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ABSTRACT

The National Radio Astronomy Observatory* (NRAO) has four major locations distributed across the continental USA. The observatory has long used audio conferencing for its internal meetings and working groups, but we began using video conferencing in 2000 both to enhance the quality of human communication and to allow sharing of visual aids and graphical presentations during inter-site meetings. The video conferencing equipment operates over our existing frame-relay network connections so the only operations cost has been its coexistence with other internal network traffic. In order to provide the necessary Quality of Service (QoS), the video conferencing equipment was placed on individual Local Area Network (LAN) segments on the site routers. A video hub (multi-conferencing unit) has allowed routine four-way conferencing between the main NRAO sites. Conferences with domestic and international colleagues over the commodity Internet and via Integrated Service Digital Network (ISDN) connections are also routinely supported. Using the existing equipment, we have also been successful in sharing auditorium presentations, such as workshops, tutorials, colloquia, and other special events to all major NRAO locations. The success and user acceptance has been such that we have recently expanded from four video installations to ten, allowing several simultaneous conferences.

Keywords: Remote collaboration, video conferencing

1. MOTIVATION

The National Radio Astronomy Observatory operates the Robert C. Byrd Green Bank Telescope (GBT) in West Virginia, the Very Large Array (VLA) in New Mexico, and the transcontinental Very Long Baseline Array (VLBA). It is also the lead agency for the North American side of the Atacama Large Millimeter Array (ALMA) project. Its staff of about 550 are geographically dispersed, but most of them work at one of four major office sites: Charlottesville VA, Green Bank WV, Socorro NM, and Tucson AZ, or at the VLA operations site (50 miles west of Socorro) on the Plains of San Agustin, NM. Many technical, scientific, managerial and administrative working groups at the NRAO use long-distance communications and digital data exchange for a significant fraction of their daily work.

Until early 2000, most inter-site meetings at the NRAO were held by telephone conferencing, sometimes augmented by advance hard-copy distribution of visual aids. Audio-only communications, even when augmented by hard-copy document distribution, have important limitations:

- **Non-verbal cues:** Most human communication is heavily nuanced by non-verbal cues ... gestures, facial expressions and body language all convey information about comprehension, agreement, and attentiveness of meeting participants. Lacking all such cues, telephone meetings convey an incomplete and sometimes inaccurate sense of meeting dynamics.

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- **Visual aids:** Face-to-face technical discussions can benefit greatly from spontaneous use of visual aids, e.g. pointing to a particular feature in a graph or line in a document, or drawing a sketch on a whiteboard. This use of visual aids cannot be emulated in telephone meetings by advance distribution of hard-copy.
- **Travel overhead:** Large project reviews, seminars, in-house tutorials and personnel interviews can all benefit from participation by staff from many different NRAO sites but often require such participation for only short parts of a day. These activities are ill-suited to telephone conferencing but incur large a travel (costs and time) overhead if done fully face-to-face. Video conferencing can reduce this overhead by letting some staff participate remotely with almost face-to-face quality of interaction.
- **New staff:** New employees can find it daunting to form a picture of the whole NRAO organization (approximately 550 staff) just through telephone meetings and occasional travel to the other NRAO sites. People quickly learn to associate names and faces; doing so is an important part of getting to know one's way around an organization, but is missing from telephone communications.

We therefore began a review of video conferencing equipment and techniques for the NRAO in 1999, with the following goals:

1. **to add routine video capability to inter-site meetings previously held by telephone** in our main conference rooms;
2. **to explore the use of video for remote participation in larger (auditorium) presentations** such as project reviews, colloquia and workshops;
3. **to explore the use of video conferencing to non-NRAO sites**, including those in other countries who are partnered with the NRAO for ALMA and for the Expanded Very Large Array (EVLA).

2. INITIAL INSTALLATION

The four major NRAO office sites were already linked by a frame-relay intranet[1] for data communications (Figure 1). We therefore specified a system with

1. use of the H.323 standard, to build on our existing investment in the NRAO intranet;
2. an ISDN (H.320) gateway for high-quality communication to non-NRAO sites;
3. multi-conferencing capability (many inter-site meetings at the NRAO involve three or four sites), and
4. modest capital and operating costs, as we operate in a tight budgetary environment.

2.1. Equipment

After a market review in 1999, we used part of a National Science Foundation networking grant to procure a four-station system that was deployed early in 2000. Each system contained a Polycom[2] 512 video conferencing system, two large-screen TV's, a secondary video camera and a document camera (Sony VID-P150 Video Presentation Stand). The systems were installed in the primary conference rooms at each of the four main NRAO offices: Charlottesville, Green Bank, Socorro and Tucson. Each of these conference rooms can accommodate several dozen meeting participants, but most inter-site meetings involve between two and a dozen staff at any site. Dual microphone pods provided with the Polycom video system are placed on the conference tables. Each pod contains three microphones; the Polycom processing unit dynamically selects whichever of the six microphones sends the strongest audio signal.

The Polycom 512 systems can communicate directly for point to point meetings but have no multi-conferencing ability. We also installed a Radvision[3] MCU- 323 multi-conferencing unit and gatekeeper in Charlottesville to support three- and four-way meetings, and a Radvision L2W ISDN gateway to provide access to outside sites over ISDN through the Charlottesville PBX.

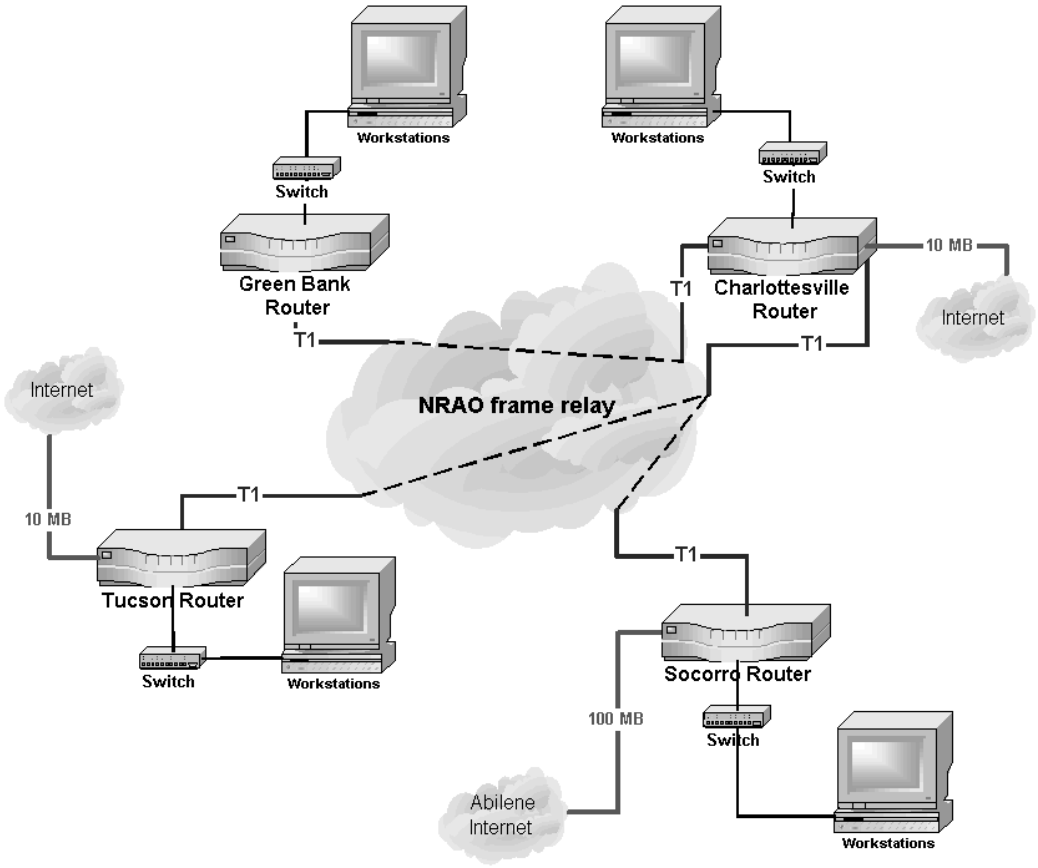

Figure 1. NRAO data intranet and connections to WAN before addition of video conferencing equipment.

Each video conferencing system was placed on its own subnet to isolate its traffic from other digital data streams on the NRAO LAN. The overall configuration is illustrated in Figure 2.

Beginning in March 2000, this equipment was used routinely for two-, three- and four-way meetings between the main NRAO conference rooms. It was also used on an experimental basis to share special presentations, workshops and seminars taking place in the auditoria at Charlottesville, Green Bank and Socorro with the other NRAO sites.

The usual operating modes are:

- Two-site (point-to-point) internal meetings: 512 kbps bandwidth (448 kbps for H.263 30 frames/s video, 64 kbps for G.722 audio giving the equivalent of a 7 kHz analog telephone signal). Each site sees the other full-screen on one TV monitor and either its own signal or a still video frame ("snapshot", see below) on the other monitor.

- Three- or four-site meetings: 512 kbps receive and 384 kbps transmit bandwidth through the Radvision MCU (448 kbps receive and 320 kbps transmit H.261 30 frames/s video, 64 kbps G.711-M audio giving the equivalent of a 4 kHz analog telephone signal). Voice activated video switching is used so that one monitor at each site shows full-screen video from the remote site that is currently providing the strongest audio, while the other monitor shows either the site's own signal or a still video frame ("snapshot", see below).

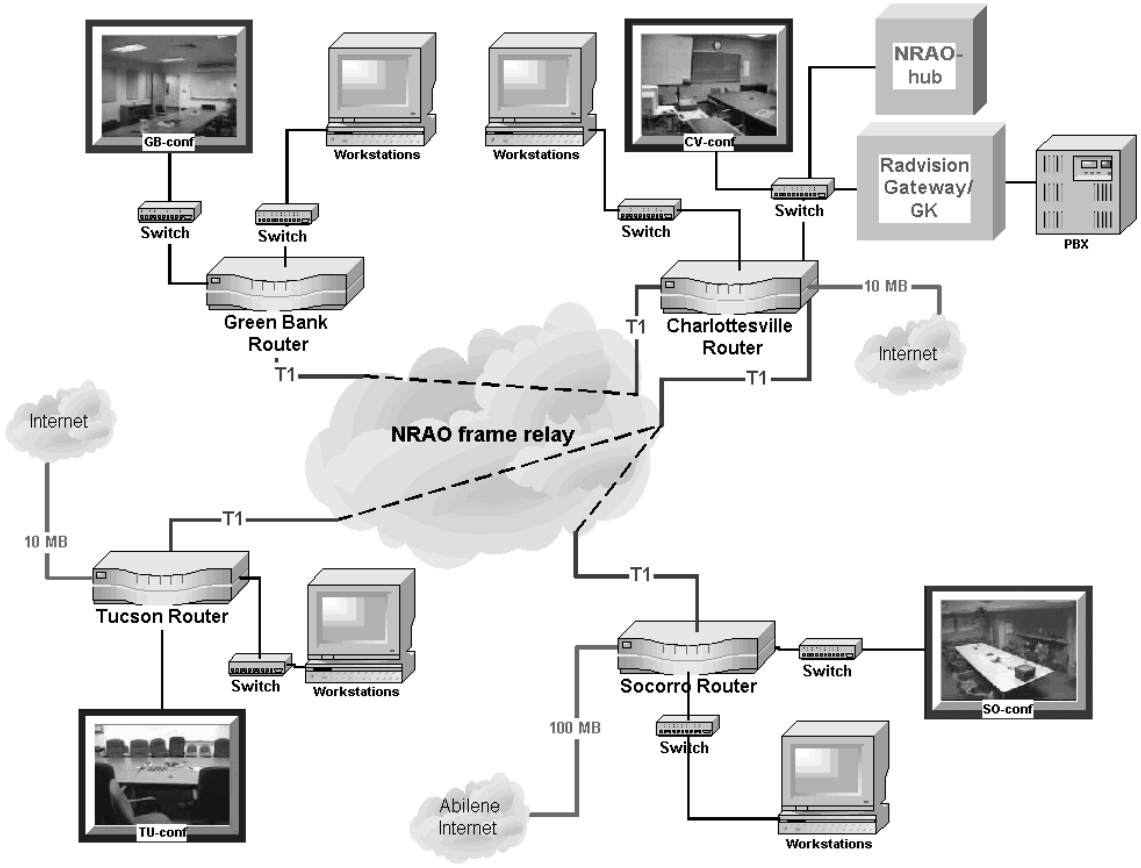

Figure 2. Our initial four-site video conferencing configuration. The Polycom 512 video conferencing systems are represented by screen captures of the conference rooms. "NRAO-hub" is a Radvision MCU-323 multi-conferencing unit. ISDN connectivity for all sites is obtained through the Gatekeeper and PBX in Charlottesville.

- Meetings with non-NRAO sites: 128 kbps bandwidth over ISDN, point-to-point, or over IP across the commodity Internet or Abilene. These are mostly point-to-point using the same display mode as in point-to-point internal meetings.

The "snapshot" video mode is particularly useful when a video presentation includes static visual aids such as overhead transparencies. Single video frames sent as "snapshots" from the presenting site usually show fine detail more clearly than in the continuous video. With a two-TV system, it is possible to show the "snapshots" from the presenting site on one TV screen in parallel with live video from the same site on the other.

2.2. Early experience

Two-way meetings with up to half-a-dozen participants in the conference rooms were straightforward once a few staff at each site became familiar with the video dialing protocol, the characteristics of the microphone systems and basic features of the video remote controls. Audio quality and video quality in point-to-point calls at 512 kbps are high, so the interactions are natural once participants get used to the presence of cameras and TV monitors. The Polycom systems allow cameras at both sites to be controlled from either site's video remote controls in point-to-point meetings. These features all make for a simple inter-site interaction that most staff adapted to quickly. The benefits of seeing meeting participants and visual aids at the other sites quickly became apparent, and many staff commented on the much greater sense of having been in a "real meeting" with colleagues at the other sites compared with phone meetings.

Three- and four-way meetings, meetings with over a dozen participants in any of the conference rooms, and "events" that use the larger auditoria, have all required significantly more preparation and support, for the reasons given below.

- **Time delay.** There is a small but noticeable extra time delay between sites in multi-site meetings because the audio and video signals must be compressed, transmitted to and from the MCU, and then decompressed. This delay makes it harder to interrupt someone at another site than it would be during a live or a telephone meeting. Adapting to the delay requires both experience of its effects on conversation and some personal discipline. Comments cannot be injected as quickly into a discussion in a far room as they can be locally. Some staff adapt to this more easily (and more willingly) than others. Meeting chairs need to be aware of the effect and to play a more active role in moderating a discussion than they might do in a face-to-face or telephone meeting. Multi-site meetings in which vigorous unstructured discussion (argument) is expected, and which do not require visual aids, may be better off carrying their audio by phone, just in order to eliminate the effect.

- **Audio quality.** Good audio quality is as critical to a successful video meeting as it is to a telephone meeting. Unfortunately, people who find it disconcerting to be "on-camera" observatory-wide may prefer to sit in visually inconspicuous places, thus putting themselves far from the conference table microphones. The Polycom microphones can pick up even quiet speakers at the edges of our larger rooms clearly *in isolation*, but their built-in switching can prevent a quiet voice in a room corner, or a speaker who faces away from the pod while pointing to a projected slide, from being heard clearly over a source closer to a microphone. Projector fans or sidebar discussions can then be much more distracting to the far sites than they are in the room itself. A small further complication has been that the Polycom microphone pod does not look like a traditional microphone, so people may rustle papers, tap pencils or cups, etc. on the table near the pods without realizing that they are creating an audio problem. With experience, most such issues can be dealt with by microphone placement to suit the actual situation, but they can create problems for novice users and in large groups. Willingness to practice appropriate "video etiquette" also varies, so it is helpful to have a moderator at each site during large meetings. (The same issues come up in telephone meetings but often go unaddressed there: video allows people at the remote sites to identify the source of any audio problem, so they are more likely to provide feedback about remedies.)

- **Camera control.** Frowns, nods, puzzled looks, inattention, all convey messages in video conferences that are absent from telephone meetings. In contexts where this extra information is significant (e.g. when technical working groups are trying to ensure that a point is equally well understood by all participants, or in meetings that are trying to reach true consensus about a difficult matter) it is important to provide clear views of the speakers at all sites. When there are more than two or three participants at a site, active camera control is necessary to obtain appropriate views of the participants. Automated (voice-activated) camera tracking is available, but it requires good room acoustics, minimal extraneous noise, and cameras with good audio directional discrimination. In our usual meeting rooms (which were not designed specifically for video conferencing) automated camera tracking with the Polycom systems falls short of being truly useful: echoes, background noise from projectors or air handlers, etc. can confuse the systems sufficiently to cause unwanted and distracting camera movement. We therefore rely on camera control by a meeting participant who is familiar with the stored camera presets. We often need to control the camera(s) at one site from another, but this cannot be done directly from the video remotes in multi-site meetings (where there is no unique 'far' site for the remote to control). We therefore developed a tool for controlling remote cameras directly over the network from a central PC keyboard independently of the video data stream. This allows one person to act as "video chair" for all sites in meetings where active remote camera control is needed. With this tool in place, the main role for voice-activated camera tracking has been to help the "video chair" locate someone who is speaking off-camera at a site other than their own.

- **Visual aids.** Overhead transparencies, documents shown on a document camera, sketches on a white-board, etc. can all greatly enhance communication. Capturing them on video at appropriate resolution

is a key ingredient in making inter-site presentations, tutorials, software demonstrations, seminars and colloquia feasible by video. Some extra care is needed to account for the color transfer functions and resolution limitations of video cameras when using visual aids. In general, however, techniques that make presentations clearer for video also make them much clearer in the live room, so the effort to do so pays off locally as well as at the remote sites. These techniques include: keeping slides simple, using more slides rather than crowding too much information onto fewer, using colors that give good contrast, and using bold font faces and large point sizes. In practice, some extra preparation time is usually needed to make full use of video presentation capabilities, including previewing the appearance of key visual aids on the video conferencing equipment. Active camera control (especially zooming in or out to an appropriate frame and resolution, and sending video "snapshots" of projected slides in parallel with live video of the speaker) is important for successful video presentations. The ability of remote site(s) to control the camera(s) during such presentations serves a dual role: it shares the extra workload between sites and ensures that the site(s) receiving the presentations by video can extract whichever video view is most appropriate for them in the context of the meeting.

- **Secondary cameras and TV monitors.** In the larger rooms, we have found it very helpful to have more than one camera available, because the sightlines that work best for small meetings around conference tables differ from those that work best for set-piece presentations, seminars, etc., with more participants in the rooms. A second TV monitor allows presenters to see a large format view of the video that they are sending to the far sites, to check what their own presentation looks like to the remote audience. Small conference rooms that are used entirely for small-group meetings or for viewing presentations from other sites can therefore be equipped satisfactorily with only one TV monitor and one video camera, whereas all of our larger rooms have a two-TV system and at least one secondary camera.

2.3. Uses

Groups who have made significant use of video conferencing at the NRAO include

- Data Management and Computing: inter-site working group meetings, observatory-wide information sessions, software demonstrations and tutorials;
- Engineering: project design, review and discussion meetings with frequent display of technical drawings, graphs, computer screens, etc.;
- Scientific staff: observatory-wide discussions and working groups, telescope and software test meetings, project reviews, seminars, colloquia;
- Human Resources: observatory-wide meetings and presentations, personnel interviews;
- Fiscal: planning meetings, in-house training and software demonstrations;
- Education and Public Outreach, Safety Officers and NRAO Management: large and small-scale "all-sites" meetings;
- non-NRAO sites: several scientific staff work with colleagues in Germany over ISDN; EVLA and ALMA project reviews are regularly attended by staff at DRAO (Canada) by video over Abilene; occasional meetings with other sites occur over the commodity Internet at 128 kbps.

3. EXPANSION

After about a year of use at the NRAO, video conferencing technology had become accepted to the point where some meeting organizers began to complain to conference room schedulers if they were asked to revert to phone meetings when the rooms with video equipment were over-booked. This created demand for video systems in alternative rooms, especially for small meetings that did not require the space available in the main conference facilities. Successful videocasting of observatory-wide events, such as colloquia, workshops, ceremonies and "all

employee" announcements by NRAO or AUI management also raised interest in permanent video installations in our three large auditoria. Video capability was also requested at the VLA Site, to enhance communication with the Array Operations Center in Socorro, to allow staff to participate in observatory-wide video meetings while at the VLA Site, and anticipating future needs for ALMA antenna testing. In early 2002, we expanded our video network from four to ten systems in response to these needs.

This expansion was done by adding four Polycom[2] 128 systems, and two Polycom FX systems with built-in MCU capability, as shown in Figure 3. The FX units replaced the original Polycom 512 systems in the heavily-used conference rooms in Charlottesville and Socorro, whose original systems were moved to their auditoria. Adding the two FX systems gave us three MCUs which can be used separately (to host simultaneous multi-way meetings at different sites) or together (to link more than four NRAO sites while minimizing traffic on the East-West leg of our intranet).

The Polycom FX systems also provide higher-quality audio performance (improved equivalent bandwidth and better signal-to-noise with the same microphones) than the Radvision MCU, and permit context-sensitive video switching between "continuous presence" mode (in which all sites are seen at once in "Hollywood squares" format) and the mode in which only the loudest site is seen full-screen everywhere. The ability to see all sites at once when appropriate helps meeting chairs to keep track of which sites, and which individuals, are in the meeting.

Use of the FX hubs to host four-way meetings, coupled with increased use of our network bandwidth for general data transfers, has led to more extensive operation in 384 kbps (64 kbps audio, 320 kbps video) mode. When using just the Polycom equipment, we have found that the small degradation of video quality that results from restricting the video bandwidth to 320 kbps has little practical impact, and is only noticeable if animations or movies are shown.

The whole NRAO video system is now in use for about 150 site-hours per month. About half of all inter-site meetings are now held by video.

A detailed description and User Manual for the NRAO video conferencing system is available on-line.[4]

3.1. Auditorium use

Expansion of video to larger rooms and events has been easier than the expansion of audio for the same purpose. Most staff wish to *participate* interactively when attending colloquia or workshops at other sites by video. It is therefore important for the remote sites to be able to hear all of the discussion in the originating room clearly, and for the event chairs to be aware of the possibility of questions from remote sites. Good sound quality is even more important than good video in many cases, but is harder to obtain in large rooms with many participants.

Some technical points are specifically relevant to large-room video conferencing:

- Ancillary microphones are essential to deal with mobile speakers (who may roam, or face away from the audience while they are pointing to slides but towards them at other times), *and* to capture audience discussion. We have had good experience with using wireless lapel mikes for speakers and sensitive wide-angle mikes for discussion, mixed appropriately with the output from Polycom microphone pods mounted on, or hung from, the auditorium ceilings.
- Remote camera control from a site that is receiving the event by video allows someone at that remote site to do most of the work needed to make an auditorium presentation available NRAO-wide by video. This shares the workload of videocasting an event between the originating and receiving sites.
- A video-capable LCD projector can be used to project the incoming video feed in large format suitable for viewing by a big group.

The Charlottesville auditorium was furnished in an era when 35mm slides were the standard visual aids, and has an enclosed projection booth. This booth has now been equipped with a video-capable LCD projector, and with video and audio controls and monitors that allow us to compose the video presentation of events in this

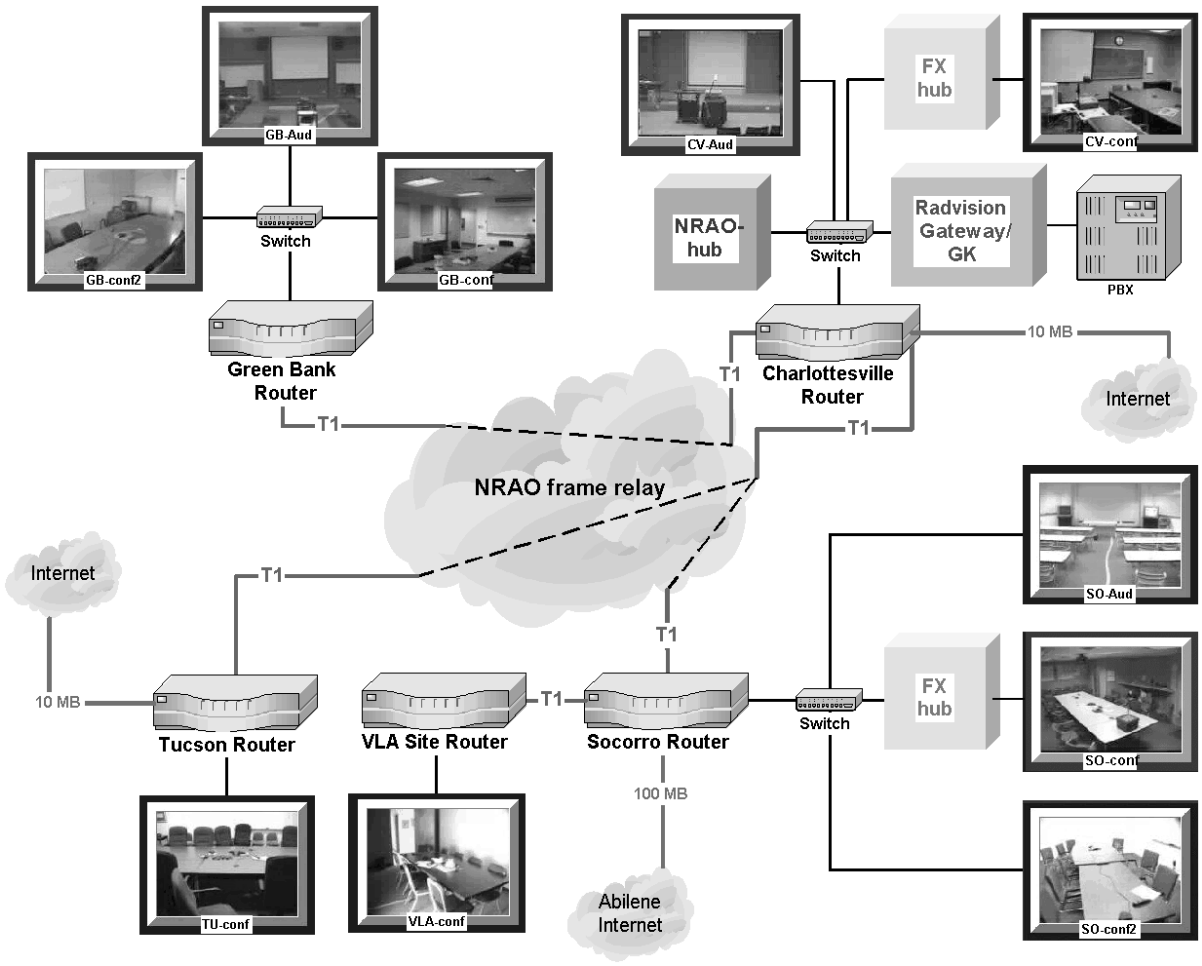

Figure 3. Current configuration of ten video conferencing rooms and three MCU's (video hubs) at the NRAO. The data-only network is not shown.

room with minimal intrusion on the event itself. This auditorium also doubles as a secondary video conference room using a small rollout table with its own microphone pod and video remote control, independent of those used when operating the system from the booth.

3.2. Quality of service issues

Audio quality and continuity are paramount issues for video conferencing. Packet loss that produces missing sound fragments is far more disruptive to a meeting or presentation than packet loss that produces occasional jerky video. Successful video conferencing requires both adequate bandwidth and good quality-of-service assurance throughout the network. Placing each video conferencing system on its own dedicated subnet, along with applying priority queuing in the routers achieved the necessary quality of service.

Video conferencing traffic is not the major user of network bandwidth on the NRAO intranet (it typically accounts for between one-sixth and one-third of the total traffic), but it is the first place in which the effects of network congestion, packet collisions or packet dropping become visible to NRAO staff. As we add bandwidth to the NRAO's intranet services, we plan to do so in ways that will maintain good QoS for the video and other real-time data streams.

Video meetings with non-NRAO sites that take place over the commodity Internet are, of course, particularly vulnerable to jitter and packet loss. Some users have been willing to accept occasional loss of contact with the non-NRAO site, others have used the telephone to ensure audio continuity and an Internet connection just for ancillary video.

3.3. System management

Central management of the video systems became more important as more systems came into use. We deployed Polycom's web-based *Global Management System* to provide system status information, to monitor network statistics and diagnose problems, to adjust and standardize system settings, to perform software updates from a central site, to log system usage, and to provide remote assistance with call placement if users have difficulty.

The combination of *Global Management System* and our centralized remote camera interface has meant that most NRAO video users do not need to learn how to place complicated calls or to control the cameras. Placing video calls is only slightly more complex than using the telephone conferencing system, but it has taken several years for a significant number of staff to become familiar with the basic dialing and camera control functions. *Global Management System* allows complicated calls to be placed remotely and eliminates call-synchronization issues if multiple hubs are required, as in five- or six-way meetings. Only a few staff understand, or wish to know about, detailed camera operation, so the remote camera interface has been particularly important to the success of multi-site meetings with large numbers of participants.

3.4. Sociology

To make the best use of video conferencing in a discussion meeting, the meeting chairs need to be as aware of, and responsive to, people at the remote video sites as they are to people at their own site. Some participants may forget they are part of a wide-area conversation since the full meeting room is virtual rather than physical. Chairs should poll remote sites for comments on important items, and form the habit of watching the video attendees as well as those in their own room when soliciting discussion.

As mentioned in Section 2.2, it is helpful to have local moderators at sites with many participants, to minimize extraneous audio at those sites, particularly from sources near a microphone pod. When listening to a presentation from a remote site, it is also good practice to mute a listening site's audio until discussion is invited; we can do this remotely from the interface that is used for central camera control, but we rarely do so because it is better for sites to learn to practice their own "video etiquette".

Effective use of document cameras or other visual aids requires a small amount of extra familiarization and setup time by presenters. We have found that engineering and computing groups make more use of document cameras and other data sharing tools than do other users, perhaps because many of the other NRAO staff have a long background of telephone meetings in which visual aids could not be used. The other side of this

coin is that simply seeing "talking heads" from other sites during video conferences has been more beneficial than many of us anticipated, because the non-verbal cues to meeting dynamics (Section 1) are indeed conveyed effectively in video meetings.

As the NRAO video conferencing system has been expanded to include more rooms and more MCU units, it became more important to schedule the rooms and MCU's on an observatory-wide basis. This accelerated demand for an observatory-wide on- line calendar and scheduling tool.

3.5. Costs

The undiscounted price for our smallest installation (Polycom 128, single TV monitor, no secondary camera) would be about $4,000. The large-room installations with a Polycom FX MCU, secondary camera and twin large-screen TV's cost about $12,000 to $15,000 without discounts; basic document cameras typically cost about $2,000. Stand-alone MCU's and gatekeepers typically cost from $10,000 to $20,000.

3.6. Future needs and uses

The resolution limits of video and the need for active camera control to capture sophisticated presentations encourage us to increase our use of direct data links (such as Microsoft *NetMeeting*[5]) between the sites to share computer displays in parallel with the video feed. We hope to install LCD projectors permanently in all video rooms where we do such "data conferencing" to increase the effectiveness of computerized inter-site presentations and software demonstrations.

Fully automated voice-tracking cameras would eliminate our current need for active camera control in meetings with many participants, but would come at the cost of more expensive camera installations (with greater physical separation between the microphones that provide audio input to the camera controls) and some remodeling to optimize the room acoustics.

We have considered the use of digital whiteboards, but have deferred using them for several reasons: partly for cost, partly because we have been able to capture sketches or notes from conventional whiteboards adequately using camera presets, and partly to minimize technological hurdles for our users until more of them are fully familiar with the basic system.

The Polycom FX systems have the capability to send presentations as streaming video, and we hope to explore this use for applications where it would be appropriate to provide video presentations to individual workstations, rather than to audiences in the designated conference rooms.

The Polycom and Radvision MCU's also enforce a "lowest common bandwidth" constraint on any conference that they host, i.e., if one connection is made at narrower bandwidth than all the others, then the entire conference proceeds at that narrower bandwidth. If future applications require interactivity with systems that have only narrow-band connections to the NRAO, a more sophisticated MCU capable of mixed-bandwidth operation may be needed.

Video conferencing between the Array Operations Center and the VLBA antenna sites could be of significant benefit to the operation of the NRAO's most widely-dispersed instrument, but we currently have neither the bandwidth nor QoS to the VLBA antenna sites to support this.

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