National Optical Astronomy Observatories

LONG RANGE PLAN

1988 - 1992

3 June 1987
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I. INTRODUCTION

The National Science Foundation (NSF), authorized to initiate and support basic and applied scientific research and to initiate and support programs to strengthen scientific research potential, entered into contract with the Association of Universities for Research in Astronomy, Inc. (AURA) in 1957 in order to establish a national optical astronomy observatory. The NSF Annual Reports highlight many milestones in the evolution of its national observatories, including the selection of the Kitt Peak site in 1958, the dedication of the McMath solar telescope in 1962, the construction of two 4-m telescopes at Kitt Peak National Observatory (KPNO) and Cerro Tololo Inter-American Observatory (CTIO) in the 1970s, the addition of Sacramento Peak Observatory in 1976, and the planning of the next generation telescope in the 1980s. During these decades of growth and development, the centers have offered a diverse range of optical facilities to the nation's astronomers and their colleagues throughout the world.

"In nighttime astronomy, KPNO and CTIO have provided the widest possible community of astronomers with equipment that compares well with that available anywhere in the world. The result is a large and growing body of astronomers who have carried out their best work using the National Optical Astronomy Observatories (NOAO), who have a deep appreciation of its strengths and a strong personal stake in its continued development." (AURA Observatories Visiting Committee Report, 11 December 1986).

Since its inception in 1958, the astronomical centers have nurtured generations of astronomers whose interests have expanded to encompass the full range of the electromagnetic spectrum. The optical studies that pioneered the exploration of the universe have been joined by other breathtaking discoveries made by our companion radio observatories, by the spectacular successes of space-borne instruments and by the initial mapping of the sky at infrared wavelengths. These breakthroughs have produced even more demands for accompanying optical and infrared data. Contemporary astrophysics attracts talents from a multitude of scientific disciplines, from particle physicists studying the first nanosecond in the creation of the Universe to microbiologists investigating the possible cosmic origin of life. We have experienced an intellectual blossoming of the science and a population boom of persons intrigued by its past and future discoveries; both events have created an urgent need for more telescope time than is available. The demand for time on the largest NOAO telescopes is now nearly four times that available.

The astronomical community is attempting to address this shortage by the formation of small groups of universities bound together in an effort to acquire a dedicated telescope. The national centers have facilitated these programs, and will continue to do
so, by supporting the frontier work on the development of borosilicate glass mirrors at the University of Arizona and by developing the accompanying technology for their mechanical support. Telescopes designed to use these mirrors promise reductions in construction costs so favorable as to enable individual or small consortia of universities to procure such telescopes. What once was considered a "large" telescope (4-m), during the early stage of the life of NOAO has evolved into a "moderate" telescope; while the adjective "large" now refers to telescopes having mirrors of diameters of 8-m or larger.

The Large Optical/Infrared Telescope Committee (LOIT) of the NSF's Astronomy Advisory Committee has recently examined the state of large telescope projects, and in particular the National New Technology Telescope (NNTT). They note that "the potential scientific results from a new generation of large telescopes makes their development irresistible" and the LOIT recommended that a program of technology development for large O/IR telescopes be given the highest priority in NSF funding during the coming decade, as recommended by the Field Committee."

..."These technology efforts should be carried on in a way that leads to a NNTT and which also maximizes the benefits to other projects to build a new generation of cost-effective telescopes." This is consistent with NOAO's planning which places the development of a large national telescope capability at the head of its list of priorities for the future. The NNTT will be an array of four 8-m telescopes placed on a common altitude/azimuth mounting. Used individually, each telescope exceeds the power of any in the world today. Used as a unit, the four telescopes possess a light-gathering power equal to that of a 16-m telescope and form a two-dimensional interferometric array with a 21-meter baseline. This development will represent a substantive step in the direction of new telescope technology for the 21st century and, together with a companion 8-m telescope for the southern hemisphere, will maintain U.S. national astronomy competitive with programs elsewhere in the world.

Keeping pace with the excitement of the discoveries made by "nighttime" astronomers are the remarkable results produced by solar astrophysicists, who have demonstrated that the Sun is "ringing" in overtones that promise the capability for us to map the interior of the Sun down to its core. The solar community has expressed broad and enthusiastic support for a major project based on this discovery to be carried out by NOAO. This Global Oscillation Network Group (GONG) project has the highest priority in our solar program and is designed to give us information on solar interior dynamics and structure. The Sun will be monitored with a network of six instruments spread around the earth and designed to provide an uninterrupted continuous sequence of ultra-stable, ultra-sensitive velocity measurements covering the full surface area of the Sun.

The GONG project, which is already underway, and the NNTT project, for which we hope to obtain approval during the period
of time covered by this Long Range Plan, are our top priority developmental elements and go hand-in-hand with our continuing program designed to exploit the great potential of detector development and its application to optical and infrared studies of the Universe. The charge-coupled devices (CCDs) now used in direct and spectroscopic modes at telescopes have increased the accuracy and efficiency of observations by orders of magnitude, often making a 1-m telescope as powerful as a 4-m of a decade ago. On the horizon are larger format CCDs and infrared detectors that offer enormous gain to the observers (and complex technical problems to the engineers and computer experts). Our plans are to install these detectors at our telescopes in as timely a manner as possible.

These new initiatives are an integral part of the national center's responsibility to provide contemporary facilities for the nation's astronomers, a responsibility that also requires substantial funds for operational support and maintenance of the excellent instruments now available and in heavy use.
II. PLAN OVERVIEW

The 5-year plan for NOAO is based on the Mission of the National Astronomy Centers as defined by the National Science Foundation:

- Provide first rate observing facilities and support to scientists on basis of merit
- Develop new techniques and instruments
- Conduct research for its value and to maintain a productive and current staff.

This three-part mission requires a balance of effort between operational support, instrumentation, and research that is reflected in this plan. No one of these has highest priority; all must be represented if NOAO is to meet its responsibilities. We have prioritized elements within each of the three areas of service (as set forth in chapters VIII and IX), instruments (new telescopes—chapters IV and V, and instrumentation—chapter VI), and staff research (chapter II and VII). Our goal would be to seek a balance between these three elements with whatever budget we are granted.

Consistent with our overall goal of the advancement of U.S. astronomy, we have identified the following broad long-range planning objectives:

- To identify and advocate new and better ways in which NOAO can serve the science—e.g., through development of new instrument concepts and construction of new observing facilities.
- To foster excellence in staff research with the aim of building a program in NOAO of international preeminence; this is the only acceptable standard for the U.S. National Optical Observatory.
- To respond effectively and imaginatively to established community needs by providing imaginative ways of working with the community in a joint effort to advance the state of U.S. astronomy and by optimizing the use of resources in all aspects of our on-going program.

Chapter III sets out some considerations which NOAO would plan to follow in developing the research environment at the observatories and thereby, to enhance the opportunities and attractiveness of NOAO for scientific staff.

Observational optical and infrared astronomical research incorporates three elements—a telescope to gather and focus the radiation, an instrument to measure the radiant energy, and an astronomer armed with a computer to make sense of it all. In advancing the capabilities of astronomical research, we have identified programs supportive of these three elements that
promise the greatest scientific yield for the investment. Chapter IV describes the FTT (Future Telescope Technology) program that represents our premier effort to develop the technology necessary to provide forefront telescopes for the community. Chapter V describes two projects of central importance to the support of solar physics in the U.S.: the GONG (which is already underway) and a new program to construct a large aperture, polarization-free telescope for detailed studies of solar magnetic fields. In Chapter VI we discuss some specific instrumentation plans for the optical/ultraviolet, the infrared, and for special studies of the Sun.

New approaches to astronomical observations depend on the development of new detectors, new observing techniques, and exploration of new concepts. Work which NOAO intends to pursue in this area is discussed in Chapter VII.

Chapter VIII contains discussions of the computer facilities necessary for full exploitation of the instrumental program and for optimizing the ability of the astronomer to reduce and analyze the data. The most urgent maintenance needs of the three Observatories are identified here in Chapter IX while some construction needs are set out in Chapter X.

Budget priorities, with particular emphasis on FY 1989, are given in Chapter XI; a Summary of the Plan is given in Chapter XII; and budgetary tables corresponding to the items discussed in the plan are presented as an Appendix.
III. SCIENTIFIC STAFF

The responsibility for successfully undertaking the programs described in this plan lies primarily with the NOAO scientific staff, which includes tenured and tenure-track staff, scientists on term or no-term appointments, long-term visitors, and postdoctoral fellows. The staff activities include assisting visitors in the use of telescopes, instrumentation, and data-reduction equipment. The staff also assumes major responsibilities for the development of new telescopes and instrumentation, for the improvement of existing research facilities, and in devising new methods to increase the efficiencies with which telescopes can be used. In the interval covered by this plan the scientific staff expects to be increasingly involved with the development of systems and concepts related to our major initiatives.

Our long range plan for enhancing the NOAO scientific staff includes developing a program of visiting resident scientists, postdoctoral fellow and summer student programs; these initiatives are very important in building and maintaining a stimulating scientific atmosphere at all NOAO observatory sites. We plan to expand a program of financial support for graduate students using the centers for research associated with their dissertation and we are seeking ways to provide closer ties between our research staff and those of academic institutions.

We propose to select a set of scientific areas for special focus in NOAO in response to staff interest and initiative, and an assessment of their significance for advancement of U.S. astronomy. One such focal area, which already exists, is solar oscillations; identification and development of others could do much to enhance the scientific environment and vitality at NOAO.

The NOAO scientific staff of some 60 astronomers will be complemented through an expanded postdoctoral and visitor program (to a level of 10 and 5 respectively, each year), and an enhanced graduate training program at a level reflecting demand. This plan also provides for the addition of four tenure-track staff over the five-year term. Additional term appointments of scientific staff are envisaged as part of the growth of the instrumentation and computer applications areas.
IV. FUTURE TELESCOPE TECHNOLOGY (FTT)

The NNTT project will be formally proposed to the National Science Foundation in 1987. It will build upon the Future Telescope Technology (FTT) program under which NOAO and universities are evaluating potential sites for national telescopes and are developing generally applicable technology, including honeycomb mirrors at the University of Arizona. A summary of all these related activities is given in the sections that follow.

A. Background and Scientific Goals

Optical/infrared telescopes remain the primary and most versatile tools for astronomical research. Being based on remote sensing, astronomy has access to physical environments and processes that are not found on or around the Earth. But the celestial objects that demonstrate these physical processes are so distant that they can be studied only by means of their emitted light. Most astronomical objects, especially galaxies and stars, furthermore, transmit the bulk of their energy at optical and infrared wavelengths. For this reason, despite the tremendous advances in opening almost the full range of electromagnetic wavelengths for astronomical observations, optical/infrared wavelengths remain central to astronomy.

During the last three centuries, progress in astronomy remained closely linked to our ability to supply the largest feasible optical/infrared telescopes capable of high resolution imaging. The 5-m telescope at Mt. Palomar, and its 4-m cousins, have given astronomers a glimpse of new classes of astronomical objects. Often the existence of these objects was first determined by space or radio observations, a process that we expect to accelerate as the full capabilities of the VLBA and the Hubble Space Telescope are realized over the next decade. Detailed optical/infrared studies go hand-in-hand with this work as a crucial part of 'identifying' the sources and exploring their composition, dynamics, and other properties.

The importance of a new generation of optical/infrared telescopes to the continued growth of astronomy is widely recognized throughout the world astronomical community. A 6-m telescope is in service in the USSR; a joint California Institute of Technology-University of California venture for a 10-m telescope is funded and is in an advanced planning phase; other projects to construct large new-technology telescopes are being considered seriously at a few U.S. universities, in Japan, and in Europe.

A major objective for the NOAO is to provide community access to a new generation of large-aperture optical/infrared telescopes in both hemispheres. We are planning to locate the 16-m NNTT, with its factor of 16 increase in light-gathering power over the 4-m telescopes, at Mauna Kea, which is a superb site offering 0.5 arcsec median seeing, and excellent conditions for infrared
observations. We would also like to place a companion telescope of 8-m aperture in the southern hemisphere. As an integral part of the FTT program we anticipate having, in addition to the 8-m mirrors, a 4-m mirror with excellent figure, support, and thermal control. This mirror offers opportunities for development of a special-purpose telescope for addressing cosmological problems and would also provide a natural test-bed for evaluating the support and thermal stabilization of the mirror.

The NNTT facility would serve the entire American astronomical community and provide the basic means for ensuring that the United States retains its leadership role in optical astronomy. Samples of the projects that can be done uniquely with the NNTT are:

- **Extragalactic Astronomy:** Classical cosmological tests appear in various guises, but they are all attempts to delimit the geometry of the universe, and they all use similar observations: surface brightness and color distributions for large numbers of galaxies in recognizable clusters, and spectroscopy of a sufficient number of galaxies to provide redshifts for the clusters studied. For the redshift-diameter relation, it is crucial that we be able to obtain reliable surface-brightness profiles for galaxies at redshifts from about 0.5 to 2 or greater. This is outside the capability of existing telescopes but well within the range of the NNTT.

If the universe evolves, galaxy populations and other local characteristics also will vary with time. Thus by observing a youthful population of galaxies (as seen at large redshifts) we can, in principle, define empirically the evolutionary paths followed by galaxies. It also becomes possible to shed further light on the many unanswered questions about galaxy formation: When did galaxies begin to form, and were galaxies of similar mass formed coevally? How well do our models reproduce the luminosity and spectral evolution of young galaxies? Can we directly detect the epoch of galaxy formation? We need answers to these questions before we can use galaxies as 'standard candles' in observational cosmology.

The study of quasar absorption lines addresses the questions of the evolution of the halo environments of galaxies at early epochs and the development and change of the intergalactic medium. The former case involves the dynamics and chemical abundance of the metal-containing absorption line systems, while the latter concerns the systems with no detected metals, the Ly-\(\alpha\) forest. The NNTT is essential because of the very high dispersion and good signal-to-noise ratio required to address these quasar probe problems.

- **Star Formation:** High spatial resolution maps in the thermal infrared are needed to define the structures associated with star formation within dense molecular clouds. With its long baseline
and infrared beam-combiner, the NNTT offers the opportunity to resolve individual protostars in their 'cocoon' phase. The NNTT's high sensitivity coupled with high spatial and spectral resolution will enable astronomers to study the dynamics of star-forming regions.

* **Stellar Planetary Systems:** The IRAS discovery of orbiting material around nearby main-sequence stars has provided a particularly worthwhile opportunity for a large ground-based telescope. These circumstellar disks are thought to be intimately connected to the process of planetary system formation and evolution. As such, they represent a unique scientific opening to observe the early phases of planetary development. Jupiter-like planets could also be detected (if they exist) orbiting about seven of the closest stars; planets with higher internal luminosity would be detectable in more remote systems.

* **Stellar Seismology:** The study of surface oscillations of the Sun has been successfully used as a powerful diagnostic in defining models of solar structure. Similarly, the surface oscillations of a star give us one of the few measures of its internal structure. Now that we have some detailed knowledge of the Sun's oscillatory modes, we can begin to apply this technique to other types of stars. Stellar oscillation studies offer the best and most exciting way to infer the internal properties of stars of different masses and ages and are especially valuable as a test of the theories of stellar evolution and convection. Such observations require the high stability, sensitivity, and spectral resolution of the NNTT.

* **Stellar Surfaces:** Speckle interferometry will be a fruitful technique for imaging the surface features of stars. The 21-m maximum baseline of the NNTT, compared with that of a 10-m telescope, produces a factor of four improvement in areal resolving power. Furthermore, compared with proposed linear or other sparsely-filled interferometer arrays, the NNTT produces the full two-dimensional image with high time resolution since rotational aperture synthesis is not required. This approach will be particularly valuable for imaging the surfaces of K and M giants of which a few dozen should be candidates for study uniquely with the NNTT.

Many fundamental investigations can be carried out with resolved stellar images. Measurements of stellar diameters, and limb darkening profiles as functions of wavelength, for some 20 - 30 stars can provide critical tests of the theories of stellar evolution and stellar atmospheres. In principle, large convective patterns and their differential rotation can be detected, as temperature or Doppler-shift patterns, as in the case of the Sun. Knowledge of how these patterns vary with changes in stellar parameters will greatly improve prospects for understanding stellar convection. Imaging can also be applied to the study of stellar nonradial oscillations. The advantage will be to be able to observe and identify many different modes of
oscillation probing different parts of the stellar interior. Imaging of transient activity (spots, plages, etc.) will greatly advance our knowledge of magnetic activity in stars.

B. The NNTT Project

The major goal of NOAO is to provide premier facilities for ground-based optical and IR astronomy in the Northern and Southern hemispheres which will serve astronomers on the basis of merit of their proposed research.

Consistent with this goal, we will develop proposals to construct a 16-m National New Technology Telescope (NNTT) in the northern hemisphere, an 8-m southern hemisphere companion, and to develop associated technology. The task of making, figuring, and stabilizing mirrors with 8-m aperture represents a fundamental technological challenge and is, correspondingly, the central focus for the program.

The 16-m NNTT will consist of four 8-m aperture mirrors, the light from which can be combined to form a single image, and for interferometry. Its complement of basic instruments includes:

- a multiple-object spectrograph
- a high-resolution optical spectrograph
- a high-resolution infrared spectrograph
- an infrared imaging system
- a CCD-array mosaic
- a visible light interferometric imaging camera.

The 8-m telescope will be designed to meet the need for public access to a large telescope in the southern hemisphere. The mirror support system, optical train, and focal configuration will be identical to that planned for the NNTT and therefore, construction of the 8-m telescope will face many parallel technical problems that the NNTT will have to address. Clearly an 8-m telescope in the south has great scientific appeal. The center of our galaxy and the Magellanic Clouds remain two of the most intensely studied areas in astronomy and they are southern hemisphere objects. The 8-m southern companion telescope is vital for the development of the science. An early step in this project is being taken in FY 1987 with the commencement of a site survey in Chile on Cerro Morado and Cerro Pachon--sites adjacent to Cerro Tololo.

Cerro Morado is 200 ft. below Tololo, and has a very broad summit which could accommodate numerous installations; Pachon is 1500 ft. higher, at an altitude of 9000 ft. Indications from previous testing are that Cerro Pachon may be an excellent site, and it merits further testing. Over the next two years NOAO proposes to obtain measurements of seeing, water vapor, temperature, humidity, and wind velocity on the summits of Tololo, Morado and Pachon in order to identify optimum sites for future large telescopes.
Our five-year plan includes defining and developing reliable cost estimates for the 16-m NNTT and the southern hemisphere companion; developing the technology for their construction; developing a proposal for, and we hope building, an 8-m mirror-polishing facility; and the beginning of construction of the NNTT and the 8-m. Achieving the full capability of these large-aperture telescopes depends on the parallel development of many other areas of technology. Three areas of particular importance are adaptive optics, ruling large gratings, and coatings research. All three are integral parts of NOAO's FTT program.

The borosilicate glass mirror development program at the University of Arizona includes the production of 4-m mirror blanks in FY 1987 and FY 1988 and of the first 8-m mirror blank in FY 1989. Such mirrors have to be figured and polished and the technology developed for mechanical support and for the maintenance of the required thermal homogeneity and thermal balance with the surrounding air. The experience gained from working with the 4-m blank will in turn be applied to the subsequent 8-m mirrors.

A polishing capability for mirrors in the 8-m class is needed and NOAO plans to construct such a facility. Techniques for polishing these large mirrors will be tested on the 4-m blank in the existing NOAO facility in Tucson.

The 4-m mirror that will be developed and tested within the NNTT program offers an attractive opportunity to undertake several important large-scale observing programs that would significantly advance our understanding of certain fundamental problems in astrophysics. Through discussions within the scientific staff of NOAO and at a series of workshops and users' committee meetings, we have come to the conclusion that the best use for this mirror would be to install it in a telescope optimized for, and dedicated to, spectroscopy in the optical and near infrared regions of the spectrum.

The telescope itself should have as large a field of view as is consistent with the constraints on f/ratio imposed by the design that is ultimately developed for the NNTT. It should also be equipped with high and low resolution spectrographs designed for multi-object spectroscopy with up to a few hundred fibers. It should, in addition, be possible to observe very faint objects with slitlets or aperture plates. The design should allow for rapid changes of instrumentation. The telescope itself should be scheduled in such a way that synoptic and large scale survey programs can be supported.

Such a telescope would be well suited for two crucial programs in cosmology. One would be a survey of all the galaxies to magnitudes 19 over approximately a steradian. The radial velocity data would be used to examine the large scale structure of the universe over a cubic volume of space to much fainter
limiting magnitudes than is feasible given the limited aperture of telescopes now available to be dedicated to this purpose. With a 2° field and 400 fibers, this proposed survey would require approximately four years on a 4-m telescope; the survey would presumably be carried out in the south galactic cap, and so would require only a small portion of the total observing time available during the year. Morphological and other information obtained as a by-product of the survey would have application to a variety of problems, including the relationship between galaxy type and environment.

A second problem of great cosmological interest that could be attacked with this telescope is the evolution of galaxies at large look-back times. A pencil beam spectroscopic survey to magnitudes 25-26 could be undertaken for a specific area of the sky by stacking multi-night exposures to obtain extremely long exposures (1000-2000 hours). An efficient spectrograph would be essential for this experiment.

Additional scientific drivers for such a telescope are too diverse to list. It would, however, meet the needs of the solar-stellar community for a 4-m class telescope to study stellar activity, particularly in cluster stars with a wide variety of ages. The great throughput of this telescope, with its capability of obtaining hundreds of spectra per night, would require new approaches to scheduling, archiving, and dissemination of data. It is important to emphasize and to recognize from the outset that the applications of the 4-m mirror are for dedicated observing for specialized projects; we are not proposing construction of another general-purpose 4-m telescope within NOAO.

The 16-m NNTT and its southern hemisphere companion continue to have our highest priority. Applications of the 4-m mirror blank, while having exciting scientific potential, will not compromise this primary goal. It is primarily for this reason that NOAO is considering joint 4-m projects, with one or more institutional partners contributing much of the capital cost and with NOAO bearing primary responsibility for operation and maintenance. An appropriate fraction of the available observing time would be available to NOAO and its community of users to pursue the kinds of synoptic and survey programs described above.

The FTT program as described here, including construction of major new telescopes, meets the near and long term goals of NOAO. It builds upon the proper role of the national center to provide premier facilities which exceed the resources available to individual institutions or which complement their facilities and programs. It builds upon the strengths of NOAO, fits into the needs of the broader astronomical community, and complements the nation's space science programs by providing facilities with which objects discovered from space can be studied and better understood. It also builds upon the strong technology base in Tucson and the experience gained at Cerro Tololo. NOAO will work
with the astronomical community in strengthening the scientific case for the project and in resolving the remaining technical questions about the mirror technology, and will strengthen and build upon its expertise and experience in the management of major projects.
V. NEW SOLAR FACILITIES

Solar physics in NOAO will continue as a vigorous component of our program. Two substantial initiatives have come forward for active consideration within the recent past. One of these, the Global Oscillations Network (GONG), is already well underway; the second responds to the clear need for a large-aperture polarization-free solar telescope capable of delivering images at the highest resolution achievable from the ground. An outline description of these projects is given below.

A. The GONG Network

Our knowledge of the structure and evolution of stars is founded on our understanding of the internal structure of the Sun. We can observe only the outer layers of the Sun and from its total dimensions and brightness we have inferred what its total constitution must be. We have, however, evidence that our models must be flawed because we have been unable to detect the solar neutrinos predicted by our theories. We now have a new observational approach to studying the solar interior—from measurements of the periodic vibration of the Sun.

The study of the resonant global oscillations of the Sun has developed during the past five years into a vigorous subdiscipline of solar physics. Techniques perfected by investigators in this field promise to map the interior of the Sun down to its core and to reveal entirely new information on the structure, composition, and differential rotation of the solar interior. The implications for stellar astrophysics of this long-term series of investigations on the Sun can hardly be overstated. The theory of stellar structure and evolution; the nature of stellar convection; the origins of stellar differential rotation, magnetic field, and stellar activity will all benefit from improved understanding of the solar interior that can be derived from future studies of solar global oscillations.

In FY 1984, NOAO staff in collaboration with the scientific community established the Global Oscillations Network Group to coordinate efforts towards the construction and utilization of a network of stations, distributed in longitude, and dedicated to obtaining a uniform set of data. In FY 1986, an interim technology development program led to the design of a variable path length Michelson interferometer with a narrow prefilter isolating a single solar line, to provide an ultra-stable, and ultra-sensitive velocity measurement. A site survey consisting of automated digital sunshine monitors at ten sites was placed in operation.

The project obtained a go-ahead in FY 1987 and is directed to completion of a prototype instrument in FY 1988, with full network observations to begin in FY 1990. Unless specific action is taken to extend the program, observations will proceed for three years and will be followed by one year of data analysis. A
data-processing facility in Tucson associated with the project will keep pace with the data coming in from the network. The processed data will be placed in an archive that can be accessed by any qualified investigator under procedures to be established by the community as represented in GONG.

B. New Solar Telescope

A recent study by an AURA Committee has identified a number of specific areas of solar physics whose elucidation requires a large aperture solar telescope. Such areas as solar convection, the structure and evolution of granules and super-granules, formation and decay of flux tubes, the multi-dimensional thermodynamic structure of the solar atmosphere, and mass and energy transport on a fine scale, all need a new facility to study. A major theme in all these studies is the fine scale structure of the solar magnetic field whose study opens the challenging area of Stokes polarimetry across solar spectral lines. The enormous promise of this technique has been further opened by recent progress in theoretical interpretation, and merits a major U.S. effort in construction of a polarization-free, large aperture telescope at the very best site we can identify. This is a natural and appropriate goal for NOAO and, as such, is properly a component of this plan.

While a high-resolution space telescope of meter-class aperture would represent an enormous asset for solar research it would by no means eliminate the need for ground-based counterparts well into the 21st century. The present NOAO solar telescopes will become increasingly less competitive in high resolution research as a new generation of European solar telescopes come on line in the Canary Islands. In the 1990s, U.S. astronomers need access to an efficient, large-aperture, state-of-the-art telescope at an excellent site. Two possible routes are open; NOAO might ally itself with the international group that is planning to build the Large Earth-Based Solar Telescope (LEST), or NOAO might pursue the route of constructing a U.S. national solar telescope. A choice between these options will be recommended by NOAO during FY 1987. The key to diffraction-limited performance will be adaptive optics systems. We plan, therefore, to focus on the development and application of such systems as an NOAO contribution to LEST and as the next technological step toward a high-resolution solar facility.

The conceptual design for the LEST telescope has been completed; it will be a 2.4-m diameter vacuum tower instrument designed for low intrinsic polarization and incorporating an adaptive optics system as an integral part. This concept represents what is generally considered to be the next generation solar telescope and will provide a significant increase in angular resolution beyond our current capability. Total cost for completion of the LEST is $25 million, of which the U.S. would be expected to pay one-third.
Site testing for this new international facility is underway at the present time at locations in the Canary Islands and Hawaii. An NSO committee is currently reviewing the desirability of participating in LEST.
VI. INSTRUMENTATION

As the link between the light-gathering telescope and the interpreting astronomer and his computer, instrumentation is vital to observational astronomy. Better and more effective use of the light collected by the telescope can improve the overall performance dramatically. For example, arrays of photoelectric detectors are replacing single channel detectors and allow the simultaneous use of up to 64,000 to 4 million times more of the light collected by the telescope than is possible with single channel detectors. Optical fibers, their ends placed to intercept the images of several distinct astronomical objects and to align them along a single spectrograph slit, permit the simultaneous study of these objects in a single observing session. Similarly, dramatic advances are being made through interferometric and other optical and infrared techniques.

Advances in astronomical instrumentation can contribute to the health and competitiveness of U.S. technology in the world, especially as they occur in close coordination with industrial and governmental laboratories who pursue related developments. NOAO is planning to develop opportunities for even closer cooperation with these laboratories.

This section lists examples of major instrumentation development efforts for optical/ultraviolet, infrared, and solar applications in an approximate order of priority in each area. Naturally one can identify specific projects only a certain distance into the future. We have, accordingly, provided a general category in each case entitled 'Future Instrumentation' which is intended to reflect the fact that new detectors, new technology, and new concept development will offer opportunities and open a demand for their application to astronomical observations.

A. Optical/Ultraviolet Instrumentation

* Imaging Spectropolarimeter: The measurement of the wavelength dependence and spatial variation of polarization can often provide information that is difficult or impossible to obtain in any other way. This polarization may result directly from the emission mechanism (Zeeman effect, synchrotron radiation) or may arise from reprocessing in the immediate vicinity of the source (electron, dust, or molecular scattering). In the former case important parameters of the source can be deduced (strength and orientation of the magnetic field), while in the latter it may be possible to infer the spatial disposition of the emitting volumes and the scattering medium. Transmission through the interstellar medium also leads to the polarization of starlight via the action of (magnetically) aligned grains. In this case it is possible to determine properties of interstellar dust and of the magnetic field in the intervening space.

The proposed instrument consists of a box containing a variable retardation plate and ancillary optics to be mounted in a
convenient position in the light path above the telescope focal plane. This serves to convert information about the polarization state of the incident light into a periodic modulation in the intensity of two orthogonally polarized beams of transmitted light. An analyzer further down the optical train then serves to separate these two rays so that they can be simultaneously recorded by a suitable detector. Because of the use of variable retarders and their location at the head of the optical train, any conventional spectrograph or imaging device can then be used for polarization measurements. We plan to construct this device for use at the 1.5-m telescope at CTIO. The availability at that telescope of facilities for spectroscopy, imaging, and photometry in both the optical and IR permits immediate use of the polarimeter in all its modes. Provision for imaging and spectro-polarimetry at the RC focus of the CTIO 4-m telescope will require larger optical components and would be carried out as a second phase of the project if deemed appropriate.

- Bench-Mounted Multi-Object Fiber Spectrograph: The advantages and importance of obtaining multi-object spectra on a large telescope are the efficient use of telescope time and increased accuracy of the data. Examples of projects that provide strong scientific motivation include studies of the detailed abundance changes with stellar evolution, the binary frequency, and the monitoring of chromospheric activity in star clusters of different ages and different stellar populations. Spectroscopy of H II regions in galaxies out to 10 - 15 Mpc will be possible. Investigations of galaxy cluster dynamics require redshifts of 50 - 100 objects per cluster in order to differentiate regions of subclustering and the overall cluster potential. The mapping of large-scale structure and voids similarly demands hundreds of galaxy redshifts. Considerable effort is now expended on the KPNO 4-m in measuring the redshifts of galaxies in the host clusters of quasars, with galaxies as faint as 23rd magnitude. All of these projects currently receive time on Kitt Peak telescopes; their data acquisition could be made far more efficient.

Essentially two approaches are taken to acquire the light from each desired object in the field. The first is that taken by the present 4-m Cryogenic Camera configuration in which a slitlet or aperture is located at each object's position in the focal plane and defines the entrance aperture of the spectrograph. The second approach is that taken by the University of Arizona, Anglo-Australian Observatory, and European Southern Observatory in which fiber optics are used to pipe the light from the object down to the slit of the spectrograph. Both techniques have their advantages and disadvantages. Aperture spectroscopy may continue to be the technique of choice for observations of faint objects that require accurate sky subtraction. However, fiber optics holds the key to much of the new instrumentation in astronomy, and NOAO plans to explore systematically the properties of such fibers, both in the optical and the infrared. Also planned is a bench-mounted spectrograph optimized in design to match the fiber
optic characteristics. The advantages of a bench-mounted system are two-fold. First is the stability introduced by taking the instrument off of the telescope (eliminating flexure-related problems) and by housing the instrument in an environmentally-controlled room (further enhancing the long-term stability of the instrument). Second is the ease of construction and alignment of the spectrograph. Due to the lack of flexure, the optical mounting can be made much more simply and much more cheaply.

B. Infrared Instrumentation

* Cryogenic Optical Bench: We are developing plans for construction of a cryogenic optical bench for use with infrared imagers at KPNO and CTIO. A simple and versatile technique to expand the capabilities of an IR imager is to install a variety of modular pre filters on an "optical bench" between the telescope and imager. This optical bench must be cooled to avoid degradation in performance arising from background radiation. The modules being considered for eventual inclusion in the Cryogenic Optical Bench include: (1) narrow filters to isolate well-known spectral features, such as the 2 μm line of molecular hydrogen (a powerful diagnostic tool in the study of shocked regions in the interstellar medium); (2) a grism which can measure the whole spectrum simultaneously with long-slit capabilities; (3) a Fabry-Perot interferometer; (4) a polarimeter; (5) a stellar coronagraph; (6) adaptive optics; (7) reimaging; (8) collimation; and (9) cold dichroic mirrors.

The concept of the Cryogenic Optical Bench is very similar to that of the Infrared Imager (IRIM) planned for the NNTT. Its design and construction represents a major engineering task; a path length of at least two meters is required. Collaboration within NOAO and with other institutions on the design, construction, and use of modules is planned. The design is versatile, powerful, and can be implemented quickly. Furthermore, the detectors themselves are modules within the present definition; it is easy to envisage simultaneous multi-frequency operation; for example, simultaneous visible CCD, near IR, and 10. μm imaging.

* Cryogenic Echelle: We are constructing a cryogenic echelle, planned as a three-year project with first light for the spectrograph in late FY 1989. This concept has application to the 4-m telescopes on Kitt Peak and Cerro Tololo in providing a high resolution spectroscopic capability in the near infrared. The revolution that this instrument will bring to infrared astronomy cannot be overestimated. Until recently, instrumentation for infrared astronomy has been severely restricted by the detectors available. These detectors have been single elements with high noise levels. An excellent example of an instrument designed for these detectors is the KPNO Fourier Transform Spectrometer (FTS). The design allows all starlight in the filter bandpass to fall on the detector, permitting photon-noise-limited high resolution spectroscopy of bright sources and
lower resolution broad-band surveys of moderately faint sources. The cryogenic echelle, on the other hand, utilizes a two dimensional detector having low dark current, low read noise, and high quantum efficiency. This spectrograph will be orders of magnitude more sensitive than the 4-m FTS and the scientific payoff will be enormous; high resolution spectroscopy in the infrared will be possible to about the same limiting magnitude now possible in the visual. In fact, the instrumental capabilities of the echelle are greater than those of any space instrumentation foreseeable in the next two decades.

**Near-IR Solar Spectrograph:** The Sun plays a unique role in astrophysics in allowing us to study many of the physical processes of interest on scales which are too large to be attainable in the laboratory and too small to be discernible on other astronomical objects. Stellar convection, the generation of magnetic fields, and the interaction of magnetic fields with convective motions are among the most important of these processes. In addition to being of inherent interest, these magnetohydrodynamic processes appear to form the basis of the heating and structuring of stellar chromospheres and coronae, and possibly of much of stellar mass loss. The observational study of the interaction processes requires: (1) high angular resolution; (2) measurement of both velocity and vector magnetic fields; and (3) access to the deepest layers in the solar atmosphere available to observation. The solar atmosphere is most transparent at 1.65 μm where the transition of bound-free to free-free H- absorption occurs. Observing at this wavelength also brings major gains in our ability to observe vector magnetic fields. Staff members of NOAO have proposed to construct a simple high resolution (~ 200,000) solar spectrograph for the 1.5 - 2.5 μm region for use with the infrared adaptive optics prototype system at the McMath telescope. It is proposed to be a straightforward Littrow spectrograph on an optical bench in the FTS room. The spectrograph will feed the 56 x 62 SBRC InSb detector. In addition to measuring Doppler shift and Zeeman splitting in weak lines near 1.65 μm, the spectrograph/adaptive optics system can be used to study other solar lines of interest such as the He I lines at 1.083 μm and 2.058 μm and the Paschen lines. At 1.65 μm the McMath with adaptive optics will give a resolution of .25 arcsecond. As configured now the f/90 output beam will feed the array to give direct imaging of an area 6.4 x 6.9 arcseconds on the Sun.

**C. Solar Instrumentation**

**High Resolution Solar Polarimetry:** Magnetic fields are responsible for nearly all the fine-structure observable in the solar atmosphere, and probably the bulk of the energy deposition in the upper atmosphere as well. Further progress in following small-scale processes, such as the interaction of convective motions and magnetic flux tubes, will require a new generation of polarimeters capable of measuring the vector magnetic field with spatial resolution of less than one arcsecond.
In NOAO we are currently upgrading the Vacuum Tower Telescope at Sunspot by reducing its instrumental polarization (e.g., by replacing its thick entrance window) and by calibrating its small residual polarization. In FY 1987 these efforts will result in a telescope capable of sub-arcsecond resolution with instrumental polarization noise at or below $10^{-3}$.

A spectropolarimeter constructed by HAO will be installed at the Vacuum Tower Telescope in 1988. This polarimeter will yield Stokes profiles with the signal-to-noise and spectral resolution necessary for an accurate determination of the vector magnetic field. The best compromise among spatial, temporal, and spectral resolutions, along with adequate polarization sensitivity, will probably limit this spectropolarimeter to a spatial resolution of one arcsecond. While this instrument represents a big advance over current polarimeters, it will probably not resolve individual flux tubes. We plan, therefore, to upgrade the Universal Birefringent Filter (UBF) at Sunspot for measurements of the longitudinal magnetic field at sub-arcsecond resolution. The UBF will receive its final polarizing element (which will produce a band pass of .125 Å at 5500 Å) and will be interfaced to the Lockheed adaptive mirror.

Upgrading began in FY 1986, on the 512 channel magnetograph at the Vacuum Tower on Kitt Peak. The full line-profile of a magnetically sensitive spectrum line will be recorded on the CCD instead of merely two bands in the wings. The Doppler shift and Zeeman splitting of the line will both be measured, leading to simultaneous velocity and magnetic field maps. The improved instrument "the spectromagnetometer" will be funded in part by NASA.

At the same time, NOAO began a program of improving the "solar seeing" within the McMath telescope. We have already demonstrated periods of better than .5 arcsecond seeing and we plan to extend this work in the near future to longer time intervals.

The video magnetograph at the Big Bear Solar Observatory samples the longitudinal magnetic field over a three arcminute field every thirtieth of a second. By averaging many frames, the device attains excellent sensitivity to weak flux regions, with good time resolution (10 seconds) and moderate (2 arcsecond) spatial resolution. The device has proved to be exceptionally useful as a complement to more precise polarimeters, and has facilitated pioneering studies of flux emergence and reconnection, despite its limited spatial resolution. We plan to build such a videomagnetograph as an auxiliary to the upgraded spectromagnetograph on Kitt Peak in FY 1989.

* Solar and Stellar Synoptic Studies: At present the worldwide observing network for solar activity is a haphazard affair suffering from very diverse capability. Only one site can record
high resolution full disk magnetograms (Kitt Peak) and many suffer from poor weather and/or seeing conditions. The investigator who wishes to study a given solar event will likely be frustrated by poor observations, communication problems, political indifference, and in any case, extremely inhomogeneous data. NOAO proposes to design a research grade telescope and instrument system, select a global network of good seeing sites at a range of longitudes such that 24-hour coverage is likely, and then to install these for purposes of the dedicated study of the activity cycle.

NOAO now provides the only generally available nighttime synoptic, spectroscopic capability for observational research. This program at the McMath telescope has proved to be very successful. Over the last decade the value of the synoptic mode of observation for the study of solar-type phenomena on other stars has been demonstrated by significant advances in our understanding of such phenomena.

In September 1986 a solar/stellar community-wide workshop was held in Tucson to define the future needs of the discipline. Their recommended course of action was to embark on a design study for an advanced spectrograph operating in the spectral region 3200 to 11000 Å, adequate in resolution and stability for the stringent needs of stellar seismology. The aim is a 'portable' instrument, probably fed by a fiber-optic system, that could be fitted to a number of as yet unspecified telescopes. Initially, such a spectrograph would be tested at the McMath telescope. Following that it might be profitably used in a 4-m telescope should that be constructed.

In summary, the workshop recommended that the NOAO/NSO embark upon an advanced spectrograph design study in collaboration with the community. The spectrograph would be for visible light studies and the specifications would be determined by the requirements of stellar seismology. Ideally, the spectrograph should be portable (in the sense that it can be easily interfaced with any telescope) and it should be relatively cheap so that replication is a realistic possibility.
VII. NEW APPROACHES TO ASTRONOMICAL INSTRUMENTATION

One of the stated long-range goals of NOAO (Chapter II) is to seek and determine imaginative ways of working with the community in a joint effort to advance the state of U.S. astronomy. The program envisaged by NOAO in this area is outlined below.

A. Interferometric Imaging

Whereas adaptive optics should be able to correct telescope images for atmospheric seeing effects before detection at long wavelengths (> 2 μm), correction at the shorter, visible wavelengths has to be done after detection. A combination of image and pupil interferometry is capable of giving reliable phase and amplitude information at all points in the (U, V) plane covered by the telescope aperture. Techniques include the equivalent of the phase closure techniques developed in radio astronomy utilizing bispectrum analysis of speckle images. We will develop a prototype instrument for high resolution imaging at the 4-m telescopes. The NNTT (U, V) plane coverage is 20 times larger. The results of the prototype instrument will be used in the design of the NNTT visible-light interferometric imaging camera where these techniques come to full fruition.

Optical interferometry has undergone a surge of interest and development in recent years, beginning with the demonstration of visible speckle interferometry in the early 70s. During the 80s, techniques of visible and infrared interferometry with single, large apertures have been studied and tested, with notable success in measurements of spatial visibilities, and limited but exciting results in full image reconstruction.

In most scientific applications, the interferometric studies conducted have been severely limited by the spatial resolution of the available apertures—that is, by the optical baseline. While small gains in spatial resolution may be eventually obtained with larger monolithic telescopes, the general solution to the spatial resolution problem, as demonstrated elegantly in radio astronomy, is the implementation of interferometric arrays; aperture synthesis is the technique employed to reconstruct complete images from an unfilled array.

In collaboration with other institutions, NOAO is defining a proposal to construct a three aperture array. In the simplest mode of operation, these apertures can function as interferometric pairs to map spatial visibilities, using techniques already verified in previous experiments. In its full operating mode the array would test the principles of phase closure at optical wavelengths. This interferometric array will be used initially in the infrared and can tackle a considerable number of important observational projects:

* Mapping the shells around copl stars to provide direct testing of mass loss model mechanisms;
• Direct measurement of long period variable star diameters to resolve the issue of the pulsation mode;

• Detection of starspots and convective structures on evolved K and M supergiants;

• Study of multiplicity in young stellar clusters;

• Study of extended structures around young stellar objects;

• Resolution of emission line regions around stars;

• Measurement of cores of galaxies.

The array will consist of three arms, each carrying one light feed; of yet-to-be-specified size and design. The concept uses alt-az mounts, providing a rigid configuration and a four mirror coude optical train. The light is transferred to the central instrument room inside a horizontal tube. The central optical correlator produces simultaneous visibility measurements for each baseline at a number of wavelengths. We can obtain an unbiased estimate of phase closure unaffected by the variations in path length introduced by the earth's atmosphere, and depending only on the source structure.

B. Detector Development

• Optical Ultraviolet: The use of sensitive CCD detectors in astronomy has enormously enhanced observational capability and the range of astrophysical problems that can now be addressed. Of immediate impact is the anticipated delivery of large format CCDs that approach the size of photographic plates but have quantum efficiencies about 10 times better than the photographic process. These devices will enable astronomers to carry out large-scale studies of regions of the sky and to address such problems as the existence of "voids" in the Universe. These new detectors are central to the formulation of NOAO's instrumentation plans, both for the nighttime and the daytime telescopes, and their effective application will be of the very highest priority for us.

Significant gains can be achieved with CCDs having lower readout noise, wide spectral response (especially improved blue response), good charge transfer characteristics, and large formats. We will seek to identify sources of good CCDs as they become available and will work to improve the performance of their control systems and to improve their blue response. We need to construct new dewars to accommodate the arrays that will be available for telescope use by the end of FY 1988 and carry out research on lab-grade chips for anti-reflection coatings and on performance evaluations. New generation CCD controllers will be required during the coming years to handle the high data rates and large dynamic range from the CCDs and other detectors.
producing large quantities of data. We plan a new CCD controller built around a modern 32-bit CPU and a standard, high-bandwidth bus. The new controller should be powerful in order to handle the data rates anticipated from the arrays but it should also be inexpensive to build and maintain because many new controllers will be required at our three observing sites.

In the immediate future the 2048 x 2048 Tektronix chips offer both the promise of substantive gains in telescope productivity and a challenge in the handling of data and in the design of electronics to provide lower noise operation. These devices represent a truly major breakthrough in detector technology and should be implemented in as many places as fiscally possible, starting first with the 4-m telescopes. The implementation of the new CCDs is not limited to imaging, although that will be the first application at the telescope, but will be extended to spectroscopic applications as well. We are also investigating several options to obtain wide-field imaging capability with a mosaic of large format Tektronix CCDs.

* Infrared: The ability to produce images in infrared astronomy has been severely limited until now by the absence of array detectors. Typically, images have been made by using a single detector and rastering the telescope, with exposures a few seconds per pixel. The advent of the 62 x 58 InSb arrays for 1 - 5 \( \mu \)m radiation will have a dramatic effect on this situation, because each pixel will outperform the single detectors presently in use. The anticipated development of infrared arrays promises an increased efficiency in observations by four orders of magnitude and will allow fast coverage of large fields (for detection and astrometry of sources) and maps with spatial resolution equal to optical and radio data.

The first step toward a 10 \( \mu \)m and 20 \( \mu \)m imaging and spectroscopic capability is the procurement of suitable arrays for this spectral range. NOAO will begin testing several of these devices in FY 1987. The second requirement is the ability to read out the detector array on a time scale much shorter than that possible with our present electronics (30 ms). The thermal background in the 10 \( \mu \)m region will saturate the detector wells in a time on the order of 1 ms; it will be necessary to read out and minimally process the data stream on less than this time scale.

C. Gratings and Coatings Development

Substantial gains in throughput can be achieved in multiple reflection telescope systems if the reflectivity can be improved. In experimental tests on Kitt Peak, coatings developed by the Optical Sciences Center at the University of Arizona have been shown to have reflectivity of greater than 90% between 0.33 and 0.5 \( \mu \)m, even after one year of exposure. The Coatings Laboratory is continuing its R&D effort aimed at increasing efficiencies of telescopes and at decreasing the emissivity of coatings in the thermal infrared.
A study of the status and future direction of the NOAO gratings program was undertaken in FY 1985 by a committee which recommended that the program concentrate on the production of very large, low-scattered-light, efficient echelle gratings. Future large telescopes using large array detectors have a vital need for this type of grating. Our goal is to produce high-quality gratings that will be made available to the astronomical community for use with spectrographs on present and future telescopes.

D. Adaptive Optics

A primary goal of the NOAO adaptive optics program is to develop the technology needed for the large telescopes of the future to be used to optimum effect by correcting for atmospheric seeing. The instrument senses the wavefront in the visible (0.8 μm) but corrects it in the infrared; the IR requires fewer adaptive elements, and a larger fraction of the sky can be covered than in the visible. Starting in FY 1987 we expect to test the system for the first time on the sun and stars using the McMath and Mayall telescopes. Using this technique it will be possible to study the environment around stars with a resolution never before achieved.

Experience gained will guide construction of a Mark II system. This may include cryogenic cooling of the optics to keep the thermal emissivity down. We plan to examine engineering options in constructing an adaptive secondary mirror and to follow this with construction of prototype flat and hyperbolic mirrors. The wavefront sensor of the adaptive optics system can be used as a research instrument for other purposes. Specifically, we will explore its use for (i) measurement of the wavefront while obtaining pupil or image plane interferograms, the signal then being used to do "after-the-fact" corrections of the interferograms; (ii) measurement of atmospheric optics and seeing; and (iii) active correction of telescope optics deformation due to gravity and thermal effects.

For application to visible-light solar studies we have plans to upgrade and make more user-friendly the experimental, 19-element segmented mirror system built by the Lockheed Palo Alto Research Labs. This system has recently undergone extensive testing at the Vacuum Tower Telescope at Sacramento Peak in order to determine what improvements should be made to it, and a three-year development program has been planned. The results of the testing have been encouraging, and we anticipate the development of a real-time wavefront correction system that can be used in conjunction with existing focal-plane instrumentation for productive high-resolution solar research.

While this device is being developed, we plan to build and install correlation trackers at the Sacramento Peak Tower and McMath telescopes. These devices lock the telescope on the low-contrast photospheric granulation with sub-arcsecond accuracy.
Such accurate tracking will permit prolonged spectroscopic and polarimetric studies at high spatial resolution of a selected region of the solar disk.
VIII. COMPUTER APPLICATIONS

Until recently, optical astronomy has been data limited, with a low data-gathering rate from relatively insensitive detectors and small telescopes. The past decade has seen an explosive growth in many areas of instrumental capability—new large telescopes, sensitive quantum-limited detectors, digital imaging techniques, exploration of new regions of the electromagnetic spectrum, and remote data acquisition from high altitude and space. Coupled with these developments has come the electronic revolution, allowing the scientist to manage vast quantities of data efficiently and creatively from a computer terminal.

Astronomy of the 1990s will place severe demands on the national observatories for growing support in the development and maintenance of software for data reduction and analysis, and in the provision of facilities for its use not only on-site but also remotely from many institutions around the world.

The Central Computer Services (CCS) unit of NOAO is responsible for coordination and planning of computer hardware and software acquisition and development for NOAO. This centralization of planning is leading to efficiencies of standardization and common development. By the end of FY 1986, each of the NOAO observatories had one or more VAX computers and one or more SUN workstations in operation, and the NOAO Interactive Reduction and Analysis Facility (IRAF) was in use at all sites. Data acquisition systems on Cerro Tololo and Kitt Peak have a large and increasing degree of commonality. NOAO-Tucson is linked by satellite to the San Diego Supercomputer Center and by a variety of computer networks to other national and university astronomy centers.

The principal features of NOAO's long range plan in this area of our program are described below.

* Vector Computer for NOAO: Recently developed techniques for image restoration and reconstruction are currently undergoing evaluation. Systematic use of these techniques in the near future will greatly surpass our data reduction capacity. Therefore, in FY 1990, we plan to replace our by-then-obsolete VAX 11/750 systems with an intermediate performance vector/multi-processor machine of the type sometimes described as a "mini-supercomputer".

Owing to rising maintenance costs of obsolete systems, our workhorse VAX 750s will require replacement beginning in FY 1991. A possible strategy would be to implement time-shared file servers networked with several types of smart terminals, ranging from PCs to diskless or fully equipped workstations.

* IRAF: The development of IRAF has been a major and highly successful initiative of NOAO. The IRAF language is a transportable programming environment for astronomical image
processing, data reduction, and data analysis that will be used both to support standard software packages and to provide a flexible framework for scientists to program their own applications. IRAF is in regular use at NOAO and STSCI. It is expected that IRAF will be in use at more than 100 institutions by mid-FY 1987. The IRAF system is designed to outlive current generations of computers and operating systems, but this longevity will require continual development of systems software and applications and a high level of support to the user community.

In IRAF applications, the frontier of astronomical software during the next five years is likely to be in the expedient processing of very large volumes of data, algorithms for the display of very high information content data, elimination of seeing blur through interferometric (e.g. speckle) observing techniques, and image restoration and enhancement.

- **Computer Communications**: Within one to two years, the need for high speed computer links between Tucson and Kitt Peak, between La Serena and Cerro Tololo, and between Tucson and Sunspot will become urgent. They are needed for effective sharing of expensive computer resources and for efficient archiving of data. NOAO was a leader in development of remote observing but left the field because of telephone costs. A direct Kitt Peak-Tucson microwave link will provide access to virtually all astronomy centers in the U.S. and many around the world. The costs of the networks is very low and generally not dependent upon the volume of usage. At night a significant bandwidth is available. Thus, remote observing can achieve the convenience and low cost required for effective use. In FY 1990 we will add high-speed links between CTIO, Kitt Peak, and Sacramento Peak.

- **Data Archiving**: During the next few years we expect to increase the rate at which digital data are placed in permanent NOAO archives by more than a factor of ten. Storage on current magnetic media is not satisfactory owing to the bulk and impermanence. Optical archiving may be a viable medium for long-term storage. Our investigations of storage media will continue, with the objective of specifying storage media and protocols before FY 1989. Instigation of archiving of NOAO data will require a significant software effort, currently under study, and long-term support for transfer of data to the archive and convenient access by the astronomical community.

- **Data Acquisition and Display**: A workstation project was begun last year to augment the image processing power available at the telescope. The initial justification was to be able to handle the data flow from large format digital detectors such as the forthcoming Tektronix 2048 x 2048 CCDs for which the PDP 11/73 computers are completely inadequate. As the project evolved, it became clear that having IRAF available for use with any digital detector would be a considerable benefit to the users of the
observatory. It is the current goal of the project to provide such single-user image processing systems for nine telescopes (five on KPNO and four on CTIO). These workstations are forming the core of plans for mountain computing for the next five years. Both the new telescope control computers and the new CCD controllers are expected to use the Sun 3/280 systems as the central hub for software development and observer control of the telescopes and CCDs.

Solar observing brings its own special set of problems imposed by the very high data rates. The readout time of large format CCDs is typically several seconds while solar exposures are only 50 ms. Thus, with the existing data acquisition equipment a large fraction of the available light is wasted and the resulting signal-to-noise ratio in magnetic or velocity maps is less than optimum. In order to optimize the performance of its auxiliary equipment, NOAO plans to build a set of high-speed data acquisition systems (CHIRP) beginning in FY 1987. These systems will read a single chip much faster, correct for gain and dark current and add (or subtract) frames. The average frame, containing high signal-to-noise data, would be recorded on tape at 30-second intervals.

The inadequacies of existing facilities for storing, displaying, and analyzing solar data are already hampering research. The advent of 1024 x 1024 and larger arrays with associated high-speed data systems will make demands far beyond current capacities. This problem must be met by dedicated image workstations and a new generation of mass storage devices.
IX. OPERATIONAL PROGRAM

An impressively large number of institutions has been served by NOAO with an impact on astronomy graduate education. During FY 1985, KPNO was visited by 196 scientists who came to the observatory as principal investigators for at least one observing proposal; this tabulation does not include co-investigators who may also have been present during the observations. There were 39 graduate student thesis investigators. 80 different U.S. institutions were represented in addition to 21 foreign ones. The quality of the NOAO research work can be estimated from surveys like the recent one by Helmut Abt who demonstrated the impressive publication record of those who use the national centers and from the excellent representation of KPNO and CTIO users in the list of winners of major astronomical prizes.

A. Site Maintenance

Service to the astronomical community will continue, and we will always have, as a high priority, the maintenance and support of our observing sites for use by the community of U.S. astronomers. In recent years, however, it has been necessary to cut back on funds for operations and maintenance. Cost-saving strategies have been adopted throughout NOAO. For example, on Kitt Peak we have closed the 16-inch telescopes and closed all but one of the remaining telescopes during most of July and August. On Cerro Tololo, houses and dormitories have been closed and most of the mountain staff commutes each day to Tololo. Throughout the nighttime observatories we have further reduced the frequency of instrument changes by block scheduling and enforced minimum lengths for observing runs. At all sites we have reduced staff available to maintain instrumentation even though this increases the risk of breakdowns and reduces our ability to respond to problems in a timely fashion. In view of the pressing need for additional funds for new instrumentation, new computers, and critical improvement projects, we shall be hard pressed to restore any of the services that have been eliminated within the core level of the budget.

Far more critical than the reduction in services to observers is the fact that the budget has for several years not included funds for major maintenance of facilities. There are serious problems at all four sites that must be corrected. Most urgent are replacement of the frequency converter at CTIO and of the roof at the headquarters building in Tucson; both of these projects should be completed in FY 1987. There are transformers at all four sites that contain PCBs. We are legally required to remove the ones in the U.S. and will probably choose to replace the ones in Chile. Replacements are scheduled for FY 1987 at Kitt Peak, FY 1988 in Tucson and Sacramento Peak, and for FY 1989 in Chile.

In subsequent years, we hope to address more routine maintenance problems. The most visible evidence of lack of maintenance is
the peeling paint on the McMath solar telescope at Kitt Peak, but this is far from the most serious problem. In fact it is unlikely that the McMath will be repainted during the next several years. Far more critical is the overall deterioration of the physical plant at Sacramento Peak. There we need to reroof and repaint the machine and electronics shop building; replace water and gas lines (there have been numerous leaks during the past several months, and these leaks are a health and safety hazard); repaint the main lab, tower telescope building, and the facilities maintenance buildings; and resurface roads. At Kitt Peak, we also need to resurface roads, and the 4-m building will need repainting in about three years. Over the next several months we will be developing a schedule for major maintenance of all NOAO facilities, but given the extent and age of NOAO buildings, it is not unreasonable to expect that adequate maintenance will require expenditures, heretofore unbudgeted, of $300,000-$400,000 annually.

Other major projects required at each site are:

* Cerro Tololo: The 23-mile unpaved road between Tololo and the public highway needs to be improved. It remains dangerous for drivers unfamiliar with its curves and steep dropoffs and guard rails for the most dangerous 10 miles of the road are proposed.

Since 1963, the generators, warehouse, garage and several shops on Tololo have been housed in "temporary" buildings of structural steel covered only with corrugated zinc sheeting. The buildings are unsuitable for the mountain weather conditions and have become less safe with age. Their replacement with prefabricated service buildings is proposed for FY 1988 and 1989.

An additional need is for added generating capacity—we plan to acquire a 500 KW converter in 1988 to improve our back-up power capabilities.

* La Serena: A supplementary emergency power generator is needed for La Serena. In 1985 there were more frequent power outages than for any year since at least 1979; we have therefore scheduled the purchase of a 150 KW back-up generator for FY 1987.

Good management dictates that the units of the vehicle fleet be replaced routinely on a carefully planned schedule. Experience shows that these are the first items to be cut when the budget is reduced. As a result, over two-thirds of the Cerro Tololo fleet is more than six years old and nearly a quarter is over 16 years old. In FY 1987 and 1988 we shall replace light duty trucks used for maintenance work.

* Sunspot: In addition to the extended program of maintenance that is urgently needed at Sunspot, some expansion of existing facilities is also required. An extension to the main lab is badly needed to provide additional office space and adequate room for data reduction equipment. Currently, office space is very
tight and we do not have adequate room for our increasing computer hardware. There is also an urgent need for a building which would provide weather-tight storage for furniture, equipment and supplies as well as covered parking for observatory vehicles. In addition, a community recreation building has long been needed at Sunspot as is a visitor center to accommodate more adequately the increasing flow of public visitors, expected to increase significantly with completion of the new access road from Cloudcroft.

* Tucson: The immediate need for a fireproof storage vault to house the collection of photographic plates was met in FY 1986. However, there is no room for the planned acquisition of the ESO Southern Hemisphere Survey plates.

* Kitt Peak: An early warning fire detection system is needed for buildings on Kitt Peak. A water well and pumping stations are required to provide a source of potable water to supplement the inadequate system for collecting rainfall and snow melt.

Additions are needed to the Kitt Peak Visitor Center to handle the very large increase in public visitors. An auditorium is highly desired. We hope to fund a major portion of this with private donations.

B. Telescope Maintenance

Priorities for telescope maintenance have been determined with the goal of achieving the following (in order of importance):

* Safety of personnel and/or equipment;
* Quality, reliability, and efficiency of observations;
* Improvements to operations or observing environment.

Several maintenance items are scheduled for the first year or two of this plan, such as rebuilding of screw jacks for the KPNO 4-m primary elevator, repairing the focus shift problem at the KPNO 2.1-m, and rebuilding the damaged #2 mirror at the Vacuum Telescope on Kitt Peak.

Concurrent with these upkeep items, we plan to replace the telescope control hardware and software. Discussions throughout NOAO have led to a view that the preferred development path for telescope and (probably) instrument control uses 68020-based computers running the VRTX (Trademark: Hunter and Ready) real-time operating system kernel, with the programming done in the "C" language. This system is designed for applications such as telescope or instrument control and is supplied in binary form on tape or in read-only memory chips. It provides the basic services a real-time system needs; priority scheduling, message passing, timer and i/o support. Once these control system conversions are underway, attention should be turned to
instrument control. The greatest need now is for more CCD
controllers, and we are considering a new design that would use
VME based hardware and VRTX. In the long term, given an adequate
number of Sun workstations, both CTIO and KPNO should end up with
the same VME hardware configuration at each telescope, with one
terminal from which telescope, CCD, and data reduction would all
be controlled; and with a software configuration consisting of
the same standard real time kernel for both telescope and
instrument, the same control software written in a standard
programming language, and with the same user interface and
commands.

New and increasingly powerful instrumentation requires improved
telescope performance. Once CCDs were installed at the KPNO #1-
0.9m telescope, it was possible to shift some observing programs
from the KPNO 4-m telescope to this smaller yet powerful
telescope. Forefront studies on the nature of accretion flows in
galaxy clusters, on galaxy formation and evolution, on the
environment of active galaxies, on extended halos around dwarf
galaxies, on the existence of jets near young stellar objects,
and on multiple shells of planetary nebulae have been
successfully carried out at this telescope. Comparable lists of
superior contemporary investigations can be produced for each of
the telescopes at the centers. The scientific productivity
associated with them is competitive with that of the 4-m
telescopes. Subscription rates indicate that when advanced
instrumentation is made available on a small telescope, the
demand increases significantly. When CCDs were first installed
on the KPNO #1-0.9m, the subscription rates for it exceeded that
of the 4-m. The rate was reduced when the CCD camera became
available at the KPNO 2.1-m and now both telescopes are
oversubscribed by 200%.

The general policy adopted by the Telescope Allocation
Committees, and endorsed by NOAO, is to schedule a proposal on
the smallest NOAO telescope with which the project can be carried
out. In the past, proposals for the 4-m telescopes have been
successfully shifted to smaller-aperture but appropriately-
instrumented telescopes. In many cases, what defines the choice
of telescope is not its aperture but its performance and its
instrumentation. Although our first priority is assigned to
proper maintenance of the 4-m telescopes, giving careful
attention and support to the smaller telescopes is a very cost-
effective way to serve the community.

The mirror support systems at the 2.1-m and 0.9-m telescopes on
Kitt Peak are complex mechanical systems and recently have not
been adequate to provide image quality commensurate with the
quality of the mirror figure. Both stellar and solar telescopes
of NOAO suffer from local sources of heat near the optics which
degrade image quality. An active program is underway to correct
this situation throughout NOAO's facilities with particular
concentration on the two 4-m telescopes and the McMath.
X. CONSTRUCTION

The principal construction item is for an addition to the Tucson office/laboratory building.

The greatly expanded role for NOAO in instrumentation, new concept development, new telescope initiatives and particularly, the NNTT project will place demands for space which are entirely beyond the capacity of the current Tucson building to satisfy. An important additional driver for added space will be the computer applications and development program with its strong emphasis on communication between telescopes, observers, and data bases; on archiving; and on computer-intensive applications for data reduction and analysis (as reflected in the budget item for a vector processor).

The natural direction for growth is to add additional floors to the east end of the Cherry Avenue building--the need for such an addition was anticipated in the original design and incorporated into the foundation. A 1985 estimate concluded that two more floors each of 15,500 square feet can be provided in this way at a cost of about $3.5 million (1987 dollars). This appears to be well matched to the added needs to accommodate this expanded program. Added space will be needed, too, to house the proposed 8-m mirror-polishing facility but the cost of that is included in the estimate for the facility itself as a part of the FTT program.
XI. BUDGET

The budget is presented in terms of two major components—a core budget, which includes the GONG project and the FTT program, and a budget for major new starts.

In the core budget, the figures for FY 1987 correspond to the program plan submitted to the NSF; the FY 1988 figures are the same as those that appear in the draft FY 1988 program plan, which is currently under review by AURA before submission to the NSF. The remaining figures are consistent with the programs outlined in this long range plan. In particular, the funding for the GONG program would allow the project to remain on schedule.

The figures for FY 1989, in addition to allowing for inflation, provide for enhancements in several areas of the core budget that we believe are essential if we are to continue to operate all of our current facilities in an effective and safe manner. In order of priority, we propose to add $200,000 to the maintenance budget so that we can undertake the major repairs of the physical plant described in Section IX at the various sites. This money would be used for outside contractors and would not increase the size of the permanent staff. Second priority is an increment of $450,000 to the non-payroll portion of the instrumentation budget. These funds would allow us to restore our program of acquiring new computers, a program that has been delayed by at least one year in order to allow for facilities maintenance. In addition, we need a higher level of funding to allow us to purchase both optical and infrared array detectors for the new instrumentation that we hope to complete during this time period.

Third priority is the addition of staff in specific key areas. We would like to add one member to the scientific staff at Sacramento Peak. A second scientific staff position would be assigned to CTIO.

Fourth priority is an increase in the size of the maintenance staffs at the operating observatories. We propose to add four people to the staff at Sacramento Peak and two each to the staffs at Kitt Peak and Cerro Tololo.

Key new starts that will be proposed during the period covered by this long range plan are the construction of a polishing facility for 8-meter mirrors; construction of a large aperture solar telescope, probably in collaboration with the LEST consortium; initiation of work on the 8-m and 16-m national telescopes described in this plan; and an expansion of the Tucson headquarters to accommodate the project staff for these construction projects and such other activities as data archiving for GONG and other projects. Approximate cost figures for the portion of these new starts that might be undertaken during the next five years are given in the budget tables, but of course detailed proposals will have to be prepared for review and approval by the NSF before any of these projects can be initiated.
XI. SUMMARY

The NOAO Long Range Plan for 1988 - 1992 reflects a vigorous program aimed at establishing the NOAO in the position of influence which it can and should hold as the U.S. national ground-based observatory. Set out here is a bold attempt to establish leadership in several key areas of technology which we believe will be of major importance to the future of the discipline, while retaining, at the same time, the vitality and sense of service at the existing telescopes that have earned for NOAO the praise and support of the contemporary astronomical community.

A primary key to our Plan is the development of technology necessary for the construction of the next generation of large telescopes including the NNTT. This development program is multi-faceted. As the text emphasizes, its objective is to provide large-aperture capabilities for the U.S. astronomical community both for the northern and southern skies. We will develop proposals for, and hope to initiate construction of, the 16-m NNTT, an 8-m southern companion, a 4-m class special-purpose telescope for multi-object spectroscopy and other cosmological applications. We will also prepare proposals for the technology development to make it all possible.

Other important and far-reaching program initiatives are described in this Plan--GONG, new instrumentation, developmental projects, computer applications--and each will have vital consequences for the attainment of NOAO's basic objective of advancing U.S. astronomy. In combination with a successful, continuing operation at our existing telescopes this program of support to the contemporary and the future astronomical community will represent a long stride towards the future health of astronomy in the U.S. and internationally.

In seeking to implement its goals NOAO must remain open to new approaches. In particular, it must continue to press its attempts to engage other institutions in cooperative ventures at all levels, large and small, of its programs. Not only can this bring direct benefit to NOAO's constituent community; successfully presented it will place the national observatories in their appropriate location as an integral and supportive component of the entire U.S. astronomical community and not, as it is too-often characterized, as something set apart.

To carry through such a program requires funding and the support of those on whose approval it depends. Above all, however, it requires the guidance and commitment of a high-quality scientific staff. The provision of the environment necessary to attract and retain such people must be uppermost in our minds if we are to move towards the realization of our goals.

John T. Jefferies, Director
3 March 1987

Sidney C. Wolff, Acting Director
3 June 1987
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**MAJOR NEW STARTS BUDGET**

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1. Includes FY-1996 carryover funds of $1,677K.
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1 Includes FY-1986 carryover funds of $1,627K.
Table 3

NATIONAL OPTICAL ASTRONOMY OBSERVATORIES
FY1988 - FY1992 LONG RANGE PLAN
(In Full Time Equivalents)

CORE BUDGET

By Long Range Plan Category

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By Function

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The schedule set out below addresses the major components of the GONG project from the initiation of the Site Survey through to completion of the initial data analysis. The budget for this program item is consistent with this schedule for the period covered by this Plan (i.e., through FY 1992).

Site Survey Network Operational  October  1986
Begin Integrated Light Tests  January  1987
Begin Imaged Testing (Breadboard)  May  1987
Begin Imaged Testing (Prototype)  September  1987
First Light Full Prototype System  April  1988
Site Selection Completed  March  1989
Begin Integration of Field Components  April  1989
Data Reduction Hardware Ordered  October  1989
Data Reduction Center Operational  March  1990
Begin Site Installation  April  1990
GONG Network Operational  October  1990
Data Acquisition Completed  September  1993
Initial Data Analysis Completed  September  1994
2. FTT Project Milestones

Set out below is a preliminary schedule (which extends beyond the period covered by this Long Range Plan) for new telescope technology development which is expected to lead to a 16-m telescope, with an 8-m telescope as an intermediate step, and a potential 4-m application along the way. Implementation of the full four-mirror capacity of the 16-m facility is controlled by delivery of the polished mirrors.

<table>
<thead>
<tr>
<th>Event</th>
<th>Date</th>
</tr>
</thead>
<tbody>
<tr>
<td>Complete Proposal for 8-m Telescope and for NNTT</td>
<td>March 1988</td>
</tr>
<tr>
<td>Complete 1.8-m Mirror Tests</td>
<td>July 1988</td>
</tr>
<tr>
<td>4-m Mirror Blank Available</td>
<td>December 1988</td>
</tr>
<tr>
<td>Polishing Facility (8-m) Design</td>
<td>December 1988</td>
</tr>
<tr>
<td>Polishing Facility Construction Complete</td>
<td>December 1990</td>
</tr>
<tr>
<td>First 8-m Blank Cast</td>
<td>December 1990</td>
</tr>
<tr>
<td>8-m Telescope Design Complete</td>
<td>December 1990</td>
</tr>
<tr>
<td>8-m Telescope Construction Begin</td>
<td>March 1991</td>
</tr>
<tr>
<td>4-m Mirror Testing Complete</td>
<td>July 1991</td>
</tr>
<tr>
<td>Complete First 8-m Mirror</td>
<td>December 1993</td>
</tr>
<tr>
<td>8-m Telescope Construction Complete</td>
<td>March 1994</td>
</tr>
</tbody>
</table>

The schedule assumes that funding will be available as needed.