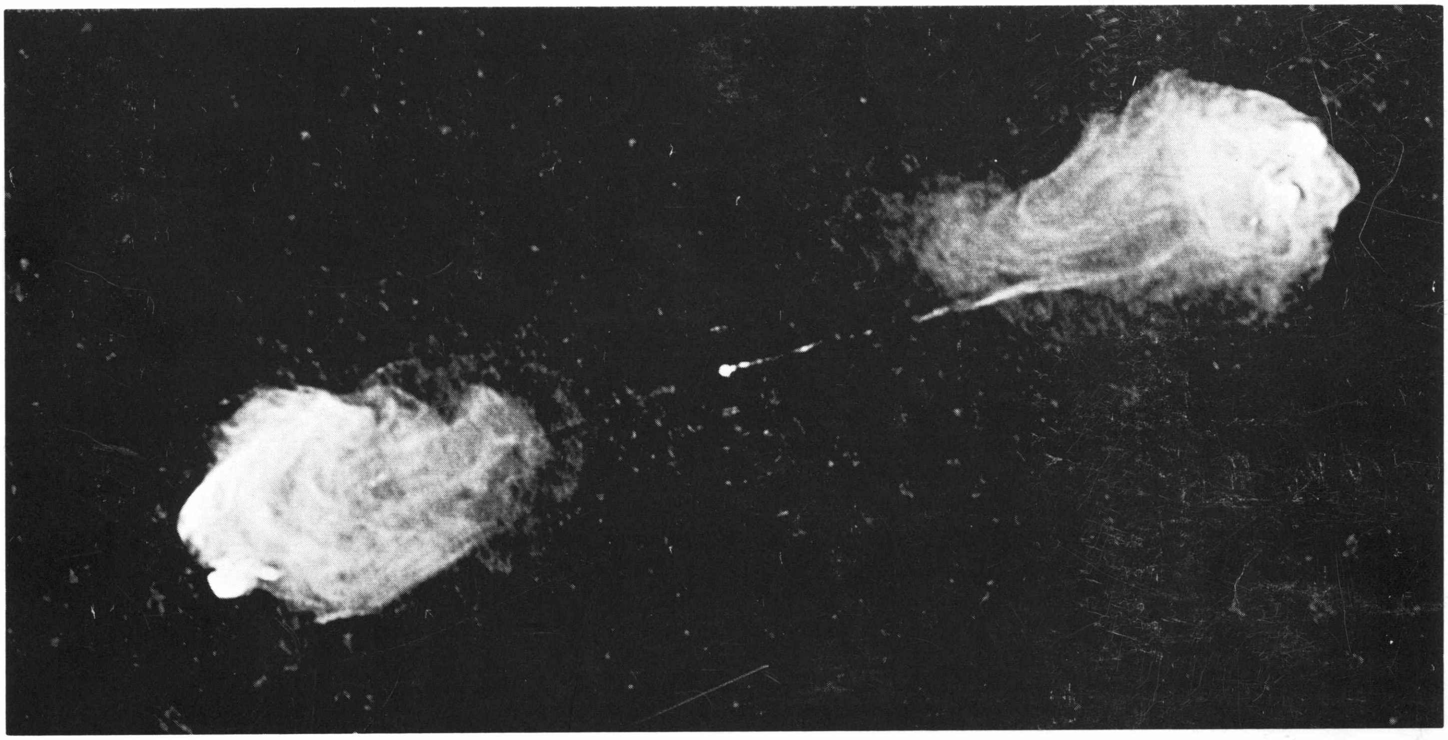
NATIONAL RADIO ASTRONOMY OBSERVATORY



NRAO

LONG RANGE PLAN 1988 - 1992

NATIONAL RADIO ASTRONOMY OBSERVATORY

LONG RANGE PLAN

1988-1992

March 1987

TABLE OF CONTENTS

I. INTRODUCTION

At the culmination of the present NSF planning period 1988-1992, the Very Long Baseline Array (VLBA) radio telescope will be complete. Five years from now this superb instrument will be available to the astronomical community through the NRAO as a full-time, visitor research facility. With it astronomers will be able routinely to make images of stars, galaxies, and the diverse enigmatic objects in the radio sky with angular resolutions finer than one-thousandth of an arcsecond over more than two decades of frequency. The VLBA is both the product of nearly two decades of development and refinement of the technique of very long baseline interferometry, and it is the instrument needed to further that development into the next century.

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 next five years of NRAO operation, the emphasis is given to facilities improvement and maintenance, consolidation of VLA and VLBA operations, re-establishment of the vitality and scope of the Observatory's instrumentation research and development efforts, and a greater realization of the scientific potential of the telescope facilities through enhanced computational resources. These are the top priorities as they can be assessed now. The completion of a major new facility such as the VLBA inevitably brings with it new science, new priorities, and new opportunities. Recognizing this, a primary responsibility of the NRAO is to preserve the flexibility to be able to respond to scientific change expeditiously. The next five years of growth can be assured of providing a wealth of exciting change to radio astronomy and the NRAO.

II. PLAN OVERVIEW

The present contract between the AUI and the NSF for operation of the NRAO expires at the end of 1988; discussions for a negotiated renewal of this contract for the period 1989-1993 are underway. As an important part of the renewal process, the AUI has submitted a proposal to the NSF which details plans, budgets, personnel levels, and new initiatives; the AUI long range plan for the NRAO 1989-1993 is therefore to be found in this proposal. The plans specific to 1988 are outlined in the following sections. Budgetary projections 1988-1993 are given in Section VI.

The NRAO Long Range Plan places particular emphasis on the implementation of new observing equipment and computing/software support. Major new initiatives described in Section V include the following:

- The Very Long Baseline Array
- The Supercomputer Initiative
- Combined VLA/VLBA Imaging
- The Millimeter Array

In addition, the Observatory computing needs, capability, and plans are reviewed in Section IV.

The Long Range Plan further recognizes 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). 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 enhancements to the major NRAO facilities planned over the next five years are described fully in the AUI proposal.

III. PLANS FOR 1988

The budgetary restraints of the last three years have been accommodated through a variety of measures which include such categories as deferred maintenance, stretch-out of construction, reduced services, and opportunities ignored or action postponed. While such measures produce needed savings, they do so at a cost which accumulates in the future. Thus it is that 1988 becomes a pivotal year for the Observatory. Specifically, the following areas will receive emphasis in 1988, as described below: (1) major maintenance and repair of the VLA railroad track and power distribution system; (2) completion of the Array Operations Center; (3) VLBA interim operations; (4) restoration of the NRAO Research Equipment program.

VLA Track and Power Distribution Repair

The VLA rail track system consists of two standard gauge railroad tracks which run along each of the 13-mile arms of the VLA wye. The 27 VLA antennas, each of which weighs nearly half a million pounds, are carried along the rails from one VLA configuration to another on a specifically-designed railroad vehicle. The configuration is changed approximately four times a year.

The entire VLA rail system--80 miles of track and 190,000 rail ties--was constructed of used materials. Since its completion in 1980, the rail system has received inspection and upkeep but major maintenance is required now. The deterioration of the system, particularly that of the ties which came from wet parts of the country, is occurring faster than can be repaired by the current maintenance program. Deterioration of groups of ties which have the potential for causing a derailment are the greatest concern. Hence the immediate goal is to repair the worst areas and gradually bring the system back to its original construction specifications. At least 300 k$ are needed for this purpose in 1988.

The full program of track system repair will require 600 k$ per yer for four years following 1988. The entire repair program is described in a separate report, "Major Maintenance Program - The Very Large Array Track and Power Systems."

Power distribution at the VLA is done with buried polyethylene insulated cable operating at 12,450 volts which was installed between 1974 and 1980 during the VLA construction. The type of cable used at the VLA was highly recommended and was installed extensively in the mid 1970's by electric utilities. However, it has since fallen from favor owing to reports of a rapidly increasing failure rate with age. The experience at the VLA is following this industry-wide pattern.

The expected service life of the type of polyethylene cable used at the VLA is now known to be only seven to ten years. A large part of the VLA system is now reaching the end of this predicted lifetime. We are seeing failures that take the form of a breakdown in the insulation and a short circuit to the grounded neutral. Prior to November 1985 we had no failures in the VLA power distribution system due to cable deterioration. Since then we have had eight failures in ten months.

Typically, a ground fault failure knocks power out on one arm of the VLA for several hours up to a couple of days while the fault is located, excavated, and repaired. At the moment, we have had eight failures in a year. By next year we can expect 10-20 failures per year. The predictions are uncertain, but in a few years the deterioration of the power cable will lead to a very serious disruption of VLA operations.

The only solution is to replace the power cable, this time using a longer life material, such as ethylene-propylene-rubber (ERP), insulated cable. Replacing all of the buried cable will cost about 1.3 M$; we expect to spread this cost over several years at the expense of down-time that will result from power failures in the interim. The program is described in the report mentioned above.

Completion of the Array Operations Center

The Array Operations Center on the campus of New Mexico Institute of Mining and Technology in Socorro, NM, will serve as the operational center for both VLA and the VLBA. Construction of this 60,000 square foot building should begin as early as the summer of 1987 and should be complete in late 1988. Half the funding for the building was provided from the State of New Mexico; the remainder has been advanced by NMIMT to be repaid as part of the VLBA construction program.

In addition to housing the VLBA control computer, and ultimately the VLBA correlator, the AOC will provide space for many of the VLA and VLBA support personnel and the scientists associated with the arrays. Common facilities, common management, and a common office environment should facilitate the merging of the two arrays into a single coherent NRAO operation in the near future.

VLBA Interim Operations

With three VLBA antennas operational in 1988--the antennas in Pie Town, MN; Kitt Peak, AZ; and Los Alamos, NM--the VLBA will begin to play an important role in U.S. network VLBI experiments. The gradual transition from the VLBA as a construction project to an operational facility managed, operated, and maintained from a central location is a critical activity which begins seriously in 1988.

The operation of a radio telescope with elements dispersed over 8000 km presents a number of unique challenges. Each of the 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/second.

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. In 1988 we will begin to see how well all this will work.

Research Equipment

Research Equipment is all equipment associated with telescope instrumentation and the development thereof: computing equipment, test equipment, receivers, spectrometers, correlators, feeds, etc. It is often considered as the life-blood of the NRAO since it is the activity that most affects the ability of the Observatory to provide its users with the best research equipment. Up to 1984, amounts of 1.5-2.0 M$ were typically available for this category. More recently the numbers have fallen well below 1 M$. It is essential to rebuild our level of effort, beginning with 1.4 M$ in 1989 and increasing gradually to 2.2 M$ in 1993 if NRAO is to continue to play the role that it has in U.S. radio astronomy.

The goals for the research equipment program through the planning period 1989-1993 are discussed at length in the AUI proposal. In 1988 specifically we intend to emphasize the areas noted below for each of the major NRAO observing facilities.

VLA

At the VLA many modifications have been incorporated in its first few years of operation, and these have had a significant effect on the scientific productivity of the VLA. In 1988 further enhancements will be made.

- 22 GHz receivers are being upgraded with new 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 will be completely installed at prime focus on all antennas. 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 arcminutes 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.

- Tests of a 75 MHz capability for the VLA will be investigated further. Several 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 eventual goal is to construct a low-frequency synthesis interferometer on the Plains of San Agustin.

300-foot Telescope

The 300-foot 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 the 300-foot 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.

In 1988, with adequate RE funding, the following should be completed:

- Spectral Processor. This device 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 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-foot. 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.

- L-band (1.3-1.8 GHz) Receiver. One of the principal uses of the 300-foot telescope is for redshift surveys. A cooled HEMT 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.

The 140-foot Telescope

In recent years a major effort has been directed toward improving the sensitivity and frequency coverage of radiometers on the 140-foot 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-foot 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-foot telescope ensure a continuing high demand for this instrument.

Future gains in sensitivity at the 140-foot telescope are realizable from additions to the available receivers, computers, and spectrometers as well as from improvements to the telescope structure. In 1988 holographic measurements of the telescope surface will be used to improve the figure of the surface for better high-frequency performance.

The 12-meter Telescope

The demand for observing time on the NRAO 12-meter 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.

In 1988 activities at the 12-meter will concentrate on the following projects requiring support from Research Equipment:

- Continued implementation of SIS receivers. In order to complement the successful NRAO 90-115 GHz SIS receiver which provides a system temperature less than 100 K (SSB), the Central Development Laboratory will develop SIS receivers at 230 and 345 GHz. Using NRAO HEMT amplifiers as second stages, these SIS receivers should also set the world's standard as low-noise millimeter wave receivers. Work on multi-beam SIS receivers will continue and benefit by the experience gained from the 8-beam 230 GHz Schottky receiver which will be in routine use in 1988.

- 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 multi-feed systems.

IV. OBSERVATORY COMPUTING

As an observational science, astronomy at its most fundamental level is concerned with the attempt to obtain increasingly precise images of the sky. 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 radio astronomy the image-forming "optics" of the radio telescopes are computers. This is readily evident for the synthesis aperture telescopes such as the VLA and VLBA in which the fundamental observational data are the Fourier transform of the sky brightness and one must use computers to obtain the inverse transform just to produce the image. But so it is also true of the single dish telescopes where computers are indispensible for combining data and removing atmospheric or instrumental effects.

As a visitor-oriented observatory, it is incumbent on the NRAO to make additional use of computers to simplify and standardize the astronomers interaction with the telescopes and his subsequent data reduction and analysis tasks. In order to provide the visiting astronomer with the full flexibility and capability of the NRAO instruments the computer user-interface needs to be both comprehensive and easily understood.

Computing at the Filled Aperture Telescopes

The on-going hardware upgrades at the single dish telescopes--lower noise receivers, multi-beam receivers, spectrometers with wider bandwidth and more channels--have the effect of greatly increasing the telescope data rate. To the astronomer this is beneficial because it provides him with a better image of the sky. But it does come at the expense of a proportional burden on the telescope computing resources. In addition, the greatest progress in recent years at the single dish telescopes has come with the introduction of new observing techniques such as the dual-beam restoration procedure used at the 12-meter to circumvent atmospheric difficulties and the ability to "clean" 21-cm HI spectra of contamination due to stray radiation. Again, these new capabilities provide new scientific opportunities but require enhanced computer resources for their support.

In 1988 and throughout the planning period, the computer facilities at the single dish telescopes will be augmented as follows:

- The control computer at the 12-meter telescope will be replaced by a VAX-11/750 + PDP-11/44 combination and a distributed network of dedicated microprocessors.
- The 140-foot control computer will be replaced with a hardware configuration identical to that at the 300-foot telescope.
- The user-interface software (the astronomers telescope control program) will be replaced at all the NRAO single dish telescopes with a single common program having only subtle variations from one telescope to another.
- The data analysis computers at the Green Bank telescope will be replaced with imaging workstations; a site computer with sufficient peripheral support will be added to accommodate the higher telescope data rate and new analysis algorithms.
- An NRAO program for the analysis of spectral line scans will be provided on a floppy disk for users who wish to carry their data home in this form for analysis on a personal computer.

Computing for Synthesis Array Telescopes

The majority of the Observatory's computing activities are concerned with the editing and calibration of data from the VLA (and, in this planning period, the VLBA), the transformation of that data to images and detailed processing/analysis of those images.

Experimentation and experience with image restoration algorithms have led to enormous gains in the speed and sensitivity of the VLA and have catapulted the scientific potential of the VLA far beyond the computing resources available to realize that potential. 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 100,000:1, 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.

Table I gives a comparison of the 1967 design goals of the VLA, the performance in 1980 when the VLA was dedicated, and the present performance for selected parameters most directly affecting the computing demand.

Table 1

Specification	1967	1980	1986
Speed (images per day)	3	100	200
Map Size - Routine (pixels)	100x100	512x512	512x512
Map Size - Maximum (pixels)	100x100	1024x1024	4096x4096
Spectral Line (27 antennas)	-	8	32
Dynamic Range	100:1	1000:1	100,000:1

Speed, map size, and spectral resolution all directly expand the amount of data to be processed. The enormous gain in dynamic range, equivalent to image quality, is made possible by the recent development of deconvolution algorithms. These require large amounts of computing if they are to be exploited.

As the growing speed and sensitivity of the VLA became apparent, NRAO took steps to provide increased computer resources to its user community. The most significant initiatives were: the development of a portable image-processing software system, known as the Astronomical Image Processing System (AIPS), which can be run on VAX computers available to users at their home institutions as well as at NRAO; and an experiment with a special processor system, known as the Pipeline, to rapidly produce images from recorded data taken in the spectral line mode. In addition, successful experiments with supercomputers have been run, algorithms have been optimized, and two mini-supercomputers have been acquired by the NRAO. The evolution of VLA computing is summarized in Table 2.

Table 2

CHRONOLOGICAL HISTORY OF VLA COMPUTING

1972	August	Congress approves construction of VLA project; 4.5 M$ budgeted for computing.
1974		CLEAN deconvolution algorithm published.

1974 June		DEC awarded subcontract for initial continuum off-line computer, a DEC 10/KI system.
1974 July		Modular Computer System awarded subcontract for on-line computer. Initially a network of 4 ModComp II minicomputers, later enhanced to 7 ModComps.
1975 December		First 2D maximum entropy deconvolution algorithm published.
1976 February		Contact with ERIM to design an optical processor for VLA image generation.
1977 May		First VLA image of an extended source.
1977 December		Optical processor development abandoned in favor of a pipelined network of PDP11's and special digital hardware--the "Pipeline."
1979 February		AIPS postprocessing software project started in Charlottesville.
1979 December		Acquire VAX 11/780 in Charlottesville.
1980 December		VAX 11/780 acquired for VLA site. Final VLA computer construction budget increased to 6.5 M$.
1980 December		Completion of VLA construction project.
1981 March		DEC 10/KI upgraded to DEC 10/KL.
1981 April		Acquire second VAX 11/780 at VLA.
1982 March		NRAO Computer Advisory Committee meets at VLA. "Need a long range plan based on astronomical requirements ... flexible and growable computer architecture ... should not depend on being at leading edge of computer technology ... requires a major new infusion of capital from NSF."
1983 September		Detailed analysis of VLA computing needs completed. Concludes that a CRAY X-MP class supercomputer best meets needs.
1983 May		DEC abandons its DEC 10 line of computers.
1983 October		Scientific Panel reviews NRAO's computing plans. Recognizes need at least in small supercomputer range and urges NRAO to make such a plan.

1983	November	Start acquisition of new VLA on-line computer. Three ModComp Classic's.
1984	July	Test of VLA deconvolution using CRAY 1-S at Los Alamos National Laboratory.
1984	September	NRAO Computer Advisory Committee meets at Green Bank and endorses plan to acquire a supercomputer system. "The most attractive option currently available and absolutely essential for the prosecution of the science."
1984	December	Proposal to NSF for 40 hours of Class VI computer time.
1985	March	4kx4k Cas A image deconvolved on Digital Productions Cray X-MP using NSF access program.
1985	March	Conceptual proposal to NSF for a Supercomputer for Radio Astronomical Imaging.
1985	April	Proposal to NSF for 160 hours of Class VI computer time.
1985	December	Acquire Convex mini-supercomputer in Charlottesville.
1986	May	Image Storage and Display System for 512 pixel cubes operational at VLA.
1986	September	Acquire Convex mini-supercomputer for VLA.

In 1983 a major study was begun of VLA computing needs and reviewed by an external panel of distinguished computing consultants. At that time the capacity required to free the potential science of the VLA from computer limitations could only be satisfied by a supercomputer. e.g., a single processor CRAY XM-P. The strong recommendation was to acquire a supercomputer dedicated to this purpose. In 1985 a conceptual proposal was submitted to the NSF describing the system required.

Since then it has become clear that a dedicated supercomputer for NRAO is at best a long term goal. The current Observatory plan is to replace and augment existing computing systems until a supercomputer can be acquired. However, that plan is now under extensive review.

The time is right for a review of the array computing plan. Since the writing of the supercomputer proposal a major development has occurred in computing hardware that was totally unanticipated, even by our external panels of computing experts. That is the introduction of the mini-supercomputers, vector architecture machines smaller than supercomputers but competitive with supercomputers in cost per computing cycle. NRAO now owns two mini-supercomputers--CONVEX C-1 machines--and our experience strongly suggests studying the potential of a cluster of <u>second-generation</u> mini-supercomputers as an alternative to a supercomputer.

Groups within the Observatory have been organized to address the following issues:

- Review science requirements, including VLBA.
- Review calculation of required capacity.
- Get technical information on the next generation of mini-supercomputers.
- Determine impact of non-NRAO data processing.
- Decide what science requires processing at external supercomputer centers and extent to which NRAO can support that activity.
- Review operating costs.
- Write plan for developing optimized code and the interface to AIPS.
- Investigate impact of availability of large memory.
- Specify a common file system and decide on centralized vs distributed structure.
- Review needs for graphics equipment.
- Check new developments in array processors and parallel processing.

The final report is expected by mid-summer.

We recognize that there will probably always be certain massive VLA and VLBA projects which require the largest computers that exist. We intend to support, to the extent we can, the reduction of these projects at computing facilities external to NRAO.

Finally, a word must be added with respect to VLBA. The software for VLBA data reduction is being written now--incorporated into AIPS. It will have several years of testing during the interim operations program of the VLBA before construction of the entire array is finished. The hardware for VLBA data processing to be purchased in 1990 and 1991 is budgeted at more than 3 M$. That amount was sufficient for the science described in the original VLBA proposal with the hardware then available. The same amount will buy much more capacity today and, probably, still more in 1990. We are convinced that the science requirements have not grown by an even larger factor.

V. MAJOR NEW INITIATIVES

One central activity of the National Observatory is the proposal of major new facilities for the benefit of U.S. astronomy. While the plan for such initiatives is developed by the NRAO in concert with its community, the realization of the initiative largely rests with the NRAO. Four major new initiatives are being developed in the planning period 1988-1992.

The Very Long Baseline Array

The VLBA is a major new initiative which will provide the scientific community with the capability of making images with resolutions at the milli-arsecond scale and of measuring positions with sufficient accuracy to provide important new data for parallax studies and for a variety of applications in geodesy and crustal dynamics. Construction of the VLBA, begun in 1984, will continue through much of the duration of this planning period. The project is described fully in the AUI Proposal; the funds necessary to complete the project are shown in the table below.

The Millimeter Array

When it became apparent that the proposed 25-meter 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, to 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 conceptual proposal describing the proposed instrument and its scientific potential is in preparation. It will be given wide circulation in 1988 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 and at a high altitude site (10,600 feet) in the Magdelena mountains. Two more automated tipping radiometers are under construction 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.

The Supercomputer Initiative

In the NRAO conceptual proposal given to the NSF, the case is made that certain areas of research with the VLA, and in the future with the VLBA, are hampered or even curtailed because of the lack of sufficient computing resources. It is proposed that the NRAO eventually acquire a supercomputer which would be devoted to these difficult imaging problems. Currently the scope and nature of this proposal is under investigation, as is described in Section IV.

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) Connect the Pie Town VLBA antenna, and later the Los Alamos VLBA antenna, to the VLA by means of a fiber optics link. 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.

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 continuous uv coverage, it will be necessary to construct three or four 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 2.7 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.

PLANS FOR MAJOR NEW INITIATIVES

	1988	1989	1990	1991	1992	1993
VLBA Construction	11,900	12,400	12,900	13,400	900	-
Millimeter Array	100	300	500	1,000	10,000	15,000
Supercomputer	-	-	6,000	6,000	6,000	2,000
Combined VLA/VLBA Imaging	-	1,000	800	1,500	6,000	6,000
Total Initiatives	12,000	13,700	20,200	21,900	22,900	23,000

VI. BUDGET PROJECTION (M$)

	1987	1988	1989	1990	1991	1992	1993
Operations							
Existing Operations[1]	16.6	18.9	19.6	20.8	22.0	23.3	24.6
VLBA Operations	0.2	1.2	2.1	3.4	4.6	5.2	5.9
Common Cost Recovery	(0.4)	(0.3)	(0.2)	–	–	–	–
Total Operations	16.4	19.8	21.5	24.2	26.6	28.5	30.5
Equipment							
Research Equipment	0.3	0.4	1.4	1.6	1.8	2.0	2.2
Operating Equipment	0.1	0.1	0.1	0.1	0.1	0.1	0.1
Total Equipment	0.4	0.5	1.5	1.7	1.9	2.1	2.3
Total Operations & Equipment	16.8	20.3	23.0	25.9	28.5	30.6	32.8
Construction							
VLBA	11.4	11.9	12.4	12.9	13.4	0.9	–
Millimeter Array	–	0.1	0.3	0.5	1.0	10.0	15.0
Computing[2]	–	–	–	4.0	4.0	4.0	–
Combined VLA/VLBA Imaging	–	–	1.0	0.8	1.5	6.0	6.0
Total Construction	11.4	12.0	13.7	18.2	19.9	20.9	21.0
TOTAL PLAN	28.2	32.3	36.7	44.1	48.4	51.5	53.8

[1] Does not include funds for operation of the Green Bank Interferometer.
[2] Capital costs of supercomputer; computing plan under review could have different total cost and distribution in time.

PERSONNEL PROJECTIONS (FULL-TIME STAFF)

	1987	1988	1989	1990	1991	1992	1993
Existing Operations[1]	302	307	313	319	325	331	337
VLBA	5	17	31	51	68	89	96
Total	307	324	344	370	393	420	433

[1] Includes (11) personnel for operation of the Green Bank Interferometer.

Addendum 1

to

National Radio Astronomy Observatory

Long Range Plan

1988-1992

Raffe

COUNCIL MEMO No. 63

RE1987D 27-Feb-87 12:05:20 PM

RESEARCH EQUIPMENT

NRAO SITE	Proj cost 1986	1987	1988	1989	1990	1987 Avail. $	1987 Addl. from site Ops. savings
TUCSON	143	142	409	200	80	135	7
GREEN BANK	148	160	695	645	740	135	25
SOCORRO-VLA	289	255	1,585	1,842	2,200	255	0
COMMON DEVELOPMENT	151	144	326	320	315	125	19
TOTAL RE PROJECTS	731	701	3,015	3,007	3,335	650	51
EXPECTED FUNDS(NRAO)	749	701					
BALANCE	19	0					

All costs in k$

TUCSON
******

PR.NR.		Proj cost 1986	Pri	1987	1988	1989	1990	Total Cost	Comments
	TEST EQUIPMENT **************								
70.200	Test Equipment-TUC	10		15	25	30	30		
	MISC. ELECTRONICS *****************								
70.800	12-M Improve.	4			15	15	15		
70.802	12-M Cryogenics	7		0	10	10	10		Postpone cryo improvement
70.803	12-M Rx Improve	5		10	15	15	15		
	Closed Projects	(1)							
	MISC. COMPUTERS ***************								
70.901	12-m Computer Misc	7		10	10	10	10		
	MAJOR ELECTRONIC PROJECTS *************************								
	F.T.S for Broad Lines	NEW				20		20	
	Dual 70-170 GHz SIS Rx	NEW			50			50	
	Bolometer Array 1 mm	NEW				50		50	
	Freq. Agile Cont. SIS Rx	NEW				50		50	
	Dual 200-300 GHz SIS Rx	NEW	2	15	40			50	
	Sun Screen	NEW	5		-60			60	
70.101	Hybrid Spectrometer	47	3	25					
70.104	SIS CO Receiver	6							
70.105	8-feed 220-230GHz Rx	17	5	8	40				
70.106	IF Proc. (Hybrid Spect.)	12	4	38	40				Operational end 1987
70.107	New Optics	1	8		35				
70.108	3mm Continuum SIS Rx	0			20				
70.109	Tel. Control Upgrade	25	1	21	49				Delayed to late 1988
	Total Test+Misc. Projects	34		35	75	80	80		
	Total Major Projects	109		107	334	120	0		
	Total all TUC Projects	143		142	409	200	80		

GREEN BANK
****

PR.NR.		Proj cost 1986	Pri	1987	1988	1989	1990	Total Cost	Comments
	TEST EQUIPMENT								
	**************								
10.200	Test Equipment-GB	0		0	30	30	35		
	MISC. ELECTRONICS								
	*****************								
10.800	Interference Protection	0							
10.801	General Front-Ends	5		5					
10.802	General Digital Equipment	0		2					
10.803	Ant Test Range	0		2					
	MISC. COMPUTERS								
	***************								
10.900	140-ft Computer Additions	4		11					
10.901	300-ft Computer Additions	0		3					
10.902	Misc.Computer Equip.-GB	1		5					
	TOTAL MISCELLANEOUS	14		28	55	60	65		
	MAJOR ELECTRONIC PROJECTS								
	*************************								
	140-ft:								
	Dual S/X Receiver	NEW				30	30	75	
	Spectral Backend	NEW				100	100	200	
	40-Ghz Receiver	NEW			20	50	20	90	
	Workstation	NEW				40		40	Data Analysis
	Spectrum Analyzer	NEW			15			15	Averaging for FE monitor.
	Control Computer	NEW	2		20	130		150	
	32-GHz Receiver	NEW	4	7	50	30		50	
	Subreflector	NEW	4		50			45	Corrects for high freqs.
	300-ft:								
	Workstation	NEW			40			40	
	1.3-1.8 GHz Rx	NEW			80			120	Multi-beams?
	5 GHz Correcting Lens	NEW						10	In Misc. Projects
	Spectrum Analyzer	NEW			15			15	
	Universal LO	NEW			20	20	20	60	Four units.
	Multibeam Arrays	NEW				50	50	?	
	Broadband Receivers	NEW				50	50	?	
	Broadband Backend	NEW					100	?	
	VLBA record. equip.-140'	NEW					250	?	
	MK3 Recorder Head Upgrade	NEW		25				25	
10.400	2-5 GHz receiver	2	7						2.2 GHz and HEMTs.
10.401	300-ft Comput./Spectrom.	111	1	85	60				
10.403	7 feed 5 GHz cont rx	19	8						Two spectral channels.
10.404	Adaptive Array Rx	3	6	15	10				450 MHz/ Butler matrix
	Closed Projects	(2)							
	MAJOR COMPUTER PROJECTS								
	***********************								
	Digital Switch	NEW						15	
	Computer Networking	NEW			30			30	
	Optical Disks	NEW				20	20	?	
10.500	GB Lab Computer	2	3		200	35			
	Total Test+Misc. Projects	14		28	85	90	100		
	Total Major Projects	134		132	510	555	640		
	Total all GB Projects	148		160	655	645	740		

VLA ELECTRONICS

PR.NR.		Proj cost 1986	Pri	1987	1988	1989	1990	Total Cost	Comments
	TEST EQUIPMENT								
	**************								
80.200	Test Equip.-VLA Electron.	1		0	35	35	35		
	MISC. ELECTRONICS								
	*****************								
80.800	Cryogenics	0							
80.801	VLBI Observing	16							
80.802	FE Test Sets	2							
80.803	LO-IF Test Sets	0							
80.804	DCS Test Sets	0							
				15	15	15			
	MAJOR ELECTRONIC PROJECTS								
	*************************								
	Fringe Rot for B/C IF's	NEW				400		400	VLB New Equipment
	Mk3 Recorder Head Upgrade	NEW			25			25	VLB New Equipment
	VLBA Record. equip.-VLA						500	500	VLB New Equipment
	Correlator Sys Controller	NEW			150			150	Computer RE ?
	1.3-1.7 GHz Tsys improve	NEW	3		150	150	150	600	Needs JPL Cryo Comp
	Ant Point. improve-Active	NEW	5		25	25	25	110	
	Total Power System	NEW	6		100	100		205	
	Frequency Agile Receiver	NEW	7		80	80		165	
	Pietown/VLA Link	NEW	11				650	650	If not Funded by VLBA
	Correlator Dev.	NEW	12				100	100	Wait for VLBA Corr Design
	Ionospheric meas. device	NEW	13		50			50	
	Pietown interface	NEW	13			50	250	300	
	44-49 GHz Receivers	NEW	14				35	1,050	HEMT or FET 6/yr
	2.2-3.2 GHz Receivers	NEW	15			240	240	1,200	Receiver and Feeds 6/yr
	4.5-5.0 GHz Tsys improve	NEW	17					600	
	Circ. Pol. Improve Study	NEW	18					50	
	5/14 GHz dual freq feeds	NEW	19					420	
80.101	327 MHz receiver *	60	2	0	25			340	8 Systems in 87
80.102	RFI Improvements *	10	4	0	35	35		195	14 Systems in 87
80.104	Delay Improve								
80.105	DCS Improve	2							
80.107	Water vapor radiometers	1	8		10	80		120	For 2 System
80.108	Ant point. imprve-Passive	18	5						To be complete in 87
80.109	K-Band Upgrade-CDL	27	1	40	45			110	12 Systems in 87
80.110	K-Band Upgrade-VLA	25	1	60	60			150	12 Systems in 87
80.111	K-Band Upgrade-GB	13	1	30	33			77	12 Systems in 87
80.112	75 MHz Receiver (VLA) *	5	9	0	42	42		125	14 Systems in 87
	Total Test+Misc. Projs.	19		15	50	50	35		
	Total Major Projects	162		130	830	1,202	1,950		
	Total all Elect. Projects	180		145	880	1,252	1,985		

* Cost to NRAO, Additional funds from NRL

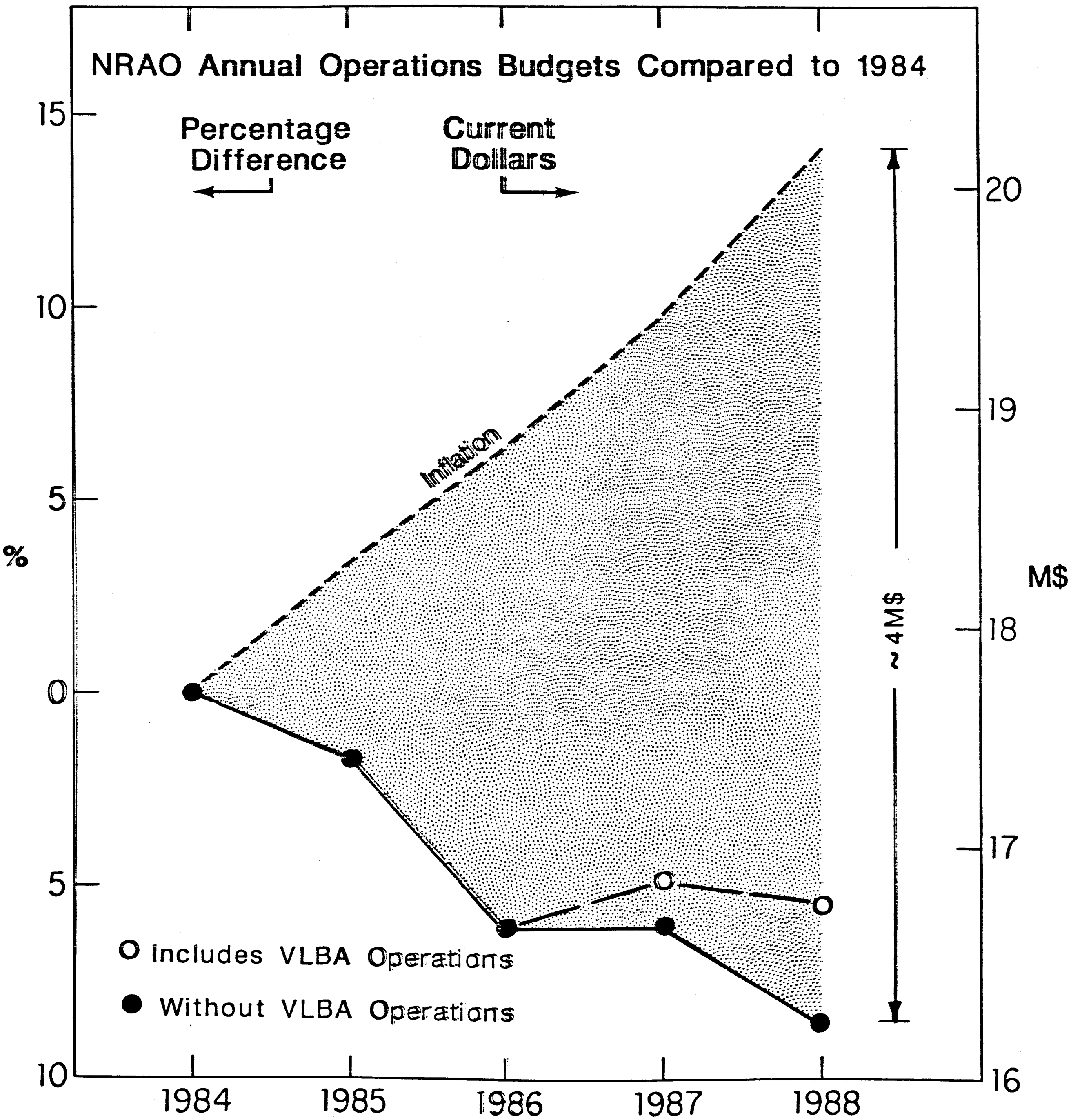
VLA COMPUTER

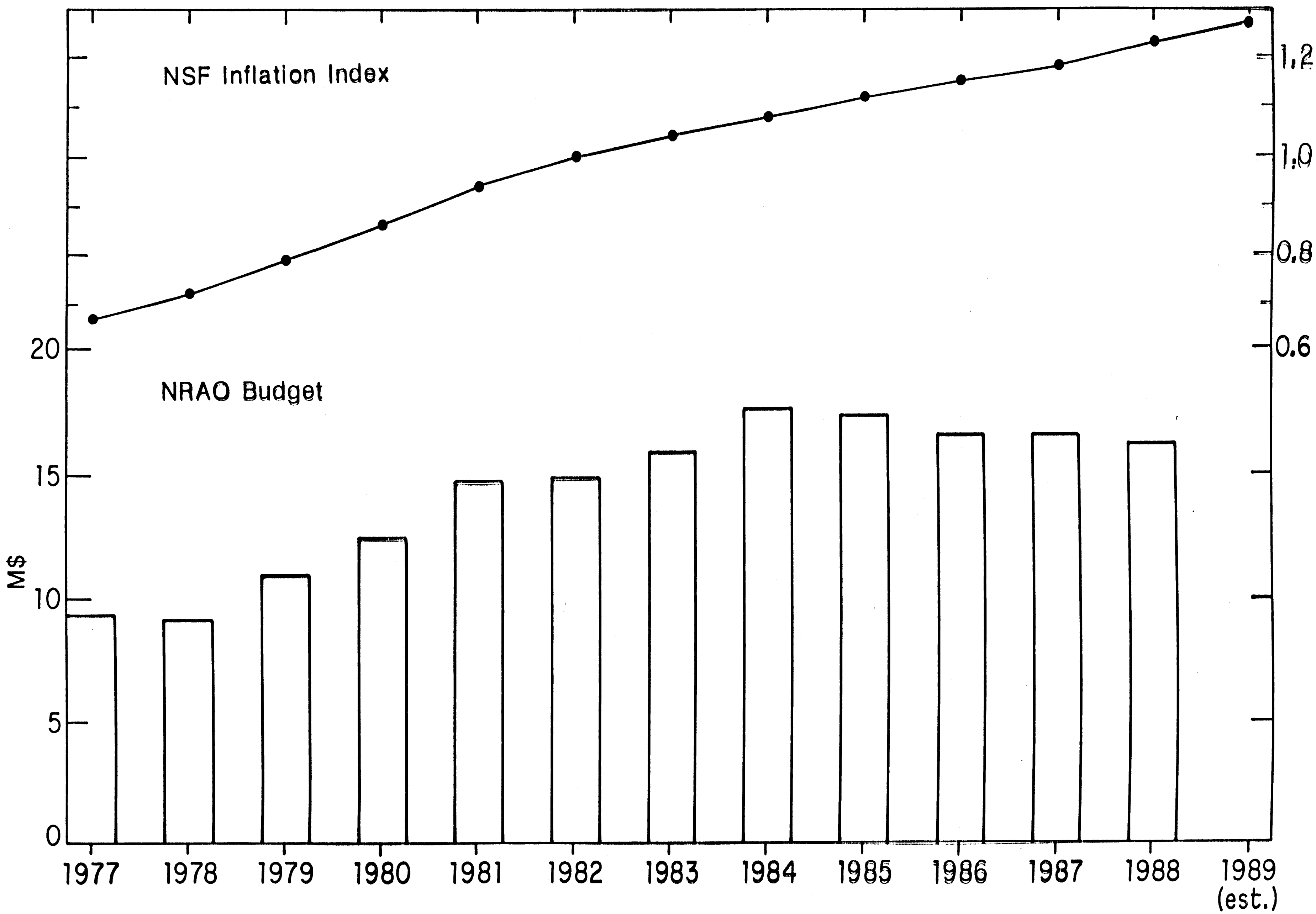
PR.NR.		Proj cost 1986	Pri	1987	1988	1989	1990	Total Cost	Comments
	TEST EQUIPMENT **************								
80.201	Test Equip.-VLA Computer	5		0	5	5	5		
	MISC. COMPUTERS ***************								
80.900	Socorro								
80.901	DEC-10 System								
80.902	Terminals								
80.903	PDP 11's								
80.904	ModComp's	(0)							
80.905	VAX's								
80.906	Communications-VLA	1							
80.907	Misc. Computer Equip.-VLA	2							
				10	25	25	25		
	MAJOR COMPUTER PROJECTS ***********************								
80.501	Image Storage Units	0	0	15	15	15		45	Upgrade: 2 new units
80.502	Sync. computer upgrade	(6)	1	10	55	110		530	Tape; Memory; Disk
80.505	Versatec replacements	0	2	40				40	
	High res. hardcopy	NEW	3	20				20	
	1kx1k display for CONVEX	NEW	4	15	15	30		60	
	Sync. system display	NEW	5		25	25		50	
80.506	CONVEX	50	5		45	30	35	200	Racks, Disks, Networking
	Convex tape drives	NEW	7	0	30			30	2 units
	Graphics	NEW	10		25	150		175	
	Phased array processor	NEW	11		65			65	
	DEC-10 tape drives	NEW	12		50			50	
	Sync. system AP	NEW	20			100		100	1988 included in VLA elec
	Sync. UVFITS writer	NEW	20		100			100	
	Database comp./software	NEW	25		150		150	300	
80.500	Mass Store (Archive)	12	25		50	100		150	
	TU-78 tape drive, VAX-3	NEW	25		50			52	
	Image work stations	NEW	30					30	
	Closed projects	5							
	Total Test+Misc. Proj.	8		10	30	30	30		
	Total Major Projects	101		100	675	560	185		
	Total all Comp. Projects	108		110	705	590	215		

COMMON DEVELOPMENT

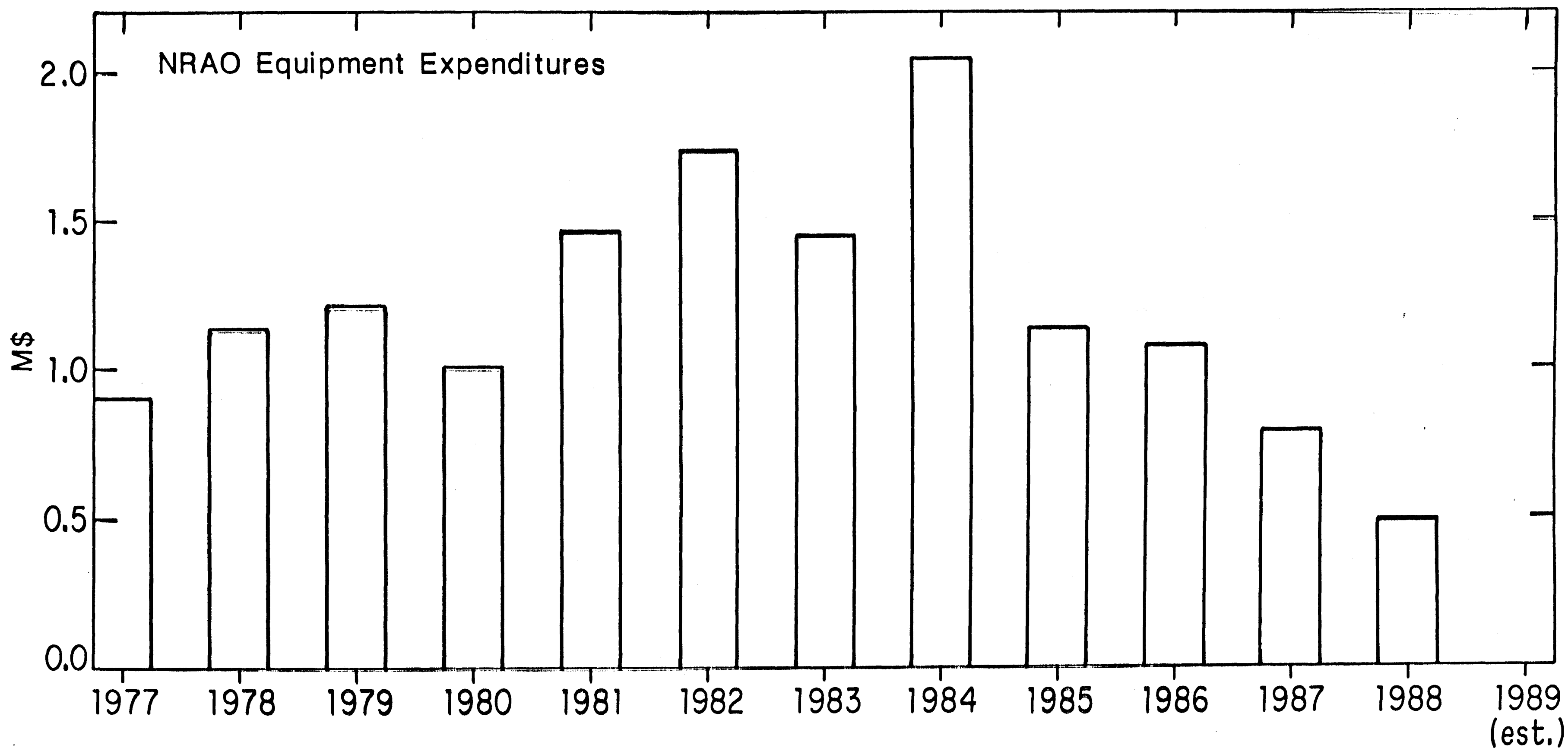
PR.NR.		Proj cost 1986	Pri 1987	1988	1989	1990	Comments
	TEST EQUIPMENT						
	**************						
20.200	Test Equipment-CDL	3	0	35	35	35	
20.201	Test Equip.-CVL Computer	0	0	5	5	5	
	MISC. ELECTRONICS-CDL						
	*********************						
20.800	MM Wave Res.	3	5	15	15	15	
20.801	2.5K Refrigerator Dev.	(11)					
	MAJOR PROJECTS-CDL						
	******************						
20.000	Diode development	23	20	55	55	60	
20.001	Cooled GASFET	8	10	25	25	25	43Ghz from VLBA
20.002	SIS development	50	60	100	100	100	
20.003	MM-wave array dev.	16	15	30	30	30	
20.004	Plnr mxr/m-beam array dev	1	0	30	30	30	
	MISC. COMPUTERS-CVL						
	******************						
20.900	VLBI						
20.901	Communications	0					
20.902	Elect Support						
20.903	VAX Systems	15					
20.904	Convex Systems	13					
20.905	Misc. Computer Equip.-CVL	5	10	15	15	15	
	MAJOR COMPUTERS-CVL						
	******************						
	Single Dish Support	NEW	4				Personal Computer
	Convex Additions	NEW		6			Disk and printer
	IBM Replacement Items	1					
20.101	Class VI Evaluation	9	10				Supercomputer interface
20.102	Networking	5	10	10	10		NRAO Interstate network
	Total CDL Misc+Test Proj.	(5)	5	50	50	50	
	Total Comp.Misc+Test.Proj	32	10	20	20	20	
	Total all CDL Projects	109	105	240	240	245	
	Total all Comp. Projects	15	24	16	10	0	
	Total all Com. Dev. Proj.	151	144	326	320	315	

PVB Info to Exec Comm 5/10/88





NSF Inflation Index
NRAO Budget
M$
0
5
10
15
20
0.6
0.8
1.0
1.2
1977
1978
1979
1980
1981
1982
1983
1984
1985
1986
1987
1988
1989
(est.)


NRAO Equipment Expenditures
M$
2.0
1.5
1.0
0.5
0.0
1977
1978
1979
1980
1981
1982
1983
1984
1985
1986
1987
1988
1989
(est.)

RIF SUMMARY

15 FULL-TIME EMPLOYEES GIVEN NOTICE
15 FULL-TIME OPEN POSITIONS CANCELLED
4 PART-TIME EMPLOYEES GIVEN NOTICE
2 FULL-TIME EMPLOYEES PUT ON PART-TIME

VLA:	DISMISSED	~~4~~ 5	VLBA HIRED ONE; GB HAS OFFER TO ONE
	OPEN	7	
GB:	DISMISSED	~~5~~ 6	2 PART-TIME DISMISSED; SUMMER HELP CUT
	OPEN	4	
TUC:	DISMISSED	2	1 PUT ON PART-TIME; 1 PART-TIME DISMISSED
CV:	DISMISSED	2	1 PUT ON PART-TIME; 1 PART-TIME DISMISSED
	OPEN	4	
FISCAL:	DISMISSED	~~2~~ 0	

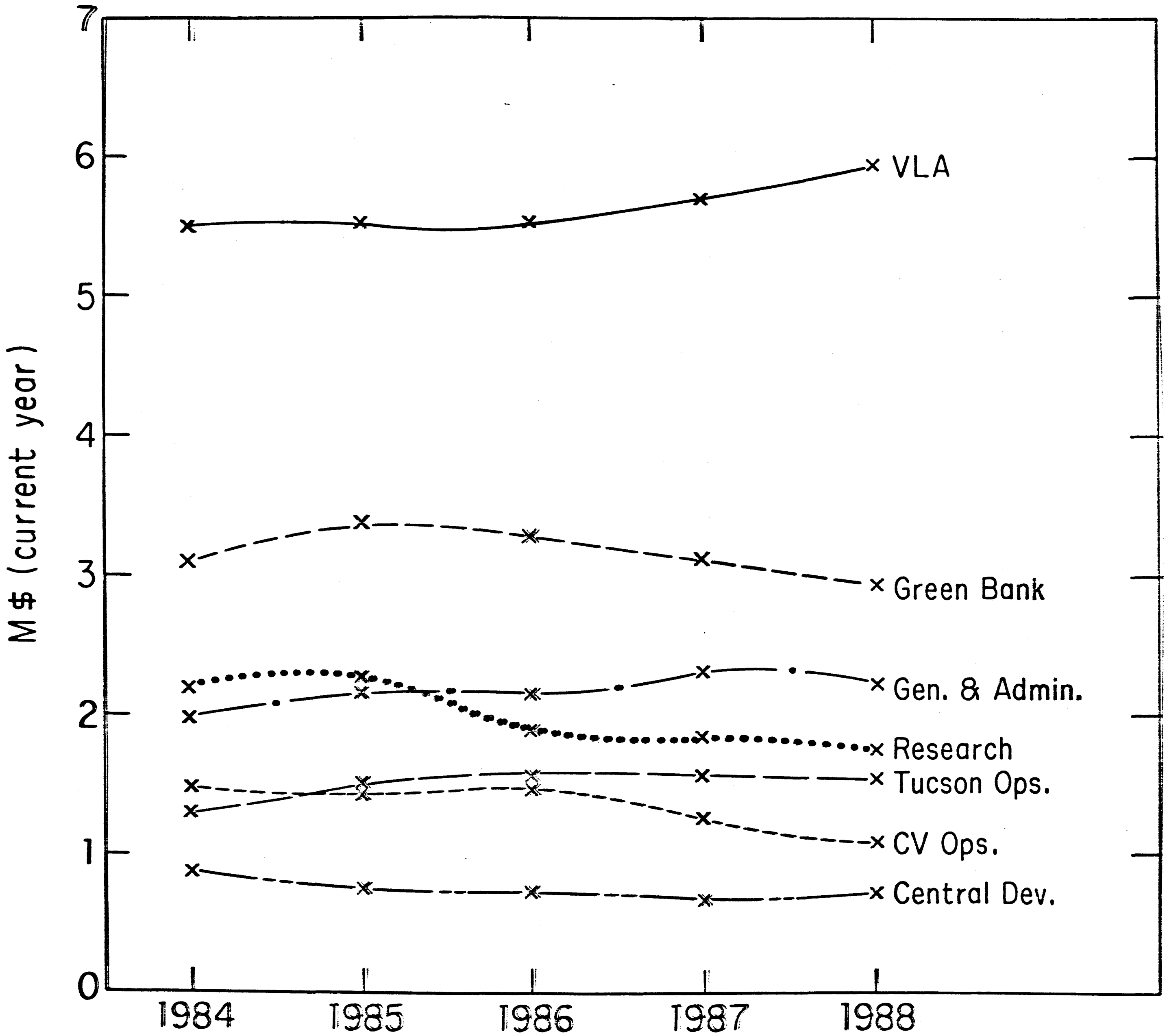
1988 SAVINGS = $600K; 1989 SAVINGS = $870K

8 MARCH 1988

1988 Summary Operating Budget

	1987 Allocation	1988 Allocation
General & Administration	2,250	2,230
Basic Research	1,822	1,716
Charlottesville	1,224	1,060
Central Development Lab	722	702
Green Bank	3,149	2,975
Tucson	1,550	1,530
Socorro	5,972	6,050
VLBA	200	500
Common Cost Recovery	(393)	(271)
	16,496	16,467
Research Equipment	650	430
Operating Equipment	87	75
	17,233	16,997
New NSF	16,830	16,760
Carryover	403	237
	17,233	16,997

8 March 1988



M$ (current year)
0
1
2
3
4
5
6
7
1984
1985
1986
1987
1988
VLA
Green Bank
Gen. & Admin.
Research
Tucson Ops.
CV Ops.
Central Dev.

1988 Summary RE Plan

Site	1987 Original Plan	1988 Plan
TUC	$142K	$102K
SOC	255	130[1]
GB	160	88
CDL	144	110[2]
	$701K[3]	$430K

1 Does not include NRL funds carried over from 1987 to be used to complete 327 MHz receiver installation.

2 Does include subcontract to the UVA for Schottky and SIS development.

3 This total exceeds the funds expected by $515K; funds were later reallocated and additional (outside) funds received to bring the 1987 Plan total to $860K.

8 March 1988

Addendum 2

to

National Radio Astronomy Observatory

Long Range Plan

1988-1992