telescope surface. This is well beyond the current state-of-the-art and would represent a very significant advance in radio telescope technology.

C. Program of Receiver Development and Construction

GaAsFET Amplifiers

The development and fabrication of cryogenically cooled GaAsFET amplifiers was pioneered at the NRAO; this work continues to define the world's standard for low-noise FET amplification not only for radio astronomy application but also in related fields such as communication. At the NRAO, cryogenic FET amplifiers have replaced parametric amplifiers as the first stage of amplification on all the NRAO telescopes for frequencies less than 15 GHz. In addition, room temperature FET amplifiers--again constructed in their entirety at the NRAO--serve as intermediate frequency (IF) amplifiers on each of the NRAO telescopes. This very successful development program will find application in the following new frequency bands proposed to enhance the frequency coverage and versatility of the VLA.

A 610-MHz capability designed to fill the gap between 350 MHz and 1370 MHz will be installed on all antennas. In addition to improving the frequency coverage of the VLA, this frequency is supported on other telescopes around the world as well as being one of the primary VLBA frequencies.

The frequency agility of the VLA will be augmented in two ways. First, the addition of S-band, 2.2-GHz GaAsFET receivers on a subset of VLA antennas (5-9) will supplement the present broadband spectroscopic facility of the VLA. It will usefully complement the 1.4 GHz band for cosmological studies by providing a large field of view but a much lower confusion limit. It will also permit the VLA to be used in conjunction with the VLBA at an important VLBA frequency. Second, simultaneous observations at two frequencies, 5 and 14 GHz, will be provided by means of a dichroic reflector system. Such a facility is vital for the study of rapidly evolving sources such as flare stars, active regions on the sun, and for observations aimed at a determination of the general relativistic gravitational bending of light rays near the solar limb.

The sensitivity of the VLA can be increased by factors as large as 2-6 at three of the present VLA operating frequencies through modest-to-major upgrades of the existing radiometers. The specific proposals are as follows:

1.3-1.7 GHz. HI and OH imaging in this frequency band at 1.4 and 1.66 GHz, respectively, are the most important classes of spectroscopic projects done with the VLA. Since such observations are always sensitivity limited, the need for improvement in radiometer performance here is most compelling. Presently, the VLA provides system temperatures of 50-60 K in this band. A significant fraction of the system temperature results from the decade-old receiver design which locates all front-ends in the same cryogenic dewar. This results in longer input waveguide runs than necessary and prevents polarization splitters from being cryogenically cooled. By adapting the VLBA receiver design to the VLA--cooled GaAsFET amplifiers in an independent L-band dewar--noise temperatures one-half the current values can be expected.

4.5-5.0 GHz. In many ways the 4.5-5.0 GHz system is the optimum VLA observing frequency. This frequency is high enough to avoid background source confusion at all VLA resolutions but not so high that there is significant degradation owing to telescope efficiency or atmospheric effects. As at 1.3-1.7 GHz noted above, if the 4.5-5.0 GHz GaAsFET receivers are mounted in a separate cryogenic dewar as in the VLBA design, a factor of approximately two improvement in system temperature is realizable.

HEMT Amplifiers

At frequencies higher than approximately 10 GHz, the thermal noise of GaAsFET amplifiers increases with increasing frequency owing to difficulties in efficiently coupling shorter wavelength radiation to the semi-conductor device which itself must become physically smaller at high frequencies. However, work on a new transistor amplifier, the high electron mobility transistor (HEMT), at the NRAO and in a few universities and industries, has demonstrated noise characteristics that are superior to those of the GaAsFET amplifiers, particularly at high frequencies. Development work is proceeding rapidly at the NRAO on a 20-25 GHz HEMT receiver for the VLA that will be installed in a cryogenic dewar in place of the existing cooled mixer.

SIS Mixers

At millimeter wavelengths (frequencies higher than 30 GHz) superb performance has been obtained from mixer amplifiers built around cryogenic superconductor-insulator-superconductor (SIS) junctions. The noise properties of these SIS mixers are several times lower than the best Schottky mixers at short millimeter wavelengths and they are rivaled only by maser amplifiers at the longest millimeter wavelengths. An active SIS development program is being carried out in the Charlottesville Central Development Laboratory which has as its proposed goal SIS receivers for the VLA, the VLBA, and the Tucson 12-m telescope in the following applications and frequency ranges:

43 GHz: Scientifically, it is very desirable to extend the frequency range of the VLA to higher frequencies. Neither the intrinsic accuracy of the VLA reflector panels nor the gravitational deformation of the antenna structure limit the VLA to the present highest operating frequency of 26 GHz. As there is considerable scientific gain to be realized by providing the capability to reach lines of the SiO molecular masers and the molecular tracer CS at 43 GHz, and since the telescopes will perform adequately at these frequencies, we intend to equip the antennas with suitable SIS radiometers. However, at 43 GHz the telescope pointing tolerance is sufficiently severe that thermal deformations leading to pointing errors will have to be greatly reduced; this will require that thermal insulation be applied to parts of the telescope structure.

70-230 GHz: SIS mixer receivers offer the prospect for greatly improved performance in the 70-230 GHz frequency range presently provided to astronomers at the Tucson 12-m telescope. Here receiver sensitivity is the single factor which is most limiting for the study of low-intensity, narrow millimeter spectral lines emitted by cold, spatially-extended astrophysical sources. Particularly at the highest frequencies, such as at the 230 GHz J=2-1 line of CO where the telescope beamwidth is smallest, the increased sensitivity gained by implementation of SIS mixers will allow astronomers to probe the detailed morphology and dynamics of the molecular components of circumstellar shells, regions of star formation where energetic bipolar flows are detected, and in a wide variety of external galaxies.

Presently, an SIS receiver is available on the 12-m for observations of the J=1-0 line of CO and its isotopes (90-115 GHz range). The proposal is to construct four additional receivers to cover the following frequency bands which are defined by a combination of scientific interest and atmospheric transmission:

70 - 90 GHz
130 - 170 GHz
200 - 220 GHz
230 - 270 GHz

The availability of sensitive SIS receivers in these broad frequency ranges, as opposed to simply at the frequency of the strongest CO line, will permit sensitive observations of additional transitions of known molecular species in the interstellar medium, and in dense molecular clouds, and it will even allow astronomers to probe thoroughly the physical environs of the clouds. In addition, prospects are excellent for detecting new species and adding to our understanding of the chemistry of the interstellar medium. In all these cases, and many unmentioned (e.g., solar system studies), the combination of the sensitivity provided by SIS receivers and the availability of such receivers over a broad frequency range is indispensible.

D. Low Frequency Synthesis Array

Several important classes of astronomical objects are not well studied by any of the existing U.S. radio telescopes, specifically those objects which are brightest at low frequencies. Here the most prominent examples are sources such as pulsars, solar bursts, the planet Jupiter, and nearby stars. In all these cases the radio radiation is emitted at frequencies much less than 1 GHz and it is impulsive. To investigate the nature of such phenomena one needs not only the capability to observe at low frequencies with exceptional sensitivity so that rapid time measurements can be made, but also good angular resolution so as to discriminate the source of emission from background confusion. Together those requirements demand a multi-element synthesis array telescope.

An even more compelling case for a low-frequency synthesis array can be made by the need to study extended extragalactic sources where the lower frequency radiation comes from the oldest relativistic electrons: A comparison of the low-frequency source image with the high-frequency VLA images of the same source directly provides a record of the source's evolutionary history. Thus, in a single pair of images we can witness the ageing of an extragalactic source such as a radio galaxy or a quasar. Similar statements are germane for galactic objects such as evolved HII regions (where the radiating particles at low frequencies are thermal electrons in the most diffuse gas) and old supernova remnants.

Low-frequency interferometers exist elsewhere in the world but none provides an angular resolution greater than a few minutes of arc at the frequencies of interest here. Scientifically, the need is for an instrument that will provide resolution of 20" or better at frequencies less than 100 MHz. Here, the major obstacle to the construction of such an array is the difficulty of dealing with ionospheric effects and in calibration of the data. However, experience at 300 MHz with the VLA self-calibration algorithms is encouraging; it is indeed possible to construct a single image extending across many isoplanatic patches. Therefore, there appears to be nothing to inhibit plans for a unique high-resolution, low-frequency synthesis array, and there is considerable scientific motivation for doing so.

The specific proposal is to construct a low-frequency synthesis interferometer on the Plains of San Agustin. This array would comprise at least 27 fully steerable banks of antennas, sited near the current "A" configuration stations. These would operate independently of the current VLA, except that the signals would be conducted by cable to the nearest 25-meter antenna for amplification and injection into the current waveguide transmission line. The low-frequency array would only be operated when the VLA was in the A configuration. These signals will be extracted from the waveguide in the control building and recorded on tape for later correlation using a special-purpose correlator. This approach will allow data from days of good ionospheric behavior to be archived without losing any information from the large (30 degree) primary beam. VLA operations would be undisturbed by the 75-MHz array.

E. Combined VLA and VLBA Imaging

The complementary nature of the VLA and the VLBA has been stressed many times. The VLA is the world's premier instrument for radio synthesis imaging; its resolution is about 1". The VLBA, on the other hand, is expected to provide images on the milli-arcsecond scale of the most compact radio structures visible in the VLA maps. Taken together, these two instruments allow us to explore the physics of radio sources over nearly three decades in frequency and five decades in angular resolution. Unfortunately, however, they cannot be "taken together" in a reliable and tractable way because the data from one array cannot be correlated with the data from the other array. The maps from the two arrays can be considered together, the (u,v)-data can be combined, but all the data cannot be cross-correlated so as to provide the astronomer with a single image. Missing also, in any case, are the telescope spacings intermediate between the longest VLA spacings and the shortest VLBA spacings. To combine the VLA and the VLBA into a single imaging instrument it will be necessary to rectify these two aspects. We propose to do this in the following two steps.

(1) Several VLA antennas can participate in VLBA observations if an independent VLBA backend (record system) is provided for each such antenna. The advantage in pursuing this approach is that in making it possible to cross-correlate a number of VLA antennas with each other and with each of the VLBA antennas "short spacing" information on complex fields would be available. This would greatly improve the image quality.

A suitable approach would be to install VLBA backends on four VLA antennas so that these antennas could be used as the innermost elements of the VLBA. This would increase the size of the field of view that could be imaged by the VLBA by a factor of 10 at all frequencies which the VLA and VLBA have in common, as well as giving sensitivity to much more extended structure in VLBA images. (The optimal configuration for this purpose would be to take the three antennas at the ends of the arms of the A configuration and one about one-third of the way down an arm.) This would leave 23 antennas in a "VLA sub-array" whenever this option was exercised--still an extremely powerful instrument.

(2) In order to combine the VLBA and the VLA with continuum uv coverage, it will be necessary to construct 3 or 4 additional antennas near the VLA that are situated so as to provide baselines longer than the longest VLA baseline but shorter than the shortest VLBA baseline. Sites for such an additional set of antennas were considered during the VLBA configuration study--a possible grouping would be Winston, New Mexico, Bernardo, New Mexico, and Holbrook, Arizona. A more detailed configuration study should, however, be undertaken before this option is finally specified. The costs would be between $4 M and $5 M per site, exclusive of further modifications to the VLA correlator and control system. Although the direct costs of the antennas at these sites might be saved (about $1.7 M per site) by relocating VLA antennas rather than constructing new ones, this would not be the preferred path scientifically. An important role for such antennas would be to provide short baselines for the VLBA at its highest operating frequencies. It would clearly be preferable in this context to use antennas of the VLBA design standards.

As NRAO has already planned for consolidation of the VLA and VLBA operations centers, this program is capital-intensive but does not require entirely new operations activity. Its principal operations cost would lie in the maintenance of additional equipment at the existing antennas and in maintenance of additional antennas if Stage 2 is implemented. Its principal indirect cost would be its load on computing facilities by increasing the demand for large image sizes in both the VLA-like and VLBA-like modes of operation. It would clearly be desirable to have enhanced image-processing facilities in place before this program is completed.

VIII. MILLIMETER ARRAY

When it became apparent that the proposed 25-m millimeter-wave telescope would not be funded, the NSF established a subcommittee of the Astronomy Advisory Committee to investigate new U.S. initiatives in millimeter-wave astronomy. The report of this subcommittee, chaired by A. H. Barrett, was issued in April, 1983. It recommends the following:

- The initiation of a design study of a millimeter-wavelength aperture synthesis array with a minimum usable wavelength of 1 mm, an angular resolution of 1 arcsecond, or better, at a wavelength of 2.6 mm, and a total collecting area of 1000-2000 square meters.

- Construction and operation of 10-meter class submillimeter-wavelength telescopes at dry sites.

- Support of astronomical research and development of millimeter and submillimeter-wavelength technology relevant to astronomy.

The NRAO has begun investigating the first of these recommendations, the design of a millimeter-wave synthesis array. Technical and scientific working groups have defined the specifications of an array that would provide a unique capability in millimeter-wave astronomy. A document describing the proposed instrument and its scientific potential is in preparation. It will be given wide circulation in early 1987 for evaluation and critical review by the astronomical community. A program of site testing has begun. Regular measurements of the atmospheric opacity at 230 GHz are being made at the VLA site. Three more automated tipping radiometers are under construciton for testing of additional sites. The expectation is that these efforts will converge toward the end of this planning period and culminate with a proposal for funding the instrument that the community seeks and supports.

IX. SPACE RADIO ASTRONOMY

Two proposals for space-based radio astronomical instruments are being discussed and reviewed by the astronomical community and NASA. One, the Large Deployable Reflector (LDR), is a 15-m class submillimeter/infrared telescope. The other, QUASAT, is an orbiting antenna for VLBI observations. NRAO staff have actively participated in the planning of these projects.

While LDR appears to be a very long-range project, QUASAT is being considered at NASA and the European Space Agency for a launch in the mid 1990's. NRAO staff members have been involved in these preliminary studies, and will continue these activities as the mission plans develop. Since the VLBA will be the key ground-based component for use with QUASAT, it is expected that NRAO will play a major role during the operations-phase of QUASAT. Discussions to define possible VLBA-QUASAT operational arrangements are already underway.

RADIOASTRON is a space mission of the USSR similar to QUASAT, but scheduled for a possible launch as early as 1990. Western radio observatories have been invited to participate in the RADIOASTRON mission and NRAO is discussing possible scientific and technical participation with the Soviet Space Research Institute.

X. BUDGETS

A. Operations Budget and Personnel Projections (1986-1991)

BUDGET ESTIMATE (M$)	1986	1987	1988	1989	1990	1991
I. OPERATIONS						
Existing Operations	16.1	16.7	17.9	19.1	20.2	21.3
New Operations (VLBA)	-	0.4	0.9	1.9	3.1	4.6
New Operations (Supercomputing)[1]	-	-	0.4	0.7	0.8	0.8
Total Operations	16.1	17.1	19.2	21.7	24.1	26.7
II. EQUIPMENT						
Research Equipment[2]	0.4	0.5	1.0	1.3	1.6	2.0
Operating Equipment	0.1	0.1	0.2	0.3	0.3	0.3
Total Equipment	0.5	0.6	1.2	1.6	1.9	2.3
Total Operations and Equipment	16.6	17.7	20.4	23.3	26.0	29.0
III. CONSTRUCTION & DESIGN						
VLBA	8.6	9.4	16.0	16.0	13.0	13.0
VLA Building (Socorro)[3]	[3.0]	-	-	-	-	-
Millimeter Array Design	-	-	-	0.1	0.5	1.0
Total Construction and Design	8.6	9.4	16.0	16.1	13.5	14.0
TOTAL PLAN[4]	25.3	27.1	36.4	39.4	39.5	43.0

PERSONNEL ESTIMATE	1986	1987	1988	1989	1990	1991
Existing Operations	319	306	315	320	325	330
New Operations (VLBA)	-	8	23	38	59	76
New Operations (Supercomputing)	-	-	8	14	14	14
TOTAL PERSONNEL[4,5]	319	314	346	372	398	420

1. Operations expenses, largely personnel, for supercomputing activities at NSF centers and/or a possible New Mexico center. Projected usage is the full capacity of a Cray XMP 14. This Plan does not schedule costs for supercomputer time, the capital costs of a dedicated center (~$18 M) for NRAO, or NRAO's share of capital costs in a NM center.
2. Does not include costs of projects in the section on New Initiatives and Directions.
3. Funded by the State of New Mexico and not included in totals.
4. Does not include funds or personnel for operation of Green Bank interferometer.
5. Does not include any personnel hired directly into construction projects.

BD54S1

VLBA BUDGET AND COST ESTIMATE

	*1983,4	*1985	1986	1987	1988	1989	1990	1991	PROJECT TOTALS	TOTALS, 1985-1991
INFLATION (%)	0	0	0	4	4	4	4	4		
ANT STARTS/INSTLS		1/1	3/1	1/3	2/1	2/2	1/2			
SITES	32	195	2,673	1,007	1,893	2,568	1,261	152	9,781	9,749
ARRAY OP CTR	0	2	30	203	2,704	236	0	0	3,175	3,175
ANTENNAS	1,088	2,457	6,453	3,480	4,864	5,542	3,662	271	27,817	26,729
ELECTRONICS	450	1,657	1,300	2,080	2,596	2,700	1,989	122	12,893	12,443
DATA RECORDING	290	424	200	520	757	787	819	584	4,381	4,091
MONITOR, CONTROL	55	102	600	432	488	497	331	210	2,715	2,660
CORRELATOR	315	139	234	431	1,217	1,220	684	0	4,240	3,925
POST PROCESSING	0	0	0	0	54	787	1,989	1,582	4,412	4,412
SYST. ENGINEERING	55	86	130	104	108	112	117	97	810	755
MISC., SPARES	0	0	0	0	0	0	0	3,194	3,194	3,194
PROJECT MAN.	224	421	634	703	593	602	628	426	4,231	4,007
OPER. TRAINING	0	12	90	73	0	0	0	0	175	175
PLANNED* EXPEND'S	2,509	5,495	12,344	9,031	15,273	15,053	11,480	6,638	77,823	75,314
CONTINGENCY	N/A	N/A	52	369	727	947	1,520	6,362	9,977	9,686
PERCENT CONT.	0.0	0.0	0.4	4.1	4.8	6.3	13.2	95.8	12.8	13
BUDGET, Current $	2,800	9,000	8,600	9,400	16,000	16,000	13,000	13,000	87,800	85,000

C. New Initiatives and Directions: Cost Schedule (1986 k$)

	1988	1989	1990	1991	1992
Sub-Arcsecond Imaging with the VLA					
- Pie Town Link	1000	-	-	-	-
- Socorro/Los Alamos Link	-	-	1500	-	-
	1000	-	1500	-	-
Development of Multi-Beam Receiver Technology					
- 8-feed, 230 GHz Receiver	100	-	-	-	-
- SIS Direct Detection Receiver	50	100	100	-	-
- Hybrid Spectrometer	100	100	-	-	-
- Adaptive Array Receiver	50	50	100	-	-
	300	250	200	-	-
Program of Receiver Development and Construction					
- 1.4 and 2.2 GHz	600	600	400	-	-
- 44 and 0.6 GHz	-	600	500	400	-
- 5, 15, and 22 GHz	-	-	600	600	600
- 12-m Telescope Systems	200	200	-	-	-
	800	1400	1500	1000	600
Low-Frequency Array	100	1000	600	-	-
Combined VLA/VLBA Imaging					
- Record Systems	-	800	-	-	-
- Intermediate Spacing Telescopes	-	-	-	6000	6000
	-	800	-	6000	6000
Annual Totals	2200	3450	3800	7000	6600