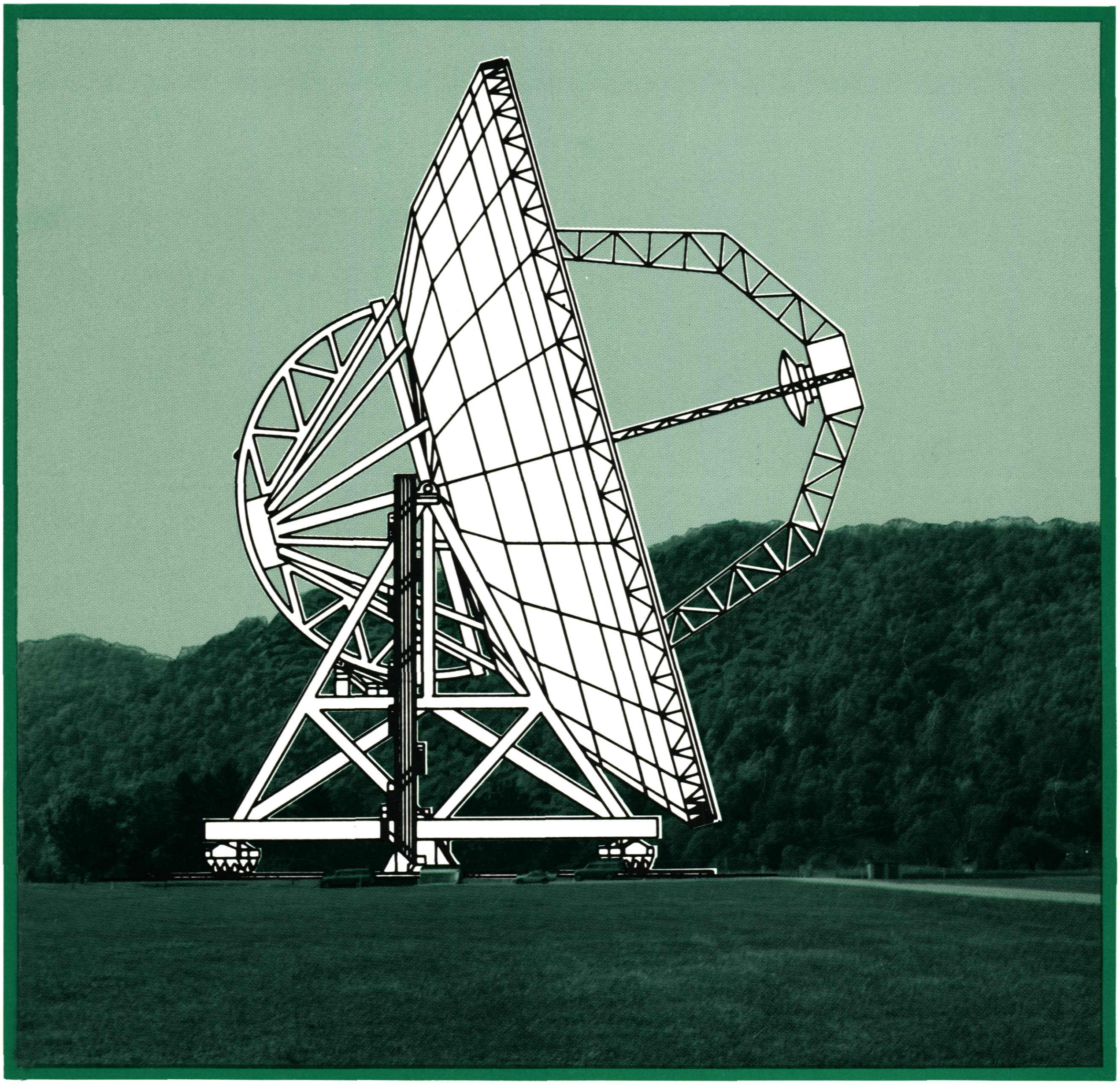
THE GREEN BANK TELESCOPE



A Radio Telescope for the Twenty-First Century

Final Proposal June 1989

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The Green Bank Telescope:
A Radio Telescope for the Twenty-First Century

Proposal to the National Science Foundation

Submitted by
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I. INTRODUCTION AND SUMMARY

The National Radio Astronomy Observatory proposes to build a new telescope for radio astronomical research in Green Bank, West Virginia. The Green Bank Telescope (GBT), with an aperture of at least 100 meters, will be the world's largest fully steerable radio telescope. The design goal is to provide a surface accuracy and optics system sufficient to support precision astronomical observations over the entire range of wavelengths from meter-waves to millimeter-waves. The design will incorporate (1) an actively-controlled primary surface to compensate for gravitational deflections; (2) a stable pointing reference system capable of achieving an rms pointing accuracy of two arcseconds or better; and (3) minimal aperture blockage for low system noise temperatures, high beam efficiency, and low sidelobe levels for rejection of interference and stray radiation. It will be further protected from interference by its location in the National Radio Quiet Zone. This modern and versatile telescope is designed with the expectation that it will efficiently support technology and research well into the twenty-first century. The telescope will begin operation by 1995 if this proposal is funded by mid-1989. The total cost is estimated to be $75,000,000.

The need for a large, fully steerable radio telescope has been recognized by astronomers for more than thirty years. The National Academy of Sciences astronomy survey committees chaired by Prof. Whitford in the 1960s, by Prof. Greenstein in the 1970s, and by Prof. Field in the 1980s all noted the limitations placed on radio astronomical research by the lack of a large, fully steerable, single-dish radio telescope in the U.S. Recent discoveries—binary and millisecond pulsars, organized structures of galaxies in the local universe—have served to underscore the salient point mentioned by the committees: the survey and discovery aspects of radio astronomy are particularly dependent on the availability of a large aperture. Unfortunately, the collapse of the 300-foot radio telescope in November 1988 severely crippled U.S. astronomers' access to large steerable telescopes. This proposal for the Green Bank Telescope is written to restore the research capabilities of the 300-foot telescope to radio astronomy and to exploit modern technology in the design of the Green Bank Telescope so as to enhance the opportunities for astronomers of the next several decades.

Technological advances have revolutionized the design of large radio telescopes. Precision surface panels ($\sigma \approx 0.1$ mm rms accuracy) can be manufactured inexpensively, and computer-controlled active surface and pointing adjustments can now correct for gravitational deformations (and to some degree thermal and wind effects) of the telescope structure. Consequently, it is no longer cost-effective to build large radio telescopes which are structurally sound but which can operate only at long (e.g., $\lambda > 6$ cm) wavelengths. The additional cost of building a precision telescope of the same size that is capable of reaching $\lambda \approx 7$ mm, or even shorter wavelengths, is relatively small. The resulting instrument opens important new fields of research, as the diverse scientific program described in Chapter II demonstrates.

Following the discussion of the scientific program, Chapter III outlines the considerations and tradeoffs that the scientific program imposes on the antenna design. Many of these considerations have not been woven into the initial design of past radio telescopes, even those built quite recently. Of particular importance for the Green Bank Telescope is the need for versatility, an exceptionally clean beam, elimination of standing wave reflections, and active control of the primary surface.

The telescope design we propose to meet these needs is derived from designs of existing telescopes, previous design studies made at the NRAO and elsewhere, and extensive recent conceptual design work at the NRAO (as compiled in the NLSRT memo series, see Appendix). This work demonstrates the feasibility of building and instrumenting a telescope with the performance described in the proposal, at the cost proposed. Many design parameters are still unspecified, or only a range of possible parameters is specified. A major task in the next stage of design is to optimize the scientific capability of the telescope and its ancillary instrumentation within the range of parameters noted here, and within the budget proposed.

Chapter IV is a discussion of the choices and possibilities for receiver systems and back-end instrumentation. Using current and projected technology one can realistically consider broadband, cryogenic receivers across the entire spectrum available to the Green Bank Telescope. Chapters V and VI discuss the telescope control, data-taking, and data processing system for the Green Bank Telescope. Here again, technology allows new assumptions to be made as an integral part of the Green Bank Telescope design. Networked computer systems, even those connected over thousands of miles, are now the norm. The transfer of data between computers and between software environments is integral to this aspect of the Green Bank Telescope, as it is to the manner in which the astronomer may choose to use the Green Bank Telescope, described in Chapter VII. Chapter VIII presents an evaluation of the environmental and logistical aspects of the Green Bank, West Virginia site for the Green Bank Telescope. Finally, the project cost, personnel projections, and a construction schedule are presented in Chapter IX.

As the world's largest fully steerable radio telescope, the Green Bank Telescope will fill a unique niche in radio astronomy. It will both supplement and complement the scientific capabilities of the Arecibo telescope, the VLA, and the VLBA. The Green Bank Telescope will permit sensitive observations to be made on those parts of the celestial sphere beyond the declination limits of Arecibo, and at higher frequencies. To the VLA it will add coverage of the shortest u-v spacings, thereby increasing the dynamic and spatial range of VLA images. To the VLBA it will add both sensitivity and more precise calibration. In addition, the Green Bank Telescope will provide the survey material from which VLA and VLBA studies begin. With new and unique scientific capabilities, with capabilities that supplant those of the imaging arrays, and with a design that anticipates the changes technology will bring, the Green Bank Telescope is the realization of past hopes and an appropriate tool for the students and scholars of the future.

II. SCIENTIFIC PROGRAM

1. INTRODUCTION

The proposed Green Bank Telescope is a sensitive and versatile instrument which will be used to observe a wide range of astronomical sources, from comets in our solar system to the cosmic microwave background bounding the observable universe. The history of radio astronomy suggests that we can anticipate only a fraction of the most exciting science that will emerge from the Green Bank Telescope—most recent programs on the 140-foot and 300-foot telescopes at Green Bank observed astronomical objects (pulsars, quasars) or phenomena (radio recombination lines, astrophysical masers) unknown when those telescopes were proposed and required equipment (low-noise solid-state amplifiers, autocorrelation spectrometers, fast data-taking computers, VLBI recorders, maser time and frequency standards) unavailable when those telescopes were constructed. The place of the Green Bank Telescope in astronomy will be determined by its basic performance characteristics, by its ability to track evolving scientific demand, and by its relationship to other radio telescopes worldwide.

Performance characteristics of the Green Bank Telescope most important to its astronomical uses are:

(1) *Sensitivity and Resolution.* The 100-m Green Bank Telescope will have a sensitivity of 2.85η K Jy^{-1}, where η is the aperture efficiency. The geometric aperture blockage ($< 3\%$) will be less than half that of conventional designs, resulting in high beam efficiency and low sidelobe levels for rejection of stray radiation and interference. System noise temperatures as low as 15 K should be possible in the 1–10 GHz frequency range, because scattering of ground radiation will be low. The FWHM beamwidth will range from 9 arcmin at $\lambda = 21$ cm to 18 arcsec at $\lambda = 7$ mm.

(2) *Reflector Surface and Pointing Accuracy.* The total error budget for the active surface is $\sigma = \lambda/16$ at $\lambda = 7$ mm. Individual surface panels will be figured to within $\sigma \approx 0.1$ mm, so that improvements in surface adjustment may eventually allow limited operation at $\lambda \approx 3$ mm. The rms pointing accuracy should be about two arcsec, sufficient for ~ 0.1 FWHM pointing of the fully illuminated aperture at $\lambda = 7$ mm and of the inner half at $\lambda = 3$ mm.

(3) *Sky Coverage.* The Green Bank Telescope will be able to observe 85% of the celestial sphere (all declinations north of $-45°$). This includes the entire ecliptic plane, the most important molecular clouds (e.g., Orion, ρ Oph), two-thirds of the galactic plane, including the galactic center, most of the nearby superclusters, etc.

(4) *Tracking.* The Green Bank Telescope will be able to track from horizon to horizon, permitting long integrations on faint sources,

VLBI observations in conjunction with earth satellites or as an adjunct to the VLBA, timing measurements of pulsars, and bistatic radar applications. The tracking capability will also increase the number of objects available for study if the telescope eventually becomes usable at wavelengths $\lambda < 7$ mm. Most such observations will be confined to winter nights, but the potential coverage in right-ascension can be maximized if observations at large hour-angles are possible.

(5) *Protection from Interference.* Man-made interference is already a serious problem for radio astronomy, and it is certain to get worse. Green Bank is located in the National Radio Quiet Zone. This unique legal protection from interfering signals permits observations at very low frequencies (where interference is most widespread), at scientifically important frequencies outside the standard radio-astronomy protected bands (needed for "protected" spectral lines at high redshifts and for most molecular lines), and with very large instantaneous bandwidths (for maximum continuum sensitivity).

(6) *Versatility.* A single-dish telescope can usually respond more quickly than an array to new scientific demands. It is now possible to equip a single large telescope with receivers that allow nearly continuous frequency coverage from a few times the ionospheric limit ($\sim$ 10 MHz) to the maximum frequency allowed by the telescope surface and pointing accuracy. Each receiver and feed can be carefully optimized for superior performance. Furthermore, state-of-the-art backends, such as the new Green Bank spectral processor, can provide signals in real time, high temporal and frequency resolution, interference excision, and the flexibility to record simultaneous spectra in several widely-spaced frequency bands. A large single dish is the ideal test bed for developing new capabilities (array feeds, for example).

The most important scientific opportunities that we foresee for the Green Bank Telescope are described briefly in the remainder of this section, derived in part from *Scientific Considerations for the Design of a Replacement for the 300-Foot Radio Telescope* (Brown and Schwab 1989), the proceedings of a workshop held in Green Bank on 1988 December 2 and 3; they are then discussed in more detail in the remainder of this chapter. Briefly, the five major areas covered are:

1.1. Pulsars, Stars, and the Solar System. Pulsar timing will measure the gravitational radiation from close binary systems. An number of millisecond pulsars serving as clocks distributed around the ecliptic plane will be used to detect or set strong upper limits to long-wavelength gravitational radiation originating at the Big Bang, thereby testing cosmic-string models of galaxy formation. Surveys for new pulsars, particularly in globular clusters, will increase the sample of known objects in the final stages of stellar evolution and will probe neutron star physics.

A great variety of radio stars will be detectable with the Green Bank Telescope. Broadband dynamic spectropolarimetry will be used to study thermal stellar winds, plasma effects in enormous "sunspots" and in the intra-stellar magnetospheres of close binaries, and precessing radio jets fueled by accretion onto neutron stars or black holes. Multifrequency imaging of the Sun will help to define conditions in the upper chromosphere and transition region above coronal holes, as well as in quiet and active solar regions.

1.2. Galactic and Extragalactic Neutral Hydrogen. The Green Bank Telescope will be sufficiently sensitive to detect H I emission from more than 10^4 galaxies distributed over 85% of the celestial sphere. Surveys for these galaxies will map the large-scale spatial distribution within $D \approx 100$ Mpc, as well as their motions relative to the smooth Hubble flow. The H I profiles of nearby galaxies also yield global properties (total mass, H I mass, mass-to-light ratio, surface density, etc.) which trace dark matter, reveal environmental effects, and show the effects of tidal interactions occurring in clusters or groups. The Green Bank Telescope will be able to find galaxies that are hidden to optical study by the dust and stars of the Milky Way. In addition, protogalaxies and other gas-rich extragalactic objects of low optical luminosity will be detectable. The evolution of galaxies at high redshifts will be probed by observations of H I in absorption against distant continuum sources and by searches for massive proto-galactic "hydrogen pancakes" in the redshift range $4 < z < 10$.

Within the Milky Way the 9 arcmin beam of the Green Bank Telescope at 21 cm will resolve structures as small as 20 pc at the distance of the galactic center. It will therefore be used to make H I maps of activity in the nuclear (central 1 kpc) region. The partition of gas between the spiral arm and inter-arm regions, H I envelopes around star-forming molecular clouds and supernova remnants, and the flaring and warping of the galactic disk outside the solar circle are other likely areas of investigation.

1.3. Spectroscopy. The unequaled sensitivity, high resolution, and frequency agility of the Green Bank Telescope at short centimeter and long millimeter wavelengths will allow the detection of CO in starburst galaxies and quasars at cosmological redshifts (up to $z \approx 3$), opening an important new field of study—the molecular content of galaxies from the epoch of galaxy formation. Multifrequency observations of CS, HC_3N, and CH_3OH transitions in the 30–50 GHz range will contribute to our understanding of molecular processes and provide the data needed for detailed multilevel models of density and temperature in the molecular clouds of our own and nearby normal galaxies. Spectroscopy of OH, H_2O, CH_3OH, and H_2CO masers will probe the kinematics and energetics of the most intense starbursts in the nuclear regions of galaxies.

In our own galaxy, maps of the *stellar* disk based on the 10^5 OH/IR stars detectable by the Green Bank Telescope will be combined with existing H I and CO maps of the atomic and molecular gas disks. The structures of these disks perpendicular to the plane are the basic data needed to determine the total mass of the galactic disk, the existence or not of the "thick disk", the nature and distribution of galactic dark matter, the history of star formation, the gravitational scattering of stars by molecular clouds, and the stability of molecular clouds to star formation. Both the physics and chemistry of the dense molecular clouds in which stars are born will be probed by multilevel spectroscopy of a wide range of molecules detectable in the $\lambda \approx 8$ mm atmospheric window. The high sensitivity and resolving power of the Green Bank Telescope will be important for such studies. Detection observations seeking the weak deuterium line at 327 MHz and the $^3He^+$ line at 8.7 GHz will critically test various cosmic nucleosynthesis models.

1.4. Continuum Radiation. The Green Bank Telescope will be able to make continuum sky maps covering ~ 10 steradians of the celestial sphere, with enough sensitivity and resolution to detect $\sim 3 \times 10^5$ sources stronger than $S \approx 5$ mJy at $\nu = 5$ GHz. The maps will be used to discover intrinsically rare objects, to detect radio emission from nearby galaxies, to provide archival records of the radio sky at various epochs, and to permit comparison with sky maps in the infrared, optical, and X-ray bands.

Sensitive searches for primordial fluctuations in the cosmic microwave background radiation on 1–10 arcmin angular scales will be made, exploiting the high beam efficiency of the Green Bank Telescope. The Telescope will be able to map temperature decrements in the microwave background produced by Compton scattering in the hot intracluster medium of rich clusters of galaxies (the Sunyaev–Zeldovich effect). This effect measures the intracluster medium's electron density and may eventually yield a direct measurement of the Hubble constant.

1.5. Very Long Baseline Interferometry. The Green Bank Telescope will be an important adjunct to the Very Long Baseline Array (VLBA) and orbiting Very Long Baseline Interferometry (VLBI) experiments because of its high sensitivity, frequency agility, and wide sky coverage. With the addition of the Green Bank Telescope, the VLBA will have the same collecting area as the VLA, permitting long coherent integrations on weak sources—such as faint structures in superluminal objects, gravitational lenses, supernovae, radio stars, and extragalactic H_2O masers. Statistical parallaxes of H_2O masers will be used to measure the distances to maser sources in our own galaxy and to nearby external galaxies.

2. PULSARS, STARS, AND THE SOLAR SYSTEM

2.1. Pulsars.

2.1.1. Searches and Surveys. Pulsars are rapidly rotating, highly magnetized neutron stars that emit beamed coherent radiation which is strongest at meter and decimeter wavelengths. Most of the approximately 450 known pulsars are concentrated in the solar vicinity—a consequence of limitations of the search telescopes and techniques, not a reflection of the true galactic distribution of pulsars. In fact, if our vicinity is typical, then there should be about 100,000 pulsars in the entire Galaxy. A critical factor in this assessment is the lower bound to pulsar luminosities determined several years ago from a survey made with the 300-foot telescope (Stokes *et al.* 1986). The galactic distribution of pulsars is essential to our understanding of the final stages of evolution of massive stars. The Green Bank Telescope should easily quadruple the number of known pulsars and should therefore have a major impact on this field.

Most pulsars are active for only a few million years. Then processes such as decay of their magnetic moments lead to a turn-off of their coherent radio emission. This means that the total reservoir of neutron stars exceeds those presently identifiable by their pulsed radio emission. The radio-quiet neutron stars may be responsible for the γ-ray burst sources. Neutron stars in binary systems accrete matter from their companions and can be detected in several wavebands. VLBI measurements of the trigonometric parallaxes and proper motions of a large number of the radio-loud pulsars are needed to complete our understanding of the galactic distribution of this entire population of neutron stars. The sensitivity of the Green Bank Telescope is essential for this faint-source astrometry.

Several pulsars are directly related to historical supernovae. The thousand-year old pulsar in the Crab Nebula supernova remnant was first detected with the 300-foot telescope (Staelin and Reifenstein 1968). The study of young pulsars such as this one and the detection of more distant, and perhaps somewhat older, pulsar–supernova associations provides a critical link between the implosion and explosion events that mark the deaths of massive stars. Most will be found in the central region of the Galaxy. The next galactic supernova may produce a pulsar visible to the northern observatories, and even an extragalactic pulsar may be found with the sensitivity of the Green Bank Telescope.

There are now eight known pulsars with millisecond periods and eleven binary pulsars whose evolutionary histories are different from those of the ordinary pulsars discussed above. We estimate that a few percent of the new pulsars that will be discovered with the Green Bank Telescope will be in these remarkable categories. Each new binary and millisecond pulsar should lead to fresh insights about the evolutionary paths of massive stars. The first binaries clearly showed that not every binary is disrupted by the supernova explosion. There is evidence for spinup of the neutron star following its formation and subsequent spindown—this is the best explanation for the 1.5 millisecond pulsar detected by Backer *et al.* (1982). The 1987 detection of a millisecond pulsar that is ablating its $0.02M_\odot$ companion illustrates again the unique nature of each pulsar in these categories.

Globular clusters produce low-mass binary stars in copious abundance. Theories for the evolution of these binaries led directly to the detection of millisecond pulsars in globular clusters. Globular clusters are concentrated around the galactic center, a region beyond the reach of the 300-foot telescope and Arecibo. Consequently, the most sensitive possible searches for globular cluster pulsars await the Green Bank Telescope. New objects will certainly be found, and nearly every new globular cluster pulsar will be an important addition to the pulsar zoo. For example, the pulsar detected in the globular cluster M15 is now showing a period spinup produced by acceleration an order-of-magnitude higher than expected in the potential well of the cluster. The precession of periastron of a pulsar in the cluster 47 Tucanae is expected to constrain the equation-of-state of its presumed white dwarf companion.

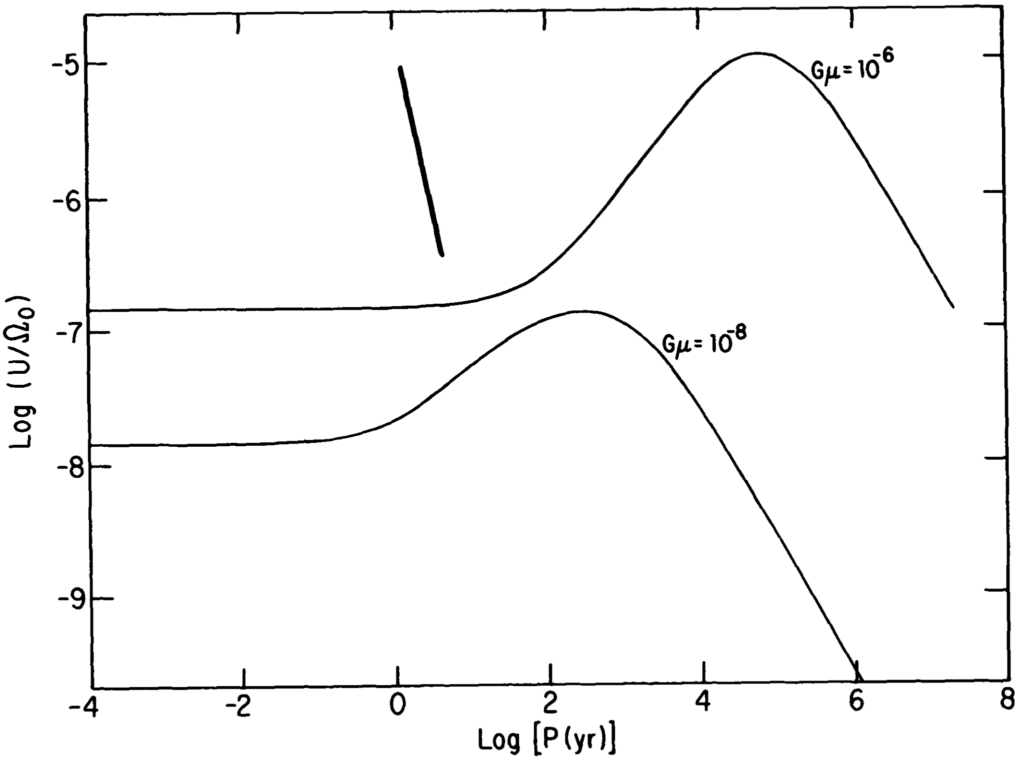

Figure II-1. Current pulsar timing limits (heavy line) on the energy density of long-period gravitational waves are close to the values expected in the models of Romani (1988a) containing cosmic strings with linear density $G\mu = 10^{-6}$ and 10^{-8}. Timing observations of pulsars distributed around the ecliptic plane should reduce these limits to $U/\Omega_0 < 10^{-9}$ or detect the radiation within ten years. *Abscissa:* Gravitational wave period (yr). *Ordinate:* Energy density of gravitational waves, divided by the density Ω_0 required to close the Universe.

2.1.2. Fundamental Physics. Millisecond and binary pulsars are the most stable clocks known. Precise measurements of their pulse arrival times have already provided data for a number of tests of general relativity and for observational limits on current theories of the early Universe and particle physics. These investigations will continue, both with more sensitive measurements of known objects and with unexpected developments involving newly discovered pulsars.

None of the eight known millisecond pulsars has exhibited a timing irregularity, even when compared against the best atomic clocks. This fact sets an already stringent limit on the presence of gravitational radiation left over from the earliest stages of cosmic expansion: broad classes of models predict the existence of long wavelength (light-years) gravitational radiation that would cause irregularities revealed by high-precision pulsar timing. The upper limit on energy density scales very favorably with timing accuracy δt and duration T of the timing effort, as $(\delta t)^2/T^4$. The existing limit ($< 4 \times 10^{-7}$ of the energy density needed to close the Universe) already comes close to excluding cosmic-string models for galaxy formation (see Fig. II-1).

Sensitivity to a gravitational wave background increases if a number of stable pulsars, widely spaced in ecliptic longitude, are compared. Searching for such pulsars and the monitoring of their pulse arrival times are ideal projects for the proposed Green Bank Telescope. With an array of pulsars one can distinguish the quadrupole (in ecliptic coordinates) signature of the gravitational radiation from monopole and dipole terms. This detection of long-wavelength gravitational radiation could precede any laboratory detection of gravitational radiation from stellar sources using the next generation of laser interferometers and bar detectors. Solution for the monopole term in the pulsar timing array will provide the most stable time standard for durations greater than one year, a prospect which has generated much interest in the worldwide time service community. Solution for the dipole term will provide fresh data on the orbit of the Earth in inertial space that can be used to improve our model of solar system dynamics. The solution for the individual positions of the pulsars in this array creates a fundamental astrometric grid that can be used to tie the ecliptic (solar system) and equatorial (extragalactic) reference frames together.

Binary pulsars continue to be our best laboratory for probing the high-velocity, dynamic predictions of general relativity, including the production of gravitational radiation and the consequent orbital decay. The original binary pulsar, PSR 1913+16, continues to yield new results on a yearly basis. The latest comparison between the precision timing observations, conducted at Arecibo, and the gravitational radiation prediction of general relativity are in agreement at the 2% level (Weisberg and Taylor 1984). *This fundamental result remains the only experimental evidence for the existence of gravitational radiation.* There are now eleven binary pulsars (six of them also millisecond pulsars) out of about 450 known pulsars. Two of these were discovered with the 300-foot telescope, and many more could be found with the Green Bank Telescope. Any new systems with reasonably short periods and measurable eccentricity will increase our opportunity to test theories of gravitation.

Another probe of general relativity comes from the search for geodetic precession of pulsar spin axes. Detection of this effect would imply discovery of a new general relativistic effect, with the subsequent ability to sample the pulsar beam in two dimensions.

2.1.3. Neutron Star Interiors and Magnetospheres. Neutron star structure and the underlying equation-of-state may be inferred from those millisecond pulsars spinning at rates near breakup. Observations of temporal variations in pulse shape and polarization would indicate forced or free precession of the spin axis, while observations of timing glitches and random-walk timing noise would reveal rotational fluctuations.

A host of observable phenomena found in pulsar radiation can be used to constrain models of the magnetosphere. Pulse intensity and polarization vary on time scales ranging from microseconds to hours. The variation of pulse shape with radio frequency suggests variable-altitude emission, but the issues of geometry, magnetic field structure, and relativistic beaming are still poorly understood. Clarifying observations will need good frequency coverage from 50 MHz to a few GHz. Better understanding of the spectra of pulse features and how they are locked to rotational phase is also required for optimizing pulse timing measurements. Multiple-frequency timing observations are needed to separate interstellar propagation perturbations from intrinsic magnetospheric terms (aberration, retardation, and gravitational ray-bending effects).

The relationship of isolated radio pulsars to such progenitor systems as low-mass X-ray binaries and quasi-periodic oscillators is not yet understood within an evolutionary framework. Searches for intermittent pulses may yield clues to this relationship. Such objects may appear for short intervals as radio pulsars (with low-density magnetospheres) which are later quenched by accretion from a companion that intermittently overflows its Roche lobe.

Many exciting studies of pulsar emission mechanisms have not been possible in recent years because of the limited tracking range of the 300-foot telescope and the limited sky and frequency coverage of the Arecibo telescope. For instance, we do not understand how the highly polarized emission from individual pulses evolves with frequency. Interstellar dispersion makes it possible to observe individual pulses over a range of widely-spaced frequencies. The Green Bank Telescope is well suited to such work because of its large collecting area and good frequency coverage. We also know little about pulsar nulling and subpulse drifting over long stretches of time (many hours to a few days) or what happens to subpulse drifting during pulsar nulls. We could, with the Green Bank Telescope, observe these phenomena continuously in a reasonably large sample of circumpolar pulsars.

2.1.4. Pulsars as Probes of the Interstellar Medium. Pulsar signals are perturbed by the interstellar medium through which they pass. We directly measure the path integrals of the thermal electron density and the product of electron density and parallel magnetic field intensity. We can also measure the absorption of signals by H I at various radial velocities. These data may be combined with direct trigonometric parallax measurements of pulsar distances to map the galactic distribution of H I, electron density, and magnetic field in the solar neighborhood.

Pulsars also provide a unique means for probing thermal electron-density microturbulence on 10^{10}–10^{13} cm scales, via diffractive and refractive scintillations and via pulse timing variations. Dynamic spectral observations yield the column densities of scattering material that show enormous (up to a factor of 10^5) variations between different lines-of-sight. The turbulence is most likely related to regions of cosmic-ray acceleration. Multiwavelength radio, X-ray, γ-ray, and cosmic-ray studies of this microturbulence will be fruitful. These propagation effects also blur the images of extragalactic sources seen through the interstellar medium. Sensitive VLBI observations using the Green Bank Telescope will contribute to this investigation, and in so doing, will improve our knowledge of the wavelength- and position-dependent limits of angular resolution. Further progress will require the sensitivity to observe as many pulsars as possible, particularly those toward the galactic center.

2.1.5. Support for Space Missions. One of the major pulsar projects planned for the 300-foot telescope at the time of its collapse was a timing program in support of the orbiting Gamma Ray Observatory (GRO), planned for launch in 1990. GRO will be searching for pulsed γ-rays from about three-hundred radio pulsars. In order to fold the γ-ray photons at the correct pulsar period and phase, contemporaneous radio timing observations are essential. The 300-foot telescope was to be the primary instrument for timing about one-hundred of these pulsars. The Green Bank Telescope could do this type of job faster and for more pulsars, because of its increased sky coverage, sensitivity, and tracking ability.

2.2. Stellar Radio Sources. A wide variety of stellar radio-emission phenomena have been found in the last two decades. However, studies with the proper sensitivity and time/frequency sampling are not yet available; and since the emission is intrinsically weak, it has only partially been studied in that small number of objects with the most favorable characteristics. In this field the scientific problems are intrinsically multi-wavelength, and in most cases the radio emission from stellar surfaces is only a part of the information available. This coupling between different observational diagnostics is ideal for scientific progress, but it poses special needs for supporting work and coordination of programs.

Most radio star phenomena are $\lambda = 2$–90 cm "events" with time scales ranging from milliseconds to seconds, minutes, hours, and days as the size- and velocity-scales change. Objects with the shortest time scales are either compact systems like black hole binaries, neutron star binaries, and white dwarfs, or they are intense, high surface-brightness phenomena associated with flare stars and certain active binaries.

Compact stellar objects exhibit the most exotic and extreme forms of stellar radio emission. X-ray binaries like Cyg X-2, SS 433, and Sco X-1, at distances of hundreds to many thousands of parsecs, sporadically produce spectacular radio emission, briefly joining the company of the strongest compact sources in the radio sky. Jets and dynamical outflows couple 10^7–10^8 cm accretion flow phenomena around black holes and neutron stars to the larger (10^{12} cm) radio jets with very high velocities ($c/4$ to $c/3$) on time scales from tens of minutes on up. SS 433 and Cyg X-3 are cases for which radio outflows or jets have been directly imaged by the VLA and VLBI instruments, but most objects are so compact that only radio-spectrum and time-evolution diagnostics are available—not images. The large collecting area and frequency agility of the Green Bank Telescope make it ideal for these studies.

Flare stars—of which some tens are known radio sources (objects like UV Ceti and AD Leo are the most extreme examples)—emit variable, coherent, and highly polarized radiation from discrete regions on their surfaces, with time scales ranging from milliseconds to seconds. Stellar surface activity is most spectacular and most commonly found in binary systems because, in them, synchronous co-rotation forces magnetic dynamo action to levels considerably above what isolated stars can achieve. Many active systems like RS CVn binaries and Algol systems probably exhibit intra-stellar magnetospheric phenomena. These are analogous to Jovian magnetospheric phenomena, but scaled up to stellar sizes; involved are field–particle exchange, induced plasma instabilities, and related relativistic effects. Often radio flares reveal field–plasma interactions on scales 10^4–10^6 times the largest ever seen on the Sun. However, distance weakens the observed signals to the extent that only the largest telescopes are sensitive enough to sample their minutes-to-hours time/frequency characteristics.

Nova shells, recurrent novae, and supernovae are all phenomena where radio observations probe explosive phenomena on stellar "surfaces". Nova shells are thermal ejecta, radio observations of which help determine mass and velocity parameters. The one spectacular recurrent nova, RS Oph, exhibits radio supernova-like phenomena as lower energy ejecta interact with external matter in the form of a pre-existing wind. Much stronger are the radio supernovae, whose explosions produce prodigious energetic radio-emitting relativistic plasmas seen as evolving radio events. X-ray binaries (e.g., GS2000+25, A0620−003, Cen X-4) have such drastic and brief changes in accretion environments that dynamical events produce huge evolving volumes of radio-emitting relativistic plasma at intervals of tens of years (or more).

Symbiotic stars, VV Cep binaries, and planetary nebulae have interacting winds and dynamical ejection phenomena producing moving structures whose evolution is traced by the form of their thermal radio emission, providing information about energies, masses, and velocities.

Stars with cool winds (Betelgeuse, Antares, etc.) contain chromospheric radio sources which provide diagnostics of density structure and mass-loss rate. This emission occurs at 1–5 stellar radii, where the winds are energized and accelerated. In some binaries (the VV Cep type) companion hot stars light up radio-emitting H II sub-regions in the cool winds. In some cases, changes are seen as our aspect angle varies with binary motion. SiO, H_2O, and OH masers are spectroscopic probes of the outer layers of these cool winds. They also play a special role in studies of galactic dynamics.

2.3. The Solar System.

2.3.1. The Sun. The Green Bank Telescope will not only supplement the high-resolution imaging capability of the VLA by filling in the hole in the *u-v* plane at several frequencies, but will also be extremely useful as a solar imaging instrument in its own right at wavelengths shorter than 10 cm. The microwave spectrum of the non-flaring Sun has never been adequately characterized. For example, there remain difficulties in the interpretation of optically-thin EUV line emission from the solar transition region and microwave emission in coronal holes and in quiet regions. The ability to image the Sun at several frequencies with moderate resolution would be extremely useful in approaching this problem. Further, solar cycle variations of solar microwave emission have never been clearly defined over a wide range of frequencies. A program of routine, low-resolution solar imaging would be useful in defining solar cycle related changes in the upper chromosphere and transition region in coronal holes, quiet, and active regions.

Following solar flares requires both a dynamic spectral capability and a frequency agility. ("Dynamic spectroscopy" means sampling a relatively narrow bandwidth with high temporal and spectral resolution; "frequency agility" implies much coarser spectral resolution over a much broader frequency range.) While good spectral information has been available in the past for solar flares, it was usually obtained with small dishes or simple interferometers. As a consequence, it was not always possible to determine where on the Sun the flare occurred. Joint experiments involving both the imaging capability of the VLA and the frequency agility of the Green Bank Telescope could determine in which active region a particular flare occurs as well as provide a low-frequency dynamic spectral capability.

2.3.2. Planetary Radar and Spacecraft Tracking.

Bi-static (dual-observatory) radar observations of the ionosphere, planets, moons, comets and asteroids are likely to use the sensitive Green Bank Telescope as a receiver in concert with the Goldstone and possibly Arecibo transmitters, as the VLA has already been used. The VLA is needed to resolve radar ambiguities for some observations, but the Green Bank Telescope will have greater correlator flexibility for narrow-band detections and be easier to use than an array for delay-Doppler mapping.

The use of the VLA for the Neptune encounter suggests possible use (and support) of the Green Bank Telescope in future deep space missions.

3. Galactic and Extragalactic Neutral Hydrogen

3.1. Extragalactic H I.

3.1.1. The Structure and Kinematics of the Local Universe. In recent years, the 21-cm H I line has proved invaluable for mapping the spatial and velocity distributions of galaxies in the "local" ($D \leq 100$ Mpc) Universe. H I observations are the most effective tracer of the widely dispersed populations of gas-rich spiral and irregular galaxies in superclusters and low-density regions. Because of recent advances in receiver and spectrometer technology and feed design, the number of H I redshifts obtained has risen tenfold in the last fifteen years.

Studies of the distribution of galaxies over large scales (see Fig. II-2) have revealed the existence of clusters and filaments with dimensions comparable to the distances sampled, so the studies must be extended to include larger volumes of the local Universe. A spiral galaxy of moderate luminosity with $v < 12{,}000$ km s^{-1} could be detected in less than one hour with the Green Bank Telescope. More than 10,000 such objects are visible from Green Bank but outside the declination range of the Arecibo telescope. The Green Bank Telescope will be able to map the large-scale structure of the Universe in 85% of the sky (while from Arecibo only one-third of the sky can be seen). The southern hemisphere, in particular, 70% of which is accessible to the Green Bank Telescope, is crucial for future studies of large-scale structures.

In addition to yielding redshift distances, the 21-cm emission spectrum can be combined with optical or infrared luminosities to provide a redshift-independent means of estimating distances. Since its recognition by Tully and Fisher (1977), this technique has been refined so that it now provides the distance estimates with the highest accuracy. In the future this method will be used to measure the local velocity field, the scale of the Universe (the Hubble constant), the possible expansion of large-scale voids, and other deviations from the Hubble flow. These programs all require large samples of high-quality 21-cm spectra.

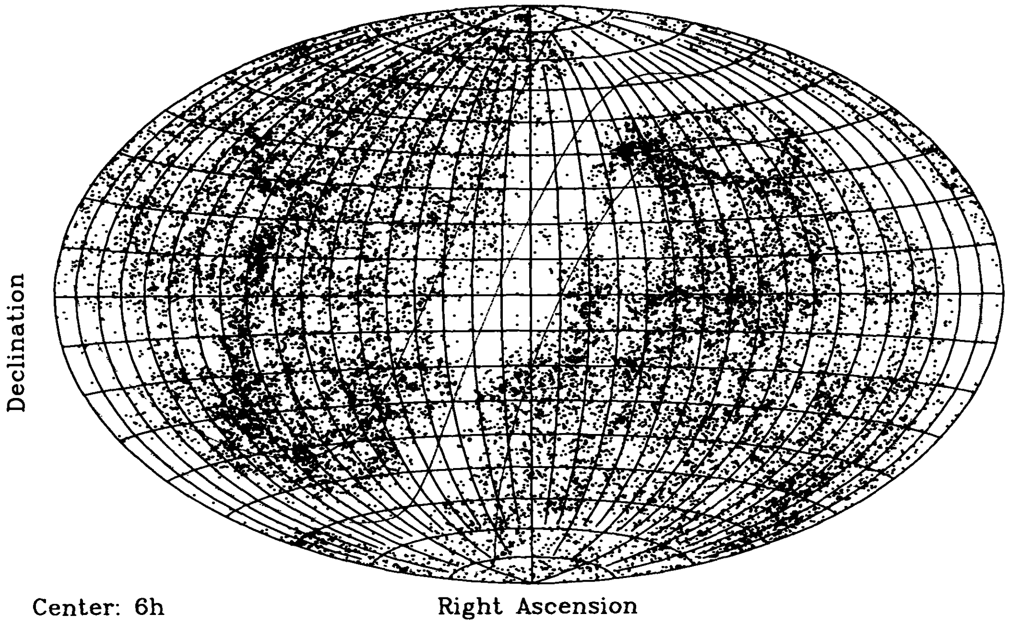

Figure II-2. Sky distribution of 25,000 nearby galaxies in equal-area equatorial coordinates, showing evidence for large-scale structure. The center of the map is at $\alpha = 6^h$, $\delta = 0°$, and the lines of $b = \pm 20°$ are drawn. The Picses–Perseus supercluster is prominent in the upper-right quadrant. The Virgo cluster and the plane of the Local Supercluster is evident on the left. The white band cutting diagonally through the center of this map is the zone of avoidance along the plane of our Galaxy. The Green Bank Telescope will cover the entire sky down to $\delta = -45°$.

3.1.2. Finding "Hidden" Galaxies. External galaxies are impossible to see in $\sim$ 20% of the sky, because of obscuration by dust and confusion produced by the high density of stars in our Galaxy. Recent pilot studies with the 300-foot telescope demonstrated that it is possible to find galaxies in this region by blind searching at $\lambda \geq 21$ cm. Such surveys require a large collecting area combined with low-noise detectors and could best be carried out with the Green Bank Telescope, using a multi-feed system for speed. Away from the immediate vicinity of the galactic plane, the search for spirals could be assisted by observing IRAS sources which have galaxy-like infrared spectra. The radio H I lines could be used to confirm their identifications as galaxies and to provide redshifts. A 21-cm census of all the spiral, irregular, and gas-rich galaxies in the zone of avoidance behind the Milky Way will be very valuable for filling in the blank areas in our picture of overall large-scale structure (see Fig. II-2).

3.1.3. Low-Luminosity Galaxies, and the Material Content of Voids. Gas-rich, low-mass extragalactic objects that are difficult to detect optically have recently been discovered. These objects are significant for theories of galaxy formation, and it is especially important to determine their density distribution, including whether or not they are found inside the voids where the larger and more massive galaxies are almost absent. The Green Bank Telescope should enable many more of these objects to be studied at 21 cm. It will then be possible to understand their relationship to other types of galaxies by working in conjunction with the Hubble Space Telescope and other space observatories.

3.1.4. Primordial Hydrogen Pancakes. Two competing theories, called the "top down" and "bottom up" scenarios, describe the development of the Universe from very smooth initial conditions to the clustering of galaxies observed now. Both scenarios are partially successful, and a critical experiment is needed to decide between them.

The key difference is the existence of "hydrogen pancakes" in the "top down" picture only. These $\sim 10^{15} M_\odot$ clumps of H I are hypothesized to be progenitors of superclusters of galaxies, but they have not yet been observed. Current surveys for the redshifted 21-cm line of H I do not have adequate sensitivity, and they are confined to the 0.33 GHz band in which both the VLA and Westerbork operate. This corresponds to $z = 3.3$, which may be too low because the onset of quasar emission at this redshift might have ionized and destroyed all but the densest hydrogen pancakes. The optimum redshift range for finding pancakes is $4 < z < 10$. A search should be conducted with both high sensitivity (the expected signals range from 0.1 mJy to 10 mJy, depending on redshift and other cosmological parameters) and broad frequency coverage in the 0.12 to 0.3 GHz range. The high sensitivity and beam efficiency of the Green Bank Telescope and the interference protection in the National Radio Quiet Zone combine to offer the best chance for detecting these primordial hydrogen pancakes.

3.1.5. High-Redshift H I Absorption. The stellar and gaseous components both play critical roles in the evolution of a galaxy to its present morphology. H I studies at high redshifts probe the gaseous disks of galaxies at early epochs. Because of the great distances involved, H I can only be detected in absorption from galaxies lying in front of powerful background radio sources. Two approaches to the study of redshifted 21-cm absorption lines have been taken in the past: (1) Radio absorption has been detected at known optical absorption redshifts of quasars. (2) Radio spectra of quasars have been searched without consideration of optical characteristics. Both techniques require high sensitivity at low frequencies outside protected radio astronomy bands, and interference is a very serious problem.

About ten systems with identical optical and radio absorption redshifts have been found. Comparison of their velocity dispersions and column densities with those of nearby objects indicate that the highly redshifted absorbers are similar to clouds in the Milky Way. Perhaps the most exciting result has been the measurement of the extent of the absorber in one source, clearly indicating that it has a disk-like structure (Brown *et al.* 1988). In studies of this kind, the radio observations are used in conjunction with those obtained at other wavelengths. Future detection of high-redshift systems with the HST, ROSAT, AXAF, and large ground-based telescopes will provide more candidates for study. Maps of the radio continuum sources will be made with the VLA or VLBA. Addition of the H I line information is critical because of the comparison with galactic clouds, and because of the unique clues that the radio observations can provide. Observations of a much larger sample are necessary to decide whether these absorbers really represent the youthful disks of today's galaxies or a more distinct population of objects found only in the early Universe.

Even without an optical absorption redshift it is possible to scan the entire radio frequency range from the H I rest frequency to the frequency corresponding to the emission-line redshift of the background radio source to look for intervening material at any intermediate redshift. (Such a broadband search is often not possible in other wavebands, because of instrumental or atmospheric restrictions.) Hence the entire path from the Milky Way to the background source can be searched. The results obtained from many lines-of-sight can be analyzed to determine the large-scale distribution of absorbers. Probing lines-of-sight through galactic (or pre-galactic) disks at varying radii will provide strong constraints for theories of galaxy formation. It will also lead to better understanding of the universal UV radiation field in the early Universe and, hence, of the UV and X-ray background radiation. Using large samples spanning the redshift range $1 < z < 3$, we might even determine important information on the structure of the Universe (e.g., the deceleration parameter q_0). Although this approach can potentially produce valuable cosmological results, its application has been limited by the lack of adequate frequency scanning and interference excision capability. Both limitations can be removed by the new spectral processor developed in Green Bank.

3.1.6. H I Content—Galaxies, Clusters, and Groups. The global properties of galaxies (total mass, H I mass, mass-to-light ratio, surface density, etc.) help us to understand the cycles of galactic evolution on a large scale. Gaseous disks are excellent tracers of the total (mostly dark) mass distribution. They determine the long-term rate of star formation and are ultimately responsible for the morphological appearance of a galaxy. Gaseous disks are also vulnerable to dynamical and thermal perturbations from the galaxy's environment. Observations of the H I content of a galaxy thus provide good probes of the surrounding physical conditions. These observations have been used to study the interactions of galaxies with their neighbors, the intergalactic gas, and the intergalactic radiation field. As a result, important inferences have been drawn on the influence of environmental conditions on galactic evolution.

The Green Bank Telescope will extend these studies to much larger samples of nearby galaxies than previously possible. More importantly, it will allow the study of the recent evolution of clusters of galaxies. Because most clusters of galaxies have not yet reached dynamical equilibrium, their integrated properties, even at look-back times as small as $z = 0.3$, should be significantly different from those exhibited at the present epoch. Analysis of the H I deficiency of cluster galaxies as a function of redshift should provide insights into the origin of the hot, metal-enriched intracluster gas. Studies with the next generation of X-ray orbiting telescopes (ROSAT and AXAF) will doubtlessly bring about renewed efforts in understanding the phenomenology of clusters of galaxies.

Because of recent major improvements in receiver and feed technology, attention has also been focused on less H I-rich objects, such as elliptical and lenticular galaxies. Very early-type galaxies had once been thought of as extremely gas-poor—and thus uninteresting to 21-cm observers. Recent advances in other wavelength domains (X-ray, optical, IR) have shown this to be untrue. The Green Bank Telescope will allow the investigation of neutral interstellar gas in early-type systems, detectable either in the form of broad, faint signals stretched over the whole velocity domain of the galaxy, or as weak, slowly infalling accretion flows of cooling gas.

In small groups of galaxies, the low relative velocities of group members and the right combination of orbital parameters can give rise to spectacular tidal effects. Gaseous disks, because they extend farther out than any other visible component of the galaxies, are ideally suited to mapping the occurrence and the dynamical details of disruptive encounters. The signatures of such disruptions are easily detected in high signal-to-noise global spectra of interactive systems. The details of the interaction can later be mapped with interferometric techniques. These systems are valuable because they can be used to test dynamical models, sample the total (mostly dark) mass distribution in groups, and probe the intergalactic UV radiation field and the incidence of mergers. The sky coverage and the sensitivity of the Green Bank Telescope will facilitate these studies.

3.2. Galactic H I. The large-scale structure of the Milky Way disk is a matter of continuing interest and controversy, three decades after the discovery of interstellar hydrogen. Specific areas of uncertainty include: the distribution of gas in the nuclear (central 1 kpc) region and the relationship between the gas reservoir and energetic phenomena observed there; the distribution of neutral material across the disk and its partition between spiral arm and interarm regions; the rotation curve of the Milky Way, from which the overall distribution of matter (stellar, gaseous, and dark) is inferred; departures of the disk from co-planarity at large galactocentric radii (warping); and flaring or broadening of the disk. The 21-cm line of neutral hydrogen is one of our most powerful tools for investigating the range of interstellar phenomena, from global galactic properties to the energy balance in the interstellar medium.

3.2.1. The Galactic Center. The central kiloparsec of the Galaxy contains an enormous reservoir of neutral gas. The gas is being processed in a variety of ways which are unique to this region of the Galaxy, resulting in a variety of prominent (continuum) structures extending both along and perpendicular to the galactic plane. Observations with existing instruments have revealed the broad outlines of these phenomena but are not sufficiently detailed to draw an overall picture of the history and evolution of the nucleus.

To specify the pattern of behavior in the nucleus, higher resolution maps of H I are required. H I samples more of the gas and more of the velocity field than does CO or other dense-gas tracers. It can, through observations in both absorption and emission, provide direct spatial information on the front-to-back placement of various gas components. These observations must be made with good spatial resolution, both to discriminate against unrelated foreground/ background H I and to minimize confusion among the many continuum sources in the central region. Furthermore, the telescope must have exceptionally low sidelobes, so that weak features can reliably be assumed to lie where they appear to be, and so that continuum sources do not appear in the sidelobes, distorting both the baseline and the emission profiles.

3.2.2. The Disk of the Milky Way, Interior to the Solar Circle. Questions remain about the distribution of the H I in the galactic plane on scales of ~ 20 pc (~ 9 arcmin) and larger, and the forces that cause this distribution.

Molecular clouds are the most spectacular components of interstellar gas inside the solar circle. Most molecular clouds not only contain an atomic component, but also are surrounded by a "halo" of H I. The Orion region, for example, is surrounded by an H I cloud that is at least as massive as the embedded molecular clouds. Limited surveys with 10-arcmin resolution reveal giant H I envelopes around all of the major star-forming regions such as W43 and W49. The H I acts as an interface between the molecular clouds where the stars form and whatever lies beyond. Our understanding of the molecular/atomic interface is primitive mainly because we lack H I observations with sufficient angular resolution and sky coverage.

Just as prominent as the gravitationally bound molecular clouds are the expanding shells of H I driven by supernovae, by groups of supernovae in stellar clusters, and by stellar winds. Some of these shells are closed, while others are driven by enough supernovae to break out of the Galaxy into the halo. They rise above the galactic plane to galactic latitudes of at least 10°. None of the existing 10-arcmin class surveys go above 2° in latitude. H I maps of these structures would quantify the filling factor of the supernova-produced bubbles and reveal the extent to which matter is injected into the galactic halo by these energetic events. Such matters are at the very heart of the basic theoretical structure of the interstellar medium.

3.2.3. Beyond the Solar Circle. Outside the solar circle, the thin gaseous disk becomes progressively thicker and shows a coherent warp which lifts it progressively farther away from the plane defined at smaller galactocentric radii. The cause of the warp is unknown, although speculation centers on a tidal encounter between the Milky Way and the companion Magellanic Clouds. The mechanism which has *maintained* the warp is even more mysterious, since it might be expected in a largely planar system that strong forces normal to the galactic plane would be a strong confining influence.

Studies of the outermost parts of the Galaxy require high angular resolution and excellent sensitivity, since there are subtle effects revealed only by very weak H I emission. Some of these involve the connection of the warp with high-velocity clouds, and some involve extensions of the lower-velocity portions of the warp to high z-distances. These cannot be reliably observed with existing telescopes because of contamination by "stray radiation" in the telescope sidelobes. The low sidelobe levels of the Green Bank Telescope are essential for these observations.

3.2.4. Halo Gas. No satisfactory inventory of halo gas exists. Copernicus and IUE observations have provided evidence that superbubbles in the galactic plane create outflowing winds of hot gas, which is expected to cool and fall back to the Plane. This cool, infalling gas probably accounts for at least some of the high- and intermediate-velocity clouds. In addition, very faint emission (0.01 K, 10 km s^{-1} broad) has been found in some regions of sky in the intermediate-velocity regime. Observations with high sensitivity, high resolution, high dynamic range, and good baselines are required to discern such emission. The existence of shock boundaries between the clouds and either halo- or intergalactic space should be recognizable through these types of observations.

3.2.5. High-Latitude H I Mapping. The study of large numbers of high-latitude H I clouds with the reasonably high angular resolution of the Green Bank Telescope would address the overall topic of interstellar gas dynamics and thermodynamics. Some of these high-latitude clouds may be radiative shocks. The 9 arcmin beam of the Green Bank Telescope would allow us to observe the detailed structure of thermal instabilities within the shocks. We expect that such instabilities will occasionally lead to structure on much smaller scales. Surveys with 9 arcmin resolution would locate the best compact regions for detailed mapping by the VLA.

Radiative shocks should produce regions with very high densities. H_2 is predicted to exist in such regions, and its presence can be inferred by comparing the 21-cm line intensity with the 100μm IR brightness derived from IRAS maps. The IR brightness is proportional to the total column density of H nuclei, both atomic and molecular, while the 21-cm brightness is sensitive only to H I. Many such regions have already been found by H I surveys with ~ 30 arcmin angular resolution. The 3 arcmin resolution IRAS data show that the clouds are clumpy at the 9 arcmin scale. Detailed comparison of the H I and IR brightnesses on this scale will reveal details about the chemistry of H_2 formation and destruction that are unobtainable by other means. Further comparison with CO observations should reveal corresponding information about the CO chemistry. The limited existing studies indicate that CO is much more highly clumped than H_2, as expected from our knowledge of CO chemistry.

The edges of clouds are fascinating places because they are the interfaces between the cold neutral matter (CNM) of the cloud and whatever lies outside. For the environment, there are three candidates: (1) warm neutral matter (WNM), (2) warm ionized matter (WIM), and (3) the hot ionized medium (HIM). Here "warm" means $\sim 10^4$ K and "hot" means $\sim 10^6$ K.

The character of the interface should differ for the three types of outside matter. The WNM can be directly observed in the 21-cm line itself. The WIM is similar to standard H II regions. The boundary between the WIM and the neutral media should be sharp and should presumably have a large pressure jump which will produce conditions not unlike those at the edge of an H II region, with its accompanying velocity and density discontinuities. Details of the HIM/H I interface depend sensitively on geometry and magnetic field configuration. This is currently a murky area, but by studying these details observationally we hope to determine if existing theories are correct and to obtain values of some of the important parameters.

More important for the overall dynamics of the interstellar medium, however, is simply the statistics: What fraction of each kind of interface is there?

This would tell us the fraction of volume occupied by each of the WNM, WIM, and HIM—a question of major importance for the large-scale models of the ISM, because it depends on supernova rate and the methods by which the supernova energy is dissipated. If we are able to classify the type of interface simply by the appearance on 9-arcmin resolution H I maps, then we will have an extremely powerful tool for studying the basic properties of all phases of the interstellar medium.

3.2.6. High-Velocity Gas. A significant quantity of H I has velocities not attributable to galactic rotation. The "high-velocity" gas label covers a number of phenomena, from the Magellanic Stream, which is almost certainly the remnant of a tidal interaction with the Magellanic Clouds; through H I clouds like those in Draco, which may be falling in from the galactic halo; to the classic high-velocity cloud (HVC) complexes whose distance, mass, and dynamics remain poorly determined more than twenty years after their discovery. Most high-velocity gas has been observed only with beamwidths > 30 arcmin. This is adequate for making an initial inventory of the material but not for detailed study or classification. For example, many HVCs contain small-scale structure, perhaps due to thermal instabilities, shocks, or ionization by intergalactic UV, that cannot be seen with the low angular resolution of most existing data.

More sensitive and extensive observations of this gas will be needed to separate objects into different populations and perhaps identify still-unresolved regions for more detailed study by aperture-synthesis instruments. The Green Bank Telescope is extremely well suited for observing this material, because it has good angular resolution, exceptional sensitivity, and freedom from systematic effects which limit dynamic range.

3.2.7. The Importance of H I for Soft X-Ray and EUV Data. Stars with active chromospheres and very hot stars emit EUV radiation. Soft X-rays provide data on various types of X-ray source, and they also provide the only information on the "hot interstellar medium", the $\geq 10^6$ K gas that may occupy up to 50% of interstellar space. All EUV and soft X-ray observations are affected by absorption in the intervening warm and cold media, so knowledge of the H I column density on reasonably small angular scales is required for their interpretation.

For 100 eV X-rays, an H I column density of only 10^{19} cm^{-2} has an optical depth of order unity. Thus, accurate determinations of H I column densities are essential to correct observed X-ray fluxes for absorption. We need this information on angular scales smaller than scales at which significant fluctuations occur in the H I column density, that is, on scales of order 9 arcmin. Regions of low H I column density, where the X-ray and EUV observations can be made over long path-lengths, are particularly interesting; in these regions, accuracies are limited by the the effects of sidelobes.

3.2.8. Interstellar Spectroscopic Studies. Optical and UV absorption-line spectroscopic studies have created a new demand for high-quality 21-cm H I spectra. Many interstellar phenomena must be studied across the electromagnetic spectrum because the lines in each waveband usually trace only a limited range of physical conditions. Moreover, the equivalent widths of most common optical/UV lines depend critically on the ionization state and depletion of a specific cloud. Thus H I spectra are needed to determine abundances and the ionization balance, and also because they provide the best estimator of the mass of gas involved in a particular spectral feature. H I spectra of the required sensitivity, dynamic range, and angular resolution do not exist in most directions of interest, but they will be obtainable with the Green Bank Telescope.

3.2.9. Magnetic Fields: The Zeeman Effect. Zeeman studies of H I in emission have given the most accurate estimates of magnetic fields in interstellar clouds, but at present such studies can be done only with ∼ 30 arcmin resolution. While this is adequate for determining the average field, it is insufficient to study the relation between the magnetic field and volume density within clouds and shocks.

Magnetic fields are also important in dense clouds. They can be studied using Zeeman splitting of either the 18-cm OH line seen in emission or the H I line seen in self-absorption. The latter is strong and easily detected, at least in some clouds, while the former is very weak and requires very long integration times. Both are needed because they sample somewhat different portions of the cloud and sometimes give different results. Studies to date have shown that magnetic fields and kinematic motions are in rough equipartition, and together are in rough virial equilibrium with self-gravity.

We would like to go further and test theories of star formation in which the magnetic field determines whether low- or high-mass stars are formed preferentially. Many star-formation theories rely on the field to remove angular momentum during the star-formation process. Understanding issues such as these will require mapping the magnetic fields within a sizable selection of clouds in both OH and H I. In some cases, mapping the field with the higher angular resolution of the VLA may be required, and the Green Bank Telescope will allow us to select the most interesting regions for such work.

4. SPECTROSCOPY

4.1. Extragalactic Studies.

4.1.1. CO at Cosmological Redshifts. The $J = 1$–0 CO line will become the transition of choice for studying galaxies and quasars at cosmological redshifts, because it can be detected at far higher redshifts than any other radio line. Per unit mass of gas, the relative sensitivity is more than two orders of magnitude greater in the CO line than in the H I line. A large "normal" galaxy such as NGC 4321 in the Virgo Cluster could be detected in the CO line by the Green Bank Telescope in one hour at $z \approx 1$! The higher CO frequency also yields a smaller beamsize for reducing confusion at high redshifts. Furthermore, it is relatively interference free. Frequency coverage between 20 GHz and 50 GHz corresponds to CO at redshifts $1 < z < 5$. Only the region $0.7 < z < 1.0$ is inaccessible, owing to opacity from telluric oxygen.

Present data suggest that the evolution of stellar populations in galaxies has been strong over look-back times corresponding to redshifts $z \lesssim 1.5$. Even at $z \approx 0.75$, galaxies in dense clusters appear bluer than those in nearby clusters (see the review by Oemler 1986; also Gunn and Dressler 1988). Star formation in these systems may occur in massive starbursts, which were more intense or more frequent in the past. The fraction of elliptical galaxies in the cores of dense clusters, almost 100% at the present epoch, was only 70% at $z \approx 0.5$. Thus ellipticals formed not only at the first epoch of galaxy formation, but also up to fairly recent times. Examples of the huge starbursts thought to herald the formation of elliptical galaxies are close enough that emission from their interstellar media could be detected and studied by a sufficiently sensitive telescope. Local examples of the starburst phenomenon are currently targets of intensive research. Do mergers between colliding galaxies initiate this process? Does total gas content determine its duration? Does the host galaxy eventually become a giant elliptical? Stars form in molecular clouds, and answers to these questions will be addressed through study of these clouds. The vital physical parameters—mass, temperature, mean density, star-forming efficiency—are measured through CO observations, which already extend to $z = 0.18$. The increase in sensitivity afforded by the Green Bank Telescope should extend these observations to look-back times when galaxies were significantly different than they are today. Quite possibly, galaxies could be observed at the epoch of their formation.

Particularly interesting are the host galaxies of QSOs. Strong CO emission has been detected in I Zw 1 (Barvainis, Alloin and Antonucci 1989) and Mrk 1014 (Sanders, Scoville and Soifer 1988), and others are being searched. Through the starburst, molecular clouds may create the stellar population which feeds the central engine of a QSO (Norman and Scoville 1988). CO observations with existing telescopes have identified galaxies in these first stages of activity. Since the QSO phenomenon has evolved strongly, being more common in more distant galaxies, the Green Bank Telescope should reveal many new objects for detailed study. With the Green Bank Telescope, galaxies such as I Zw 1 and Mrk 1014 will be detectable in CO at redshifts of 3 [CO ($J = 1\text{–}0$) redshifted to 29 GHz] with line antenna temperatures exceeding 5 mK. Not only would the Green Bank Telescope be an effective "redshift machine", but it would also allow us to explore the evolution of the molecular content in galaxies from the epoch of galaxy formation to the present.

4.1.2. Other Molecules. A variety of global configurations of molecular gas have been found in emission in external galaxies: (1) a central source plus disk; (2) a central source plus annulus; (3) an annulus without a central source; and finally, (4) emission from isolated regions. How are these large-scale morphological characteristics of galaxies related to the relatively microscopic process of star formation? How is star formation affected by the chemical evolution of the galaxy? To answer these questions, it is necessary to study the physics of the individual clouds, as derived from spectroscopy, and to seek correlations between morphological and chemical parameters. Some molecules have several radio-frequency transitions. Spectroscopic comparisons among them provide densities and temperatures of the radiating region. Thorough, multi-transition studies are scarce, though first steps have been taken in the study of ammonia emission. In addition, CS, HCN, and HCO^+ have been used successfully to map the molecular structure of nearby galaxies. As an example, M82 has a molecular ring of

200 pc radius, to which CS emission is confined. The Green Bank Telescope will permit observations of a variety of molecular lines in an extended sample of extragalactic sources, thus allowing the determination of densities, temperatures, and abundances. To illustrate the Telescope's potential, note that recent searches with the 30-m IRAM telescope in the galaxies NGC 253, IC 342, and M82 have detected CN, C_2H, HNC, CH_3OH, and possibly HC_3N. But such detailed observations have always been sensitivity-limited. The Green Bank Telescope will cover the 30–50 GHz frequency range (containing transitions of CS, HC_3N and CH_3OH) with unequalled sensitivity. It should contribute greatly to the understanding of molecular processes in other galaxies.

Molecular gas in other galaxies has also been detected in absorption against their centimeter-wave nuclear continuum sources. Naturally, absorption searches have concentrated on galaxies with strong continuum emission and on molecules with centimeter-wave lines, such as OH, CH, H_2CO, and C_3H_2. About 30 extragalactic absorption lines have been found to date, mostly in edge-on disk systems. These observations are most useful for determining the near-nuclear kinematics of the molecular gas. Many of the extragalactic 1667 MHz OH absorption-line profiles are asymmetric—a possible clue to the kinematics and distribution of the absorbing cloud within the host galaxy. For example, some nearby galaxies with extended radio nuclei exhibit strong H I, OH, and H_2CO absorption in their edge-on disks. Observations at the VLA resolved the absorption features so that the disk kinematic structure could be determined, revealing a rotating disk accompanied by an outflowing shell of gas. Its resemblance to the outflowing gas seen in our Galaxy suggests that the shell is a relic of past nuclear activity. Although OH at 18 cm has received the most attention, the line ratios for the different 18-cm transitions do not provide sufficient information to determine the physics of the gas. Searches conducted for the excited OH lines at 4.8 and 6.0 GHz, for the 4.8 GHz line of H_2CO, and for C_3H_2 at 18.2 and 21.6 GHz have achieved some success, but the improved sensitivity of the Green Bank Telescope will be needed to study these intrinsically weak lines in detail.

4.1.3. Masers. Strong OH maser emission from the peculiar galaxy IC 4553 (Arp 220) was discovered in 1982. This source was dubbed a "megamaser", since its luminosity is about 7×10^7 that of the W3(OH) masers in our Galaxy. A total of 21 OH megamasers with isotropic luminosities in the 1667 MHz OH line ranging from 2 to 1100 solar luminosities have since been found. Water and formaldehyde (H_2O and H_2CO) also exhibit masing characteristics. H_2O masers with luminosities similar to those found in our Galaxy have been known in external galaxies for the past ten years, but recently H_2O masers with luminosities up to 500 times the Sun's and six H_2O megamasers have been found.

These powerful extragalactic masers all seem to be associated with nuclear activity or a burst of star formation. It has been suggested that all OH megamaser activity occurs in the very early evolutionary stages of Seyfert activity and that it could be triggered by the merger of two galaxies. Most (if not all) megamasers appear to be superimposed on the continuum radio emission originating in the nuclear region of the host galaxy. OH megamaser galaxies are among the strongest sources in the IRAS Point Source Catalogue, with far-infrared (FIR) luminosities $> 10^{11}\ L_\odot$.

A generally accepted model for megamaser galaxies involves low-gain amplification of the nuclear radio continuum by foreground molecular gas. In the case of the OH sources, strong FIR radiation in the nuclear region provides a pump for inversion of the OH molecular population. For H_2CO the nuclear radio continuum can act as a pump, while for H_2O strong shocks may generate densities high enough that collisional processes invert the H_2 population in the shocked layer. The radial distance of the amplifying gas ranges from 300 to 50 parsecs, and some recent OH results suggest distances of 10 pc or less.

The megamaser phenomenon has some very interesting implications for the molecular regions in the nuclei of galaxies. The amplifying clouds are located very close to the nucleus—even inside the narrow-line region—and they all lie along one line of sight. Hence observation of molecular megamasers probes the nuclear regions of active galaxies. Without a doubt, more molecules will be detected in the future via their masing transitions, allowing for new insights into the physics of active nuclei. The Green Bank Telescope will have the flexibility to exploit these future detections.

4.2. Galactic Studies.

4.2.1. The Stellar Disk. Galactic OH/IR stars are excellent test particles for mapping the structure and kinematics of the galactic stellar disk. About 10^5 such stars could be detected by the Green Bank Telescope, but only 2,000 are now known (te Lintel Hekkert and Habing 1988). A very large sample of these stars is needed for kinematic distance estimates so that the three-dimensional structure of the galactic stellar disk can be mapped as a function of distance from the galactic center, in the same way that observations of the H I and CO gas give the three-dimensional structure of the gas layer. The vertical structure of the gaseous and stellar disks can be used together to constrain the nature and distribution of galactic dark matter, the history of star formation, the total mass of the galactic disk (the "Oort limit"), the existence or not of the "thick disk", the scattering of stars by molecular clouds, and the stability of the gaseous disk to star formation. The present sample is not large enough to do this—the intrinsic stellar velocity dispersion (interesting in its own right) means that a sample of $\sim 10^4$ stars is needed. The line of interest, the OH 1612 MHz line, is badly affected by interference from satellites, so the low sidelobe level of the Green Bank Telescope is needed for interference suppression to continue this work.

4.2.2. Evolved Stars. While H_2O masers have been used primarily for measuring stellar kinematics, SiO masers yield information on the near-stellar environment. The ground state and $J = 2\text{–}1$ transitions at 43 and 86 GHz provide keys to understanding the transition-to-transition variations in the lines.

H_2O emission from evolved stars is a relatively unexplored area. For example, observations of a large sample may well find a number of those rare objects which are currently evolving toward the planetary nebula stage. Some of these stars appear to be expelling molecular gas at speeds in excess of 200 km s^{-1} (Likkel and Morris 1988; Gammie *et al.* 1989). This field is likely to become a lively one at millimeter and submillimeter wavelengths in the immediate future, and H_2O observations both complement these observations and allow the statistics of the objects (and hence the lifetimes in various phases) to be examined.

4.2.3. Cores of Dense Clouds. With a beam size < 30 arcsec at all frequencies > 25 GHz, the Green Bank Telescope is well suited to study the physics of dense cloud cores. Most methods for estimating densities in clouds rely on determining the excitation temperature of a particular molecular transition and relating it through the equations of statistical equilibrium to the total gas density via the collisional excitation rates. At centimeter wavelengths, NH_3 and H_2CO are useful diagnostics of the temperature and density of cloud cores. The Green Bank Telescope will also access a number of new diagnostic molecules such as HC_3N, C_3H_2, CH_3OH, HNCO, and SO.

As an illustration, consider HC_3N. It is a good density probe of cold, moderate-density clouds (Vanden Bout *et al.* 1983)—numerous transitions are excited and easily observable; and the lines are likely to be optically thin, so that problems of interpretation in the presence of radiative trapping effects are minimized. At temperatures of 10–20 K and densities below $\sim 5 \times 10^4$ cm^{-3}, the strongest transitions of HC_3N are the 3–2, 4–3, and 5–4 lines at 27, 36, and 45 GHz. Higher lines are quite weak, apparently as a result of a lack of excitation capacity in the clouds.

The C_3H_2 molecule produces a number of spectral line combinations whose frequencies, although close together, arise from levels at differing energies (Avery and Green 1988). This attribute makes C_3H_2 an unusually useful species for the precise determination of physical conditions in diffuse clouds and in dense cloud cores of all temperatures.

The detections of strong new maser lines from the 4_{-1}–3_0 E-type transition of methanol (CH_3OH) at 36.1 GHz (Haschick and Baan 1989) and from the 7_0–6_1 A^+ transition at 44.1 GHz (Menten *et al.* in preparation) underline the importance of the scarcely explored frequency range from 25 GHz to 50 GHz toward an understanding of the physics of molecular clouds. These lines provided the missing link for an understanding of one aspect of the maser phenomenon in methanol. For example, in the molecular cloud toward DR21(OH) the 2_0–3_{-1} line at 12.1 GHz is seen in absorption against the microwave background since no centimeter-continuum is associated with the source (Batrla *et al.* 1987), while the 5_{-1}–4_0 line at 84.5 GHz exhibits a 145 K maser emission line (Batrla and Menten 1988). The 4_{-1}–3_0 E-line is a maser as well, with an almost identical line shape to that of the 84.5 GHz line. Model calculations of radiative transfer show that this behavior of three lines out of consecutive J-levels in the same K-ladder of E-type methanol can be explained only by collisions in a low-temperature, high-density environment (Walmsley *et al.* 1988).

Under completely different excitation conditions, toward compact H II regions, the 12.1 GHz line—seen in absorption against the microwave background in cold clouds—is detected in maser emission at flux densities exceeding those of OH masers associated with the same sources. The multitude of masing molecules and lines over vastly different excitation conditions offers a unique chance to solve the problem of maser excitation.

4.2.4. Magnetic Fields and the Zeeman Effect. Magnetic fields play a fundamental role in the dense cores which are about to form protostars. Molecules such as OH, C_4H, C_2S, and SO are well suited to Zeeman measurements of magnetic field strength. The Zeeman effect is largest at the lowest rotational levels, which lie in the 9 to 23 GHz region for these species. The large Green Bank Telescope is needed to detect and resolve the small star-forming cores adequately in this frequency range.

4.2.5. Diffuse Clouds. Radio molecular observations are particularly important inputs for models of diffuse interstellar clouds, because they have higher velocity resolution than can be achieved optically. Exceptionally narrow line components can hide substantial abundances of species whose chemistry would be misinterpreted on the basis of insufficiently high resolution data (Liszt 1979). Also, molecular regions often have numerous narrow velocity components and an exceedingly clumpy structure (Langer, Glassgold, and Wilson 1987). High spatial- and velocity-resolution observations are needed to refine models of diffuse clouds.

Some lines observed in diffuse clouds are stronger than expected, suggesting electron collisions may augment neutral collisions as a source of excitation. Since this phenomenon is more important for molecules with larger dipole moments and the since stronger transitions of heavy molecules lie within it, the centimeter window is crucial to its study. While the physics and interpretation of the observations are currently unclear, progress may eventually provide a tool for tracking electron abundances in diffuse clouds.

4.2.6. Astrochemistry. The study of chemistry requires maximum frequency coverage, because the most important transitions of different types of molecules, under differing physical conditions, occur at wavelengths ranging from the centimeter to the sub-millimeter. This dependence of spectral features on molecular structure and physical conditions is outlined below for linear molecules. (Nonlinear molecules behave similarly, but they are more difficult to treat.)

The integrated brightness temperature for a given molecular line is proportional to the square of the frequency of the line, multiplied by the population of the initial energy level involved in the transition. For a linear molecule in thermal equilibrium among its rotational energy levels, these two factors result in a transition frequency of maximum intensity which is proportional to the square root of the product of the molecular constant B and the temperature. Since the rotation constant is roughly proportional to the inverse cube of the number N of heavy (non-hydrogen) atoms in the linear molecule, the frequency of the most intense spectral feature of a linear molecule is proportional to $\sqrt{B}$, or to $1/\sqrt{N^3}$. The strong spectral features of larger molecules will be in the centimeter range, whereas those of smaller molecules will be in the millimeter or even the submillimeter range. *Thus, the centimeter spectral region, in addition to playing an important role in the astrophysics of molecular clouds, is now being recognized as highly important in clarifying the astrochemistry as well, a role previously emphasized more for the millimeter and submillimeter spectral regions.*

4.2.7. Dark Cloud Astrochemistry. Compared with giant molecular clouds, dark clouds are nearer, less massive, colder, and lacking in formation sites for massive stars. They are excellent laboratories for astrochemistry, since high spatial resolution allows accurate determination of local physical conditions and the absence of high temperature processes simplifies the chemical models that need be considered. Although there are some basic similarities in the observed abundances in dark clouds to those in the more quiescent portions of large, warm molecular clouds, there are also fascinating differences, both among clouds and, apparently, within a given cloud. A well-studied example is TMC–1, in which condensations are found with linear dimensions approximately equal to those of the Oort cloud and masses approximately equal to a few solar masses. To evaluate chemical models properly, multi-transition, multi-species maps are required to compare such physical conditions as kinetic temperature, density, and UV radiation field with derived abundances. Since structure is seen in these clouds down to the scale of current single-dish beams, the higher angular resolution that the Green Bank Telescope will provide is clearly desirable. Dark clouds are formation sites for low-mass stars, and TMC–1 has been referred to as a "proto-solar nebula". A search for chemical effects in truly solar system-sized regions in such nebulae would be very exciting. Dark clouds have been fertile sites for recent searches for new molecules, many of which have been long-chain carbon molecules. For example, the Nobeyama survey of the 36–50 GHz spectrum of TMC–1 has detected 60 lines of 19 molecules, as well as 13 lines from 9 isotopomers of these molecules and 20–30 unidentified lines (Kaifu *et al.* 1989). Figure II-3 displays an interesting portion of the TMC–1 spectrum. The additional sensitivity of the Green Bank Telescope should reveal weaker species in the same band.

Frequency agility is needed to identify individual molecular types, since it is risky to base an identification on a single transition. Consider the molecule CH_3C_5N, which has been tentatively identified in TMC–1 via a transition at 20.2 GHz. Confirmation will require observations of other transitions at frequencies spaced every 1.5 GHz. The most useful confirming transitions are ones separated rather widely in frequency. In addition to the desirability of frequency agility for the purpose of identification, such a capability enables simultaneous mapping of two or more transition frequencies of known molecules in order to determine excitation conditions and abundances.

4.2.8. Rare Isotopes of Cosmological Interest. The Green Bank Telescope would offer significantly improved opportunities to observe rare isotopes formed during the era of cosmological nucleosynthesis—deuterium (D) and helium 3 ($^3He^+$), for example.

The abundance of D establishes an upper limit to the baryon-to-photon ratio of the universe. Every previous measurement of D abundance, optical or radio, has been surrounded by controversy. The abundance anywhere outside the solar system is uncertain by a factor of ten, and even the protosolar value is affected by many uncertainties. One of the most promising ways to determine the D abundance is via the 327 MHz hyperfine line of D I. Many recent efforts at measuring this line have been thwarted because of interference. The large

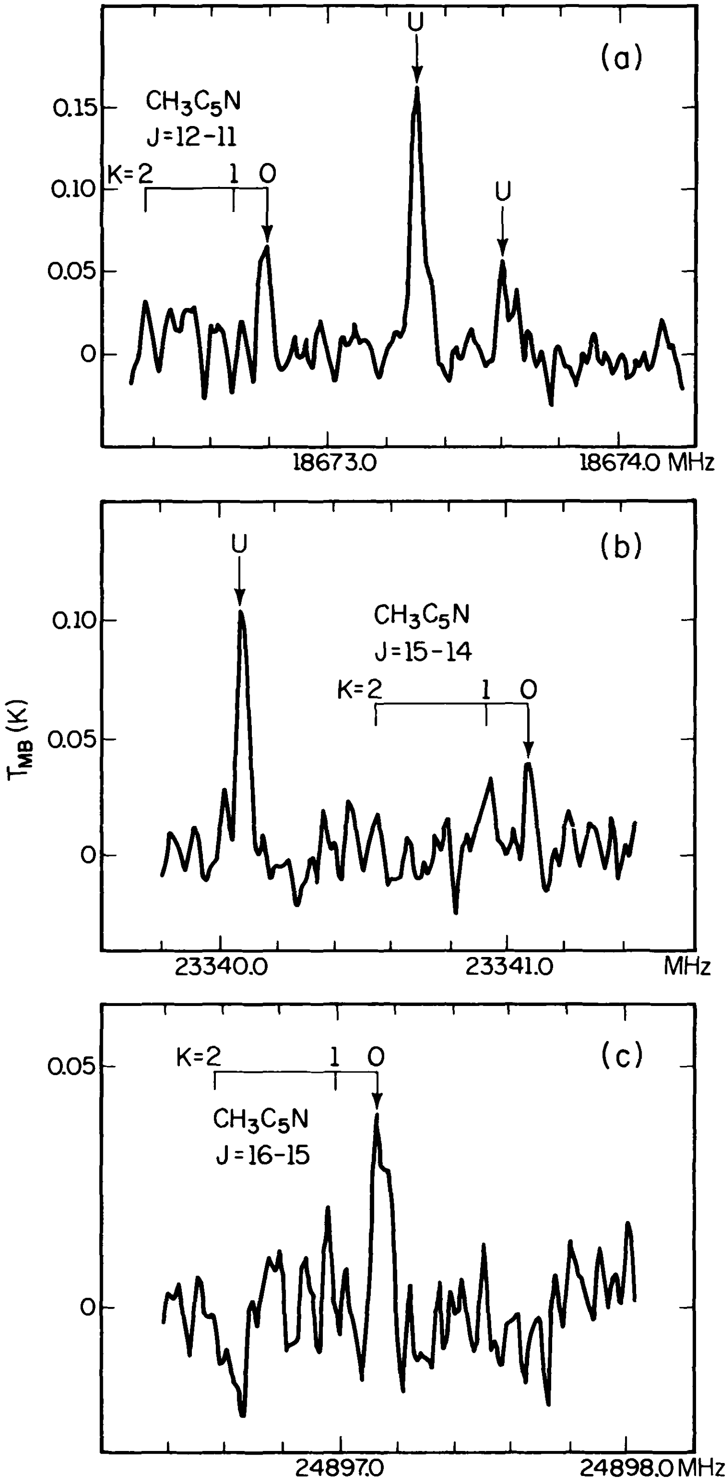

Figure II-3. Spectroscopic observations of TMC–1, showing a multitude of unidentified lines in the one-centimeter wavelength regime (Snyder, Wilson, Henkel, Jewell, Walmsley, and Batrla, unpublished).

Green Bank Telescope, with its excellent interference rejection, should make the measurement possible wherever the line is found in emission.

^{3}He can provide a lower limit to the baryon-to-photon ratio and may serve as a probe of the quark–hadron phase transition. It is also an important diagnostic of nucleosynthesis in low-mass stars. The abundance of $^3He^+$ can be obtained via its 8.7 GHz line (Bania, Rood, and Wilson 1987). Published measurements show that this line is very weak and can be seen only after extremely long integrations. The new Green Bank Telescope should make it possible to measure abundances in many more sources, including planetary nebulae—one of the sites of its nucleosynthesis—and perhaps even extragalactic H II regions. Since $^3He^+$ must be observed in H II regions, there is always background continuum emission. This causes baseline problems in current measurements, so the very clean aperture of the Green Bank Telescope should lead to significant improvements.

4.3. Comets. Solution of the cometary OH problem requires a fully steerable telescope with high sensitivity and freedom from interference—the Green Bank Telescope would be of clear benefit. Radio images of Comet Halley (de Pater, Palmer, and Snyder 1986) show that no OH maser emission comes from the direction of the nucleus, but previously unknown and unexpected small-scale OH structure (or emission clumps) was detected close to the nucleus. These clumps surround a pronounced emission void, probably caused by collisional quenching of the maser in the high-density region within $\sim 50,000$ km of the nucleus. The significance of this result will remain an open question until other comets can be observed, but it appears possible that the OH maser quenching radius may be related to the cometopause, the important boundary that marks the front-side interaction between the cometosheath and heavy-ion mantle region, which is controlled by the solar wind, and the cometary plasma region.

Perhaps the most exciting cometary research that would be done with the Green Bank Telescope would be searches for new cometary molecules with potential biological significance, or biomolecules. One such example is cometary formaldehyde (H_2CO). Snyder, Palmer, and de Pater (1989) have reported the radio detection of H_2CO in Comet Halley. They suggest that it was produced from an extended source in the coma as well as directly from the nucleus, and that it was not refrigerated as in interstellar dark nebulae. The detection of H_2CO in Comet Halley provides an impressive demonstration of the molecular-detection potential of a large collecting area (such as that of the Green Bank Telescope) for future cometary observations. Two other biomolecules of immediate interest are cyanoacetylene (HC_3N) and urea [$(NH_2)_2CO$]. HC_3N may be a reservoir of carbon and a source of cometary CN. Urea, excreted by most terrestrial vertebrates, is one of the simplest biological molecules. It is one of the twenty major molecules identified in the Miller–Urey experiment (to date, formic acid is the only Miller–Urey molecule to have been found in the interstellar molecular clouds) and it would be an extremely exciting biomolecule to find in comets. An excellent line for cometary urea searches would be the 1|10–1|01 transition of urea at 5.2 cm because it is analogous to the 1|10–1|11 transition of formaldehyde at 6 cm detected in Comet Halley. The molecular structures and chemical compositions of urea and formaldehyde also are similar.

5. CONTINUUM RADIATION

5.1. Continuum Sky Maps. The Green Bank Telescope will be able to map 85% of the celestial sphere with enough sensitivity and resolution to detect $\sim 3 \times 10^5$ sources stronger than $S \approx 5$ mJy at $\nu = 5$ GHz. Such maps provide the "raw material" for further study with aperture-synthesis radio telescopes or with telescopes in other wavebands. Some of their uses are:

(1) Discovering intrinsically rare objects: The MIT–Green Bank survey used the 300-foot telescope to find gravitational lens candidates; a large survey was required because only about one source in three hundred is gravitationally lensed.

(2) Detecting radio emission from "nearby" extragalactic sources: Radio source evolution is so strong that only a tiny fraction of extragalactic radio sources are reasonably local—of the $\sim 2 \times 10^4$ sources stronger than 150 mJy at 1.4 GHz in the northern hemisphere, only 176 can be identified with galaxies greater than one arcmin in diameter (≤ 300 Mpc distant), and even fewer are associated with infrared galaxies in the IRAS point-source catalog.

(3) Providing historical records of the sky at high frequencies (about 5 GHz) at several different epochs. All-sky maps are the radio analogs of the Harvard plate collection at optical wavelengths, revealing radio emission (or lack of it) from interesting objects yet to be recognized. Maps covering the galactic plane have also been used to discover exotic radio stars and stellar remnants, evidenced by their radio variability or flaring on time scales of days.

(4) Comparing with sky maps made in other wavebands (the IRAS infrared survey, the Palomar Observatory Sky Survey, the planned ROSAT X-ray survey).

The number of sources that can be detected in a continuum sky survey is limited by receiver noise, confusion, and observing time. For a given telescope size, the rms confusion from unresolved blends of faint sources decreases with frequency ν approximately as $\nu^{-2.7}$, while receiver noise varies only slowly with frequency. With current receivers and reasonable observing times (<1 year), the greatest number of sources can be detected at $\nu \approx 5$ GHz. Figure II-4 compares 1.4 and 4.85 GHz maps made with the 300-foot telescope of the region containing the supernova remnant Aur A and numerous extragalactic sources (Condon, Broderick, and Seielstad 1989). With foreseeable improvements in receiver and feed technology (array feeds producing hundreds of beams, system temperatures approaching 10 K), surveys might be made at $\nu \approx 10$ GHz, at which frequency the Green Bank Telescope should ultimately be able to detect about 10^6 sources stronger than 1 mJy. Bandwidths of at least several hundred MHz are necessary to achieve the required sensitivity, so the National Radio Quiet Zone is essential to avoid interference.

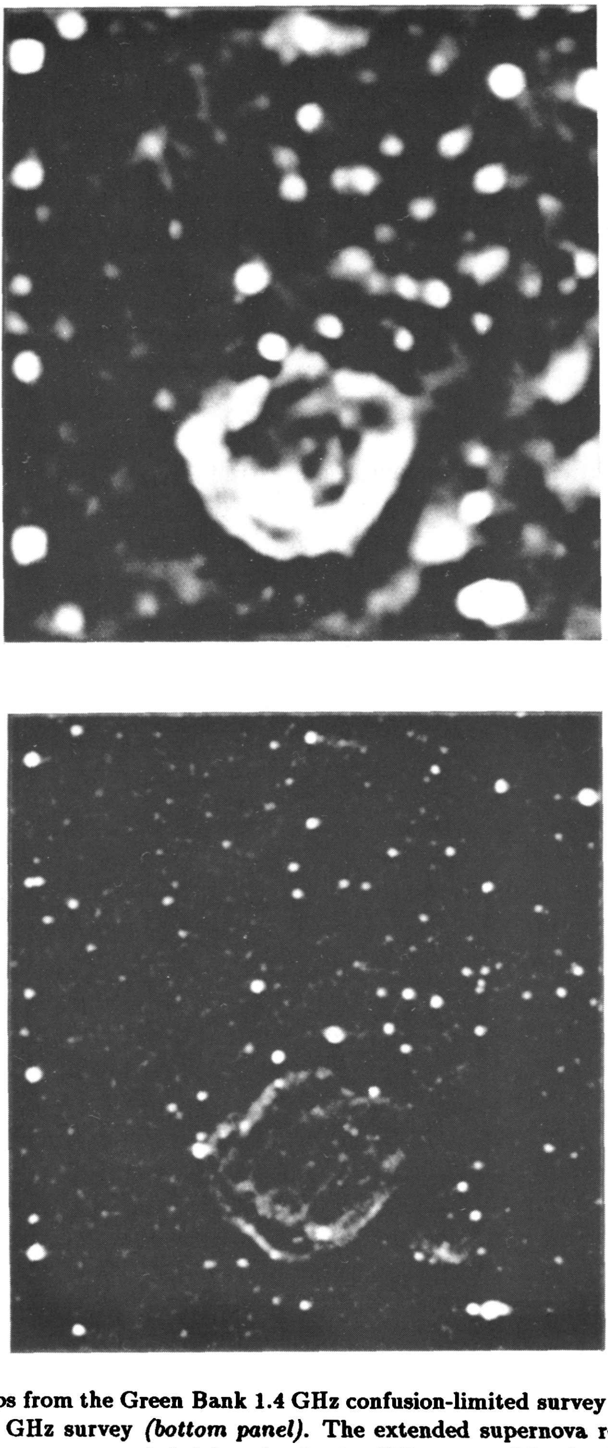

Figure II-4. Maps from the Green Bank 1.4 GHz confusion-limited survey *(top panel)* and the noise-limited 4.85 GHz survey *(bottom panel)*. The extended supernova remnant Aur A near the bottom center appears much brighter in the 1.4 GHz map, while the (mostly) unresolved extragalactic sources are relatively prominent in the higher-resolution 4.85 GHz map. Some of the extragalactic "sources" in the 1.4 GHz map have been resolved into two or more sources at 4.85 GHz.

5.2. The Cosmic Microwave Background.

5.2.1. Microwave Background Anisotropy. The blackbody spectrum and high degree of isotropy of the microwave background radiation support its origin in the hot Big Bang. In "standard" theories, primordial density fluctuations with mass M at the epoch of recombination cause temperature fluctuations in the microwave background on angular scales $\theta \propto M^{1/3}$. The fractional temperature fluctuations are predicted to saturate at some low value $\Delta T/T < 10^{-4}$ for angular scales $\geq$ 10 arcmin, the angle subtended by masses $M \approx 10^{15} M_{\odot}$, because larger masses are opaque. $\Delta T/T$ is smaller below $\sim$ 10 arcminutes, being roughly proportional to the angular separation for commonly assumed density perturbation spectra and other model-dependent parameters. Theoretical predictions, much refined in recent years, indicate a "necessary minimum" anisotropy in the microwave background of $\Delta T/T \approx 10^{-6}$, regardless of the composition (i.e., baryonic or dark-matter dominated) of the Universe.

It will be difficult to improve on existing observational limits $\Delta T/T < 2 \times 10^{-5}$ with presently available equipment. Also, the measurements are beginning to be limited by confusing radio sources (below 20 GHz) and by galactic dust emission (above 90 GHz). The exceptionally high beam-efficiency and high angular resolution of the Green Bank Telescope could be exploited by two strategies designed to improve the observational limits: (1) Operate at 5 or 8 GHz to avoid atmospheric contamination, using the high resolution of the Green Bank Telescope and supplemental VLA maps to find and subtract confusing sources. (2) Observe at $\nu \approx 33$ GHz using a focal-plane array with many receivers to minimize noise and to correct for atmospheric emission fluctuations.

5.2.2. The Sunyaev–Zel'dovich Effect. Another small-scale imprint on the microwave background is the Sunyaev–Zel'dovich effect, caused by inverse-Compton scattering of microwave background photons off the very hot ($T \approx 10^{8}$ K) X-ray emitting gas in dense clusters of galaxies (Sunyaev and Zel'dovich 1972). This interaction shifts the photons to higher frequencies and causes a decrement in the intensity of the background radiation observed through a cluster of galaxies at frequencies below about 200 GHz. This effect has been detected at the $\sim$ 1 mK level at 20 GHz. It is an important cosmological tool. Combining measurements of the microwave background decrement with X-ray measurements of the same cluster allows a direct determination of the cluster distance and hence of the Hubble constant (Gunn 1978). In addition, the Sunyaev–Zel'dovich effect measures the intracluster electron density N_e, complementing the X-ray measurement of N_e^2. Finally, peculiar motions of the cluster with respect to the microwave background reference frame contribute to the Sunyaev–Zel'dovich signal (Sunyaev and Zel'dovich 1980). If the large-scale galaxy flows measured locally are common throughout the Universe, the peculiar-velocity signal will be comparable in magnitude with the Sunyaev–Zel'dovich effect, and separable because it is independent of frequency.

So far, detections of the Sunyaev–Zel'dovich effect have provided only weak constraints on the Hubble constant ($H_0 > 17$ km s^{-1} Mpc^{-1}). This is due to the uncertainty in the clumpiness of the gas and in the variation of gas temperature with distance from the cluster center. The next generation of X-ray satellites

(ROSAT, AXAF) will address this problem and provide spatially resolved X-ray spectra. It will then be necessary to remeasure the Sunyaev–Zel'dovich effect with higher sensitivity and angular resolution, a task perfectly matched to the Green Bank Telescope.

5.3. Source Variability. The centimeter-wavelength flux of compact sources is often modulated by refractive scattering in the interstellar medium. Manifestations of this are flickering of compact sources (Heeschen 1984; Simonetti, Cordes, and Heeschen 1985), and relatively rare extreme scattering events (ESEs) (Fiedler *et al.* 1987). Flickering is most likely refractive scintillation. ESEs appear to be strong focusing events. The associated abrupt flux changes can be interpreted as the passage of a caustic surface. Essentially nothing is known about the nature of the focusing structures in the ISM, except that the column density of ionized gas varies greatly on AU scales. Very probably these structures are filaments or sheets of dense ionized gas, in which case an ESE occurs at the time of a rare alignment of the structure along the line-of-sight to a compact background source. An appealing hypothesis is that the focusing occurs in cooling substructures in interstellar shocks (Romani 1988b). The Green Bank Telescope would be most valuable for monitoring fairly weak sources over special regions of the sky (e.g., near supernova shells).

Low-frequency ($\nu < 1$ GHz) variability appears to be a combination of intrinsic changes and extrinsic refractive scintillation. Future work will probably be directed towards disentangling the two where possible, characterizing the relevant intrinsic source properties and the properties of the interstellar medium. Further programs of this nature will require a large (~ 100 m) aperture with low blockage (to avoid solar interference scattered into the beam by the feed support structure), protection against man-made interference, and frequency agility.

5.4. Polarization of the Galactic Background. High-resolution measurements of the polarization of the galactic background radiation at 408, 465, 610, 820, and 1400 MHz allow the direction and strength of the magnetic field in the local spiral arm to be determined. When combined with H I emission-measure data, the polarization observations give information on the scale lengths of the depolarizing medium. Scale lengths of 1 pc in the galactic plane and up to 20 pc at $b = +40°$ are revealed in the available high-frequency data, which are related back to the 408 MHz beam of $2\overset{\circ}{.}3$ used in the Dutch surveys. Depolarization appears to be associated with structure in the stellar distribution within Gould's belt. Test observations at 408 MHz with the 300-foot telescope (34 arcmin beamwidth) showed unresolved structure with polarization temperature more than three times that found with the $2\overset{\circ}{.}3$ beam. This structure is present in the North Polar Spur and in the region of high polarization around $\ell = 140°$.

The 20 arcmin beam of the Green Bank Telescope in the 610 MHz radioastronomy band will resolve the Faraday rotation effects produced in Strömgren spheres around B and A stars out to distances of several hundred parsecs and O stars to several kiloparsecs. Small-scale structure of the magnetic field and the associated depolarizing medium in the spurs of continuum radiation will allow detailed mapping, and hence modeling, of these objects. The Green Bank

Telescope is an ideal instrument for undertaking an all-sky polarization survey at low frequencies. It is better by a factor of four in resolution over the only existing survey. This is the most effective way to obtain extensive data on the interstellar magnetic field in the local spiral arm as well as in nearby arms.

6. VERY LONG BASELINE INTERFEROMETRY

The Green Bank Telescope will greatly enhance the sensitivity and dynamic range in high resolution (VLBI) images of a wide variety of galactic and extragalactic radio sources. This will have important applications in essentially all areas of astronomy.

The Green Bank Telescope alone will have more collecting area than all ten 25-m elements of the Very Long Baseline Array (VLBA). With the addition of the Green Bank Telescope, the VLBA will have about the same collecting area as the VLA. Depending on the type of observation, the VLBA with the Green Bank Telescope will have from two to four times the sensitivity of the VLBA alone. For detecting unresolved sources or for mapping sources in which an unresolved component is used as a phase reference, the combined instruments will have about 2.5 times the sensitivity of the VLBA alone.

Each of the baselines between the Green Bank Telescope and any one of the ten elements of the VLBA will, on average, have four times the sensitivity of baselines between the individual 25-meter antennas. Improvements in image quality will result for two reasons: (1) Much shorter integration times will be needed to establish a signal-to-noise ratio on each baseline adequate for self-calibration. (2) Weaker phase-reference sources closer to the target source may be used, thus reducing atmospheric phase errors and improving dynamic range. Alternatively, the same reference source may be used, but it need be observed for much less time. This ability to observe nearby phase reference sources in a short period of time extends the coherence time from a few minutes to many hours, yielding images of greatly improved sensitivity and dynamic range. Moreover, because the Green Bank Telescope is located near the outer part of the VLBA, the ten baselines between it and the VLBA elements will greatly improve sensitivity in the outer parts of the u-v plane and correspondingly reduce the noise of the highest-resolution maps. This complements the large collecting area of the phased VLA, which improves the sensitivity primarily in the central portion of the u-v plane.

6.1. Galactic Research. Within our own Galaxy, a variety of radio sources of solar-system size are unresolved by conventional radio telescopes but can be mapped with VLBI. Two examples are interstellar masers and active binaries.

One of the most important problems in galactic astronomy is to understand the life-cycle of stars. Interstellar maser clouds of OH, H_2O, and SiO are often found in regions where stars are forming and in the atmospheres of very old stars. VLBI images will be able to probe the dynamics and magnetic fields in these regions on a scale of 10^{13} to 10^{18} cm, thereby giving information about each end of the cycle of stellar evolution.

OH masers contain magnetic fields of the order of a few milligauss which split spectral features via the Zeeman effect. Observations of this splitting reveal the three-dimensional magnetic field vectors throughout these regions, giving some insight into the manner in which the magnetic field affects cloud collapse and star formation. Maser sources radiate in very narrow bandwidths, so sensitivity cannot be improved merely by increasing the bandwidth. The improvement in sensitivity made possible by using the Green Bank Telescope together with the VLBA will increase the number of maser sources which can be studied by a factor of about four.

The milli-arcsecond imaging capabilities of VLBI will be used to make "movies" of the variable radio structures known to exist in the merged magnetospheres of nearby active binary stars. For systems like Algol and the RS CVn binaries, this will allow detailed studies of plasma phenomena that are many orders of magnitude more energetic than the strongest ever seen in the magnetospheres of Jupiter and the Sun. Galactic X-ray binaries such as SS 433 and Cyg X-3 can also be observed via VLBI to study the evolution of the time-variable synchrotron-emitting jets and relativistic plasmoids that are commonly produced in these stellar systems. The early phases of evolution of the structure of explosive ejecta in some novae, recurrent novae, and other interacting wind objects, which now can be resolved only when they reach VLA resolution scales of 0.1 arcsec, will also be studied. Since all these stellar radio sources are very weak, the improved sensitivity granted to the VLBA by adding the Green Bank Telescope will enable study of many more of these objects, and in more detail.

6.2. Extragalactic Research. Perhaps the greatest impact so far of VLBI research has been in the study of the active compact cores of radio galaxies and quasars. Only at radio wavelengths is it possible to obtain high resolution images so close to the "central engine". The observed alignment in radio galaxies and quasars of the parsec-sized jets found in their nuclei with the more extended jet features mapped by the VLA indicate each has a common axis collimating activity on a scale of a parsec or less, but focusing it for distances up to megaparsecs. The axes must consequently remain fixed in space for at least millions of years. Nearly all of the several dozen sources which have been studied in detail with VLBI exhibit superluminal motions apparently due to bulk relativistic motion of the emitting region. Because the radiation from an object moving at relativistic speed is focused along the line of sight, a suitably oriented observer will observe both an apparent enhancement of the radiated luminosity by factors of thousands and an apparent superluminal motion due to the differential signal propagation times from different parts of the moving source. These effects have important implications for the theory of active galactic nuclei, particularly if the radiation in other parts of the spectrum also is enhanced by relativistic effects.

So far, only a few, relatively strong, compact sources have been observed in even moderate detail. The situation may be compared with that existing for the large-scale structure of radio galaxies and quasars before the VLA and the Westerbork Synthesis Radio Telescope. The VLBA will have greater sensitivity, resolution, and image quality, which together will allow the study of much larger samples in much greater detail. The larger complete samples will provide statistically significant databases for testing inferences of the relativistic beaming models. The still greater sensitivity resulting from the addition of the Green

Bank Telescope will permit individual moving components to be followed for longer times and to greater distances. Superluminal motions in a much wider variety of sources—including, say, the weak central components of radio galaxies and optically selected quasars—will also be observable.

6.3. Astrometry and Distance Measurements. The high resolution of the VLBA will enable it to extend the range of direct distance measurements by trigonometric parallax. Observations of proper motions will be possible both throughout our galaxy and in other galaxies. These new, precise, astrometric results will be applied to the important problems of the structure and rotation of the Galaxy. But suitable astrometric sources are very weak, and the accuracy of these important astrometric measurements will be greatly enhanced by the improved sensitivity of the Green Bank Telescope.

One type of H_2O maser source contains hundreds of individual bright spots whose relative motions are nearly random. The distances to such sources can be determined by statistical parallax methods. The distances to the maser sources in Orion and W51, 1,600 and 23,000 light years, respectively, have been measured using this technique to an accuracy of about 20%. With the improvement in sensitivity that the Green Bank Telescope provides to the VLBA, similar measurements will be possible on a much larger number of objects, including H_2O masers in nearby galaxies. Cosmology will benefit, since knowledge of the correct scale of the universe (the Hubble constant) is fundamental to determining the universe's mass, energy content, age, and eventual evolution.

6.4. Space VLBI. The Green Bank Telescope will be especially important as an earth-based element of space-to-ground VLBI systems. Major space VLBI programs are currently being developed in Japan and the USSR with expected launches in the mid-1990s, more or less coincident with the commissioning of the Green Bank Telescope. These programs will improve the resolution of Earth-based VLBI systems by at least an order of magnitude. But the space element in both cases is small, only 10-m in diameter, so a large Earth-based element is necessary for adequate sensitivity. Maximum resolution of the space VLBI missions will be at their highest operating frequency of 22 GHz. Operation at this frequency is also necessary for the study of H_2O maser sources. The Green Bank Telescope, with its large collecting area and good performance at 22 GHz, will be uniquely suited to this task. It will allow the US to play a major role in the two international space VLBI projects and to share in the scientific returns.

6.5. Millimeter VLBI. VLBI observations at millimeter wavelengths achieve much higher resolution than otherwise possible from the Earth. The VLBA will work at wavelengths as short as 3.5 mm, but its sensitivity will be limited by low antenna efficiency. With the addition of the new Green Bank antenna, the improvement at 7 mm and perhaps at 3.5 mm will be dramatic and will yield images of unprecedented resolution and quality.

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III. THE ANTENNA

1. GENERAL DESCRIPTION

The scientific goals for the next-generation radio telescope are numerous and varied. To meet them, we propose an antenna whose primary reflector is an axially symmetric paraboloid of diameter at least 100 meters. The antenna is supported on a wheel-and-track mount and is fully steerable. A drawing of the overall configuration is given in Figure III-1.

The primary focal ratio is 0.42, and the effective focal ratio at the Cassegrain focus is 4.97 with a secondary hyperboloid of 8-m diameter. This provides for efficient operation with practical feeds either from the prime focus or, at high frequencies, from the secondary focus. A sketch of the optical arrangement is given in Figure III-2.

Our design is intended to meet these major objectives, derived from the scientific goals for the telescope: (1) the antenna should provide full-sky coverage; (2) it should operate efficiently to the shortest possible wavelength that can be reached in a cost-effective way; (3) it should operate efficiently at meter wavelengths as well; (4) blockage of the aperture should be minimized in order to minimize interference entering via far sidelobes and also to minimize standing waves within the antenna; and (5) rapid changes between frequency bands should be possible, primarily so that weather-dependent observations and time-specific scientific opportunities can be optimally exploited.

To meet these objectives, several important innovations are proposed. These include: (a) *active surface control*—the surface panels will be continually reset during operation, to maintain the correct reflector shape; (b) *stabilized pointing reference platform*—a platform near the intersection of the azimuth and elevation axes will be stabilized relative to fixed points on the ground, and pointing of the antenna will be measured mechanically with respect to this platform; (c) *passive thermal control*—radiation shields around the main reflector's backup structure and around the main structural elements of the pedestal will minimize deformations due to solar radiation (day) and ground radiation (night); and (d) *special design of the focus support structure*—the effects of aperture blockage will be minimized by carefully selecting the shapes and dimensions of members and of the overall structure.

2. DESIGN CONSIDERATIONS AND TRADEOFFS

2.1. Strength, Surface Accuracy, and Cost. Here we consider the requirements on the main antenna structure and their effects on the short-wavelength limit of the telescope. In particular, we consider the deformations due to wind, temperature differentials, and gravity.

An essential requirement on the antenna structure is that it survive in strong winds. If the reflector is a solid surface (rather than mesh), then the

III. THE ANTENNA

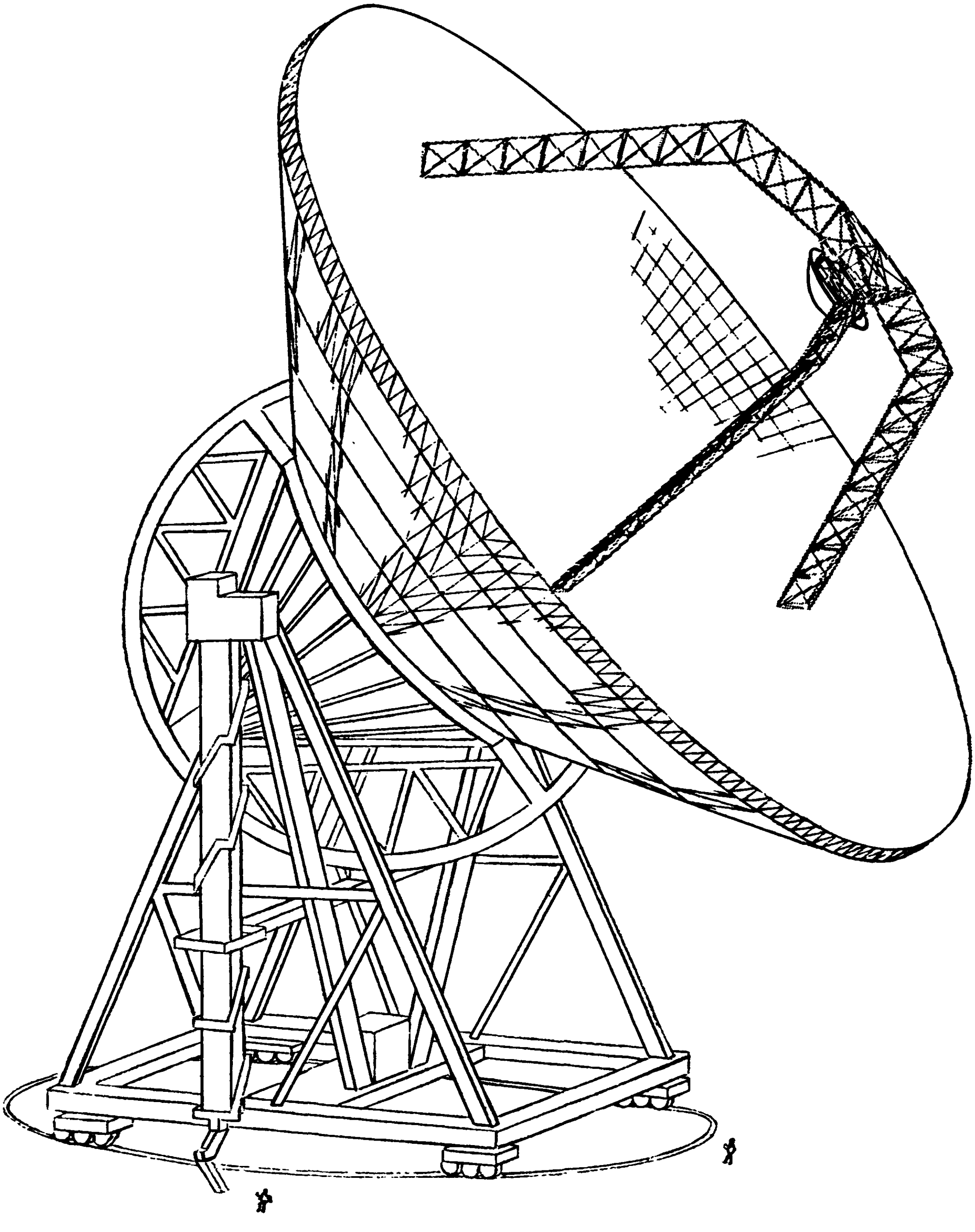

Figure III-1. 100-m Telescope Concept.

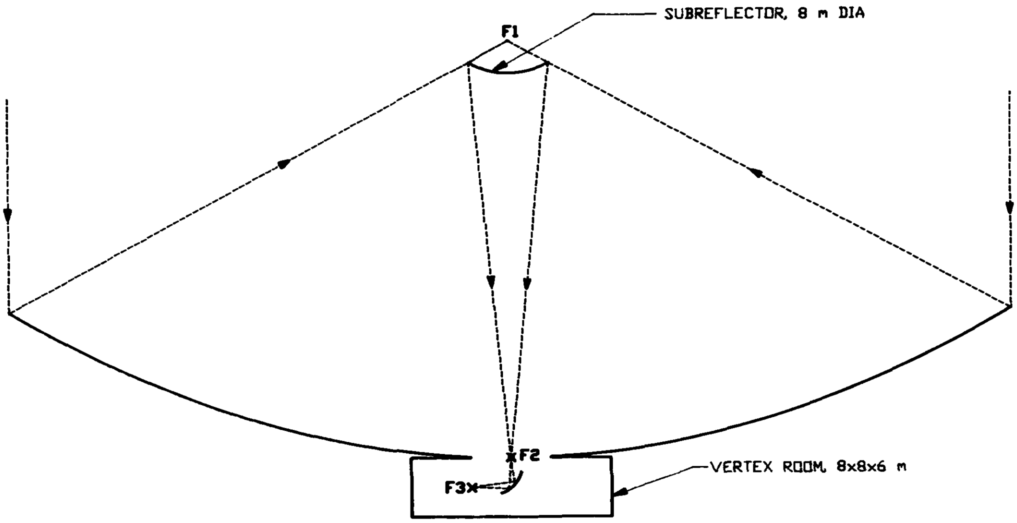

Figure III-2. A possible optical arrangement for the Green Bank Telescope. The focal ratio is 0.42, the subreflector diameter is 8.0 m, and the secondary focus is at the vertex of the main reflector. Also shown is a possible tertiary mirror and focus, which may be useful at the highest frequencies. There will be sufficient room for a 20-m square vertex cabin, whose outline is shown.

structure required for survival is independent of the wavelength limit.[1] For a mesh surface, the wind loading may be somewhat less (proportional to $1/\lambda_{\min}$), but insignificantly so in the stow position. Since we are interested in $\lambda < 6\,\mathrm{cm}$, we assume a solid surface. If the structure is built only for survival, the amount of surface deformation due to typical winds winds will determine the wavelength limit of the telescope (neglecting gravitational and thermal deformations, considered separately). Conversely, the desired operating wavelength will set the maximum wind speed under which the telescope will operate.

Assuming that the antenna is designed to survive a particular maximum wind speed, then, in more moderate winds, a (large) antenna will suffer greater deformations due to gravity than due to winds (although the converse will be true for a small antenna). Under certain assumptions, von Hoerner [1] finds that the crossover occurs for $D > 100\,\mathrm{m}$ if the survival and operational winds are 50 and 10 m/s, respectively; and further that the wavelength limit for $D = 100\,\mathrm{m}$ is 8 cm under these conditions. Under no-wind conditions, the wavelength limit can be improved by stiffening the load-bearing part of the structure against gravity; but a point is soon reached where the weight of further stiffening causes as much gravitational deformation as it resists. Under von Hoerner's assumptions, this gravitational wavelength limit is $\lambda_g = 6\,\mathrm{cm}$ at $D = 100\,\mathrm{m}$. The stiffening required to approach this limit is very expensive, with the total structural mass proportional to $\lambda_g/(\lambda_{\min} - \lambda_g)$.

One way to surpass the gravitational limit without additional mass is to

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[1] By convention, the "wavelength limit" $\lambda_{\min}$ is herein defined to be 16 times the rms deviation of the main reflector from its ideal shape.

use the homology principle [2]. But the same effect can be achieved by active surface control, which is potentially much more accurate and can correct non-gravitational deformations as well; this will be discussed in detail later. The wind limit can be improved, if necessary, at the cost of more structure, but an alternate strategy is to accept operation at the shortest wavelengths only during times of low wind. This strategy is especially attractive if there is sufficient flexibility in scheduling to permit rapid switch-over to long-wavelength backup programs.

Once gravity and wind are overcome, the wavelength limit is determined by thermal deformations and reflector manufacturing errors. Overcoming the thermal limit is also discussed later, but for a steel structure with $D = 100\,\mathrm{m}$ and maximum temperature difference of $\Delta T = 1\,^\circ\mathrm{C}$ (probably achievable at night) this limit is about $\lambda_T = 5\,\mathrm{mm}$.

Thus the cost of the mechanical structure depends almost entirely on its size and not on the wavelength limit. The remaining costs which do depend on $\lambda_{\min}$ are *panel manufacturing*, *panel setting*, and *pointing control*. Pointing control may determine the ultimate wavelength limit; it is considered in detail later. Panel manufacturing cost is a nearly piecewise constant function of surface accuracy, increasing sharply when the limit of a particular manufacturing technique must be surpassed. With aluminum skin and stiffeners shaped to a machined mold (as in the VLBA and VLA antennas), panel rms errors of 0.125 mm are now routine, corresponding to a wavelength limit (from this cause alone) of 2 mm. A factor-of-two improvement in panel accuracy now seems possible at the same cost per unit area as the VLBA panels. For $D = 100\,\mathrm{m}$ the panel cost is then less than 25% of the structure cost and less than 10% of the total cost, so we assume that this panel type will be used.

We finally conclude that *the cost of an antenna in the size range of interest depends very weakly on the wavelength limit and is determined almost entirely by the size.*

2.2. Optics. The arrangement of the optical path depends most strongly on the wavelength range to be supported. As the Scientific Program Chapter (Ch. II) emphasized, this range must be very large—ideally, from a few millimeters to a few meters. Operational considerations (e.g., speed of frequency changes, access for maintenance) also influence the optics. To maximize the flexibility of this new instrument, we will provide for feeds positioned both at the primary (Newtonian) and the secondary (Cassegrain) foci.

Feeds at the lower frequencies get unreasonably large if located at the secondary focus. They either become bigger than the subreflector itself, thereby adding to aperture blockage, or are too big to fabricate. Even for some higher frequency observations it may be desirable to utilize the prime focus, particularly if there is a requirement for several beams tightly grouped on the sky. But, for most observations at frequencies of a few GHz and higher, one will wish to exploit the advantages of the secondary focus: larger fields of view, due to the longer effective focal length; more space for feeds and receivers, in a more accessible location; and less blockage from feed support legs.

For the Green Bank Telescope, we have tentatively selected the dimensions presented in Table III-1. These choices appear to give excellent performance in the range 0.1 to 50 GHz. During the preliminary design stage, detailed considerations of feed design and placement may lead to slightly altered dimensions; better performance at some frequencies may be possible.

Table III-1. Parameters of the Optical System

Basic dimensions:		
Main reflector diameter, paraboloid	D	100 m
Focal length (primary)	F	42 m
Subreflector diameter, hyperboloid	d	8 m
Secondary focus height above vertex	h	0 m
Derived dimensions:		
Focus to subreflector distance	L	38.74 m
Effective focal length at secondary	F_e	497 m
Prime focus half angle		$61\overset{\circ}{.}52$
Primary feed diameter, single hybrid mode		0.58λ
Primary feed diameter, dual hybrid mode		1.18λ
Secondary focus half angle		$5\overset{\circ}{.}74$
Secondary feed diameter, single hybrid mode	d_f	12.7λ
Secondary feed diameter, dual hybrid mode	d_f	23.9λ

An important consideration in the antenna's design has been the desire for multiple beams on the sky. There are at least three reasons for this: (a) beam switching for reduction of atmospheric effects in continuum mapping; (b) use of focal plane arrays to increase the speed with which areas of sky much larger than the antenna beam can be mapped; and (c) use of focal plane arrays to correct for various aberrations in the antenna. We realize that there is a difficult and important choice to make between the on-axis aperture efficiency and the distance off-axis at which the performance (aperture efficiency and coma lobe) deteriorates significantly. With Cassegrain optics, it is possible to shape the reflectors to maximize either the on-axis efficiency (as was done for the VLA and VLBA antennas) or the field of view (as is sometimes done for optical telescopes). Since the first choice leads to an unacceptably small field of view (less than two beamwidths), we have, for the moment, chosen to use a classical paraboloid–hyperboloid system, so that is the basis of the performance estimates given here; but a careful determination of the best shape will be made during the preliminary design, and may lead to slightly better aperture efficiency at the secondary focus.

2.3. Aperture Blockage. The 8-m diameter subreflector will block only 0.64% of the aperture, so (as in most existing telescopes) the blockage will be dominated by the support structure. The extent to which this blockage can be minimized is limited by the required mechanical stiffness of the supports. The latter is dominated by the need to maintain a sufficiently high natural frequency so that the pointing servo bandwidth can be large enough for tight pointing control (considerations of survival strength, wind deformations, and gravitational deformations are less stringent).

Our early studies have shown that it is probably possible to limit the support structure blockage to about 2%, but not less. This would represent a factor of two to three improvement over existing open-air telescopes, and would be comparable to telescopes enclosed in radomes. Further details are given in Section 4.

The blockage contributes to production of sidelobes, loss of gain, increase in system noise (due to scattering of ground radiation), and production of standing waves. To minimize the last effect, we need to consider not only the total amount of blockage but the extent to which it causes backscatter to the feed. There have been suggestions in the literature that careful choice of shapes of the structural members and the placing of spoilers along the edges of members can produce large reductions in backscatter without increasing the total blockage. Such measures will be considered during the preliminary design.

3. SPECIFICATIONS

Table III-2 lists the dimensional and performance specifications that we expect to be able to achieve. Many of these are tentative, pending more thorough analysis during the preliminary design phase.

Table III-2. Specifications

Mechanical:		
Panel manufacturing accuracy		.07 mm rms
Surface adjuster resolution and repeatability		.025 mm
Subreflector manufacturing accuracy		.07 mm rms
Pointing reference platform stability		1 arcsec
Focal support tripod geometric shadowing		2.3%
Sky coverage	elevation	0° to 110°
	azimuth	−270° to +270°
Wind conditions	precision	to 7 m/s
	stow	27 m/s
	survival	45 m/s
Performance:		
Wavelength limit ($16\sigma_{rms}$)		
Without active surface adjustment		2.0 cm
Expected for initial system		0.7 cm
Ultimate, with perfect surface adjustment		0.16 cm
Pointing error, non-repeatable, 7 m/s wind		
Without stable reference platform		14 arcsec
With stable reference platform		2 arcsec

4. STRUCTURAL AND MECHANICAL CONSIDERATIONS

As discussed earlier, the mechanical structure need not be made stiffer than is required for survival in the strongest winds. The design is straightforward and conventional.

4.1. Reflector Panels. Each elementary panel is constructed of aluminum sheet and Z-sections and is less than 2 m by 2.5 m in size, with four corner supports. These panels are assembled at the factory into structures consisting

4.7. Foundation. The foundation is a reinforced concrete structure. An outer ring is designed to anchor the rail for all the vertical forces, and a center ring supports the pintle bearing. There are eight connection beams between the rings. Trenches are provided to accommodate cables between the antenna and the control building.

5. Active Surface Control

The estimated gravitational deformations for the design described in the preceding section result in a wavelength limit of 1.5–2 cm, which already surpasses von Hoerner's gravitational limit [1] of 6 cm. This is because von Hoerner considered total deviations from a nominal shape, whereas we consider only deviations from the best-fit focus location; that is, the design is partially homologous. Two ways to reduce further the residual deformations and improve the wavelength limit are: (1) to approach a fully homologous design; or (2) to install motorized surface adjusters at sufficiently many points that the surface can be reset continuously as a function of elevation. We now discuss the limitations of these techniques.

Homology has been used in the IRAM (15-m and 30-m) and Nobeyama (45-m) millimeter telescopes, the MPIfR Effelsberg (100-m) telescope, the NRAO 65-m design (never built), and the Bonn–Arizona submillimeter telescope (10-m, under construction). The performance of the existing homologous telescopes exceeds the gravitational limit by factors of three to five; in most cases the performance is then limited by thermal effects or surface fabrication accuracy, so the reduction factor for gravitational residuals may actually be greater. Nevertheless, the approach to perfect homology is always limited by the accuracy of computer modeling of the structures and by tolerances of fabrication. The total deformation in large structures can be modeled to an estimated accuracy of 5–10%; this is good enough to put the gravitational deformations well below the thermal limit for small antennas, but for sizes exceeding about 80 m the computer modeling errors dominate the residuals. In addition, there are practical limits to homology, even assuming the models to be perfect: large numbers of different-sized members are needed in the backup structure, and these are expensive to fabricate. Thus, recent designs have intentionally been only partially homologous (including the VLBA antennas and the JPL 70-m upgrades).

The other method to reduce the gravitational residuals is to continuously readjust the surface. Motorized adjusters at all support points of each panel can in principle remove all deformations except those of the panels themselves. The latter can be made smaller than the manufacturing error by keeping the panels sufficiently small. The adjustment algorithm may be based on either (1) calculated deformations from a computer model, resulting in the same limitations imposed on homologous design; (2) occasional "calibration" measurements of deformations; or (3) real-time measurements of deformations. At present, we are not confident that a sufficiently accurate method of real-time measurements exists, so we base our performance estimates on a combination of (1) and (2): calibration measurements based on holography would be used to provide corrections to the computer model. Eventual development of techniques for accurate real-time measurements would allow further improvements.

Some limitations and difficulties with this technique are: (1) it has not yet been attempted on a large antenna, although there is some relevant experience (the IRAM 15-m antennas and the Nobeyama 45-m antenna include motorized adjusters, but no real-time adjustment is done); (2) it is dependent on accurate mapping of the deformations over the surface, and this will limit the achievable improvement; (3) a large number of adjusters may be required, and their reliability must be very high, resulting in potentially high operating cost. We believe that all of these difficulties can be overcome at the level of 0.2 mm rms residuals ($\lambda_{\rm min} \approx 3\,{\rm mm}$).

6. POINTING CONTROL

A fundamental problem in building increasingly large reflector antennas is that (for a given wavelength) the beamwidth decreases linearly with D while most deformations cause pointing errors that increase with D, so unless special efforts are made the pointing accuracy as a fraction of the beamwidth becomes rapidly worse. Gravitational deformations cause pointing errors proportional to D^2, but they are repeatable, so that once calibrated they can be removed. Thermal deformations, which are not so predictable, increase as D, so the error in beamwidths from this cause goes as D^2. Even at $D = 25\,{\rm m}$, thermally induced pointing errors are a major problem; they limit high-frequency operation of nearly all radiotelescopes in the daytime. Finally, wind-induced deformations go as D^2 (for a fixed operating wind speed and structural stiffness), giving a pointing error proportional to D^3 beamwidths. These problems have been alleviated for various existing radio telescopes by under-illuminating the primary reflector, hence creating a broader beam, at short wavelengths. Since this option sacrifices collecting area, it will be considered only as a last resort for the Green Bank Telescope.

Experience at the VLA has shown [4] that most of the sunlight-induced pointing error is due to uneven heating of the pedestal and yoke, rather than of the reflector and its support structure. If the orientation of the elevation axis in space (or relative to the stable ground) and its rotation can be continuously measured, then all pointing errors due to the lower structure can be removed, including both wind and thermal causes. (However, removal of rapidly varying disturbances such as wind gusts will be limited by the dynamics of the structure.)

As a step in this direction, sensitive inclinometers have been installed on each end of the elevation axis of some VLA antennas. These provide information about the axis orientation, but cannot sense distortions that cause purely azimuthal pointing errors. The inclinometers' only external reference is gravity, so they cannot be used during accelerated motion of the antennas, nor during any significant vibration.

These approaches will not suffice for the Green Bank Telescope. For a $D = 100\,{\rm m}$ telescope to operate at 7-mm wavelength, a pointing accuracy of 1.8 arcsec is needed to be within 0.1 beamwidth. This is possible only if some of the special stabilization techniques, outlined below, are used. Even at wavelengths as long as 3 cm, a conventional design would achieve the required pointing accuracy only under benign conditions of solar radiation and wind.

A promising design for improved pointing accuracy was pursued for the NRAO 65-Meter Telescope [5]. Here a gimbaled platform at the intersection of the antenna's axes was to be stabilized in orientation by optical measurements from stable reference points on the ground. Two high-resolution angle transducers (inductosyns) would then measure the azimuth and elevation of the elevation shaft relative to the platform. Tests on the critical optical components and servo system showed that the platform could be stabilized to about 2 arcsec in spite of atmospheric fluctuations in the optical path. Based on these tests, we propose to include a precisely stabilized pointing reference platform at the axis intersection point. It might be possible to stabilize such a platform to similar or better accuracy by using gyroscopes, thereby avoiding the need for optical paths. During the preliminary design phase, we will investigate a variety of alternative techniques (including gyroscopes and microwave methods) before selecting the final method.

7. THERMAL CONTROL

As mentioned earlier, thermally induced distortions of the antenna may be the most difficult to overcome. For a steel structure with $D = 100\,\mathrm{m}$ and a maximum temperature difference of 1 °C, the short wavelength limit (from this cause alone) is about 5 mm; and if the range is 5 °C—typical of daytime operation in current antennas—then the limit becomes about 3 cm. Improvements are possible by reducing the temperature differences, by using lower temperature coefficient materials, and by actively compensating for measured temperature variations.

7.1. Thermal Stabilization. Until recently, most radio astronomy antennas have been built with minimal thermal stabilization, other than proper choice of paint. Insulation has been added to major elements of the VLA antennas' pedestals in order to improve pointing performance; the VLBA antennas include a provision to circulate liquid coolant in the pedestals, but no effort has been made to stabilize the reflector structures; for these antennas with $D = 25\,\mathrm{m}$, λ_{min} is not thermally limited. Extensive experimentation with insulation has been done on the NRAO 140-ft telescope. The Australia Telescope antennas ($D = 22\,\mathrm{m}$) have heavily insulated pedestals and yoke structures, with blowers to circulate ambient air for reducing gradients. The Pico Veleta (30-m) antenna goes further by fully enclosing the reflector backup structure and blowing in temperature-controlled air. In this case, performance surpasses von Hoerner's thermal limit [1] even in daytime.

Although we have not yet done detailed studies, it appears that any attempt to actively control the temperature of the antenna structure becomes prohibitively expensive for large D. Power consumption could be excessive. The 30-m antenna may be the largest size amenable to such an approach.

Passive temperature control, however, appears quite feasible and should be very effective. We propose to provide lightweight radiation shields over all critical parts of the antenna, including the reflector backup structure and the main structure of the pedestal. The shields will include louvers to allow free air circulation. The option of adding forced circulation of ambient air will be considered during the preliminary design, but natural convection may suffice to keep the structure nearly isothermal. In this way, the sunlit performance may approach that achievable at night. Furthermore, the nighttime performance may be somewhat improved by shielding the reflector structure from ground radiation. We still expect a limit of $\lambda_{\min} \approx 5\,\text{mm}$ due to thermal effects, even at night.

7.2. Low-Coefficient Materials. For small antennas, it is feasible to construct the entire reflector and backup structure from materials having nearly zero temperature coefficient of expansion. The favored material is carbon fiber reinforced plastic (CFRP), because it also has good stiffness and strength-to-weight ratio. CFRP members with invar joints are planned for the Bonn–Arizona Submillimeter Telescope. Unfortunately, these materials are 10–20 times more expensive than steel for the same stiffness. For our 100-m class instrument the cost seems completely prohibitive. At best, we might consider CFRP for only a few critical members.

7.3. Active Surface Correction. Since motorized surface adjusters will be installed to cancel gravitational deformations, they can also be used to reduce thermal deformations, provided that adequate measurements of temperature distribution and a good thermal model are available. We expect that, during the lifetime of the Green Bank Telescope, adequate models can be developed. We will then be able to improve upon the thermal limit, but whereas we know of no experience with such an approach, we are at this time unable to quantify the improvement.

8. UNBLOCKED APERTURE OPTION

The scientific usefulness of the Green Bank Telescope is enhanced if it is free from interference and from standing waves created by multiple reflections between structural components. To minimize both interference and standing waves, we propose minimizing obstructions in front of the antenna's geometric aperture. Obviously, the ideal case is no obstruction whatsoever. For the same diameter, the asymmetric geometry needed to avoid aperture blockage will be more expensive than the symmetric geometry of a center-fed reflector. But the unblocked-aperture antenna will have higher effective area and lower system temperature, in addition to lower scattering sidelobes and standing waves. Aside from the effective area (which improves directly with the blockage reduction), we have not yet been able to quantify these parameters very accurately. A tradeoff is apparent: one could absorb the extra cost of the unblocked antenna by reducing its size, at least to the point where its *effective* area became equal to that of the conventional telescope.

During the preliminary design phase for the new telescope, we will continue actively to study the clear aperture option. If it can be shown to be cost effective, we will pursue an unblocked design in detail. Otherwise, the more conventional, symmetrical design (which forms the basis of this proposal) will be built. The following is a brief summary of the considerations involved and the analysis that has been completed to date.

8.1. Advantages.

8.1.1. High A/T Ratio. The gain is higher and the noise temperature lower for unblocked antennas than for symmetric ones *of the same size.* Consider a symmetric antenna with 3% geometrical blockage, which we believe represents the minimum blockage currently achievable. The loss in effective area will be 6–9%, depending on the RF cross-section of the blocking structure. But the increase in noise temperature may be much more significant. The fraction of the resulting sidelobes that is intercepted by the ground will be about 0.2 at the zenith and about 0.5 at the horizon. The addition to the antenna temperature from these sidelobes is 2–7 K. This is a large fraction of the system temperature when the best low-noise receivers are used. An example of a clear-aperture antenna is the Crawford Hill horn reflector [6], which has only 1 K of antenna temperature due to losses, spillover, and scattering.

8.1.2. Low Sidelobes for Interference Protection. The sidelobe levels for an offset reflector antenna can fall to the isotropic level as close as 5° to the main beam, whereas for a symmetric antenna the sidelobes typically remain above the isotropic level for angular distances of about 20° from the main beam. Thus, the portion of the sky surrounding an interfering source in which observations are significantly degraded will generally be smaller for the offset reflector. The value of the improvement depends on the strength of the interfering source, since a sufficiently strong source will be harmful over the whole sky, for either antenna type.

8.1.3. Protection Against Interference from Celestial Sources. Strong celestial sources in the sidelobes, including the Sun, the galactic center, Cassiopeia A, etc., cause significant interference for some observations. Galactic hydrogen line observations are also plagued by confusing signals entering through sidelobes from directions besides the one in which the telescope is aimed. These effects are reduced in direct proportion to the sidelobe level reduction.

8.1.4. Reduction of Standing Waves on the Antenna. Multiple reflections between the feed and the main reflector or subreflector cause periodic ripple in spectroscopic baselines of axially symmetric radio telescopes. The problem has received considerable attention but has not been solved in any satisfactory way. A detailed discussion is given in [7]. In an unblocked antenna the largest reflection (from the vertex of the main reflector or subreflector) is eliminated, and scattering from the support structure is drastically reduced. Only diffraction from the edges of the reflectors and backscattering from reflector imperfections are left. (The latter include the edges of the surface panels; if the panels are mounted in the usual way, following the contours of the paraboloidal surface, then the edges follow lines of equal distance from the focus, and reflections add in phase.) Little experimental data is available, but a detailed and accurate calculation should be possible during our preliminary design phase. We expect that the unblocked design will be greatly superior.

8.2. Disadvantages.

8.2.1. Polarization Properties. The cross-polarization sidelobes of offset feed antennas are usually larger than those of symmetric antennas. In the case of circularly polarized feeds, the beam is offset from the paraboloid axis, in a direction normal to the plane of symmetry, by a small angle. This effect is often referred to as beam squint, and since the squint angles deflect in opposite directions for opposite polarizations, the beams are separated by twice the squint angle. Small squints are tolerable for many observations. These polarization effects can be effectively eliminated in two-reflector (Cassegrain or Gregorian) systems by including a compensating offset of the feed from the reflector axis [8], or in a prime focus system by using a special feed [9]. Without compensation, the unwanted polarization effects decrease with increasing focal ratio, and an analysis [10] shows that a focal ratio[2] of ≥ 0.6 should give beam squint < 0.1 beamwidth and linear polarization sidelobes $< -20\,\mathrm{dB}$, both satisfactory for most observations.

8.2.2. Cost. For a given diameter, the unblocked design is more costly because more panels of different shapes are needed, and because the focus support structure is more cantilevered. This is further analyzed below. With a fixed budget, the physical aperture would be somewhat smaller than for a symmetric antenna, although this would be partially compensated by the larger effective aperture.

*8.2.3. **Risk.*** To our knowledge, the largest unblocked antenna yet built is 11.5-m in diameter. Thus in building a very large one we would be breaking new ground, and a very careful and detailed analysis would be required to obtain sufficient confidence in the design.

8.3. A Conceptual Design. We concentrated on finding an unblocked aperture configuration that would be feasible at 100-m diameter. The offset geometry results in several degrees of freedom not present in the symmetrical case, so that we considered several radically different configurations.

The first major choice is the relationship of the elevation motion axis to the plane of symmetry defined by the beam axis and the (offset) focal point. If these are parallel, then the elevation axis can be made to pass through the focal point. The focal point is then always at the same height above the ground. This was done with the Bell Labs horn reflector antenna [6] (aperture about 6-m square). While this has some advantages, our preliminary study showed that its extrapolation to 100-m size encounters severe mechanical problems.

If the elevation axis is perpendicular to the symmetry plane, then the focal point moves substantially with elevation change, and the feed or subreflector must be supported by an arm that is rigidly attached to the main reflector. At low elevations, this arm is either below or above the reflector. Having the arm below the reflector is advantageous in that any spillover from the primary or secondary is at a higher elevation than the main beam and hence falls mostly on cold sky; most existing offset-feed reflectors use this arrangement, including the Crawford Hill 7-m telescope [11]. However, when extrapolated to 100 m, this arrangement is structurally more difficult than having the arm at the top. Since the arm must clear the ground when observing at low elevations, the elevation bearings must be both higher and farther apart. For this reason, we

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[2] For the offset reflector, we define the focal length to be that of the parent paraboloid and the diameter to be that of the constructed aperture.

have tentatively selected the top-arm configuration for further study.

8.3.1. Description. A possible configuration is shown in Figure III-3.

A focal ratio of 0.6 assures satisfactory polarization performance and illumination efficiency [12] at the prime focus. The reflector then has a much shallower curvature than the symmetric antenna. The backup structure uses the conventional hoop-and-rib geometry, with its center at the middle of the reflector; the shapes of the hoops are ellipses rather than circles (axis ratio 1.12), but otherwise the backup structure looks much like that of a symmetric reflector. All features of the symmetric backup structure may be applied, including homology. (Alternative arrangements were considered, including ribs centered on the paraboloid vertex, but these are much less attractive.)

The panels, on the other hand, are arranged in a pattern whose center is at the vertex of the paraboloid. This produces a repetitive pattern along circles, so that the number of differently shaped panels is minimized. There are 48 tiers along the radial direction. Because of the different symmetries of the panel pattern and the backup structure, a complex interface is needed; to reduce this complexity, 250 intermediate substructures are constructed, each designed to support 16 panels. The equal-softness deflection concept (as in the 65-meter telescope [5]) should be considered for the substructure design. The substructures are then supported at four corners by adjusting devices from the backup structure.

The subreflector or the prime focus feed is supported by a long cantilever arm extended over the top edge of the backup structure. The arm is braced by two struts, creating a stable tripod. The structure is designed to meet the deflection specifications. Cables may be used to provide additional stiffness, if needed. The tripod is counter-balanced over the elevation axis. At this time, prior to any detailed structural analysis, this structure is the largest uncertainty in the design. Innovative materials and configurations will be explored early in the design process. The structure may be an integrated part of the backup structure to reduce the vertical deflection.

The counterweight support structure and the azimuth tower structure are similar to those of the symmetric antenna.

Just as in the symmetric concept, we include motorized surface adjustment and a stabilized pointing reference platform.

8.3.2. Performance Estimates. The major performance parameters, including minimum wavelength and pointing accuracy, are dependent on the same mechanical considerations as for the symmetric antenna. We therefore expect the same performance, with the obvious exception of the effective area, which will be 6–9% larger because of the absence of blockage, if the diameters of both telescopes are identical.

The reasons, though, for pursuing an unblocked design are reduced sidelobes and reflections. The unblocked design should provide a substantial improvement, which we are working to quantify.

8.4. Cost Analysis. In order to estimate the cost of an unblocked design, we first accepted cost estimates for each of the major elements of a standard antenna and then incremented them according to the added difficulties, if any,

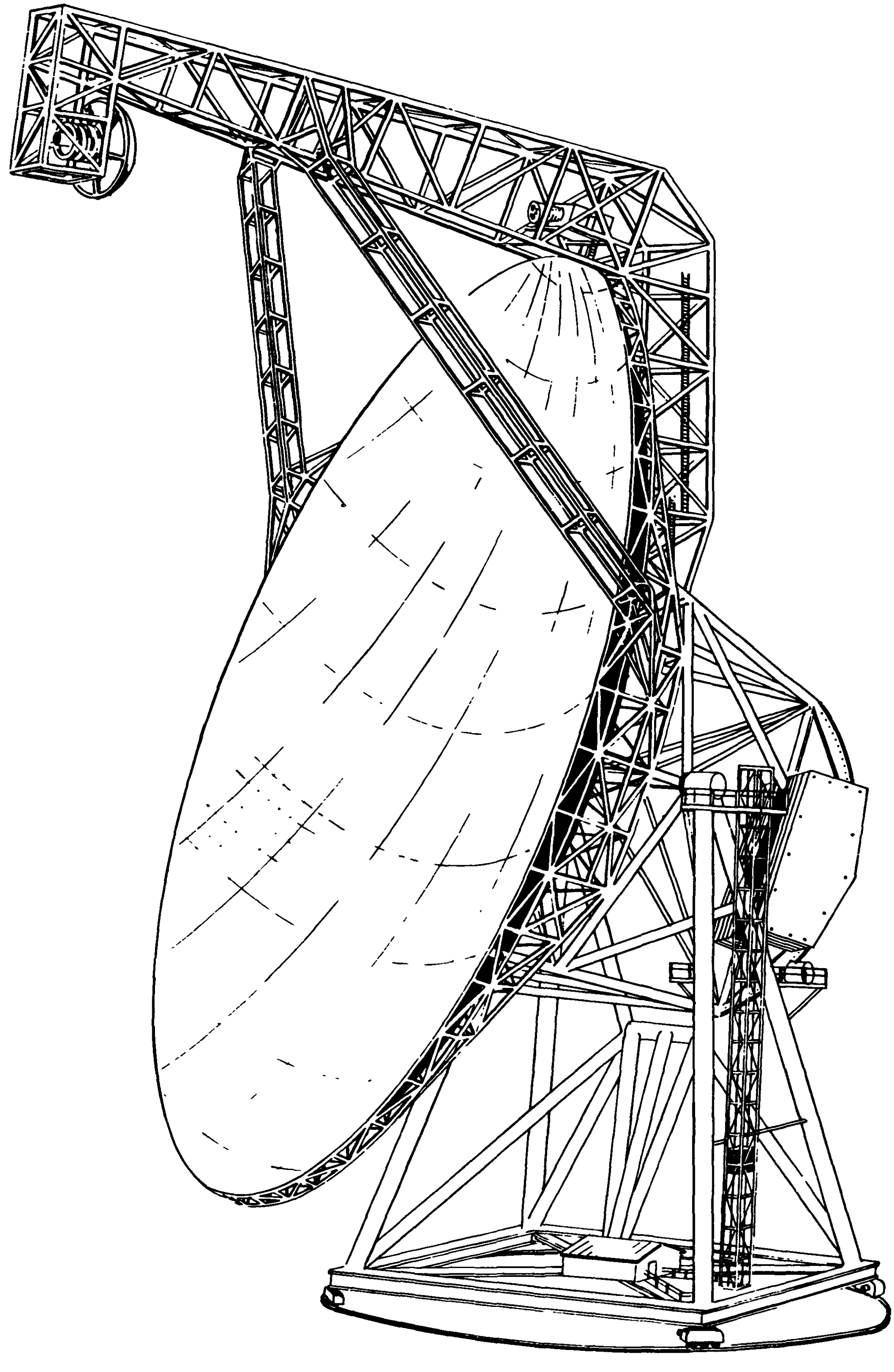

Figure III-3. A conceptual portrayal of an unblocked-aperture design for the Green Bank Telescope.

associated with the asymmetry. The result is given in Table III-3. The largest uncertainty in this calculation is in the focal support tripod. Other items are either nearly the same as in the symmetrical case or only a small fraction of the total. An exception is the panels, significantly more expensive because of the larger number of different shapes; but we are able to account for this accurately. Note that Table III-3 considers only the antenna proper, and does not include the receivers, feeds, computers, surface adjusters, or pointing reference platform; these should be the same as in the symmetrical design.

Table III-3. Relative Cost Estimate for 100-m Unblocked Aperture Antenna

Cost Items	Symmetric	Ratio	Unblocked	Comments
I. Panels				
Tooling	3.8%	2.0	7.6%	Twice as many tools.
Construction	11.9%	1.1	13.1%	More surface area.
II. Engineering and Design				
Structural	3.2%	1.5	4.8%	Complex geometry.
Servo, encoder, gearbox	1.7%	1.0	1.7%	Same as symmetric.
Mgt, documentation	0.46%	1.2	0.56%	More paper work.
III. Construction				
Engineering drawings	0.16%	1.5	0.24%	More drawings.
Steel Structure	39.4%	1.3	51.3%	Complex panel interface and feed support structure.
Servo, encoder	4.0%	1.0	4.0%	Same as symmetric.
Subreflector	2.0%	1.5	3.0%	Asymmetric geometry.
Other mechanical and electrical	18.7%	1.0	18.7%	Same as symmetric.
Management	2.6%	1.1	2.9%	More paper work.
IV. Erection				
	8.8%	1.5	13.1%	More complex structure.
V. Foundation				
	3.4%	1.0	3.4%	Same as symmetric.
Total	100%		124%	

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III. THE ANTENNA

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IV. ELECTRONICS

1. INTRODUCTION

Technological innovation has traditionally provided the impetus for scientific progress in radio astronomy. The technology used to build instrumentation for antennas, most of which have productive lifetimes measured in decades, evolves continuously and often radically. This will be as true in the future as it has been in the past. The expertise developed at the NRAO and elsewhere in the design of low-noise amplifiers, receivers, spectrometers, and other critical electronics systems will be carried over to provide the new Green Bank Telescope with the next generation of instrumentation. We foresee possibilities of significant advances over current instrumentation in new electronics systems that will be constructed. A few examples are:

- New multibeam receivers and multiple backend systems will be provided for multibeam spectral line, continuum, and pulsar observations.
- New technologies (e.g., optical fibers) will be used where improvement in system performance will result.
- Flexibility and user convenience will be improved by allowing automated interconnection between any of several front-ends and backends.
- Systems will be designed in modular form where possible, to simplify future expansion and upgrades.
- More than one observing option will be available at all times, so that the telescope's use-factor will be maximized.

This chapter will consider the requirements of the electronics systems not related to antenna pointing or monitor and control. These are discussed elsewhere. Figure IV-1 shows a simplified block diagram of the systems involved, those used primarily for the amplification and detection of the observed signals. Other electronic sub-systems will be required, but will not be considered in any detail.

2. RECEIVER FRONT-ENDS

The types of astronomical observations that will be expected of the Green Bank Telescope include spectral line, pulsar, continuum, and VLBI. The scientific discussion of Chapter II made clear that the frequency range necessary for applying the Green Bank Telescope to these astronomical observations will be from $\lesssim$ 100 MHz to the useful upper frequency limit of the telescope, expected to be at least 45 GHz initially and perhaps higher eventually. The functions of the receiver front-ends are to provide low-noise amplification of the observed signal, and in most cases to convert the signal frequency to an intermediate frequency (IF) for input to various detection systems. Because of the many different observational modes expected, and the broad frequency range that must

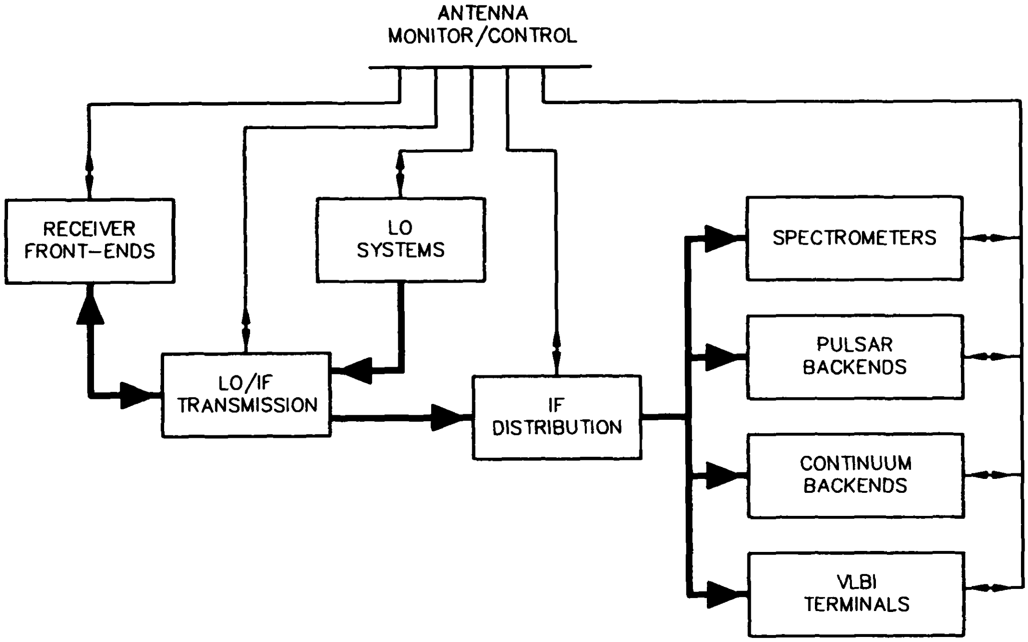

Figure IV-1. Major Electronic Systems.

be covered, the complement of receivers made available for use on the telescope will be limited only by practical considerations and economic reality. Initially we will provide the front-ends expected to receive the heaviest demand, but others will be added throughout the life of the telescope to accommodate shifting user pressure.

2.1. Spectral Line Front-Ends. Requirements on front-ends imposed by spectral line observations are good sensitivity, support for frequency switching, and broad frequency coverage. Table IV-1 lists some important molecular lines and their associated rest frequencies.

Of course, observations of extragalactic objects require receivers to cover frequencies below the rest frequencies. (It is expected that the Green Bank Telescope sensitivity will allow observations of strong transitions down to one-fourth of the rest frequency.) Further compounding the need for nearly continuous frequency coverage are recombination lines, which can occur at virtually any frequency in the telescope spectrum, even below 100 MHz. In order to compare different transitions or species, users may also wish to observe at widely spaced frequencies simultaneously, with coincident or slightly offset beams. In summary, the demands of spectroscopy drive the receiver requirements to nearly continuous frequency coverage and high sensitivity.

2.2. Pulsar Front-Ends. Pulsar observations are performed primarily in the frequency range 0.1–5.0 GHz. Demands on the receiver are extremely good sensitivity, simultaneous orthogonal polarizations, and enough frequency flexibility to avoid interference. The instantaneous bandwidth that is required is usually set by the backends, and currently is less than 50 MHz. Observers would like to

Table IV-1. Selected Spectral Line Frequencies

Molecule	Rest Frequency (GHz)
D	0.33
H I	1.42
OH	1.61–1.72, 4.8, 6.0, 13.2
CH	3.26–3.35
H_2CO	4.8, 14.5, 29.0, 48.3
$^3He^+$	8.7
C_2S	11, 22, 33, 44
CH_3OH	12.1, 36.1, 44.1, 48.4
SO	13.0, 30.0, 36.2
C_3H_2	18.2, 21.6, 46.7, 51.8
HC_3N	18.4, 27, 36, 45
H_2O	22.2
NH_3	23.7–26.5
SiO	42.5–43.5, 86
CS	49.0
DCO^+, HCO^+	72, 89
DCN, HCN	74, 86
CO	115

be able to switch in a few minutes between center frequencies spaced at roughly 2:1. This desire for fairly rapid selection of observing frequency is shared by observers of stellar sources.

2.3. Continuum Front-Ends. Continuum observations are performed both for their intrinsic value and to determine the pointing coefficients of the telescope. The requirements imposed on receivers by continuum observations are relatively wide instantaneous bandwidths, stability, and, often, simultaneous multiple beams. Wide receiver bandwidths and stability improve observational sensitivity. Multibeaming speeds mapping observations and permits some type of beam switching. Switching rates of 1–5 Hz are usually required above 5 GHz for cancellation of atmospheric variations. Several methods may be employed to accomplish the beam switching, including multibeam receivers with electronic or software switching techniques and mechanical nutation of a reflector in the antenna optics. The method chosen will depend on the antenna optical design and the observing frequency.

Since the exact frequency of a continuum observation is usually not critical, frequency bands that have been set aside for the primary use of radio astronomers by international frequency allocation conventions are often used. Appendix A discusses the protection afforded to radio astronomy by these regulations and lists most of the primary protected bands within the expected frequency range of the Green Bank Telescope.

2.4. Very Long Baseline Interferometry Front-Ends. Receiver requirements for VLBI are similar to those for continuum observations. Since the VLBA will be the primary dedicated instrument for these investigations in the 1990s, the Green Bank Telescope will support the VLBA observing frequencies to the extent possible. Table IV-2 shows the VLBA observing bands.

Table IV-2. VLBA Observing Frequencies

Band (GHz)	Frequency Range (GHz)
0.33	0.312–0.342
0.61	0.580–0.640
1.5	1.35–1.75
2.3	2.15–2.35
4.8	4.6–5.1
8.4	8.0–8.8
15	14.4–15.4
23	21.7–24.1
43	42.3–43.5

In addition, dual-frequency observations are supported for the frequency pair 2.3 and 8.4 GHz. (Dual-frequency operation with other pairs may be added in the future.) This capability is necessary for geodesy and astrometry.

2.5. Existing NRAO Front-Ends. The NRAO instruments that most closely match the expected observing modes of the new Green Bank Telescope are the 300-foot (until November 1988) and the 140-foot telescopes. The receiver complements of these telescopes have evolved throughout the last thirty years in response to the needs of the users, taking advantage of advances in technology when appropriate. Consequently they provide some indication of the type of instrumentation that has been most valued by the users. When instrumenting the Green Bank Telescope, we will draw heavily upon the experience acquired in the design and operation of these receivers, those on other radio telescopes, and those now being constructed by NRAO for the VLBA project. Table IV-3 shows the existing Green Bank receivers and some of their characteristics.

The 300-foot was used strictly from the prime focus and up to 5 GHz. The 140-foot is used at prime focus below 5 GHz, and at the Cassegrain focus above. The last five receivers listed in Table IV-3 are therefore "built-into" the 140-foot vertex cabin, but the others are packaged in stand-alone front-end boxes. If necessary, the existing prime focus receivers could be used without modification on the new Green Bank Telescope. That, however, is not our preference. Instead we wish to consider other package designs and to take advantage of new technology. For instance, receivers on the new Green Bank Telescope should interface with the telescope Monitor/Control system and will probably use fiber-optic systems to transmit LO and IF signals, as discussed in Section 3.

2.6. Proposed Receiver Front-Ends. Table IV-4 lists the suggested initial set of receivers for the Green Bank Telescope. The list is separated into primary and secondary receivers. The primary receivers are those needed to accommodate the highest priority science projects or are those that are similar to existing designs. Secondary receivers are those that will require more technical development, or those for which we expect lower initial demand. They may not be

Table IV-3. Existing Green Bank Receiver Front-Ends

Frequency Range	Comments
50–250 MHz	Frequency range covered by two sets of room-temperature transistor amplifiers. Dicke or frequency switching supported.
300–1000 MHz	Frequency range covered by three sets of balanced, cooled MESFET amplifiers. Frequency switching supported.
1.0–1.45 GHz	Cooled MESFET amplifiers. Frequency switching supported.
1.3–1.5 GHz	Room-temperature MESFET amplifiers, four single polarization beams. Used primarily for continuum mapping on the 300-foot.
1.3–1.8 GHz	Cooled HEMT amplifiers. Frequency switching supported.
2.9–3.4 GHz	Cooled MESFET. Upgrade to HEMT under construction. Frequency switching supported.
4.6–5.0 GHz	Cooled HEMT. Frequency switching supported.
4.6–5.1 GHz	Fourteen channel, cooled HEMT amplifiers, with seven beams. Total power, continuum mapping.
4.7–7.2 GHz	Cooled upconverter/maser; HEMT replacement under construction. Frequency switching or beam switching via subreflector nutation.
7.6–11.2 GHz	Same as above.
12.0–16.2 GHz	Same as above.
18.2–25.2 GHz	Tunable maser. Frequency switching or beam switching via subreflector nutation.
25–34 GHz	Cooled HEMT amplifiers; under construction.

available at start-up of the telescope but should follow shortly. Receivers for frequencies > 45 GHz will be provided as soon as the telescope's performance has been demonstrated to warrant them.

All the receivers are assumed to accept dual polarizations. This presents a technical challenge for conventional orthomode junctions at many of the bandwidths given. A broadband quasi-optical approach is feasible at the higher frequencies. If implemented, it offers advantages in frequency flexibility. For example, a polarization beam splitter in use on the 140-foot covers the 8–25 GHz frequency range, and any two frequencies within this range can be observed simultaneously, each with a single polarization. The ability to observe at several frequencies with coincident or offset beams will be highly desirable for many types of observations. Therefore, the opportunity to use the beam-splitter or similar devices will not be excluded by the telescope optics system.

Most VLBI observations require circular polarization, and achievement of high performance in circular polarizers, without serious noise penalty, is limited with today's technology to bandwidths of about 20 percent. Therefore, special consideration will be required for VLBI observations. Several approaches are feasible. Among them are providing a different set of receivers for VLBI, inserting circular polarizers into the broadband receivers when VLBI observations are required, or combining linear polarizations to generate circular following the low-noise amplifiers.

In most cases, it is clear that HEMT technology should be used for the new receivers. However, reflected-wave tunable maser amplifiers are used currently on the 140-foot in the 18–25 GHz range, and their noise performance is superior to that currently achievable with HEMT amplifiers. These masers could conceivably be moved to the new Green Bank Telescope. Maser or SIS mixer receivers

Table IV-4. Suggested Green Bank Telescope Receivers

Frequency Range	$T_{\rm rcvr}$	Comments
Primary Importance:		
50–300 MHz	300 K	Room-temperature transistor amplifiers.
300–1000 MHz	15 K	Cryogenically cooled balanced HEMT amplifiers. Three amplifier sets will be required to cover the frequency range indicated. A design similar to the existing receiver will be used, with updated amplifiers.
1.3–1.8 GHz	5 K	Cryogenically cooled polarizer and HEMT amplifiers. A design similar to the existing receiver (since it achieves the specified level of performance) will be used, with minor upgrades to the monitor and control.
2.0–2.7 GHz	6 K	Cryogenically cooled polarizer and HEMT amplifiers. Front-ends now being produced for the VLBA achieve this level of performance.
2.7–3.4 GHz	8 K	Cryogenically cooled polarizer and HEMT amplifiers. A design similar to the existing receiver will be used, with improved amplifiers.
4.5–5.1 GHz	10 K	Cryogenically cooled polarizer and HEMT amplifiers. Front-ends now being produced for the VLBA achieve this level of performance.
4.5–5.1 GHz	10 K	Seven beams with seven cryogenically cooled polarizers and fourteen HEMT amplifiers. A design similar to the existing receiver will be used.
7–12 GHz	15 K	Cryogenically cooled HEMT amplifiers. A similar receiver, which can serve as a prototype, is now under construction for the 140-foot.
12–18 GHz	20 K	Same as above.
18–25 GHz	30 K	Same as above.
41–45 GHz	80 K	Cryogenically cooled HEMT amplifiers. A prototype receiver for the VLBA project is now under development.
Secondary Importance:		
1.0–1.4 GHz	8 K	Cryogenically cooled HEMT amplifiers.
5–7 GHz	12 K	Cryogenically cooled HEMT amplifiers.
25–32 GHz	40 K	Cryogenically cooled HEMT amplifiers.
32–38 GHz	70 K	Cryogenically cooled HEMT amplifiers.
1.2–1.5 GHz	5 K	Multibeam (four to seven) for continuum and H I mapping.
600 MHz	10 K	Multibeam for pulsar searches.

for frequencies above 25 GHz may also be lower-noise than HEMT devices, but the latter are improving rapidly at high frequencies, so a decision as to which technology to utilize should be deferred as long as possible.

The receivers will be integrated into the telescope monitor and control system. Monitor and control of them will be accomplished via a digital link to the control room over multimode optical fibers. The most recent receivers constructed in Green Bank successfully utilize such a system, which has significant advantages in lightning protection and EMI/RFI susceptibility compared with copper wire transmission.

In general, the receiver front-ends proposed are considered to be low in risk, because NRAO has extensive experience with receiver development on our existing telescopes. We are therefore well-positioned to build an extensive complement of front-ends for the Green Bank Telescope, taking advantage of the best in today's low-noise amplifier technology, and we will be prepared to incorporate improved technology as it becomes available.

3. IF AND LO SYSTEMS

The functions of the intermediate frequency (IF) and local oscillator (LO) systems are to generate stable LO signals and then to transmit them to the receiver front-ends, to transmit IF signals from the front-ends to the telescope control room, and to buffer and distribute the IF signals to multiple backends for detection and data acquisition. This is a mature technology in radio astronomy, but we feel that several advances in performance, flexibility, and user convenience can be made when given the opportunity to design completely new systems.

3.1. LO Generation. Specifications for receiver LO signals are driven by the phase-stability requirements of interferometry and the frequency-resolution requirements of spectroscopy.

Geodetic or astrometric VLBI, as well as phase-reference mapping applications at short centimeter wavelengths, require phase stabilities of less than 20°/hour [**3**]. At the present time, this can be provided only by hydrogen masers. The system phase-stability requirements are usually met by locking all synthesizers in the system to a hydrogen maser frequency reference and by taking proper care in distribution of the reference signals. A maser frequency reference is already available in Green Bank, and will be used initially. Given its age, however, a replacement may eventually be necessary.

The minimum channel bandwidth of current spectrometers is approximately 80 Hz. The frequency resolution of the receiver LO systems should be better than one-tenth of this, or 8 Hz. Frequency switching during observations requires the LO synthesizers to switch by a few megahertz in less than about 10 milliseconds, at a one Hertz rate. We expect to use a commercial synthesizer to generate a high-resolution frequency that can either serve directly as an LO signal or be used as a reference to phase-lock microwave oscillators.

Figure IV-2 shows a simplified block diagram of an LO system, similar to units that NRAO has designed and used, that covers the 8–18 GHz range. Three of these LO systems, plus the commercial high-resolution synthesizer and the hydrogen maser, will constitute the basis of the Green Bank Telescope local oscillator systems.

3.2. IF/LO Transmission. We propose to use optical fiber systems for the transmission of the IF and LO signals between the front-ends and the control room. In early 1989, a system was installed in Green Bank using single-mode optical fibers to transmit LO reference signals from the 140-foot control room to an 85-foot antenna (a distance of 2500 meters), and also to transmit IF signals in the opposite direction [**1**]. Our experience with these systems has been good. The optical transceivers and fiber cable show relatively flat gain and phase responses over the 0.01–1.0 GHz frequency range.

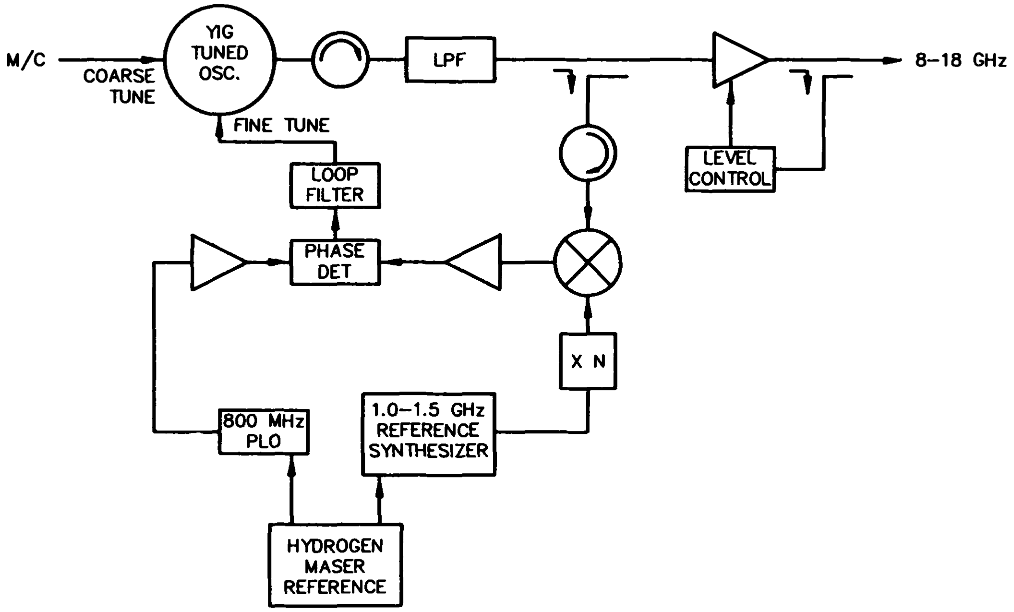

Figure IV-2. Block diagram of a typical phase-locked oscillator.

With the type of fibers used currently, the cable delay temperature coefficient would require active electrical phase compensation for VLBI observations. But a type of fiber has a temperature coefficient of delay lower by a factor of ten [2]. (In tests made at JPL it was found that the low T_c fiber now available is superior to the best available coaxial cable by a factor of twenty at 25 °C.) Even so, some type of active phase monitoring system will be required for VLBI at the higher frequencies, which will require that the phase delay of adjacent fibers track well over temperature and when subjected to mechanical stress. Comparison tests of delay tracking variations in a cable pair installed on the Green Bank 85-foot telescope showed less than $0\overset{\circ}{.}25$ of phase variation at 500 MHz under diurnal temperature variations and antenna motion. This performance translates to approximately 23° of phase variation at 45 GHz, which is believed to be satisfactory and can probably be improved by using the newer cables having lower T_c. Accordingly, active phase compensation on optical fiber transmission systems should work satisfactorily with proper care in the design.

In summary, the optical fiber systems appear to offer significant technical advantages over coaxial cable for long cable runs, and we propose to utilize them for the paths between the receiver front-ends and the telescope control room.

3.3. IF Distribution. Once the IF signals are transmitted to the control room, they must be buffered and distributed to various detection backends throughout the control room. For efficient operation of the Green Bank Telescope, several front-ends will be available for use, from among which the observer will select any one by issuing computer commands. The observer will also be able to select any of the available backends (or use more than one simultaneously) in the same manner. An IF distribution system that will allow this is achievable with today's technology. This system will be designed to handle a fairly broad range of frequencies, say 0.05–1.5 GHz, to anticipate the needs of future backends.

4. BACKENDS

Any instrument that must meet the wide variety of observing modes anticipated for the Green Bank Telescope will necessarily need to provide many different types of detection and data acquisition systems. The general needs are discussed in this section.

4.1. Spectrometers. The Spectral Processor now being installed at the 140-foot will be made available for use on the Green Bank Telescope. This is an excellent instrument for general-purpose use, having 2048 channels, up to sixteen IF inputs, a broad range of bandwidth selections up to 40 MHz, and a great deal of flexibility. It also has excellent timing features that make it a good processor for pulsar data. However, spectroscopy places such heavy demands on the backend that it is difficult to meet all the requirements with one instrument. For some types of observations (e.g., H I searches of galaxies of unknown redshift, or spectral surveys), many more channels and more bandwidth are desirable. We conclude that more than one spectrometer will be necessary to meet the diverse observational goals of the Green Bank Telescope. Several approaches may be considered, including autocorrelators, FFT processors, hybrid analog/digital correlators, and acousto-optic spectrometers (AOS). NRAO has substantial experience in the design of digital signal processors (including autocorrelators, the VLA correlator, the Spectral Processor, and the VLBA correlator) and hybrid spectrometers, and currently is developing a prototype AOS. During the telescope design phase, the spectrometer needs of expected Green Bank Telescope users will be determined and the appropriate design approach selected to meet those needs.

4.2. Continuum Backends. The backends for continuum observations must sample the detected signals with a wide range of sample rates or integration times, and must provide flexible switching cycles for the wide range of observing techniques and equipment that must be supported. We propose the construction of a microprocessor-controlled continuum backend using voltage–frequency converters and digital counting integrators. The equipment will be designed in a modular fashion for expansion as the required number of channels increases. This backend will also contain multiplexed A/D converters which may be required for the rapid sampling of multiple inputs. These are proven techniques, and equipment using similar approaches is now in use at NRAO telescopes. The improvements to be expected from the next generation of equipment include modularity, increased flexibility, and improved integration with the telescope control and data acquisition systems.

4.3. VLBI Terminals. Recording terminals for VLBI observations must, of course, be coordinated throughout the network of telescopes in use. The VLBA is expected to be the most heavily used network by the mid-1990s, so a VLBA recorder will be provided at the Green Bank Telescope.

4.4. Other Considerations. Single-dish observers often bring their own backends to the telescope for special observing programs. Furthermore, backends will be upgraded or replaced frequently during the lifetime of the telescope. Therefore, the electronics systems must be designed with enough flexibility to allow the introduction of new backends with a minimum of problems.

5. HOLOGRAPHY INSTRUMENTATION

Holographic observations will be the primary diagnostic tool for monitoring the accuracy of the active surface of the Green Bank Telescope. The related instrumentation and data processing tasks should be integrated fully with the other telescope operations. The measurements required fall into two classes: those necessary to measure the large-scale gravitational deformations of the antenna, and those necessary to measure the fine-scale errors for setting of the antenna surface. The large-scale measurements can be done with relatively few data points, and can be performed fairly quickly. The fine-scale measurements can take much longer (by roughly the ratio of the required resolutions across the main reflector raised to the fourth power). Measurement time can be reduced by increasing the signal-to-noise ratio of each grid point, for example, by using a larger reference antenna. An eight- to ten-meter reference antenna could quickly perform the fine-scale measurements necessary to set one-meter size panels to 0.1 mm accuracy.

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APPENDIX A. PROTECTED RADIO ASTRONOMY BANDS

Radio astronomy is fortunate in that it has been recognized to have special requirements by various world telecommunications regulatory bodies. Therefore, certain frequency bands have been set aside for the use of radio astronomy, with various levels of protection. These bands are listed in the attached table. The various levels of protection are explained in the following excerpt from an article by Vernon Pankonin taken from *Sky and Telescope* magazine, April 1981, pp. 308–310.

> "Telecommunications is categorized into services with similar types of operation or function. Frequency bands are allotted exclusively or for sharing with compatible services. There are four formal levels of allocation, and one informal, with services being protected from interference on the basis of their status.
>
> "The highest level of protection is primary, with a service being given an exclusive band. The second level is also a primary one, but the band is shared with a compatible service. A third level is called permitted, which is equivalent to primary status except that a primary service in that band has priority in choice of frequencies. Lowest is secondary status, which means a service is authorized to use a particular band but may not interfere with or claim protection from a primary service in the band.
>
> "A notification of use (*nou*) is the informal level and has no legal status. It is simply a statement in a footnote to the allocation table saying that a service is operating in a band. The *nou* is quite often employed in radio astronomy to indicate spectral lines lying in unprotected bands."

U.S. Allocations of Radio Astronomy Bands
(25.0 MHz to 50.0 GHz)

Frequency Band	*Allocation Status / Remarks*
25.550–25.670 MHz	Primary: exclusive allocation.
37.500–38.000 MHz	Secondary allocation. Shared with non-government land mobile service.
38.000–38.250 MHz	Primary: shared allocation. Shared with government fixed and mobile services.
73.000–74.600 MHz	Primary: exclusive allocation.
406.1–410.0 MHz	Primary: shared allocation. Shared with government fixed and mobile services.
608.0–614.0 MHz	Primary: exclusive allocation.
1330.0–1400.0 MHz	Notification of use allocation.

1400.0–1427.0 MHz	Primary: exclusive allocation.
1610.6–1613.8 MHz	Secondary: shared with radio-determination satellite service.
1660.0–1660.5 MHz	Primary: shared allocation. Shared with government and non-government aeronautical mobile to satellite service.
1660.5–1668.4 MHz	Primary: exclusive allocation.
1668.4–1670.0 MHz	Primary: shared allocation. Shared with government and non-government meteorological aids (radiosonde) service.
2655.0–2690.0 MHz	Secondary allocation. Primary allocation is to non-government satellite broadcasting and fixed services. Additional secondary allocation to government and non-government passive earth exploration satellite and space research services.
2690.0–2700.0 MHz	Primary: exclusive allocation.
4990.0–5000.0 MHz	Primary: exclusive allocation.
10.6–10.68 GHz	Primary: shared allocation. The radio astronomy service shall not receive protection from stations in the fixed service which are licensed to operate in the one hundred most populous urbanized areas as defined by the U.S. Census Bureau.
10.68–10.7 GHz	Primary: exclusive allocation.
15.35–15.4 GHz	Primary: exclusive allocation.
22.21–22.5 GHz	Primary: shared allocation. Shared with government and non-government fixed and mobile services except aeronautical mobile.
23.6–24.0 GHz	Primary: exclusive allocation.
31.3–31.8 GHz	Primary: exclusive allocation.
42.5–43.5 GHz	Primary: shared allocation. Shared with government and non-government fixed, fixed-satellite (earth to space) and mobile (except aeronautical mobile) services.
48.94–49.04 GHz	Primary: shared allocation. Shared with fixed, mobile, and fixed-satellite (earth to space) services.

Note: Due to the passive nature of radio astronomy, observations are permitted in all bands, protected or not. Exclusive allocation to radio astronomy means that emission is not permitted within that band.

In addition, notification of use by radio astronomy is given in the footnotes to the U.S. allocation tables for the following bands: 1330–1400 MHz, 1718.8–1722.2 MHz, 3260–3267 MHz, 3332–3339 MHz, 3345.8–3352.5 MHz, 4825–4835 MHz, 4950–4990 MHz, 14.47–14.50 GHz, 22.01–22.21 GHz, 22.81–22.86 GHz, 23.07–23.12 GHz, 31.2–31.3 GHz, and 36.43–36.5 GHz.

V. CONTROL AND MONITOR SYSTEM

1. INTRODUCTION

The control system of a telescope provides the necessary coordination between the various hardware components. It also performs a monitoring function to ensure that each component is operating in the expected manner and interacting correctly with every other part of the system. Furthermore, the control system provides the human interface through which the telescope operator and observers control the operation of the telescope in order to optimize the scientific output of the instrument. Finally, the control and monitor system is a vital safety feature. It monitors all parts of the telescope system for correct operation—alerting the operations staff in instances of anomalous behavior—and it prevents human error from placing the telescope in a potentially dangerous situation, such as might occur under adverse weather conditions.

The Green Bank Telescope will emphasize efficient use. That means observing programs using it must be capable of rapid interchangeability. In this way opportunities granted by exceptionally favorable observing conditions or by scientific urgency can be seized quickly. The need to change programs rapidly and with a minimum of effort means that the changeover must be possible automatically, using equipment under computer control.

2. OVERVIEW

Our plan is that all time-critical operations will be performed by localized micro-processors (local intelligence), initiated by and under the control of a master control computer. The various modules—examples are the telescope positioning servo or data acquisition devices—will be controlled via a standard control bus and, where necessary, synchronized via a standard timing bus. Each of the intelligent modules will be able to function in a stand-alone mode, controlled and operated as a stand-alone system, which should prove an invaluable asset during the initial engineering and debugging stage of the project, and in subsequent upgrades and general maintenance. The system should not be thought of as a multi-processing environment of tightly coupled CPUs, but rather as separate peripheral devices directed by a single control computer, which itself is not required to perform time-critical tasks. Like most modern peripherals, the various individual devices contain their own local intelligence. In this scheme, depicted in Figure V-1, little or no communication will take place between the "peripheral devices", other than that through the master control computer. The system will be totally modular, at both the hardware and the software level. This approach has already been proven successful within NRAO at the 12-meter telescope and within the VLBA project.

The heart of the proposed system is the standard control bus. The master control computer will send commands along this bus at relatively infrequent intervals, measured usually in seconds. Sample commands are, "track this position" to the telescope positioning servo system, or "prepare to record data in

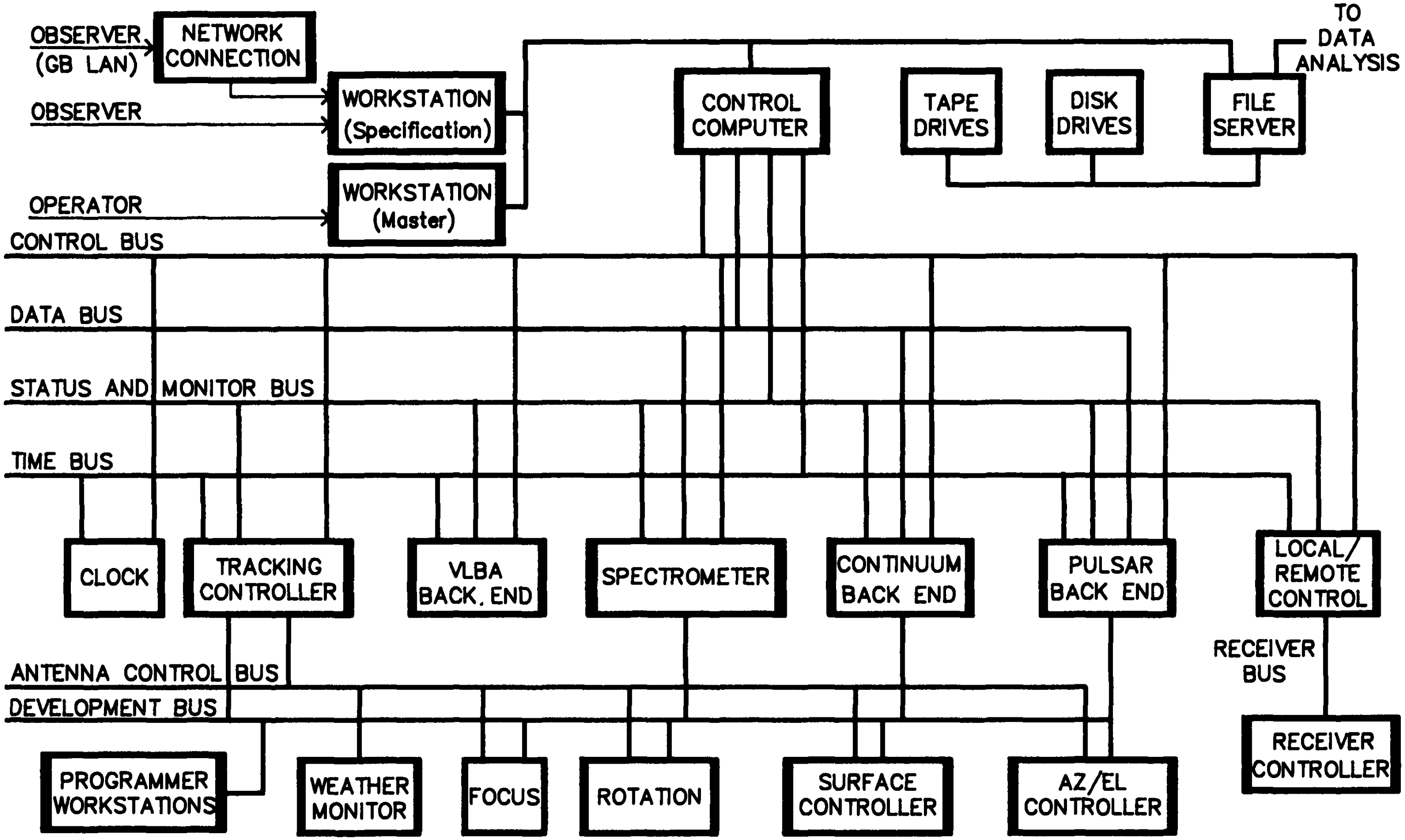

Figure V-1. Control and Monitor System block diagram.

the following configuration" to a specific data acquisition device. The control computer will remain master of the bus, but any peripheral device may ask for attention at any time in order to communicate some event or status information back to the control computer.

Data acquisition devices will in general return data to the control computer along a standard DATA bus. The control computer will add identification and header information to the data blocks, and write merged information to one or two disk storage devices, via the file server. These same disks are accessed directly by the analysis system network. Keeping the data bus and control bus separate greatly eases the system design and will give much higher system performance. It will also simplify changes to either the control or data analysis systems throughout the lifetime of the telescope.

Some events, such as the detection of interference, may require "instant" action, say on the order of microseconds. In addition, some devices will require nanosecond-level synchronization to the site time standard. In these cases, the delay inherent in obtaining access to the control bus and setting up the communications protocol along this standard command bus may be inappropriate. A Status and Monitor (SAM) bus will be reserved for such cases. This supplies a simple, reliable way of communicating events from one module to another by setting or reading individual bits on the bus—in fact, this SAM bus will be the only mechanism allowed for direct device-to-device communication. Permitting limited communication along this bus is consistent with the modular system design, keeping the coupling between modules as loose as possible.

The operation of the telescope control system will be synchronous. That is, different devices may initiate preset sequences of operations at the same time, synchronized either from the SAM bus for devices requiring event or time interval information, or from the TIME bus for devices such as the tracking controller, VLBA, or pulsar backend that require absolute Universal Time.

3. PROGRAMMING ENVIRONMENT

The intelligent modules will run programs either from code stored internally in ROM, or from code downloaded into RAM from the control computer, or from the programming development environment. Separate workstations will be used for program development. They will be tightly coupled, via appropriate software, to the multi-tasking real-time kernel of more complicated devices such as the tracking/servo module, or to the bootstrap loader of simpler devices such as status monitors. The workstation will provide a high-level development, monitor, and debugging environment for the real-time software running in each intelligent module. Commercial software, which is already available to support this arrangement, has been adopted elsewhere within NRAO (the VLBA correlator and the 12-meter telescope control system) as well as at other institutes (e.g., the Keck Telescope, the Global Oscillation Network Group, and NOAO).

4. USER INTERFACE

The user interface gives both the observers and the telescope operators the ability to configure, control and monitor the telescope system. The learning curve for a new observer to be able to use the telescope efficiently must be as short as possible.

Because of the very modular software design, the interface software can be developed to a large extent independently of the remainder of the control system development. Early in the development stage, we intend to create a stand-alone telescope emulator, which will run on commonly available computer systems, and which will be made available to a number of future observers. The emulator will enable future telescope users to experiment with observing strategies in a reasonably realistic environment, giving feedback to the programmers on whether a given prototype interface is likely to be successful or not. Some of these prototypes will be modeled after existing telescope control systems and user interfaces. In this way, we expect the user interface software design and philosophy to evolve, and to do so simultaneously with the development of the rest of the control system. When the telescope becomes operational, the interface will already have become a tried and tested system.

Aspects to be explored with the help of future users include:

- The relative usefulness of available commercial interface packages, using windows, menus, etc.
- Expert systems. With the great versatility planned for the new telescope, software may be able to give considerable guidance to an inexperienced user as to the best telescope configuration to be used for a given scientific problem.
- Real-time interaction. Some observing sequences can be predefined, while other programs require considerable interaction with the user during the observations. There are various ways of providing this combination of batch and real-time operation.
- Graphical displays of configuration information, and status information of various telescope sub-systems.
- On-line access to astronomical data bases, including source catalogs, and all-sky or source maps. These can aid an observer in choosing, for instance, an blank area of sky to be used as an empty reference position.
- Data quality monitoring. Although the analysis system will provide immediate analysis of incoming data, there should be some real-time indication of data quality (e.g., running rms during a long integration) presented automatically to the user as part of this interface.

5. REMOTE OBSERVING

One aspect of the operation of the Green Bank Telescope that may become important in the future is remote operation. Reasonably straightforward observations should be possible for observers, located remotely, who are linked to the Telescope via one of the standard networks. This will become particularly critical when the telescope is used at frequencies which are dependent on favorable atmospheric or ionospheric conditions. If observing conditions deteriorate, then, in order to use the telescope efficiently, a proposal at a different, less weather-dependent wavelength may, at short notice, be substituted for the weather-dependent project. Neither observing team would have to be on site, because both could communicate with the telescope over one of the existing computer networks. However, in order to protect the pseudo real-time environment of the master control computer against overloading by network activity, and to provide security against inadvertent, malicious, or illegal operation of the telescope, a network server will be used between observers and the control computer itself. This buffer computer will provide the appropriate user-friendly, high-level interface to all observers, whether they be on site or at the end of an international computer network.

6. Software Standards

As observing techniques evolve and as new hardware is added to the telescope, the software requirements for the monitor and control system will change. To minimize the disruption to observing caused by these changes and to maximize the productivity of software engineers, the software design will be very modular, both within and between programs. Modularity will also ease the initial hardware and software design by allowing individual software and hardware components to be engineered, implemented, and tested with little or no dependence on the rest of the system. Portability will be another guiding principle. Adherence to this principle will allow existing libraries and routines to be shared, and will permit off-line development and testing of software and hardware.

7. Structure of the Control System Hardware

The heart of the control and monitor system is its various bus systems. If constructed today, it would follow the bus implementation described below. However, this is a rapidly evolving area of technology, and we recognize that other, even more appropriate, standards may emerge in the near future.

7.1. Control Bus. The master control computer will retain control of this bus. The control computer will send configuration information to the intelligent peripheral modules along this bus, and will receive, either on demand from the control computer or when initiated by one or more of these modules, various status reports. Today, the IEEE-488 standard would be appropriate for this bus.

7.2. Data Bus. In general, data from the various data acquisition backends will be routed back to the master control computer along this bus. The control computer will attach header and identification information to these data and will then write the data via (e.g.) a standard Ethernet bus to one or more disk drives. The data on these disks will be accessible to the data analysis system along the same, or a similar, Ethernet bus. An exception to this rule might be some device with exceptionally high data acquisition rate, such as a VLBI recorder. In this case the device will provide separate data storage, either on its own storage device or directly via a fast bus, to one of the system storage disks.

7.3. Status and Monitor (SAM) Bus. This is a differential parallel 16-bit bus, conforming to RS485. Bits on this bus will be set or read by individual modules whenever, for the sake of critical timing or for simplicity, it would not be appropriate to signal the information with the usual protocol along the regular command bus.

7.4. Time Bus. This bus will disseminate absolute (UT) time information, using the standard IRIG serial format. Standard interfaces are available to interpret this format, which can be used both for time interval and absolute time information.

7.5. Antenna Control Bus. This is part of the subsystem of antenna tracking and control. The tracking controller module will control the servo loop that points the telescope, the surface panel adjusters, and the focus positioning and other active components of the antenna. In order to do so, it requires absolute time, demanded azimuth and elevation coordinates as functions of time, and other data, such as weather, temperatures of parts of the telescope structure, etc., in order to correct the telescope pointing model for atmospheric refraction and telescope thermal distortions. These sensors and controllers form a complete subsystem under direction of the "Tracking Controller". This bus will be independent of the Control Bus, but will conform to the same mechanical and electrical standards, and will use the same protocol.

7.6. Receiver Bus. This represents another subsystem, although, as shown on the diagram, it is merely an extension between a local controller, physically located in the telescope control room, and the receiver controller, which will be located adjacent to the receivers at either the prime or the secondary focus position. Again, this would conform to the same standards as the Control Bus, although the bus would be physically extended using a fiber-optic transmission medium.

7.7. Development Bus. This bus joins the workstations used for programming development to the processors in individual modules. The capability for programming development will be retained throughout the life of the telescope in order to retain flexibility in future developments in hardware and software. Today, the choice would be for an Ethernet link.

VI. DATA PROCESSING

1. INTRODUCTION

The immediately preceding chapter dealing with the Green Bank Telescope's Control and Monitor System addressed the way in which the antenna and all its equipment will be coordinated to provide astronomical data to storage media and to a data analysis system. This chapter picks up the story at that point, namely, after devices attached to the IF chain of the telescope—spectrometers, radiometers, pulse processors, etc.—have finished their tasks. At this point, incoming radio waves have been converted into a bit stream which can readily be blocked-out, time-stamped, and labeled by a header containing descriptive astronomical information. The radio waves have been transformed into the basic, manageable elements of astronomical "data".

Data processing involves specification of both hardware and software. Even though the basic manipulations of astronomical information can in principle be performed on almost any machine, high data rates and specialized processing of large amounts of information necessitate sophisticated storage and display devices, and specialized code.

The variety of scientific uses for the Green Bank Telescope (Chapter II), and the electronics components needed to exploit them (Chapter IV), together will provide data at rates and in quantities not encountered before for single-dish radio telescopes. Consequently the design for processing these data, described in the following, must accommodate greater sophistication and more power than ever before.

2. DATA HANDLING CAPABILITIES REQUIRED FOR DATA PROCESSING

Data processing hardware associated with the Green Bank Telescope must function in near real time for receipt, validation, and temporary storage of currently incoming data, and for interactive processing and display of both new and old databases. It must be available on a continuing basis for down- or off-loading of data to long-term archival media (for storage or export) and for uploading of previously archived data that the astronomer wants to re-examine. Below we give some examples, based on current observing practices and ideas, of the data rates and database sizes that the hardware will have to support.

2.1. Rates of Incoming Data.

1. Search for line radiation in 1024 correlator channels: 1024 2-byte channels are received from the telescope every thirty seconds (+50% overhead for header information)—typical of current astrochemistry experiments,

100 bytes/s = 6 kbytes/minute = 360 kbytes/hour = 8.4 Mbytes/day.

2. Continuum sky-survey at one frequency with 14 receivers: 140 dumps per second of (approx.) 20 bytes—the Broderick–Condon experiments recently undertaken on the 300-foot, not at all hypothetical,

2.8 kbytes/s = 168 kbytes/minute = 10 Mbytes/hour = 240 Mbytes/day.

3. H I coarse sky survey: with eight IFs each feeding 1024 spectral-line correlator channels—once envisioned as a future project for the 300-foot telescope. Entails the receipt of 8×1024 2-byte channels every ten seconds. With fifty percent overhead for header information, the data rates are essentially identical to those of the actual continuum survey noted in (2) just above. (This experiment is hypothetical, however.)

4. Pulsar search mode: a 1024-channel correlator dumps a few bits/channel at 125 Hz—this is the current observing mode at Arecibo (1024×125 Hz $\times$ $\frac{3}{8}$ bytes/channel =)

48 kbytes/s = 32 Mbytes/min = 175 Mbytes/hour = 4 Gbytes/day (!).

2.2. Database Sizes.

1. All-sky 408 MHz continuum map made at 15′ beam spacing (HPBW/2 for a 100-m antenna):

6.5×10^5 pixels, two bytes/pixel $\Longrightarrow$ 1.3 Mbytes in total.

2. All-sky 5 GHz continuum map made at 1.′2 spacing:

1×10^8 pixels, two bytes/pixel $\Longrightarrow$ 200 Mbytes in total.

3. All-sky H I emission survey at HPBW spacing:

2×10^6 pixels $\times$ 1024 chans $\times$ 2 bytes/pixel $\Longrightarrow$ 4 Gbytes in total.

4. Pulsar-search mode at Arecibo after a two-week observing run of 3-hour days:

10 Gbytes in total.

These data-taking rates and database sizes span wide ranges. The smallest rates, only a few Mbytes per day, require only the simplest of computers (a large PC or small workstation). The highest rates, though, are so large that no substantial fraction of the data could reside on any current system for very long without choking it. (One present mode of processing pulsar data, for example, is to carry it away, on magnetic tape, to a supercomputing center.) In the future, wider availability of high-density digital storage media will greatly enhance the ease with which extremely large databases are stored and manipulated.

3. SOFTWARE REQUIREMENTS

3.1. Generalized Description. Single-dish telescopes are inherently flexible devices which allow the astronomer great latitude in the design and execution of observational programs. To capitalize on this flexibility and to ensure that data, once taken, are fully utilized for the intended astronomical purposes, the Observatory will provide a core package of software routines to support calibration, editing, analysis, display, and presentation of data.

The most basic product of the majority of observing modes will be a set or array of datapoints corresponding to: intensity vs. velocity or frequency (for spectral-line work); intensity vs. sky position (continuum); or intensity vs. time (pulsars). In mapping observations, such arrays are stacked side-by-side to produce two-dimensional grids corresponding to intensity as a function of sky position at one or (for a map of emission from various gas species) $\gtrsim$ 1024 frequencies. Alternatively, spectroscopists might wish to generate a single, longer array corresponding to a broad-band spectrum of emission, and pulsar observers might require that a long time-series be parsed into individual shorter arrays corresponding to one pulse cycle each.

Before the data are assembled in these ways, a wide variety of procedures may have been applied. Instrumental and other spurious influences must be removed (typical effects are receiver gain variations and varying sky opacity); the data might need to be regridded on the sky (interpolated to a more regular set of positions); and some data might be so seriously affected as to be worthless, or be missing due to equipment failure, necessitating further observation and some database management.

After the data have been assembled into an approximation of the final database, the Observatory's software will afford the ability to view it, ascertain its overall quality and integrity, and extract relevant information for analysis and presentation. Separate routines will be developed for three areas: spectroscopy and spectral line mapping; continuum observations and mapping; and pulsars. The programming effort needed to extrapolate beyond existing data-handling capacities will be major.

3.2. On-Line Services Required During Telescope Operations. While an experiment is being executed on the telescope, the astronomer or telescope operator will be able to access and manipulate the incoming data to a degree sufficient to ensure that matters are progressing satisfactorily. If they are not, immediate discovery of the situation will prevent substantial waste of observing time. The more automatic portions of this functionality—simple data validation and existence checks—can be subsumed by the database system that accepts data from the telescope. More subtle inspection of the data will be afforded by the software systems used to analyze and display data generally. The onsite network described in Section 4 of this chapter will provide a high degree of feedback between the telescope operator, telescope, and observer for such purposes.

3.3. Software Required in Support of Spectral Line Observing. The spectral-line software package will provide the capability to manipulate the data gathered by multi-beam mapping receivers. Its ability to image these data into presentable maps will be comparable in sophistication to the techniques currently applied to VLA images.

Implementation of software support for spectral line observations will involve development of database management techniques, algorithm development for application of image deconvolution and other sophisticated techniques, and integration with powerful display and analysis tools.

3.4. Continuum Observations (exclusive of VLB). An adequate model for handling single-dish continuum mapping observations exists in the form of the NOD2 program developed at Bonn by C. G. T. Haslam. If it were feasible to adopt NOD2 for our purposes, a large programming effort might be avoided and, *de facto*, a single, worldwide software standard would result. Benefiting from and contributing to a common worldwide pool of single-dish analysis programs will be a goal of the software developed for the Green Bank Telescope. If successful, the package for the Green Bank Telescope could provide the same degree of standardization as NRAO's AIPS package has for array observations.

3.5. Pulsar Observations. Pulsar studies have historically been conducted by a relatively small band of observers who took and analyzed their data using proprietary hardware and software. To some extent this observing mode will continue, for instance in the case of searches where present-day supercomputers are employed to process the enormous amounts of data (see above) generated in even a few days time.

However, the Observatory had, with the advent of the spectral processor in Green Bank, already taken steps to provide significantly stronger support than previously of pulsar observations. The "phase-resolved pulsar spectrum"—a history of the continuum pulse profile—is produced and analyzed using special-purpose, but straightforwardly specified operations that are being implemented in a software package. The existence of such support will greatly broaden the base of possible pulsar observers and of those observers who use pulsars as beacons of known distance in the nearby regions of the Galaxy. The data-analysis software package for the Green Bank Telescope will therefore be extended and expanded to serve the anticipated large pool of pulsar observers.

3.6. VLB Observations. When the new telescope performs Very Long Baseline Interferometry in collaboration with other instruments, it will use the systems common to all other telescopes. Use of the new telescope for VLBI requires only that a standard VLBA recording terminal be present on-site.

3.7. Required Level of Support for Off-Site/Remote Single-Dish Processing. The next generation of NRAO single-dish software will be supported at a level comparable to that of AIPS. That is, the system will be available for export to a user's home institution, and it will be sufficiently capable that most users will import it for their own use elsewhere. Some significant amount of the data will be processed on NRAO machines during remote observing, however. Access to the site, the telescope, and its database will be afforded by national and on-site networks.

4. An Outline of the On-Site Computing Facility

4.1. Server, Network, and Archive. A prototype for the telescope-site computing system is sketched in Figure VI-1. It is predicated on the existence of a fast, site-wide local area network over which astronomers can access a central file server responsible for maintaining databases consisting of new, newly processed (by the astronomer), and old data. Given the degree of connectivity currently projected to occur within the next ten years, the existence of such

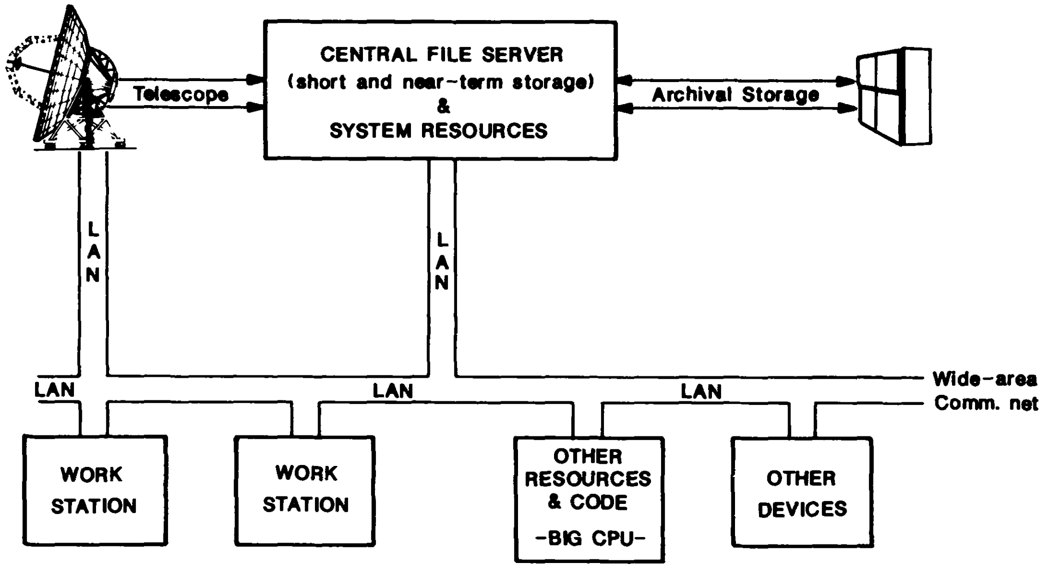

Figure VI-1. Schematic diagram of a prototype telescope-site computing system.

a network should provide nearly seamless integration with the outside world as well. This will facilitate use of the telescope and its complement of data processing software by remote observers.

The central file server will need many Gbytes of fast-access storage to contain the new, reprocessed, and old data that flow within the system. It will also need access to efficient means of archiving and restoring large databases—a task now relegated to magnetic tape, but one which in the future will be better handled by other technology.

4.2. Computational Power Needed On-Site. For many present purposes, the computing power needed to process data could be distributed throughout the system. A well-equipped workstation would suffice for the interactive reduction and display that occupy much of the work-load involved in processing a typical spectral line or continuum experiment today. Some substantial fraction of the Green Bank Telescope's time will also be spent on projects whose computing needs are of this small order.

Larger experiments, some of which are conducted today and which we expect will become increasingly common, will require the services of a machine as powerful as a CONVEX vector mini-supercomputer. Such a machine could be positioned in the system as the central file server, but might then be too heavily taxed to support the telescope directly. More likely it will be supported elsewhere on the local area network.

The very largest experiments will (almost by definition) require the degree of computing power embodied in a supercomputer. By the mid-1990s, however, the cost of today's CONVEX-class machines will probably purchase the power of the now-extant CRAY MP-class machines. Thus, even very demanding experiments could be handled entirely by an on-site computer when the new telescope goes on-line.

Specification of the precise data processing hardware for the Green Bank Telescope will be coordinated within the formulation of the NRAO Array Computing Plan. This will allow the Green Bank computational environment to be integrated with the other resources of the Observatory in an efficient and cost-effective manner.

4.3. Workstations/Peripheral Devices. The workstations shown in Figure VI-1 will contain local graphics display devices. All stations will be capable of producing copies of images, as well as line-drawings, on commercial film recorders or laser printers located on the network. A few could be diskless, but several will resemble the stand-alone system that a user might have at his home institution—with substantial storage capacity and the ability to export/import databases.

5. Development Path

The twin tasks of database management and calibration/reduction/analysis must have a transparent interface; the database manager must coordinate with the telescope operating system in a manner that is invisible to the user of the telescope. The database facility and the purely astronomical applications will be prototyped together and developed in parallel. During the preliminary design phase of the Green Bank Telescope, the data processing development will proceed according to the following plan:

1. For the database management facility we will:

(a) Specify the computer and network hardware responsible for maintaining the telescope database.

(b) Design/purchase the database management software responsible for maintaining the flow of:

new data arriving fresh from the telescope,
old data being restored from the archive,
data being fed back into the database after reduction, analysis, etc.

2. To implement calibration/reduction/analysis/presentation of the data we will:

(a) Specify the computer and network hardware directly supporting the reduction and analysis of data.

(b) Implement data reduction software for:

spectral line work,
continuum work,
pulsar work.

We shall require that both the hardware and the software observe international standards, where such exist. A few examples might be the UNIX software operating system, Ethernet protocol for networking, X Windows for graphics, Post Script for hard copies, IEEE-standard buses, etc. The motivation behind this is to ensure hardware independence and compatibility with facilities at other institutions. Hardware independence is critical to permit continuous upgrading in a rapidly changing area of technology, without sacrificing the accumulated software investment. All development will aim to integrate the on-site data-processing capabilities into the emerging national networks.

VII. OPERATIONS

1. INTRODUCTION

The operational style of an instrument as versatile as the Green Bank Telescope must evolve continually to meet changing scientific needs. However, the main operational consideration from which all others will derive is that the Green Bank Telescope will be a visitor facility, and operations will aim to maximize the quality and number of successful observations that are performed by visiting scientists. The following sections contain a brief discussion of our general approach to telescope operations, with emphasis on areas where it may differ from past NRAO practice.

2. OPERATIONAL GUIDELINES

The Green Bank Telescope will be operated like other facilities of the NRAO. Observations will be scheduled 24 hours a day, seven days a week, except, perhaps, on a few holidays each year. The telescope will be used solely for astronomical observations, except for periods of routine maintenance and repair and for major equipment upgrades. Experience at Green Bank with the 140-foot telescope indicates that about 85% of the annual total time can be expected to go to astronomical observing once the telescope enters routine operation.

Telescope time will be assigned to scientific programs chosen on a competitive basis. Prospective users of the telescope will submit a proposal outlining the intended research and its scientific justification. They will also specify what equipment is needed and how much telescope time is required. The proposal will be reviewed by several scientists unaffiliated with the NRAO who will advise on the scientific merit of the proposal, its feasibility, and the potential impact of the proposed research. The judgement of the referees forms the basis upon which the telescope is scheduled. The telescope will be open for use by any qualified scientist. NRAO staff wishing to use the telescope will receive the same consideration as visiting scientists.

3. SPECIAL OPERATIONAL CONSIDERATIONS

3.1. Weather-Dependent Scheduling. Since the Green Bank Telescope will be used for projects that are sensitive to the exact weather conditions, and it is NRAO's goal to maximize the use of the telescope, it is planned that at least two receiving systems will be available simultaneously: one for a weather-dependent program and the other for a weather-independent program. These will most likely involve high- and low-frequency receivers that can be interchanged quickly. If the weather conditions are suitable, the high-frequency program will proceed. But if the weather conditions preclude work at high frequencies, the low frequency programs will be switched in. Weather data will be available to remote observers as part of the telescope status information to help them judge the atmospheric suitability. On the site, telescope operations-and-support systems scientists will choose which observing program is best matched to the observing conditions. Proposals will be scheduled on their merits, not on their wavelength requirements, but a given proposal will be granted the time necessary to complete it within a certain time window rather than on specific dates. The length of the window within which an observation is completed will be determined as experience with operating the Green Bank Telescope grows.

3.2. Observing *in absentia*. Scientists will be encouraged to come to Green Bank for their observations. The direct interaction of visitors with the telescope and with NRAO staff constitutes an essential feedback loop for instrumental evaluation and improvement. But the Green Bank Telescope will also operate in two other ways, remotely and by proxy. In remote observing, the scientist has real-time access over a digital data link to telescope status information, to a computer for editing schedule files, and to the incoming data stream. Thus the actual observing can be done from an arbitrary location. Observers will guide their experiment just as actively as if they were on the site, and will be expected to be on-call during the entire time their observations are being made. In principle, remote observing will be just as flexible as on-site observing.

The Green Bank Telescope may support some limited "proxy" observations, in which NRAO personnel will control the telescope and take the data, in lieu of the scientist doing so. Most VLBI observations are now done by proxy, and this practice can be extended usefully to support other kinds of programs.

The added capabilities of the remote and proxy observing modes should make dynamic weather-dependent scheduling feasible for many different projects. Depending on the exact weather conditions, the telescope might be accessed remotely by any of a number of potential observers.

3.3. Survey Programs. One of the great strengths of the 300-foot telescope was its suitability and availability for large-scale surveys of the sky. The survey work done on the 300-foot is recognized in the community as a valuable resource; operations of the Green Bank Telescope will strive to preserve this capability for its users. Because of the long time often needed to complete major surveys, special provisions will be made for conducting them without the need for the observer to be present during the full course of the observations.

3.4. Coordinated Observations. A major advantage of the flexibility being designed into the Green Bank Telescope is that special, one-time observations can easily be accommodated. Coordinated observations, whereby measurements are conducted simultaneously with other instruments (e.g., VLBA, HST, AXAF), will also be possible. Involvement of other instruments in a project does not, of course, guarantee time on the Green Bank Telescope. The scientific proposals will be judged by the same standards as stand-alone projects. A similar policy will apply to observations that require use of the telescope at regular intervals for monitoring programs.

Coordinated programs will benefit greatly from the Green Bank Telescope capability for remote or proxy observation. Scientists can be physically present at whatever instrument is most convenient and can use the Green Bank Telescope from that location.

4. INSTITUTIONAL SUPPORT

Many user programs, particularly the demanding or exploratory experiments, will benefit from a close cooperation between the astronomer and the NRAO technical and scientific staff. Since users often suggest new ideas for equipment and software, the staff strives to work closely with visitors to extract the peak performance from all equipment, to implement new equipment, to assist in the operation of components that visitors may bring with them, and to provide adequate facilities for data reduction.

Plans for electronics and computing equipment are given elsewhere in this proposal. The Observatory's priorities for additional equipment design and construction will be set by user demand.

VIII. THE TELESCOPE SITE

1. INTRODUCTION

The principal criteria for the site of a radio telescope are driven by the specifications of the instrument itself. In Chapter II, which discusses the scientific objectives of the Green Bank Telescope, studies of the OH radical, of the neutral hydrogen in the Milky Way, and of the hydrogen content of other galaxies, especially those of higher redshift, were highlighted. For the relevant frequencies, between approximately 1300 and 1720 MHz, protection from radio frequency interference (RFI) is a major consideration. The telescope will also be an important resource in the study of pulsars because it will enable sensitive surveys for new pulsars, will provide detailed studies of neutron-star physics, and will use pulsars to test General Relativity. Most such observations are made at meter and decimeter wavelengths, where the pulsar emission is strong, but where terrestrial interference can be troublesome. For general continuum work the RFI environment is important even at centimeter wavelengths, because larger bandwidths are much used to achieve greater system sensitivity.

The Green Bank Telescope will be used at much higher frequencies to study the line radiation from, among others, molecules of water and ammonia (in the range 22–25 GHz) and from carbon monosulphide, silicon monoxide, and other molecules in the range 40–50 GHz. Also of importance at high frequencies will be observations of the redshifted line of CO emitted by distant galaxies. For these molecular observations the atmosphere limits both the quality and the times during which the observations can be made. The proposed site should therefore offer periods of adequate atmospheric transmission and stability.

Another scientific discipline to which the Green Bank Telescope will contribute significantly is VLBI. The most sensitive experiments require the high sensitivity that can only be provided by large collecting areas. The individual collecting areas must be properly spaced globally, however, if they are to contribute optimally to high-resolution, high dynamic-range images. A large telescope near the east coast of the U.S. nicely fills an existing gap between the phased VLA in New Mexico and the major European telescopes (the MPIfR Bonn Telescope, the phased Westerbork Synthesis Radio Telescope, and the Jodrell Bank Mark I Telescope).

The success of the telescope will be determined by the quality of the ancillary electronic equipment. The 300-foot and the 140-foot telescopes both achieved successes beyond their design goals because of the superior radiometers with which they were equipped. The new telescope must be located where it can be provided the high level of technical support needed to maintain state-of-the-art radiometers, IF processors, and data analysis systems.

In terms of these criteria, the Green Bank, WV site of the National Radio Astronomy Observatory is excellent from the standpoint of low RFI, is excellent from the standpoint of logistical and technical support, is well placed to complement existing large VLBI antennas, and has an adequate number of periods of good atmospheric transmission and stability. It is therefore a superior location for the new telescope.

The following sections give additional details about each of the site selection criteria.

2. Site Selection

2.1. The Radio Frequency Environment. The Green Bank Observatory is unique in the level of protection it receives against interference at radio wavelengths. This protection is achieved through the National Radio Quiet Zone and through the Radio Astronomy Zoning Act of the State of West Virginia. In addition, the Observatory monitors the local RFI environment and has received extensive cooperation from the surrounding community in the elimination of interfering radio signals.

2.1.1. The National Radio Quiet Zone (NRQZ). The National Radio Quiet Zone was established in 1958 by the Federal Communications Commission in order to protect the radio frequency environment of the NRAO telescopes at Green Bank and of those at the U.S. Naval Receiving Station at nearby Sugar Grove, WV. FCC regulations grant NRAO the authority to review applications for radio services within the Zone to ensure that the power flux density produced at the Observatory site by any fixed transmitter anywhere in the NRQZ does not exceed the following levels:

for frequencies less than 54 MHz:	1×10^{-8} W m^{-2},
for frequencies from 54 to 108 MHz:	1×10^{-12} W m^{-2},
for frequencies from 108 to 470 MHz:	1×10^{-14} W m^{-2},
for frequencies from 470 to 1000 MHz:	1×10^{-17} W m^{-2},
for frequencies f (GHz) above 1 GHz:	$f^2 \times 10^{-17}$ W m^{-2}.

Additional specifications are in place for the several frequency bands assigned to radio astronomy as a service, or for which radio astronomy receives "footnote" protection. A more detailed list of Power Flux Density Limits is given in Appendix A.

The National Radio Quiet Zone covers an area of approximately 13,000 square miles. The boundaries in longitude are 80.5 degrees (near Weston, WV) and 78.5 degrees (near Charlottesville, VA). In latitude they are 39.25 degrees (near Clarksburg WV), and 37.5 degrees (north of Lynchburg, VA). The outline of the NRQZ is shown in Figure VIII-1.

An applicant for a permit to locate a fixed transmitter in the NRQZ sends to the NRAO a summary of the characteristics of the transmitter, from which is deduced the power level that the new transmitter will produce at the Green Bank site. If the level is above that mandated by the NRQZ, the NRAO will offer technical advice to the applicant about possible means to reduce the potential for interference, e.g., shaping the radiation pattern of the transmitting antenna. Occasionally it has not been possible to reduce the expected power to safe levels. In these cases NRAO has the legal standing to object. To date, no licenses have been granted by the FCC to applicants to whom the NRAO has objected.

The importance to the radio astronomy research at Green Bank can be judged by the statistic that in the calendar year 1988 the NRAO processed

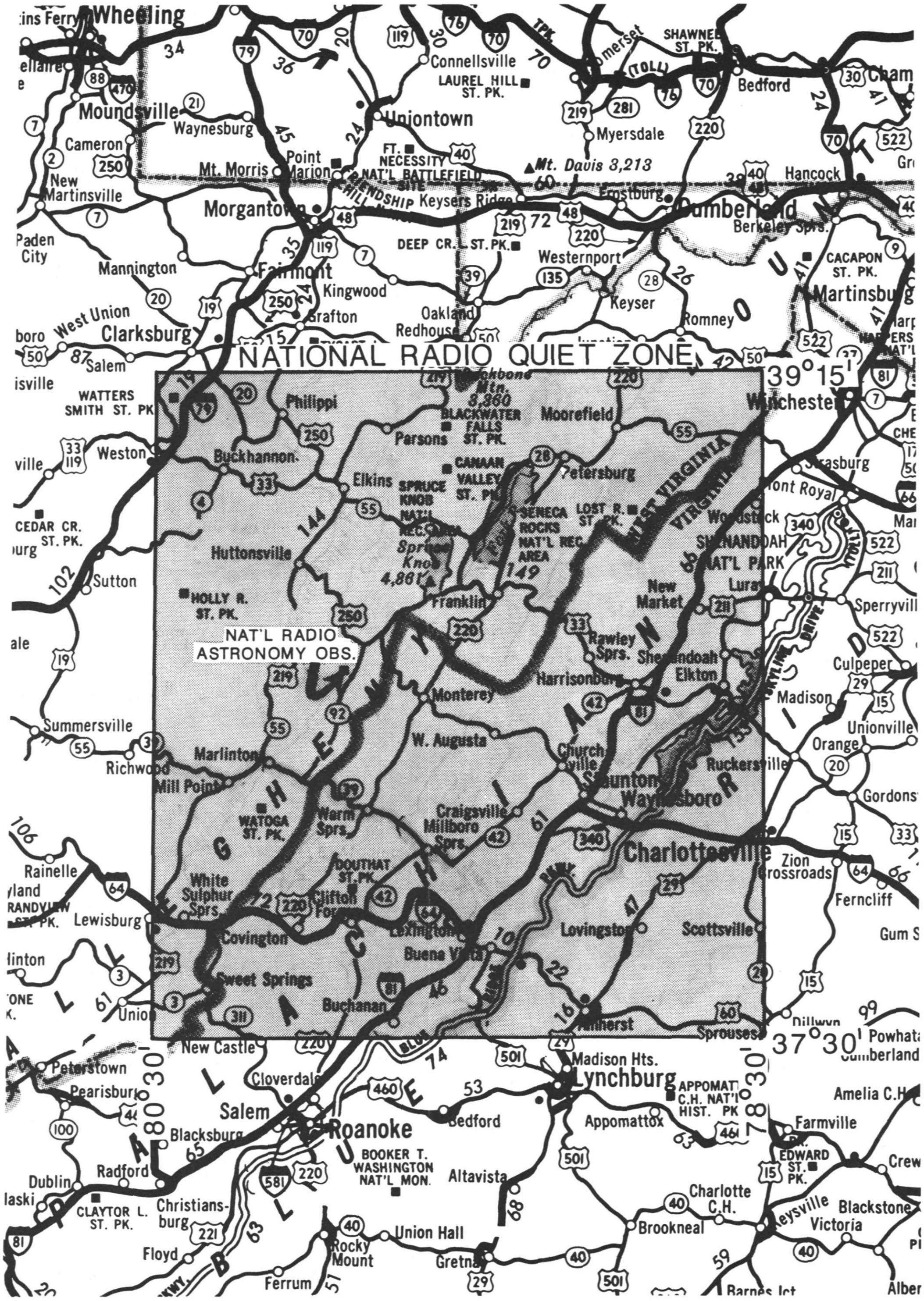

Figure VIII-1. The location and extent of the National Radio Quiet Zone.

approximately 250 applications for approximately 350 fixed radio transmitters in the NRQZ. In addition, 50 requests for preliminary evaluations to be used in subsequent applications were processed. Because of the NRQZ these transmitters could be installed only if the RFI at the Observatory would not be significantly worsened; without the NRQZ these transmitters would have been installed with no regard to the possible damage to the Green Bank Observatory. Of special importance to the Green Bank Telescope is the fact that the NRQZ assures that this protection will continue in the future.

2.1.2. The Radio Astronomy Zoning Act and Local Protection. The Radio Astronomy Zoning Act of West Virginia was passed by the Legislature in 1956 to provide relief to the Green Bank Observatory from all immediately local sources of RFI. Thus, for example, the Act requires that electrical equipment in operation within three miles of the Observatory radiate no more than ten microvolts per meter, measured at a distance of ten feet from such equipment. The Act covers equipment out to a distance of ten miles from the Observatory. Details of these limits are given in Appendix B. The Act gives the NRAO a unique opportunity to work with the community to suppress harmful interference.

The NRAO has devoted a considerable effort in the years since the establishment of the Observatory to the identification and elimination of sources of radio interference arising near it. Special efforts have been made to solicit the cooperation and help of the citizens and industry in the surrounding area. The NRAO has commissioned the burial of power lines whose occasional arcing, especially during wet weather, generated intense interference at meter wavelengths. The NRAO has either repaired or replaced a number of television booster-amplifiers and electric fences, both of which, with age, had begun to generate damaging RFI. The cooperation of the community and of local industry has been of paramount importance.

2.1.3. The Present and Future RFI Environment. As a result of the efforts of the past three decades, coupled with the leverage provided by the National Radio Quiet Zone, the radio frequency environment in Green Bank is undoubtedly better than in any other inhabited part of the United States. This is borne out by comparing some typical background levels of signal strength measured at Green Bank (see Fig. VIII-2, adapted from Sizemore 1987) with those recently measured at the ten sites selected for NRAO's Very Long Baseline Array. Although these ten were chosen primarily for their geographical location, they were secondarily required to be relatively free of interference, at least in the radio bands of interest to the VLBA. The background levels at Green Bank are lower than those at all ten VLBA sites, often by more than an order of magnitude in mean power level.

The National Radio Quiet Zone is a unique national resource for radio astronomy. It has protected Green Bank in a manner not possible at other sites, where the increase of interfering transmissions can grow (and has grown) without limit. Moreover, the NRQZ will continue to protect the Green Bank Observatory. For reasons of the RFI environment, then, Green Bank is the best site in the United States for a telescope operating in the meter-to-centimeter wavelength ranges.

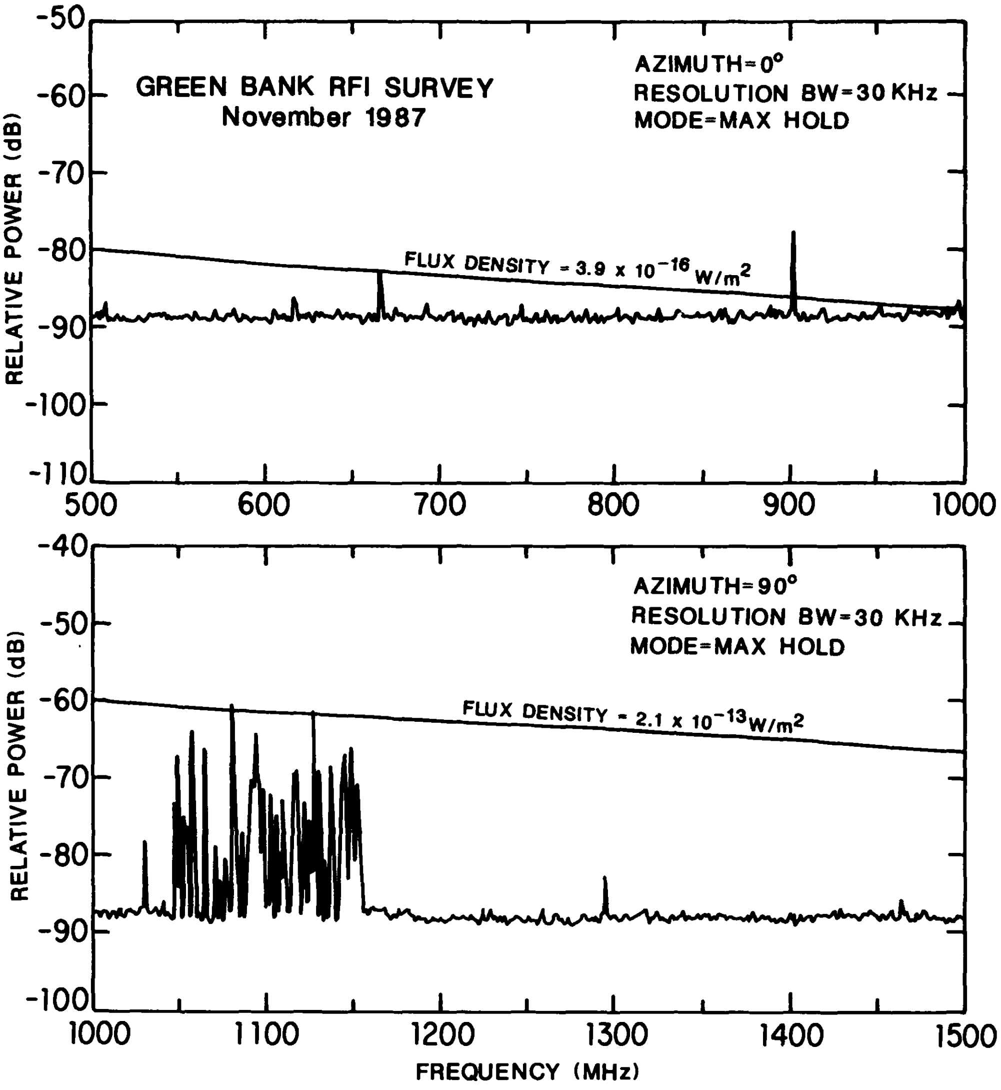

Figure VIII-2. Some typical background power levels over the wavelength range 60 cm (500 MHz) to 20 cm (1500 MHz). The levels over most of the range are acceptable.

2.2. Atmospheric Transmission and Stability. The quality and reliability of radio astronomy observations at frequencies greater than 15 GHz for spectroscopy, and greater than 5 GHz for continuum work, are determined by the transmission and stability of the atmosphere. At most frequencies these characteristics are dominated by the effects of water, in both its liquid and its vapor form, but for certain frequency ranges, notably near 61 and 119 GHz, absorption due to oxygen (O_2) is more important (*cf.* H. J. Liebe and D. H. Layton 1987). Water vapor absorbs incoming radiation, although the effect is generally small at frequencies below the molecular water line at 22 GHz. Liquid water, in clouds, emits radiation whose strength depends on the optical thickness of the clouds and which varies with time as the clouds pass in front of the telescope;

this particularly affects continuum observations. Thus a site characterized by low incidence of cloudiness and by low total precipitable water vapor is to be preferred for telescopes designed to operate at short wavelengths.

Sites in the northeastern United States are generally less favorable from the standpoint of water vapor and cloud cover than are those in the southwest. However, three highly successful millimeter wavelength telescopes—the Five College Radio Astronomy Observatory (FCRAO) telescope in Massachusetts, the Bell Telephone Laboratories telescope at Crawford Hill, NJ, and the Columbia–Goddard telescope in New York City—have operated for many years and have produced many important scientific results. Thus, if it can be shown that the atmosphere over Green Bank is comparable in quality to those over these sites, we may be confident that for a reasonable part of the year observations above 30 GHz will be possible.

Too few direct measurements of the precipitable water content over Green Bank are available to provide a statistically significant sampling. However, R. N. Martin (private communication) and Schwab, Hogg, and Owen (1989), following up on Martin's work, have shown that characterizations of atmospheric water vapor content derived from on-site measurements with a millimeter radiometer agree in a statistical sense with characterizations inferred from radiosonde data. Accordingly, the radiosonde data from Huntington, WV and Pittsburgh, PA have been used to estimate the water vapor content of the atmosphere at Green Bank. Then, to "normalize" this estimate, a comparison has been made with the radiosonde data from Albany, NY, which should be representative of the atmosphere at the FCRAO, some eighty miles away.

Radiosonde data from the U.S. Weather Bureau are integrated to give the total amount of water vapor in the atmosphere for each radiosonde launch. Of greater interest, however, is water vapor's effect as a function of frequency. The total opacity inferred from the radiosonde data has been estimated, using the Millimeter-Wave Propagation Model (MPM) of Liebe and Layton (1987), for frequencies of 24, 45, 90, and 110 GHz. The application of MPM to the radiosonde data is reasonable in the case of clear weather, but suffers if there is significant cloud cover, because the distribution of sizes of the suspended droplets is poorly known.

Figure VIII-3 shows the annual variation of the median value of opacity at each of four frequencies for the three sites, as derived from the radiosonde data. For Pittsburgh and Huntington the integration of the quantities measured by the radiosonde was begun at a height of 2750 feet, the elevation of Green Bank. Integration of the Albany radiosonde was begun at 1030 feet, the elevation of FCRAO.

The data from Pittsburgh and Huntington generally agree, although Pittsburgh shows slightly lower opacities. Because of the prevailing weather patterns it is likely that Huntington provides the better representation of the Green Bank conditions. However, both sites are comparable with Albany, which suggests that the observing conditions in Green Bank will be comparable in quality to those obtaining at the FCRAO and other northeastern sites. At the FCRAO observations at frequencies as high as 115 GHz are typically made between September

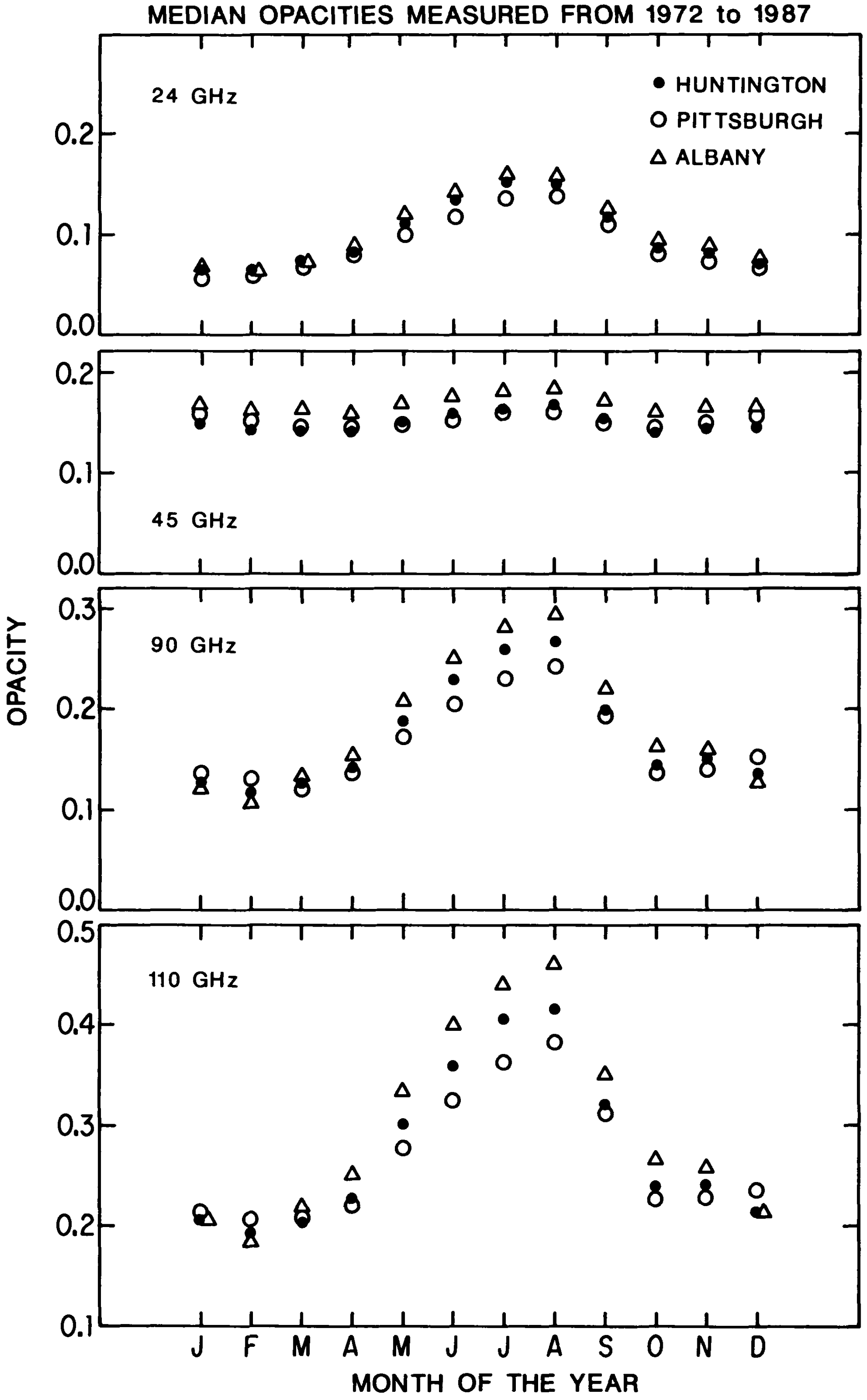

Figure VIII-3. The opacities at four frequencies, inferred from radiosonde measurements. The values that are shown are medians for each month for the sixteen years sampled.

and June, with about 180 observing days scheduled each year near 3 mm wavelength.

In order to minimize the uncertainty introduced by the modeling technique, a comparison among the three sites of the total precipitable water is given in Figure VIII-4. The figure shows the annual variation of the median and of the first and third quartiles for each of the three sites. The sites are comparable both in water vapor and in the annual variation in water vapor content.

In conclusion, the atmosphere at Green Bank will permit high frequency observations during a significant part of the year. The few direct observations support this conclusion. Low and Davidson (1965) found that on occasion the amount of precipitable water falls to 1.5 mm, and that it can remain below 5 mm for several days at a time. Moreover, it must be emphasized that much of the observing done with the Green Bank Telescope will be at wavelengths where the effects of the atmosphere are unimportant. The telescope will be designed to maximize its scientific productivity: weather-dependent programs will be able to seize opportunities of favorable atmospheric conditions; less weather-critical programs, switch-over to which will be rapid, will utilize the rest of the time completely.

2.3. Instrumentation and Technical Support. A critical factor in determining the productivity of a telescope is the level of technical support and innovative instrumentation with which it is provided. In this context, the location of the new telescope at the Green Bank site will be a major advantage. The Jansky Laboratory in Green Bank has a well-earned reputation for developing and deploying state-of-the-art instrumentation for radio astronomy. Chapter IV describes plans for applying this expertise to the new Green Bank Telescope. The development of low-noise amplifiers will continue, with a particular focus on High Electron Mobility Transistor (HEMT) devices. In addition to basic research in amplifier design, members of the Green Bank staff will extend their studies of antenna feeds and the general problem of aperture illumination, since the noise contribution of the antenna is now a significant contributor to overall system temperatures. The Jansky Laboratory has much experience in the application of digital correlation techniques to radio astronomy, and currently is building an advanced signal processor which offers great flexibility and power in interference excision, pulsar signal analysis, and spectral line observations. Locating the new telescope in Green Bank, where it can be supported by the technical groups of the Jansky Laboratory, gives it access to excellent instrumentation.

2.4. Infrastructure and Logistics. Using the existing Green Bank site saves all land acquisition costs. It also greatly reduces the costs of developing water, power, and roads. The services needed to support the operation of a major radio telescope—services such as a machine shop, welding shop, cryogenics laboratory, and antenna test range—are already in place. In addition, existing visitor facilities, office buildings, and vehicles represent significant savings since they are quite suitable for use by observers coming to the new telescope.

3. THE LOCATION OF THE TELESCOPE AT GREEN BANK

The Green Bank Observatory offers several possible specific sites for the

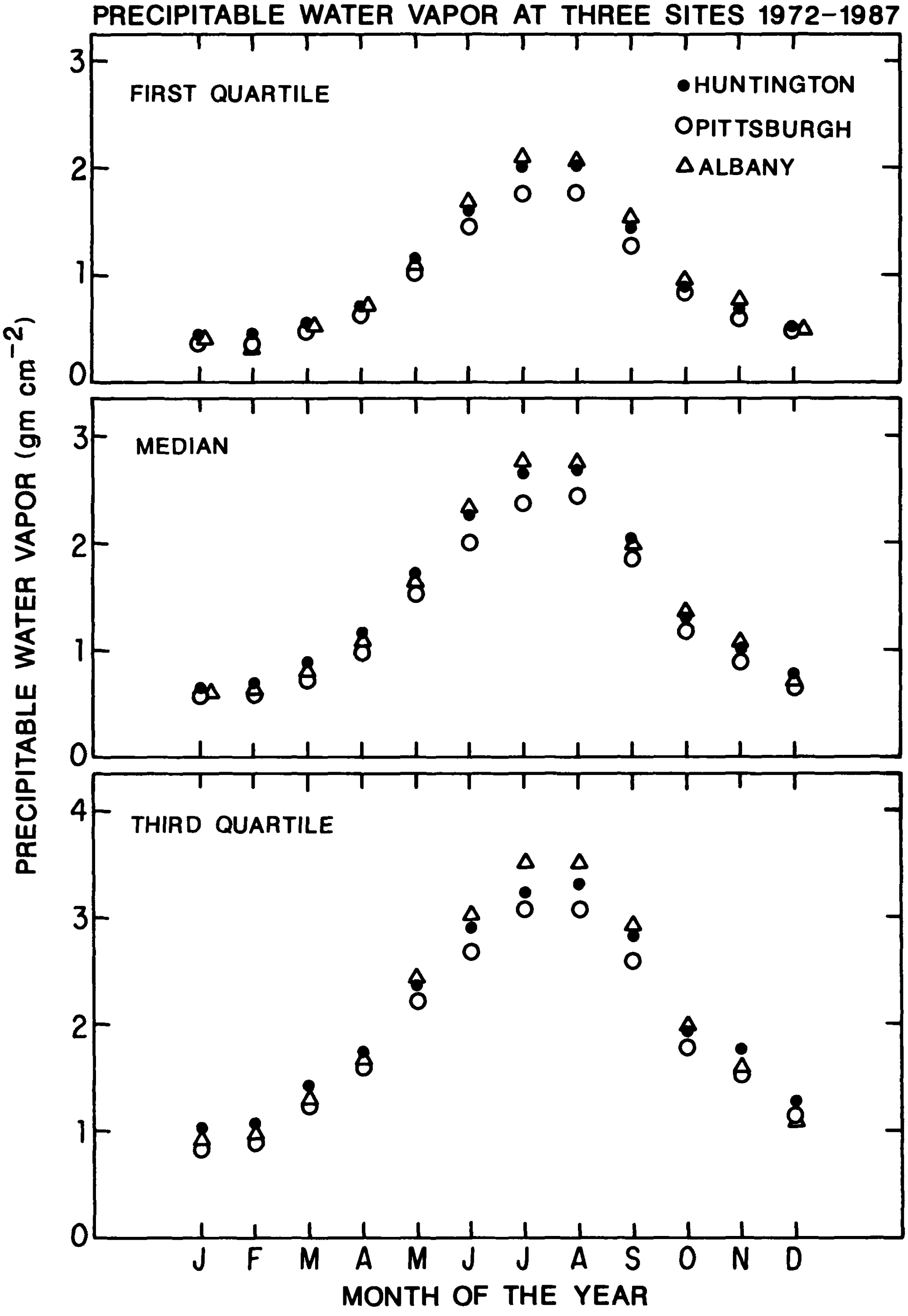

Figure VIII-4. The annual variation of precipitable water vapor measured at three radiosonde sites. Values are the amount lying above 2750 ft for Huntington and Pittsburgh, and above 1030 ft for Albany.

telescope. In order to select the best particular location, additional studies will be undertaken during the preliminary design phase. Factors influencing the choice of site fall into three broad categories.

3.1. The Safety and Integrity of the Structure. The antenna site should allow the foundations to be built directly on bedrock. The existing ground surface and the top of bedrock should be close to horizontal for at least 200 feet in all directions from the center of the foundation to avoid problems due to solifluction. The natural drainage of the site should be such that excessive accumulation of ground water is avoided.

3.2. Performance of the Telescope.

3.2.1. Wind Statistics. The precision of the Green Bank Telescope's surface and its pointing accuracy will likely be limited by thermal gradients in the structure and by wind. It might be possible to minimize thermal gradients, either in the design of the telescope or by undertaking most high frequency observations at night. Then wind would become the fundamental limit.

From the standpoint of structural survival, the wind is not a problem. The median wind speed in Green Bank is 10 miles per hour (von Hoerner 1966). In the thirty-year history of the Observatory the highest recorded winds have been approximately 65 miles per hour. The existing telescopes stop observing when wind speeds reach 35 miles per hour. Typically only about 48 hours per year are lost due to wind.

Wind statistics now available (von Hoerner 1966) show that there are significant differences between various locations on the site. A thorough examination of the microstructure of the wind will permit the optimum location to be chosen.

3.2.2. Interference. Since interference there is probably least, the western edge of the Green Bank site is preferred for the new telescope. Once a small number of potential specific sites have been chosen, the RFI environment of each will be monitored and compared.

3.2.3. Horizon Limits. As discussed by A. R. Thompson (1988), blockage by terrain near the horizon can help minimize interference from nearby low-power mobile transmitters. Terrain providing blockage to elevations of up to 5° would be most effective. This may be more important in the future as the deployment of mobile systems becomes widespread.

Astronomical observations, on the other hand, favor low horizons, especially towards the south where every degree of elevation lost is a degree of sky that is lost. The telescope will be used at elevations below ten degrees only occasionally, because of the severe effects of the atmosphere. But geodetic VLBI may require observations to at least five degrees of elevation. Galactic programs will push the southern elevation limit in order to extend the available range of galactic longitude.

Selection of the Green Bank Telescope's specific site will require balancing these demands. The elevation profiles of potential sites will be carefully studied.

3.3. Logistics. The cost of developing the telescope site and its associated support building will be minimized if they are placed near one of the existing site roads. Water will probably have to be supplied from a new well. The Green

Bank site is served by a dedicated 2500 KVA service. The current maximum demand is 1000 KVA, so there is ample capacity for the new telescope. The cost will be low, since it involves only a local hookup.

If the telescope is located near one of the main site roads, it can easily be integrated into the fiber-optic network already deployed at Green Bank. This will enable users of the new telescope to take advantage of the computing support provided in the Jansky Lab as well as at the telescope control building itself. The local network also provides convenient access to major national and international networks.

4. THE TELESCOPE CONTROL BUILDING

The primary function of a modern telescope control building is to provide a secure place for the electronics that processes the signals received by the telescope, as well as for the system which controls and monitors the activity of the telescope. Because of the diversity of instrumentation with which the Green Bank Telescope will be equipped, the area required for these activities is large. Moreover, the equipment involving high-speed logic will need to be isolated from the telescope electronics to eliminate interference. This is usually accomplished by putting the digital electronics in a shielded room. Noisy equipment—magnetic tape drives, equipment requiring cooling fans, and the like—should also be isolated from the areas where staff and visitors must work.

The control building will provide an area for the staging of equipment going on or coming off the telescope. Long-term storage of electronics will continue to be at the Jansky Lab, where it is convenient to the engineering staff. In the short term, though, the reliability of equipment is kept high by not moving it; if it will be needed soon at the telescope, it will be stored there temporarily.

Finally, the control building will serve as the focus for data acquisition, recording, and analysis by the staff and the observers. Some analysis will be done in the Jansky Lab, to which data will be brought by fiber-optic cable. Other analysis will be done off-site, via the national networks into which Green Bank will be integrated. But the technically challenging programs that require the highest level of interaction between scientist and equipment will be done with the scientist right at the telescope, and provision will have to be made to enable this.

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APPENDIX A. NRQZ POWER FLUX DENSITY LIMITS[1]

The National Radio Quiet Zone was established to provide interference protection to radio astronomy beyond that provided by the frequency allocation process. The NRQZ regulations give the National Radio Astronomy Observatory an opportunity to comment on the interference potential of any fixed radio transmitter requesting license in the Quiet Zone.

The NRAO's comments to the FCC are based on the power level that the proposed transmitter is expected to produce at the focal point of the 43-meter telescope near Green Bank, West Virginia. This power level is predicted from the effective radiated power from the proposed transmitter, standard propagation equations published by the National Bureau of Standards (Technical Note 101), and the detailed topography between the transmitter and the 43-meter telescope. Because of varying propagation conditions, the predictions specify average expected power and not exactly what would be measured at a specific instant. Since the predictions are based on empirically verified propagation models, they provide the best forecast of the power levels to be expected with the current state-of-the-art.

The NRAO has established power flux density limits which, if exceeded by new transmitters in the Quiet Zone, will result in significant degradation in the interference environment for radio astronomy observations at Green Bank. These limits are set by demonstrable receiver sensitivities and standards for antenna sidelobe responses (CCIR Report 224-6), proximity of the transmitter's radio frequency to a protected radio astronomy band, and existing interference conditions over which the NRQZ has no control, e.g., radiation propagated into the Quiet Zone by the ionosphere.

The accompanying documents entitled "Power Density Limits at the National Radio Astronomy Observatory, Green Bank, West Virginia" and "NRAO Criteria for Maximum Power Density at Green Bank in Radio Astronomy Bands and Adjacent Bands per CCIR Report 224-4 (Mod I) Study Programme 5A/2" [Tables VIII-A1 and VIII-A2, resp.] give the power flux density limits for all frequencies that would affect observations at Green Bank. Any radiation in a frequency band in which radio astronomy is the sole primary service is considered harmful. In other radio astronomy bands and in small bands immediately adjacent to all radio astronomy bands the limit is set to the CCIR Report 224-4 level. At all other frequencies the limits depend on the existing environment and are from 10 to 90 dB higher than the CCIR Report 224-4 levels.

International radio astronomy frequency allocations are summarized in "Radio Astronomy and Spectrum Management: The Impact of WARC-79" by V. Pankonin and R. M. Price, *IEEE Transactions on Electromagnetic Compatibility*, Vol. EMC-23, No. 3, August 1981.

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[1] Reprint, with minor revisions, of an NRAO technical report by J. Richard Fisher, first issued on March 10, 1987.

Table VIII-A1. Power Flux Density Limits at the NRAO, Green Bank, WV

Frequency (MHz)	Limit (W m^{-2})	Remarks
< 13.34	1×10^{-8}	
13.34–13.43	1×10^{-17}	Radio astronomy band.
13.43–25.49	1×10^{-8}	
25.49–25.73	— *	Radio astronomy band.
25.73–37.40	1×10^{-8}	
37.40–37.50	1×10^{-17}	
37.50–38.25	1×10^{-20}	Radio astronomy band.
38.25–38.35	1×10^{-17}	
38.35–54.00	1×10^{-8}	
54.00–72.60	1×10^{-12}	
72.60–73.00	1×10^{-17}	
73.00–74.60	— *	Radio astronomy band (primary).
74.60–75.00	1×10^{-17}	
75.00–108.00	1×10^{-12}	
108.00–318.70	1×10^{-14}	
318.70–331.90	4×10^{-21}	Radio astronomy band.
331.90–404.15	1×10^{-14}	
404.15–411.95	1×10^{-19}	Radio astronomy band.
411.95–470.00	1×10^{-14}	
470.00–605.00	1×10^{-17}	
605.00–608.00	3×10^{-19}	
608.00–614.00	— *	Radio astronomy band (primary).
614.00–617.00	3×10^{-19}	
617.00–1000.00	1×10^{-17}	
1000.00–1300.00	$f^2 \times 10^{-17}$	(f in GHz).
1300.00–1400.00	2×10^{-20}	
1400.00–1427.00	— *	Radio astronomy band (primary).
1427.00–1455.00	2×10^{-20}	
1455.00–1609.00	$f^2 \times 10^{-17}$	(f in GHz).
1609.00–1615.40	4×10^{-20}	Radio astronomy band.
1615.40–1655.00	$f^2 \times 10^{-17}$	(f in GHz).
1655.00–1675.00	4×10^{-20}	Radio astronomy band.
1675.00–1717.10	$f^2 \times 10^{-17}$	(f in GHz).
1717.10–1723.90	4×10^{-20}	Radio astronomy band.
1723.90–2633.00	$f^2 \times 10^{-17}$	(f in GHz).
2633.00–2690.00	2×10^{-18}	
2690.00–2700.00	— *	Radio astronomy band (primary).
2700.00–2722.00	2×10^{-18}	
2722.00–3257.00	$f^2 \times 10^{-17}$	(f in GHz).
3257.00–3270.00	2×10^{-19}	Radio astronomy band.
3270.00–3329.00	$f^2 \times 10^{-17}$	(f in GHz).
3329.00–3356.00	2×10^{-19}	Radio astronomy band.
3356.00–4700.00	$f^2 \times 10^{-17}$	(f in GHz).
4700.00–4990.00	5×10^{-19}	Radio astronomy band.
4990.00–5100.00	8×10^{-18}	Radio astronomy band.
5100.00–10550.00	$f^2 \times 10^{-17}$	(f in GHz).
10550.00–10680.00	1×10^{-16}	
10680.00–10700.00	— *	Radio astronomy band (primary).
10700.00–10750.00	1×10^{-16}	
10750.00–14455.00	$f^2 \times 10^{-17}$	(f in GHz).
14455.00–14515.00	1×10^{-17}	Radio astronomy band.
14515.00–15325.00	$f^2 \times 10^{-17}$	(f in GHz).
15325.00–15350.00	1×10^{-17}	

Table VIII-A1 *(Continued).*

Frequency (MHz)	Limit (W m^{-2})	Remarks
15350.00–15400.00	—*	Radio astronomy band (primary).
15400.00–15425.00	1×10^{-17}	
15425.00–21770.00	$f^2 \times 10^{-17}$	(f in GHz).
21770.00–22740.00	6×10^{-17}	Radio astronomy band.
22740.00–22790.00	$f^2 \times 10^{-17}$	(f in GHz).
22790.00–22880.00	6×10^{-17}	Radio astronomy band.
22880.00–23050.00	$f^2 \times 10^{-17}$	(f in GHz).
23050.00–23140.00	6×10^{-17}	Radio astronomy band.
23140.00–23400.00	$f^2 \times 10^{-17}$	(f in GHz).
23400.00–23600.00	8×10^{-17}	
23600.00–24000.00	—*	Radio astronomy band (primary).
24000.00–24200.00	8×10^{-17}	
> 24200.00	$f^2 \times 10^{-17}$	(f in GHz).

*No transmissions within primary exclusive radio astronomy band.

Table VIII-A2.

NRAO CRITERIA FOR MAXIMUM POWER DENSITY AT GREEN BANK IN
RADIO ASTRONOMY BANDS AND NARROW GUARD-BANDS PER
CCIR REPORT 224-4 (MOD I) STUDY PROGRAMME 5A/2 [1]
ADOPTED MAY 1981

Frequency Limits including Guard Band [2] (MHz)	Radio Astronomy Frequency Band [3] (MHz)	CCIR-224 Power Density (dB(W/m^2))	CCIR-224 Power Density (W/m^2)
13.34 - 13.43	13.36 - 13.41	-201	(1 x 10^{-17}) [6]
25.49 - 25.73	25.55 - 25.67	-199	(1 x 10^{-17}) [6]
37.13 - 38.63	37.50 - 38.25	-199	(1 x 10^{-17}) [6]
72.20 - 75.40	73.00 - 74.60 [5]	-196	(1 x 10^{-17}) [6]
318.70 - 331.90	322.0 - 328.6	-204	4 x 10^{-21}
404.15 - 411.95	406.1 - 410.0	-189	1 x 10^{-19}
605.00 - 617.00	608.0 - 614.0	-185	3 x 10^{-19}
1281.5 - 1400.0	1330.0 - 1400.0	(-196) [4]	(2 x 10^{-20}) [4]
1400.0 - 1475.5	1400.0 - 1427.0 [5]	-196	2 x 10^{-20}
1609.0 - 1615.4	1610.6 - 1613.8	-194	4 x 10^{-20}
1655.0 - 1675.0	1660.0 - 1670.0	-194	4 x 10^{-20}
1717.1 - 1723.9	1718.8 - 1722.2	-194	4 x 10^{-20}
2633 - 2690	2655 - 2690	-177	2 x 10^{-18}
2690 - 2722	2690 - 2700 [5]	-177	2 x 10^{-18}
3257 - 3270	3260 - 3267	(-187) [4]	(2 x 10^{-19}) [4]
3329 - 3342	3332 - 3339	(-187) [4]	(2 x 10^{-19}) [4]
3343 - 3356	3345.8 - 3352.5	(-187) [4]	(2 x 10^{-19}) [4]
4700 - 4990	4800 - 4990	-183	5 x 10^{-19}
4990 - 5100	4990 - 5000	-171	8 x 10^{-18}
10550 - 10680	10600 - 10680	-160	1 x 10^{-16}
10680 - 10750	10680 - 10700 [5]	-160	1 x 10^{-16}
14455 - 14515	14470 - 14500	-169	1 x 10^{-17}
15325 - 15425	15350 - 15400 [5]	-169	1 x 10^{-17}
21770 - 22210	22010 - 22210	(-162) [4]	(6 x 10^{-17}) [4]
22210 - 22740	22210 - 22500	-162	6 x 10^{-17}
22790 - 22880	22810 - 22860	(-162) [4]	(6 x 10^{-17}) [4]
23050 - 23140	23070 - 23120	(-162) [4]	(6 x 10^{-17}) [4]
23400 - 24200	23600 - 24000 [5]	-161	8 x 10^{-17}

Higher frequency bands are not included at this time.

NOTES:

[1] NRAO upper limit is the lower power flux density of Table I (continuum observation) or Table II (spectral line observations) of harmful interference levels for radio astronomy.

[2] Upper and lower guard-band width is approximately 50% of bandwidth of the radio astronomy band.

[3] Radio astronomy bands are those designated for Region 2 by WARC-79 as Primary exclusive, Primary shared, Secondary, and Notification of Use.

[4] WARC-79 designates these bands as Notification of Use. Power density for harmful interference levels are either explicit or implied in CCIR Report 224-4 (MOD I), Tables I and II. See footnote of Table II.

[5] WARC-79 designates these bands as Primary (exclusive or passive); all emissions are prohibited.

[6] For frequencies below 300 MHz, existing power densities which originate from outside the NRQZ exceed the CCIR levels. Therefore, the original NRAO criteria of 1 x 10^{-17} W/m^2 applies instead of the much lower CCIR level.

Appendix B. Some Provisions of the Radio Astronomy Zoning Act of West Virginia

The article known as the "Radio Astronomy Zoning Act" includes the following provisions:

> "*Restrictions Within Two Miles of Facility.*—It shall be illegal to operate or cause to be operated any electrical equipment within a two-mile radius of the reception equipment of any radio astronomy facility if such operation causes interference with reception by said radio astronomy facility of radio waves emanating from any nonterrestrial source.
>
> "*Restrictions Within Ten Miles of Facility.*—It shall be unlawful to operate or cause to be operated any electrical equipment within a radius of ten miles of the reception equipment of any radio astronomy facility, if the instantaneous peak field strength of the emanation from such electrical equipment is in excess of:
>
> "Ten microvolts per meter measured at a distance of ten feet from such electrical equipment, if such electrical equipment is located less than three miles from said reception equipment; ten microvolts per meter measured at a distance of fifteen feet from such electrical equipment, if such electrical equipment is located less than four miles from said reception equipment; ten microvolts per meter measured at a distance of twenty feet from such electrical equipment, if such electrical equipment is located less than five miles from said reception equipment; five microvolts per meter measured at a distance of fifty feet from such electrical equipment, if such electrical equipment is located less than six miles from said reception equipment; six microvolts per meter measured at a distance of fifty feet from such electrical equipment, if such electrical equipment is located less than seven miles from said reception equipment; seven microvolts per meter measured at distance of fifty feet from such electrical equipment, if such electrical equipment is located less than eight miles from said reception equipment; eight microvolts per meter measured at a distance of fifty feet from such electrical equipment, if such electrical equipment is located less than nine miles from such reception equipment; nine microvolts per meter measured at a distance of fifty feet from such electrical equipment, if such electrical equipment is located less than ten miles from said reception equipment: *Provided, however,* That notwithstanding the provisions of this section, it shall not be unlawful to operate or cause to be operated any electrical equipment so constructed or shielded as not to cause interference with the reception by such radio astronomy facility of radio waves emanating from a nonterrestrial source."

IX. COST ESTIMATES

1. DESIGN AND CONSTRUCTION COSTS

This section discusses a plan for the design and construction of the telescope and its associated observing systems. Figure IX-1 shows the timing of the various stages of the project, as it can best be predicted. A preliminary design commences in mid-1989, leading to a full engineering design to be completed by the end of 1990. The main tasks required during this preliminary design stage are mechanical and electromagnetic studies of the antenna structure, focused on choosing early between symmetrical and offset-feed configurations. Once this choice has been made, all other major details can be decided, so that the mechanical and electromagnetic performance can be predicted with accuracy. The engineering design, which would be performed in 1990, verifies the specified performance and produces the drawings and specifications needed to obtain bids for site improvements, foundation construction, and fabrication and erection of the telescope. The construction contracts would be let in early 1991, and the telescope completed by the end of 1994.

The various tasks for the entire project and the estimated NRAO staffing requirements to complete them are listed in Table IX-1. The initial major inhouse effort is the mechanical and systems engineering. The control and monitor function of the antenna would also be primarily NRAO's responsibility, but site development and construction of a control building would be contracted out. Instrumentation includes all of the receiving equipment, from the feeds to the raw-data outputs of the detectors, correlators, or fast time-sampling devices. Data processing includes the computers and their peripheral devices, as well as software packages for final data reduction. The required staffing levels are shown on a yearly basis. The mechanical engineering group must reach full capacity as quickly as possible, if the main construction contract is to be let in early 1991. Systems engineering, monitor and control, instrumentation, and data processing groups can be built up more slowly. The more gradual buildup of personnel in these areas fits well with other activities within the observatory: for example, the completion of the VLBA project in 1992 will release a number of engineers fully experienced in state-of-the-art design of cryogenic front ends, digital correlators, etc. Also, the programmers developing data reduction software for the 140-foot and the 12-m antennas can contribute to the software packages for the Green Bank Telescope. To ensure that the packages fit within the AIPS framework, programmers from that group can be utilized as needed.

Table IX-2 is a schedule of estimated yearly costs in 1989 dollars for all aspects of the project, including outside contracts. The engineering design is shown as a separate contract from that for the fabrication and erection. In practice, there is some advantage in combining the design and the fabrication and erection contracts, since the construction preferences of different manufacturers affect the final engineering drawings they require. The contract for fabrication

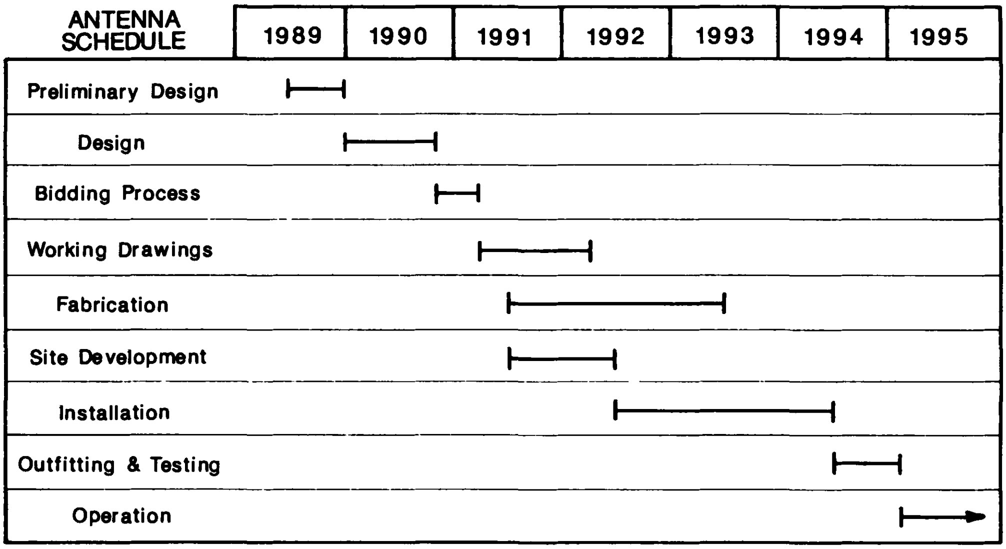

Figure IX-1. Antenna Schedule.

and erection is much the largest item, and here the yearly distribution of costs is a tentative estimate that can be accurately predicted only after the initial design studies are completed and the contractor selected. The method for estimating the cost for fabrication and erection was based on scaling the costs of antennas previously built by the NRAO, particularly the VLBA antennas, and on discussions with experienced, knowledgeable antenna experts.

Table IX-3 summarizes costs by task. The costs are again in 1989 dollars, and the inflation figure is computed assuming a 5% annual rate and the yearly spending pattern shown in Table IX-2. Contingency funds in the amount of 15% of the estimated overall costs have been included to cover unforeseen problems.

2. OPERATIONS COSTS

A major advantage of locating the new telescope in Green Bank is the existence there of a fully operational observatory: site infrastructure, machine shop, electronics laboratory, cryogenics laboratory, warehouse, maintenance shops, residence and dining halls, together with a skilled and experienced staff. On completion of the Green Bank Telescope, all this can be directed toward its operation. We are assuming that in 1995, upon completion of the Green Bank Telescope, the rationale for operating the 140-ft telescope as an NSF-funded user facility will no longer exist.

However, it must be recognized that the staff in Green Bank has been cut severely over the past five years, largely as a result of declining NRAO operations funding. An adequate operations staff for the Green Bank Telescope therefore requires some rebuilding from present levels. We estimate that a twenty-percent increase in the present base is required. In 1989 dollars that is an increase of about $600,000. The increase would be concentrated in the technical areas needed to keep the telescope at the forefront of technology.

IX. COST ESTIMATES

Table IX-1. Staffing Plan (numbers of individuals, by calendar year)

	1989*	1990	1991	1992	1993	1994
Mechanical Engineering	4	4	5	5	5	5
Systems Engineering	4	5	6	8	8	8
Control and Monitor	3	4	5	5	5	5
Instrumentation:						
servo, optics, LO/IF systems	—	—	3	6	6	6
receivers	—	2	4	9	9	9
spectrometers	—	—	—	6	6	6
Data Processing	1	2	4	4	4	4
Management	2	4	5	5	5	5
TOTALS	14	21	32	48	48	48

*Starting July 1989

Table IX-2. Schedule of Estimated Costs (k\$ — 1989)[†]

	1989*	1990	1991	1992	1993	1994	Total
Mechanical Engineering	250	250	250	250	250	250	1500
Systems Engineering	40	160	350	350	350	350	1600
Control and Monitor	50	200	250	300	400	400	1600
Instrumentation	—	100	450	1150	1150	1350	4200
Data Processing	100	200	200	200	600	200	1500
Management	75	225	250	250	250	250	1300
Subtotal	515	1135	1750	2500	3000	2800	11700
Design Contract		2700					2700
Fabrication & Erection Contr.			16000	9000	9000	9000	43000
Site Development & Building		600					600
TOTAL	515	4435	17750	11500	12000	11800	58000

*Starting July 1989

[†] By calendar year, excluding contingency and allowance for inflation

Table IX-3. Summary of Cost Estimates (M$ — 1989)

Antenna:	
Mechanical Engineering (incl. preliminary design)	1.5
Systems Engineering (incl. pointing and surface control)	1.6
Engineering Design Contract	2.7
Antenna Fabrication and Erection Contract	43.0
Control and Monitor System (hardware and software)	1.6
Site Development and Building	0.6
Total Antenna Costs	51.0
Instrumentation	4.0
Data Processing	1.5
Management	1.5
Subtotal	58.0
Contingency (15%)	8.5
Allowance for Inflation (5% annual rate)	8.5
TOTAL	75.0

APPENDIX. NLSRT MEMORANDA

The following is a list of all memoranda which have appeared in the NRAO's *New Large Steerable Radio Telescope* (NLSRT) series. The NLSRT memorandum series commenced in early 1988. However, some of the early memoranda, dated 1987, are papers that were presented at the twenty-fifth anniversary celebration for the 300-Foot Telescope, held in September 1987.

Copies of selected memoranda may be obtained by contacting Ms. Carolyn Bickley, NRAO, Edgemont Road, Charlottesville, VA 22901-2475 (tel. 804–296–0224). A few of the memoranda—those containing privileged information, such as manufacturers' cost estimates—are restricted in availability.

1. Ken Kellermann, “New Large Steerable Radio Telescope”, 07 Feb. 1988.
2. Dr. Sebastian von Hoerner, “WHAT NEXT? Suggestions for Future Radio Telescopes”, 25 Sep. 1987.
3. Rick Fisher, “New Single Dishes”, 07 Dec. 1987.
4. F. J. Lockman, “The NLSRT: a proposal for a BFD”, 13 May 1988.
5. Dr. Sebastian von Hoerner, “Some Remarks for Future Telescopes”, May 1988.
6. F. J. Lockman, “What a BFD would give us that we don't now have”, 09 Sep. 1988.
7. Carl Heiles, “300′ Replacement”, 22 Nov. 1988.
8. B. E. Turner, “What New Telescope for Green Bank?”, 25 Nov. 1988.
9. Steve Schneider, “300′ Replacement”, Nov. 1988.
10. J. N. Bregman, “Comments on a new telescope”, 28 Nov. 1988.
11. Al Wootten, “New telescope for Green Bank”, 29 Nov. 1988.
12. D. Hogg, “300′ Meeting”, 29 Nov. 1988.
13. F. Clark, “Potential Big Dish for Green Bank”, 29 Nov. 1988.
14. B. Burke, “KIK 300′ Replacement Memo of 22 November 1988”, 21 Nov. 1988.
15. A. Rots, “300′ Replacement”, 30 Nov. 1988.
16. P. Jewell, “Thoughts on a new, centimeter-wave dish(s)”, 2 Dec. 1988.
17. D. C. Backer, “Comments on New GB Dish”, 30 Nov. 1988.
18. B. Cotton, “Use of the VLD in VLB”, 1 Dec. 1988.
19. Wm. J. Welch, “300′ Replacement”, 1 Dec. 1988.
20. D. Emerson, “300′ Replacement Telescope”, 2 Dec. 1988.
21. F. J. Lockman, “A Solution to the ‘Long Arm’ problem for Offset Reflectors”, 4 Dec. 1988.
22. G. Heiligman, “New NRAO Dish Requirements”, 6 Dec. 1988.
23. A. Bridle, “Reactions to Dec. 2/3 Meeting”, 5 Dec. 1988.
24. T. Cornwell, “300′ Replacement”, 6 Dec. 1988.
25. K. Kellermann, “Antenna Costs”, 6 Dec. 1988.

26. D. Emerson, "Very Slightly Revised LSD memo", 8 Dec. 1988.
27. F. J. Lockman, "A Horn-reflector Configuration for the 300′ Replacement", 8 Dec. 1988.
28. A. Bridle, "More on 300′ Replacement", 9 Dec. 1988.
29. A. R. Thompson, "The Feasibility of Building a Large Radio Telescope of Offset-Feed Parabolic Design", 9 Dec. 1988.
30. P. D. Usher, "Almucantar Radio Telescope", Dec. 1988.
31. R. C. Immel, "300′ Replacement", Dec. 1988.
32. G. Seielstad, "Proceedings of a Green Bank Workshop", Dec. 1988.
33. T. Legg, "A Suggestion for a cm-λ Telescope", 12 Dec. 1988.
34. R. J. Wallace, "Antenna Diameter Trade-off Study", 12 Dec. 1988.
35. R. J. Wallace, "Antenna Implementation Costs", 12 Dec. 1988.
36. K. Kellermann, "Typical Antenna Costs", 12 Dec. 1988.
37. R. Thomas, "RSI Cost Estimates", 30 Nov. 1988.
38. W. Jeske, "MAN Cost Estimates", 28 Nov. 1988.
39. K. Kellermann, "A Very Large Dish (VLD) Radiotelescope", Dec. 1988.
40. K. Kellermann, "NLSRT Memo List", Dec. 1988.
41. K. Kellermann, "Problems with the Bonn 100 m Telescope", Dec. 1988.
42. P. C. Crane, "Comments on New Green Bank Telescope", Dec. 1988.
43. A. R. Thompson, "Possibly-Feasible Approaches to the Design of a Large Offset-Feed Radio Telescope", 20 Dec. 1988.
44. A. R. Thompson, "Polarization Effects and Some Other Considerations in Offset-Feed Antennas", 9 Jan. 1989.
45. L. D'Addario, "Cassegrain vs. Prime Focus Operation", 16 Jan. 1989.
46. P. Napier, "Beam Scan Properties of Nonparabolic Reflectors", Jan. 1989.
47. R. Fisher, "Design Considerations for a Reflector Antenna for Good Spectral Baselines", Jan. 1989.
48. Dr. von Hoerner, "The Field of View of Various Systems", 20 Jan. 1989.
49. D. Thompson, "Rsi Proposed Horizontal Axis Offset Design", 9 Feb. 1989.
50. A. Thompson, "Some Thoughts on an Active Surface, Pointing Accuracy, and the Offset-feed Design for Green Bank Antenna.", 13 Mar. 1989.
51. L. R. D'Addario, "A Study of Technical Issues and Tradeoffs in the Design of the New Green Bank Telescope", Feb. 1989 (revised April 1989).
52. F. Schwab, "Analysis of Radiosonde Data From Huntington WV, Pittsburgh PA, and Albany NY", 23 Feb. 1989.
53. "Report of the Technical Assessment Panel for the 300 foot Radio Telescope at Green Bank WV", undated.

54. R. Norrod, "Comparisons of Symmetric and Asymmetric Antennas", 05 May 1989.
55. J. Coe, "An Unblocked Aperture Reflector Design", 09 May 1989.
56. B. Burke, Letter dated 15 May 1989.
57. A. Thompson and W. Sizemore, "Possible Antenna Site by the Greenbrier River", 18 May 1989.
58. S. Srikanth, "Subreflector Diameter and f/D Ratio for an Axisymmetric Antenna", 19 May 1989.
59. R. Fisher, "Comments on Recent Technical Design", 24 May 1989.
60. F. Lockman, "On Aperture Blockage and Its Consequences for Astronomical Observations", 26 May 1989.
61. J. Coe, "Computed Field Patterns for Symmetrical and Asymmetrical Antennas", 31 May 1989.
62. A. Thompson, "Prime-Focus and Cassegrain Operation, and the Focal Ratio of the Green Bank Telescope", 06 June 1989.
63. S. von Hoerner, "Suggestions After the Meeting on May 22 at Charlottesville", 09 June 1989.
64. S. von Hoerner, "Green Bank Wind Data", 14 June 1989.
65. R. Brown, "CO Emission at High Redshift", 15 June 1989.
66. S. Srikanth, "Sidelobe Levels, Aperture Efficiency and Sensitivity Comparisons of Axisymmetric and Asymmetric Antennas", 27 June 1989.