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High Speed Data Access to the Green Bank Telescope

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ABSTRACT

On completion in 2000, the Green Bank Telescope (GBT) will be the largest fully steerable radio telescope in the world. It has a clear aperture design, an active surface, and an advanced laser metrology system designed to give the enormous structure precision performance at radio wavelengths of less than 3mm. To realize the full scientific potential of such a telescope, we must dynamically match the requirements of the most meritorious scientific programs to the changing observing conditions. This requires (a) flexible scheduling so that the most demanding programs are scheduled only when conditions are appropriate for them, and (b) interactive real-time access to the data by astronomers so they can judge how best to meet their scientific goals under the prevailing conditions. Because of Green Bank's isolated location, we expect that a substantial fraction of the observing will be done remotely. Facilities to interact with the GBT must therefore be available at the observers' home institutions. The National Radio Astronomy Observatory (NRAO) seeks to establish a DS-3 or higher network connection to Green Bank. This poses special problems due to the remoteness of the facility.

Keywords: Remote Observing,Dynamic Scheduling,High Speed Networking

1. INTRODUCTION

As radio astronomy advances into more challenging wavebands, and seeks ever-fainter signals, the very best observing conditions have become essential for some work.

To realize the full scientific potential of a state-of-the-art radio telescope we must dynamically match the requirements of the most meritorious scientific programs to the changing observing conditions. This requires (a) flexible scheduling, so that the most demanding programs are scheduled only when conditions are appropriate for them, and (b) interactive real-time access to the data by astronomers, so they can judge how best to meet their scientific goals under the prevailing conditions. For example, in detection experiments, the astronomer may decide not to observe for as long on a source detected quickly at a high significance level, or to observe longer to reach the required signal-to-noise level.

In many cases, good science can be done in imperfect conditions if the astronomer can optimize the observing strategy for the conditions in real time. Implicit in such optimization is the ability for the astronomer (a) to interact with, and control, the observation and (b) to have reliable access to the astronomical data and to ancillary data, so that informed decisions can be made quickly.

The rich tradition of interactive observing in the single-dish radio-astronomy community has been fundamental to its scientific success. Radio telescopes are, of necessity, remote from highly populated areas which are intense sources of radio frequency interference. Improved wide-area connectivity can play a vital role in letting researchers work interactively with telescopes from distant locations at the short notice needed to take full advantage of the best high-frequency observing conditions, or to respond to astronomical transients.

Our goal is that observers at U.S. universities and laboratories should be able to interact with their data, with the NRAO support staff, and with the NRAO telescopes as efficiently from their home institutions as they could if they were in the telescope control room.

To achieve this for the new Green Bank Telescope (GBT), we plan to provide remote observers and telescope operators with a suite of real-time data communication and status display applications. To realize the full potential of more interactive modes of operation, and to enable real-time loading of data from the telescope to observers' home institutions, we must also have reliable (high quality of service) connectivity to the GBT user community at high data rates. We therefore propose to connect the Green Bank site to the high speed backbone of the vBNS or Internet2.

*The National Radio Astronomy Observatory is a facility of the National Science Foundation operated under cooperative agreement by Associated Universities, Inc.

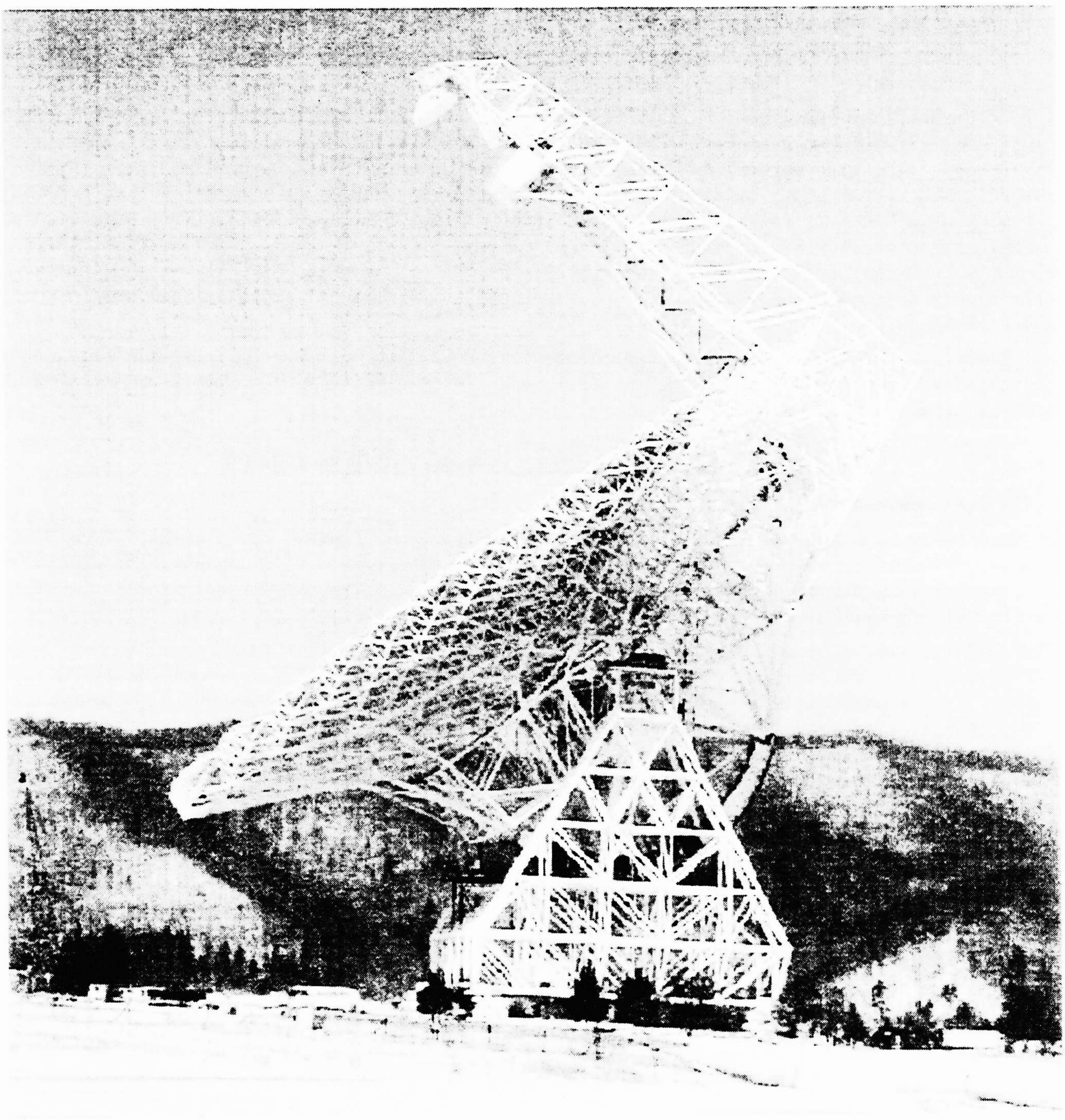

Figure 1. The Green Bank Telescope — 21 January 2000

2. GREEN BANK TELESCOPE: OVERVIEW

Green Bank is the site of a new state-of-the-art, 100-meter diameter radio telescope – the Green Bank Telescope – scheduled for completion in 2000. The GBT will be the largest fully steerable radio telescope in the world. It has a clear-aperture design, an active surface, and an advanced laser metrology system designed to give the enormous structure precision performance at radio wavelengths of less than 3 mm.

This new telescope (Figure 1 shows a recent image) will be one of the world's foremost astronomical facilities in the next century; observing time will be awarded to qualified scientists whose research proposals are judged to be meritorious by a peer review process.

Several aspects of the GBT lead to a critical requirement for high-bandwidth connectivity if it is to realize its full scientific potential.

The GBT will operate over three decades of frequency, from ~100 MHz to over 100 GHz. At the low end of this frequency range, and with ever-increasing incidence rates, terrestrial and space-borne interference can be debilitating to observations. Man-made signals are typically much stronger than the celestial signals, and radio frequency interference (RFI) is often highly variable (depending on transmission activities and propagation characteristics). Assessing changing RFI conditions will therefore be a critical element of successful low-frequency observing with the GBT. For work above ~15 GHz, weather can also have a large effect on the quality of observations. Adaptive scheduling will therefore play a vital role in maximizing the scientific output of the GBT, but the remote location will inhibit physical access to the telescope by users at the short notice required to exploit the best high-frequency observing conditions.

Reliable high-bandwidth connectivity to a wide area network(WAN) that extends to the major university centers and laboratories within the GBT user community will therefore be crucial to achieving many of the new scientific goals of this telescope.

3. GREEN BANK TELESCOPE: REQUIREMENTS

3.1. RFI protection

Green Bank is located in a unique national resource — an "electromagnetic reserve" known as the National Radio Quiet Zone (NRQZ). The NRQZ † was established by the Federal Communications Commission (FCC) and by the Interdepartment Radio Advisory Committee (IRAC) in 1958 to minimize possible harmful interference to the NRAO and to the U.S. Navy facilities in Sugar Grove, WV.

The NRAO reviews all frequency assignments or applications for new or modified fixed transmitters within the NRQZ to ensure that the computed power flux density does not exceed thresholds considered harmful to radio astronomy. Non-compliant applicants are asked to discuss possible modifications to their transmitters, and in most cases a technical solution is found to provide the area coverage desired by the applicant while minimizing the impact of interference at Green Bank. If differences between the applicant's desires and the NRAO's evaluation cannot be resolved, both the applicant and the NRAO forward comments on the transmitter installation to the FCC or IRAC for a final resolution.

Such exceptional protection from "local" RFI can be achieved only in a relatively remote mountainous area with good terrain shielding. This protection is essential to the success of the GBT's mission, but adds logistical difficulties. There are no universities or major industrial facilities close to Green Bank, and only modest telecommunications infrastructure. Physical access is also difficult at times: the closest regional airports are over two hours' drive, major airports are four hours' drive, and the mountains complicate access in winter, when high-frequency observing conditions are their best.

3.2. Adaptive scheduling

High-frequency observations with the GBT will be sensitive to three variable quantities: signal absorption by atmospheric water vapor, atmospheric stability owing to small-scale water vapor fluctuations, and wind speed that can affect pointing accuracy. These factors will be particularly acute for work in the 3 mm wavelength band, but preliminary transmission measurements show that good quality 3 mm observations will be possible in Green Bank for about 30% of the year.

The GBT's observing schedule must therefore, at certain times, be decided hour by hour, depending on weather and other factors. Observers will be told when their program is near the top of the queue and may be contacted on short notice if it is about to be executed. They will then establish a remote observing session from their home location, including audio/visual contact with the telescope operator and support staff.

†The NRQZ is bounded by meridians of longitude at 78d 30m W and 80d 30m W and latitudes of 37d 30m N and 39d 15m N, and encloses about 13,000 square miles near the border between Virginia and West Virginia.

3.3. Data rates

Large-scale imaging in continuum and spectroscopic modes will be emphasized on the GBT. The need for high bandwidth connectivity is driven by the use of modern focal-plane array receivers for wide-field spectroscopic imaging at the highest frequencies (the 40-50 GHz band: SiO, CS, HC_3N spectroscopy and the 80-115 GHz band: molecular spectroscopy with CO, HCN, HCO^+, etc.)

The fields of view required for spectroscopic imaging will range from a few arc minutes to a few degrees. These are much greater than the fields that can be instantaneously sampled by array feeds, so the observing mode requires that the telescope scan its observing pixels (beams) over the field of interest and the data be interlaced to form an image. For 1024-channel spectroscopy and the fastest scanning rates, data cubes of order 1 Gbit can be acquired in about 100 seconds. These must be transferred to remote observers in real time for them to assess the progress of the observations fully. Allowing for overhead in telescope control and repositioning, guaranteed bandwidths of order 6-12 Mbps will be required; data rates could be higher in some observing configurations.

Pulsar observing will require even higher data rates. For example, with the FFT machine that Cornell University built for the Arecibo Observatory, the maximum rate is 16 Mbps. The data are now shipped directly to high-capacity disk or tape and are processed off-line in supercomputers. The ability to process initial data on-line at remote supercomputers would be of interest to pulsar observers as a way to improve the feedback between initial survey results and confirmation.

3.4. Telecollaboration

NRAO staff will act as "friends of the telescope" to advise and assist users before, during, and after their GBT observing runs. These interactions could also be greatly enhanced if reliable wider-bandwidth communications allowed audio/visual aids, imaging and other data displays to supplement dialogues that now occur mainly by telephone (or when observers are physically at the NRAO). When new instruments such as the GBT are being commissioned, there is a particularly strong need for up-to-date status and "how-to" information to be exchanged between observatory staff and users. The limitations of voice-only communications, fax and e-mail for such work are clear. Higher bandwidth would allow use of video clips and two-way interaction with technical diagrams and images, making this process more effective. With sufficient bandwidth, GBT staff and users could also share in talks, seminars, and colloquia. Green Bank needs higher-bandwidth connectivity to explore such applications in competition with data transfers.

3.5. Summary

Real-time transfer of typical large-scale spectral line datasets will require *sustained* bandwidths of 6-12 Mbps; peak bandwidth requirements could be several times greater for some observing configurations. Sustained bandwidths of 16 Mbps will be required for real time remote processing of pulsar data. As remote observing requires time-critical operations and decision-making, high quality of service (low latency and dedicated bandwidth) will also be required.

To allow for all activities that will be in progress on site, including off-line data reduction and image transfer and support of telecollaboration, connectivity to the WAN at DS-3 rate is desirable.

4. NRAO EXPERIENCE WITH REMOTE OBSERVING

The NRAO has more than three decades of experience in operation of its flagship telescopes (the 140 Foot and the 12 Meter) supporting a large research community throughout the USA, and is at the forefront of the development and use of algorithms for observations with single dish radio telescopes at a large range of wavebands.

An effective prototype of a remote observing system was developed for the NRAO 12 Meter telescope on Kitt Peak, AZ (see http://www.tuc.nrao.edu/remote.html and links therein). This system provides a remote observing package control screen, system status screens, real-time data displays (including image displays), weather data, a "digital chart recorder," telescope operational information (motor currents, etc.), source catalogs and position charts, a "chat" window to the operator, and freeze-frame video (various views). Figures 2 and 3 show examples of these displays.

The remote observing system for the 12 Meter telescope has been popular with NRAO users. The main limitation that prevents it from bringing the control room environment directly to the observer is a lack of high bandwidth audio/visual connections. (It currently relies on chat windows or telephone calls to communicate with the operator,

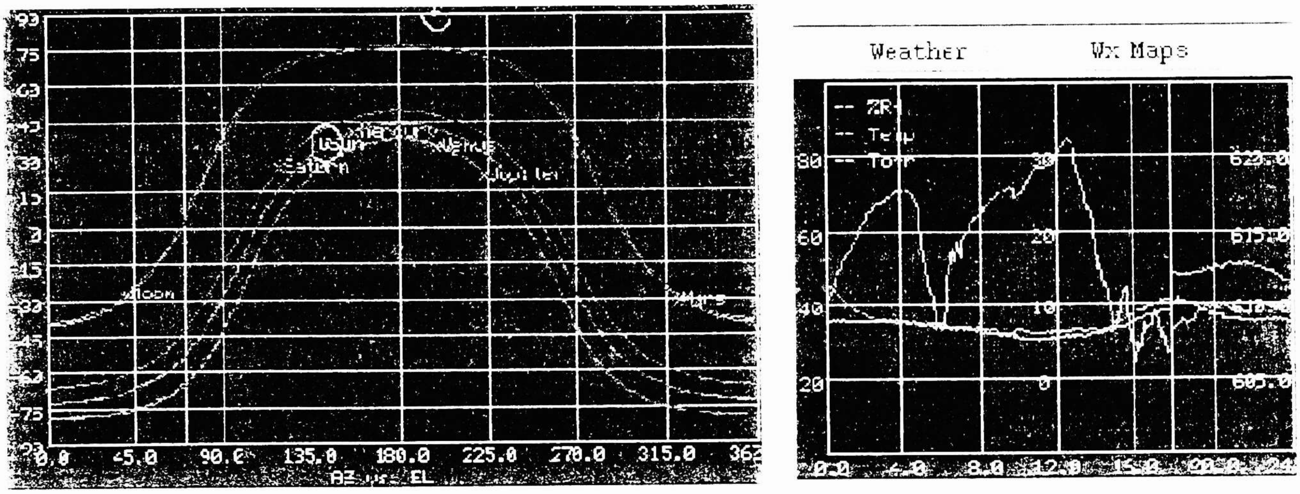

Figure 2. Interactive observing screens for 12 M telescope

and the video is constrained to freeze-frame transmissions by lack of bandwidth.) Especially in the early days of telescope commissioning, the expected complexity and nuances of GBT remote observing will require wider-bandwidth audio/visual connections in addition that required for real-time data transfer.

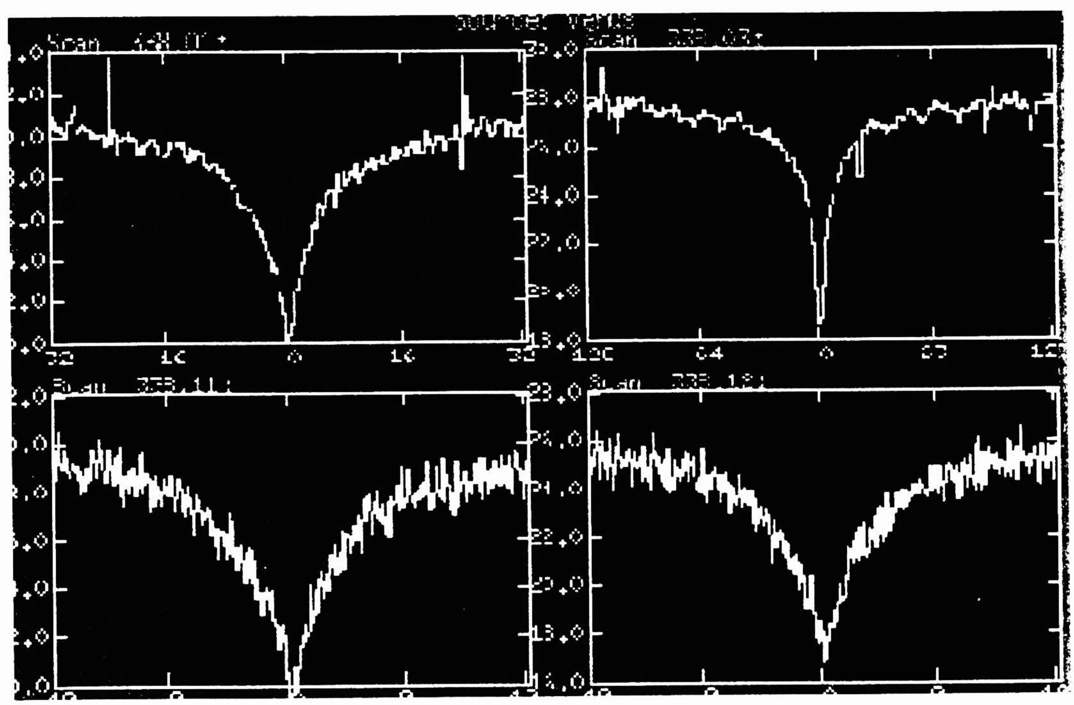

Figure 3. Real-time data display from 12 M telescope

5. APPLICATIONS

The remote observing applications to be developed fall into several categories. First, the remote observer and the local telescope operator and support staff must have good audio/visual tools to promote personal communication — the exchange of instructions and explanations, and general discussions. The remote observer also needs a suite of monitoring tools that indicate the status of the telescope and all instruments in use. Tools that display site environmental conditions are needed, including recent history so that trends can be identified. The remote observer also needs quick-look data displays so that the quality of incoming data can be assessed continuously and a suite of data reduction tools to analyze fully the incoming data. Finally, they must have tools for adaptive scheduling and for requesting changes to the configuration of the antenna, instruments and software in consultation with the telescope operator.

The NRAO will develop a server for GBT astronomical data and status information, building on its experience with the remote observing system for the 12 Meter telescope, and including enhanced audio/visual tools. This will provide the remote observer an interactive ability to display many details of the GBT status information similar to that being displayed by the telescope operator in Green Bank.

Software to display the data being taken on the telescope must also be available to researchers at their desks. We plan to provide a set of tools for all aspects of the analysis of telescope data running in a readily portable environment. We propose to implement these tools in the Astronomical Information Processing System (AIPS++), which is being developed by an international consortium of radio observatories lead by the NRAO. AIPS++ provides a large increment in capability over existing reduction packages and will run on many different platforms, including most major flavors of Unix. As well as substantially improving capabilities for off-line data analysis, AIPS++ breaks new ground in enabling tight integration with an on-line, real-time system, thus allowing data display, analysis and reduction at observing time. The latter capability is crucial for this proposal. AIPS++ has been used within the consortium for connecting real-time systems to analysis systems (as we propose to do here) for several years.

To prepare for observations of target sources, independent of which type of observations are to be made, researchers will make routine observations of well known sources. Tools to support the rapid analysis of these calibration observations will include the timely display of a representative portion of the data as they are taken, as well as automatic reduction of standard calibration procedures (pointing, tipping, focus, etc.). These tools are vital for monitoring the data quality and the health of the telescope, as well as for planning upcoming observations.

A number of distinct astronomical applications are required for nearly-real-time observing: imaging, spectroscopy, and pulsar observations. The major application for use in making images with a single dish telescope is the "on-the-fly" (OTF) algorithm. Originally developed at the NRAO for the 12 Meter telescope, this approach provides almost twice the sensitivity of previously used observation methods. It requires that data be sampled at a high rate, to be corrected for instrumental instabilities, telescope tracking uncertainties, etc. and to be converted into a gridded image. It is vital that the resulting image be displayed and updated as the observations continue so that the observer can direct the extent and direction of the remainder of the on-the-fly data for that field of view. Figure 4 shows an example of the real-time OTF image display during an observation with the NRAO 12 Meter telescope.

The software for spectroscopy must be extremely adaptable and flexible. Observers typically need to manipulate stacks of one-dimensional images (or spectra) containing over 256,000 pixels. These data must be manipulated mathematically, individually and in combination, to correct for instrumental errors, to excise radio frequency interference, and thus to determine whether signal has been detected and whether more observations of that source are useful.

Full analysis tools for observations of pulsars are not in our current plans, but simple displays of representative portions of pulsar data must be available in real time so that pulsar observers can check that data quality is adequate. The efficient export of pulsar data to user-provided applications on remote computers will be an important goal, as these observations will produce the highest data rates from the GBT.

Applications for adaptive scheduling are also required. Some of these, including database management and queue priorities, will be used primarily by scientific managers on the NRAO staff. However, remote observers will also require tools for monitoring the position of their program in the execution queue and for rescheduling and controlling the receivers and telescopes in consultation with the on-site operators while the observations are in progress.

The NRAO will build applications to allow a remote observer to request specific changes in configurations of the telescope instruments and control electronics, to request software configuration changes to control the speed and mode of writing of the output data to file and/or tape, and to request that the telescope be moved to a new radio source for observation with the new configuration. This will have a complete database of the available configuration options, a database of standard radio sources, and an optional database of other sources created by the observer. The actual control of the telescope motion will be done by the operator through interactive contact with the remote observer.

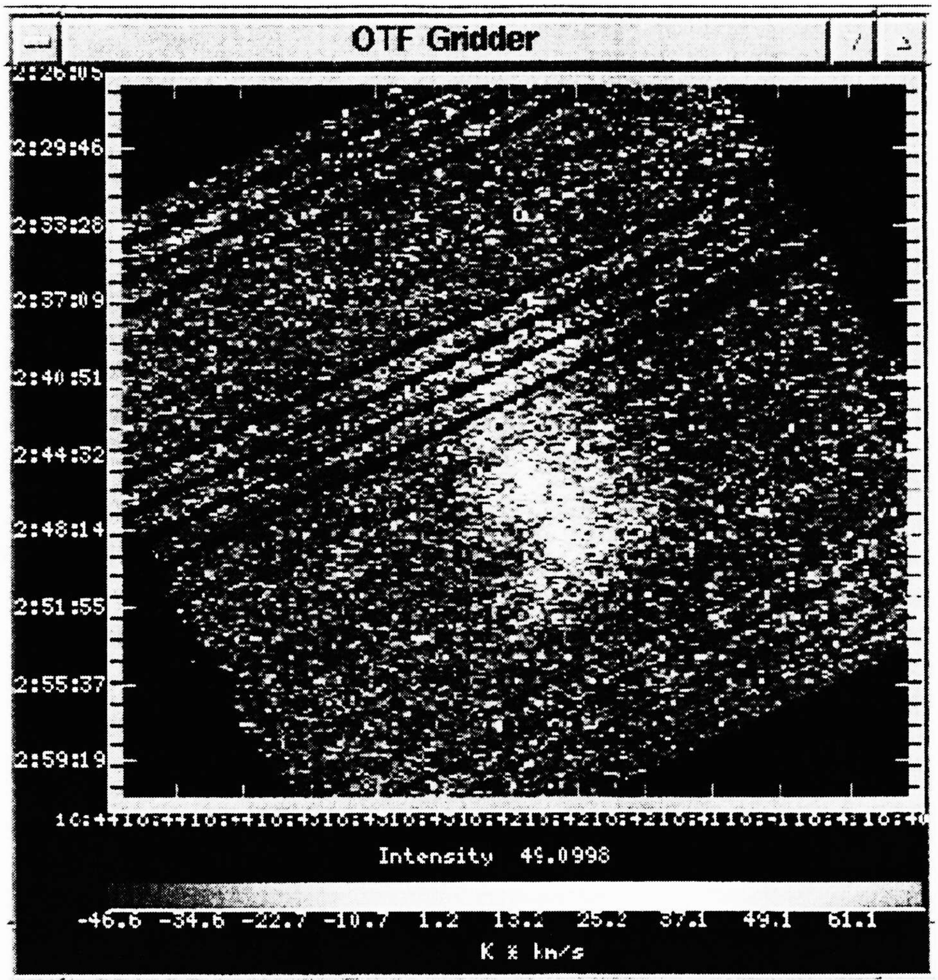

Figure 4. Real time OTF image display from 12-m telescope

6. EDUCATION AND OUTREACH

Green Bank currently has very active programs in science education, aimed at all ages (K-12) of school children and their teachers. These children and teachers frequently travel to Green Bank to use a small radio telescope that has been dedicated to educational purposes, and to participate in other educational programs. With improved connectivity to the WAN, some of these educational programs could also be offered on a remote basis — not just to the local area, but around the country. Students could, for example, acquire and view data remotely from the educational telescope. In planned sessions, they could also view data and consult with scientists using the major research instruments at the Observatory. This could be a valuable tool in teaching youngsters how scientific research is carried out.

7. CURRENT CONNECTIVITY

7.1. The NRAO intranet

The NRAO operates radio telescope sites in St. Croix VI, Hancock NH, Green Bank WV, North Liberty IA, Fort Davis TX, Los Alamos NM, the Plains of San Augustin NM, Pie Town NM, Kitt Peak AZ, Owens Valley CA, Brewster WA, and Mauna Kea HI. It also has offices on the grounds of the University of Virginia in Charlottesville VA, an Array Operations center (AOC) for the Very Large Array (VLA) and the Very Long Baseline Array (VLBA) on the campus of the New Mexico Institute of Mining and Technology (NMIMT) in Socorro NM, and on the campus of the University of Arizona in Tucson, AZ. To provide a reliable, secure, and effective means for routine network connectivity between our sites, all but three were connected by a frame-relay intranet provided by AT&T in 1996:

the exceptions are Mauna Kea (which connects to the Internet through the University of Hawaii), Los Alamos (which connects to the Internet via New Mexico Technet) and Kitt Peak (which connects to the Internet through the intranet of the National Optical Astronomy Observatories).

The Green Bank, Socorro, Charlottesville and Tucson offices currently all have T1 (1.544 Mbps) connections to this intranet.

7.2. WAN access

The Charlottesville office now has 10 Mbps access over fiber to the University of Virginia. This connection provides access to Network Virginia and thus both to the commodity Internet and (de facto) a connection to the vBNS through the access point in Washington, DC.

The AOC in Socorro now has 10 Mbps access over fiber to NMIMT, thence currently to the commodity Internet over a T1 line.

The Tucson office now has access at 10 Mbps over fiber to the University of Arizona, thence to the commodity Internet and by DS-3 to the MCI Denver vBNS access point, again giving a de facto vBNS connection.

8. PROPOSED CONNECTIVITY

8.1. Context

For the immediate future, the NRAO will retain its existing frame-relay based intranet for low volume transactions. This is highly desirable for security, including internal e-mail and accounting transactions, and for guaranteed service to the NRAO's minor sites (such as the VLBA stations). The intranet cannot, however, meet our growing needs for large data transfers. We are therefore pursuing formal connections to vBNS and Internet2 at all four major NRAO locations. This will provide service between these sites for high speed connections to the NRAO user communities at major universities and laboratories throughout the USA as well as for data transfers among the NRAO sites that require higher bandwidth than provided by the intranet.

A fiber link between the NRAO 12 Meter telescope and the National Optical Astronomy Observatories (NOAO) administration building on Kitt Peak was funded as part of a previous proposal to NSF. The data from the 12 Meter are then carried by the NOAO to the University of Arizona. These bodies are negotiating an improvement of the connection from Kitt peak to the University of Arizona campus to full DS-3. The connection to vBNS is then by DS-3 through the MCI access point in Denver. This will support our future needs for real-time data transfers from the 12 Meter telescope to remote users.

The Socorro site is on the campus of NMIMT, which is joining with the University of New Mexico, New Mexico State University and the Southwest Indian Polytechnic Institute to propose to the NSF for high-speed network connectivity which will include a Gigapop in Albuquerque. This will have DS-3 connectivity to the MCI vBNS network access point in Denver and will also provide a DS-3 connection between NMIMT and Albuquerque. NMIMT will give the NRAO access to this DS-3 connection over the existing fiber from the AOC. The NRAO plans to increase the bandwidth of its interface to this fiber as needed to support real-time data transfers from the VLA to remote users, and remote access to the VLA and VLBA data archives.

The NRAO offices in Charlottesville, VA are on the grounds of the University of Virginia and Charlottesville addresses are already connected over fiber to vBNS. The present connection at 10 Mbps meets current needs but will be upgraded as required.

We therefore request funds only to connect the Green Bank, WV site at DS-3 bandwidth to a high-speed backbone, so that the most data-intensive observations supported by the GBT can be provided to remote users reliably over a high-performance network connection such as the vBNS or Internet2.

8.2. Green Bank

Green Bank is the most isolated of all the NRAO's major sites and has no immediately nearby facilities with which to share resources. Several options are therefore being pursued, of which three are outlined here.

1. **Connection to West Virginia University:** WVU (84 air miles from Green Bank) is connected to vBNS through the Gigapop at the Pittsburgh Supercomputer Center via a DS-3 circuit. Costs are being solicited for a direct DS-3 connection between Green Bank and Morgantown, sharing the DS-3 circuit from WVU to the Gigapop. Other possibilities would include the participation in the West Virginia State Unified Network (SUN) for this connection.

2. **Connection to Virginia Tech:** We are exploring options with Virginia Tech (90 air miles from Green Bank) to connect through them to the Mid-Atlantic Crossroads and Network Virginia and thence to vBNS. One attractive possibility is for a direct connection to Network Virginia at Bluefield, WV (109 air miles from Green Bank). This is a major hub and would provide access not only to vBNS but also connections to Internet2, the Defense Research and Energy Network (DREN), and the NASA Research and Education Network (NREN). This location is served by the same Local Exchange Carrier (LEC) as Green Bank (Citizens Telecom), although unfortunately not in the same Local Access and Transport Area (LATA).

3. **Connection to University of Virginia:** This is our currently preferred option. Many staff in the Charlottesville office (79 air miles from Green Bank) are involved in the development, commissioning and operation of the GBT. Since Green Bank is an isolated facility, good network connection with the scientific and engineering staff at the headquarters is extremely desirable. As described above, the NRAO offices in Charlottesville already have direct fiber access to the University of Virginia, thence to Network Virginia and vBNS.

Although all of these are apparently separate configurations, the cost and the availability of any of these connections ultimately depend on the local connection in Green Bank. Estimated costs are included in the existing quotes, but the local access charge remains somewhat uncertain due to the lack of similar services in the region. Our criterion for choosing the final configuration will be to minimize the total cost of high-performance networking services (not of access alone).

At present, all communication services to the NRAO Green Bank communications center are provided over copper from the Central Office (CO) in Arbovale, WV. The NRAO is presently negotiating with the LEC to upgrade these to fiber. Since adequate spare conduit capacity is readily available, this is straightforward and should be complete by the summer of 2000.

Services between the local CO and Marlinton, WV were upgraded to use fiber as recently as June 1996. There is sufficient available capacity to support additional services, such as the proposed DS-3 service, but is still not clear whether the LEC's local switch equipment will support ATM DS-3. The initial connection may have to be with multiple-T1 service. However, that is considered here to be an implementation detail. In all of our pricing exercises, we have assumed that DS-3 will be available. We have approached the LEC and they are interested in providing the service, but will have no need to do so unless this proposal is funded. We intend to proceed as if the DS-3 service is available, and, if not, to request that they upgrade the service to full DS-3 as soon as is practical.

The NRAO is making the transition to a higher speed campus network in Green Bank to meet the growing local needs for higher bandwidth connectivity and to provide high quality integrated video transport. The plan is to support current Ethernet LAN services at both 10 and 100 Megabits with a view to introducing Gigabit Ethernet as soon as appropriate. This will include a network analysis and management system, an enhanced router, and three additional switches. In order to protect against unwanted radio emissions, the entire network will be engineered using fiber. The LAN is presently connected to the outside world through a single Cisco 2500 router, using frame relay to connect to the NRAO intranet. This router will be replaced with a more capable router, adding support for the integrated video services and for the high speed external vBNS or Internet2 connection. All Internet traffic is presently carried by the frame relay Permanent Virtual Circuit (PVC) to Charlottesville, thence though the University of Virginia. Depending on the final choice of high speed network connection, this PVC will be removed.

9. COST BREAKDOWN

We obtained budget quotes for all of the options mentioned in the previous section from AT&T. In addition, for comparison, we also obtained quotes from Sprint for the connection between Green Bank and Charlottesville. The detailed cost quotes are proprietary.

Since Green Bank is in a remote location, the costs of providing the local service is dominated by the distance between Green Bank and the Point Of Presence (POP) for the long distance carrier. For AT&T, the POP is 90 miles from Green Bank. Independent of which service is selected, this is quoted with a Monthly Recurring Cost (MRC) of ~$10k.

In addition to the line charges, we must also consider the vBNS or Internet2 membership fee and the share of the cost of the connection from the contact point to the nearest Gigapop.

Clearly, if a connection is practical to Bluefield, WV, this is the cheapest option *for access alone* using a dedicated DTS circuit. However, the NRAO would then be a single access point and solely responsible for the access fees. Service through the major universities would allow us to share the fees, and would also enable us to take advantage of the expertise and services already in place at those institutions.

The costs of each of the options was very similar, summing to a recurring cost of ~$350k per year. Because of this, our preferred solution is the most natural connection for the NRAO, viz. via an ATM PVC in the AT&T cloud from Green Bank to Charlottesville and through the University of Virginia to Network Virginia and the vBNS.

10. CONCLUSION

Based on the foregoing, we believe that we have made a very good case for a connection from Green Bank to the high speed backbones connecting the research facilities in the USA. However, because Green Bank is in a remote location, the cost of such a connection is extremely high. Early in 1999, it appeared that there was an opportunity to obtain a special grant from the NSF to fund this effort. However, the grant would only have been able to cover the cost of the first year of operation; the NRAO operational budget would have to cover further years. It was clear that we would not be able to continue to operate the link even if we were successful in being awarded a grant to cover the first year's costs. Regrettably, therefore, we therefore decided not to submit a proposal.

The trend is clearly for communication costs to continue to drop. In the process of this work we have forged many contacts. If the budget climate changes, we will be in a very good position to pursue this project aggressively once again.

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