Remote observing with the Keck Telescopes from the U.S. mainland

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ABSTRACT

We describe the current status of efforts to establish a high-bandwidth network from the U.S. mainland to Mauna Kea and a facility in California to support Keck remote observing and engineering via the Internet. The California facility will be an extension of the existing Keck remote operations facility located in Waimea, Hawaii. It will be targeted towards short-duration observing runs which now comprise roughly half of all scheduled science runs on the Keck Telescopes. Keck technical staff in Hawaii will support remote observers on the mainland via video conferencing and collaborative software tools. Advantages and disadvantages of remote operation from California versus Hawaii are explored, and costs of alternative communications paths examined. We describe a plan for a backup communications path to protect against failure of the primary network. Alternative software models for remote operation are explored, and recent operational results described.

Keywords: remote observing, remote operation of telescopes and instruments, video conferencing

1. INTRODUCTION

Remote observing has become the dominant mode of operation for both Keck Telescopes and their associated instruments. Nearly 90% of all Keck observations are now carried out remotely from the Keck Headquarters in Waimea, Hawaii. Remote observers in Waimea avoid the ill effects of working at high altitude,[1] yet they are able to maintain effective communication with the telescope operations staff at the Keck summit via a 45-Mbit/sec circuit which supports both high speed networking and video conferencing.

The majority of Keck observers, however, are affiliated with institutions located on the U.S. mainland, primarily in California. To observe with the Keck Telescopes, these astronomers currently travel several thousand kilometers to sit in a Keck remote control room which itself is located tens of kilometers from the telescopes. In principle, such observations could be conducted directly from the U.S. mainland, given the necessary network infrastructure and facilities. Remote operation from the mainland offers particular advantages for short duration runs involving routine observing programs, while remote operation from Waimea offers advantages for longer duration runs.

1.1. Motivation

Keck Telescope time is scheduled in terms of a classical observing model in which astronomers are assigned a specific set of dates for each observing run. Unlike some recent telescopes,[2] the Keck Telescopes were not designed to support queue-scheduled observing, nor is such a mode of operation planned for the future. While Keck observations have occasionally been carried out by local service observers on behalf of remote astronomers, service observing is usually not requested by Keck observers nor generally supported by the Observatory. Nearly all Keck observations are performed directly by the astronomers (and their observing teams) who have been allocated telescope time.

Observing time on the Keck Telescopes is shared between astronomers from the University of California (UC), California Institute of Technology (CIT), National Aeronautics and Spaces Administration (NASA), and the University of Hawaii (UH). Collectively, these institutions (and the various grant funding agencies that support their respective researchers) expend several hundred thousand dollars each year on direct travel costs (e.g., airfare, ground transportation, lodging) incurred by astronomers commuting to the remote operations facility in Waimea.

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In addition to these direct costs are the indirect costs of researchers' time consumed in travel. Such travel time is particularly inefficient for observing runs that last only a single night or one-half of a night. For such short duration runs, more time is consumed in travel from the mainland to Waimea than in observation. During the past year, 43% of the scheduled science observing runs on Keck I were either a single night or a half-night in duration, while on Keck II, 58% of the runs were of such short duration. Tables 1 and 2 show the distribution of run lengths on Keck I and Keck II from February 1, 1999 through January 31, 2000. These statistics exclude nights spent on telescope engineering or instrument commissioning. (The smaller total number of scheduled science observing nights on Keck II is due to three new instruments being commissioned on that telescope during 1999.)

Length	Number	Per-cent	Cumulative
0.5	16	8.6	8.6
1.0	65	34.8	43.4
2.0	71	38.0	81.4
3.0	27	14.4	95.8
4.0	8	4.3	100.0
> 4.0	0	0.0	100.0

Table 1. Keck I observing run length distribution

Length	Number	Per-cent	Cumulative
0.5	31	14.9	14.9
1.0	90	43.3	58.2
2.0	76	36.5	94.7
3.0	10	4.8	99.5
4.0	1	0.5	100.0
> 4.0	0.0	0.0	100.0

Table 2. Keck II observing run length distribution

Remote operation from the mainland is also particularly attractive in several other situations. Even for longer duration runs, travel to Waimea can prove difficult in cases where health issues (e.g., sinus or ear infections) make airplane travel problematic, or when family considerations (e.g., impending birth of a child) or academic obligations (e.g., teaching classes) make it difficult to be away. In addition, since most Keck instruments were designed and built by institutions in California, mainland remote operation allows engineers and technical support staff at those sites to run instrument diagnostics, conduct performance analysis, or perform system calibrations remotely.[3] Finally, it allows a remote astronomer to periodically check on the status of observations being obtained by a service observer at Keck.

1.2. History

While there is a clear mandate and policy at Keck Observatory to provide remote observing from its headquarters in Waimea, there is currently no similar mandate or policy for the Observatory to directly support remote observing from the mainland. Various segments of the Keck observing community, however, have expressed significant interest in developing such a capability. Toward that end, several experiments and demonstrations have been conducted over the last several years at U.C. Santa Cruz (Lick Observatory) and at CIT.

Initial tests of mainland remote operation of Keck instruments via the Internet began in late 1993 with efforts to operate the Keck High Resolution Echelle Spectrometer[4] (HIRES) from Santa Cruz. Those initial efforts met with only limited success. Engineering tests and completion of commissioning of the HIRES image rotator[5] were conducted remotely from Santa Cruz in late 1996 and early 1997. During 1996, a suite of software tools was developed at Santa Cruz to allow collaborators on the mainland to obtain data efficiently from observers working in Waimea.[6] Partial remote-operation of the Low-Resolution Imaging Spectrograph[7] (LRIS) on Keck I via the Internet was successfully demonstrated from the San Diego Convention Center at the SPIE telescope control conference held in July 1997.[8] In October 1997, a test of multi-site operation of LRIS was successfully conducted, with real-time readout of CCD image data flowing simultaneously to Mauna Kea, Waimea and Santa Cruz. Between 1997 and 1998, astronomers at CIT remotely operated LRIS from Pasadena via a high bandwidth channel on NASA's experimental Advanced Communication Technology Satellite (ACTS).[9]

Except for this last project, all of these previous efforts were significantly impaired by the limited bandwidth and reliability of the commodity Internet link between the Mauna Kea summit and the mainland. In an effort to initiate cooperative efforts to improve the performance of this link, a joint discussion was organized at the SPIE Astronomy conference held in Kona, Hawaii in March 1998*. This discussion brought together representatives from the Mauna Kea observatories, UH technical staff responsible for operating the Hawaii portions of the Mauna Kea to

*For details, see http://www.ucolick.org/~kibrick/remoteobs/spiebof.summary.html mainland link, UC and NASA technical staff responsible for the California portions of the link, technical staff from the University Corporation for Advanced Internet Development (which is responsible for the Internet-2 initiative and the Abilene network) [†], and mainland astronomers who observe at Mauna Kea observatories. Later that month, further discussions took place at Keck Headquarters between Keck technical and policy staff, the UH Director of Information Technology, and members of NASA's IRTF/Keck Management Operations Working Group.

Issues and ideas that arose from these meetings contributed to several initiatives by UH. In July 1998, UH submitted a High Performance Computing (HPC) grant proposal to National Science Foundation (NSF).[10] In October 1998, UH upgraded the bandwidth of its commodity Internet connection from Oahu to the mainland from 6.0 Mbits/sec to 45.0 Mbit/sec. The UH HPC proposal was funded by NSF in February 1999, and in March 1999 resulted in a 45 Mbit/sec connection between the UH Manoa campus and the Oahu point-of-presence (PoP) of the Defense Research and Engineering Network (DREN) operated by the U.S. Department of Defense (DoD). Under an agreement worked out between NSF and DoD, Hawaiian Internet-2 traffic is permitted to share an existing DREN 45 Mbit/sec circuit to the mainland and peers with the Abilene network at the NASA Ames Research Center in California. The UH HPC proposal also included plans to upgrade the Oahu to Mauna Kea link from 1.5 Mbit/sec to 6.0 Mbit/sec. However, a related network upgrades proposal submitted to NSF by the Gemini Telescope consortium was approved in April 1999[‡], and in partnership with the UH HPC proposal,[11] will result in upgrading the existing link between Oahu and Mauna Kea from 1.5 Mbit/sec to 45 Mbit/sec in early 2000.

In California, similar efforts were also made to improve network connectivity. A consortium of universities and research institutions formed the Corporation for Education Network Initiatives in California (CENIC), and submitted a proposal to NSF in January 1997. That proposal resulted in the funding of the CalREN-2 network, which now provides high-speed network connectivity between most major California universities, including CIT and all campuses of UC. The CalREN-2 network links these sites to both the vBNS and Abilene national high-speed networks, and to Hawaii via DREN.

Thanks to the collective efforts of the NSF, DoD, Gemini, UH, and CENIC, a 45 Mbit/sec Internet-2 path from Mauna Kea to the relevant mainland sites should become operational by the Spring of 2000. Gemini will reserve a portion of the bandwidth between Hilo and Oahu for its own operations, and the remainder will be shared among the various Mauna Kea observatories along with other Hawaii research institutions.

1.3. Goals

In anticipation of the improved network bandwidth and reliability that will soon become available between Mauna Kea and the mainland, astronomers at several UC campuses (Santa Cruz, San Diego, Berkeley, and Los Angeles) have started planning and, in some cases, equipping Keck remote observing facilities. The goals for the Santa Cruz facility are:

1. Provide equivalent operational *capabilities* to what is provided at the Keck remote operations facilities in Waimea;
2. Provide tools to support effective interactive on-line collaboration between the mainland remote observer and the relevant Keck support staff in Waimea and the Mauna Kea summit;
3. Provide a cost-effective backup network path to Mauna Kea to protect against temporary outages of the primary network path;
4. Coordinate with other institutions and agencies in maintaining the network bandwidth and reliability needed to support these capabilities;
5. Develop a funding model that recovers the operational costs of the facility (e.g., equipment maintenance and network/communications costs);
6. Design the facility so that it can be replicated at other mainland sites.

Before discussing our plans for implementing these goals, it is necessary to review the facilities and remote observing operational capabilities provided at the Keck headquarters in Waimea.

[†]For details regarding high speed network backbones and the Internet-2 initiative, see http://www.ucaid.edu, http://www.internet2.edu/abilene, and http://www.vbns.net

[‡]See http://www.gemini.edu/project/announcements/press/99-0.html

2. REMOTE OBSERVING FROM KECK HEADQUARTERS IN WAIMEA

The town of Waimea is located 32 kilometers northwest of the Mauna Kea summit. Observers who work from Waimea operate from one of the two remote operations rooms located at Keck Headquarters. The work stations in these rooms communicate with data taking and telescope control computers at the summit via a dedicated, 45 Mbit/sec DS3 link.

The observer is supported by an observing assistant (OA), who operates the telescope, and an instrument specialist (IS), who assists the observer in setting up and operating the instrument. During the first part of the night, an IS is present in the remote operations room and during the latter part an on-call IS can be reached by telephone at home. The OA is usually located at the summit, but in some cases, will operate the telescope from the same control room in Waimea from which the observer is running the instrument.

A dedicated, point-to-point video-conferencing system (PictureTel Venue 2000) links each remote operations room in Waimea with its corresponding telescope control room at the summit. In the typical case, where the observer and the OA are separated, this system has proven to be critical for successful observing. We have found that the visual cues that come from body language and from knowing who else is in the room are essential for two people collaborating on the operation of the telescope and instrument. Audio quality has also proved to be essential. The audio quality of this system is superior to that delivered by a standard telephone connection.

The Waimea facility also provides a very well appointed visiting scientists quarters (VSQ) located a short walk from the remote operations rooms. The VSQ provides ten separate suites, each affording a quiet and dark location where observers can sleep during the day. The VSQ also includes a common kitchen and dining area, a library, a laundry room, and a recreation room. A shopping center with a supermarket and several restaurants is within walking distance from the Keck HQ. Such amenities are of particular importance for observers engaged in longer duration observing runs.

A further attraction of the Waimea facility is the availability of the full complement of Keck support staff during the daytime. We have found that greater accessibility to telescope management, instrument specialists, and the engineering staff, all of whom have their offices near the remote operations rooms, has helped visiting observers to utilize the facility more efficiently. Direct contact between observers and technical staff stands out as one of the primary advantages of remote observing from Waimea.

3. PLANS FOR KECK REMOTE OBSERVING FACILITIES ON THE MAINLAND

3.1. Assumptions

The remote observing facility in Santa Cruz is primarily targeted towards observers who are scheduled for short duration observing runs and who live within commuting distance to the facility. It is not intended to duplicate the Waimea facility nor to operate independently of it. Rather, the Santa Cruz facility is an extension of the facility in Waimea. The two are intended to operate in collaboration, sharing resources where practical.

Accordingly, there are no plans to provide facilities equivalent to the Keck VSQ, since it is clearly not practical nor cost-effective to replicate such facilities at each mainland remote observing site. Remote observers using the Santa Cruz facility will be expected to make their own eating and daytime sleeping arrangements. Most will probably choose to sleep at home during the day. Similarly, we have no plans nor budget to provide on-site instrument specialists. Rather, we intend to rely on the existing instrument support staff at Waimea and to provide video-conferencing and shared software environments so that they can most effectively support the observers at the mainland site. First-time users of an instrument will be required to observe from Waimea so that the Keck instrument specialists will not be required to train novice users remotely.

Given the goals and assumptions under which the Santa Cruz facility will operate, there are several reasons why observers with longer duration runs may prefer to observe from Waimea. First, it is easier to justify the travel costs and travel time to Waimea when these can be amortized over multiple nights of observing. Second, the homes of many mainland observers are neither dark nor quiet during the daytime. Thus, for runs that last longer than one night, observer efficiency on subsequent nights may be significantly higher as a result of the superior daytime sleeping arrangements provided at the Keck VSQ. Third, Waimea provides a certain level of isolation from on-campus sources of interruptions and distractions that can sometimes interfere with observation planning or data reduction activities. While such interruptions can possibly be deferred for a one-night run, they become harder to avoid when a run lasts several nights.

In some cases, an observing run may be conducted by an observing team in which some of its members observe from Waimea while others elect to observe from the mainland. In particular, the mainland remote observing facility can provide opportunities for students to participate in observing runs despite limited availability of travel funds. In the case of observing teams having 4 or more active participants, CARA support staff foresee advantages to distributing such teams between sites rather than trying to fit the entire team into the limited space of the remote operations room in Waimea. If an observing team is composed of observers from widely separated mainland sites (e.g., Berkeley and San Diego), then simultaneous remote operation for multiple mainland sites may prove desirable.

A key objective of the mainland facility is to provide observers with the flexibility to choose the observing site that is most practical and productive for them. That choice depends on the needs of the members of their observing team and the specific circumstances and duration of a given observing run. That objective can best be achieved if the mainland sites are operated in close collaboration and cooperation with the Waimea facility.

3.2. Equipment and services provided

The remote observing facility in Santa Cruz will provide a subset of the equipment and services provided in Waimea. These include:

1. A similar complement of remote observing workstations that run the same software as those in Waimea;
2. External disk and tape drives for image storage and transport;
3. A video-conferencing system that connects to Waimea and Mauna Kea via IP-based H.323 protocol;
4. ISDN telephone lines and routers to provide a backup data path to Mauna Kea;
5. An uninterruptible power supply (UPS) to protect against brief power outages;
6. Support equipment including printer, copy machine, and FAX;
7. Amenities including a couch, microwave oven, refrigerator, and bottled water dispenser with hot and cold taps.

These items are divided between two adjacent rooms, with the computing and video-conferencing equipment in one room and the support equipment and amenities in the other. Most of this equipment is now installed and operational, and the remainder should be in place by June 2000. Items not yet installed include the ISDN phone lines and routers in Santa Cruz and at the Keck summit, the multi-point H.323 video-conferencing units for the Keck I and Keck II control rooms, and the UPS and couch for Santa Cruz.

These two rooms are located adjacent to the offices of the UCO/Lick Observatory Scientific Programming Group. That group developed the software for several of the Keck optical instruments [§]. During the day, its staff can provide expert software assistance to observers using those instruments and assist in resolving any initial configuration or instrument start-up problems that arise during the afternoon. Because of the 2 to 3 hour time difference between California and Hawaii, the remote observers' end-of-night activities will overlap with the start of the work day at the remote site. This enables the software staff to hear first hand from the observer about any software problems that occurred during the night or about any suggestions for software improvements. Such direct contact between the observers and the software staff should prove beneficial to both and result in improved software for current and future instruments.

4. NETWORK ISSUES

Remote observing from the mainland requires a reliable and reasonably secure data link that provides adequate bandwidth and minimal propagation delay between the remote site, the Keck summit, and Waimea at a cost that is not prohibitive. Much of our effort to date has focused on providing such a link.

[§] The Keck High Resolution Echelle Spectrometer (HIRES), the Echellette Imager and Spectrograph (ESI), and the Deep Extra-galactic Imaging Multi-Object Spectrograph (DEIMOS)

4.1. Costs

At earlier stages of this project, we considered obtaining a dedicated, leased-line between California and Mauna Kea. When this option was last explored in mid-1998, a leased T1 (1.5 Mbit/sec) circuit cost approximately $10,000/month, while market pricing for a DS3 (45 Mbit/sec) circuit was about $200,000/month. Because these circuits would remain mostly idle both during much of the day as well as on those nights when remote observations were not being conducted, we would be paying for thousands of hours of bandwidth that we would not use. Accordingly, these options would not provide a cost effective solution, nor were they even close to affordable within the constraints of our budget. As an alternative, we also investigated frame relay solutions, but dismissed these as well due to concerns about highly variable latency and relatively high fixed costs.

We also considered the possibility of using inverse-multiplexed, dial-on-demand ISDN telephone circuits to provide our primary network path to Hawaii. An adjustable bandwidth link with a peak bandwidth of approximately 1.1 Mbit/sec could be obtained by installing ten ISDN lines at each end. This option would have been considerably less expensive than a comparable leased-line solution, given that our need for bandwidth is not continuous. Long distance telephone charges for each night of remote operation were estimated at about $400/night. In addition, fixed lease charges (independent of usage) for the ISDN lines in California and Hawaii were estimated at about $15,000/year. If one assumes that these lines might be used at most 50% of the nights in each year, then these fixed lease charges translate to an additional cost of at least $80 per night of remote operation, or a total cost of $480/night. This does not include the cost of amortizing or maintaining the inverse multiplexing hardware at both sites. In the case of a longer duration observing run conducted by a single observer, these communications costs would exceed the comparable travel costs to Waimea. Neither would such lines provide adequate bandwidth to accommodate the peak demands of many of the Keck instruments.

The Internet-2 path that is nearing completion and which we plan to use should provide adequate bandwidth to meet the peak demands required to support remote operation. It should also provide a more cost-effective solution by sharing the costs of the circuits over a much wider base of users and institutions. During the daytime hours, these circuits will also serve the needs of researchers in other academic disciplines in both California and Hawaii. Accordingly, UH is committed to the long term operation of the high-bandwidth link from Oahu to California, and CENIC is committed to maintaining the high-bandwidth links that connect the various universities and research institutions within California.

During the two year terms of the UH and Gemini NSF awards, the costs of operating the tail circuits from Oahu to Mauna Kea will be covered by those two grants. At the end of that period, the Mauna Kea observatories and their respective headquarters facilities in Waimea and Hilo will need to assume these operating costs, and that will be the subject of future negotiations. In developing the funding model for mainland remote observing facilities, we need to factor in an appropriate contribution towards the operating costs of those tail circuits.

4.2. Reliability and Bandwidth

The successful operation of a mainland remote observing facility is critically dependent on the reliability and bandwidth of the network connections between Waimea, Mauna Kea, and the mainland facility. Astronomers are unlikely to embrace this mode of operation unless they can be confident that potential network performance problems will not reduce observing time or efficiency.

4.2.1. Experience with the Waimea to summit link

Remote operation from Waimea was initially viewed with considerable skepticism by a number of observers. That skepticism was due in part to concerns about the performance of the network between Waimea and Mauna Kea. The record, however, indicates that the reliability of the summit to Waimea link has been extremely high. It has earned the confidence of most astronomers, despite the fact that its initial bandwidth was suboptimal. When first implemented in 1996, this link provided only 1.5 Mbits/sec bandwidth, which was not adequate to support remote operation of both telescopes (and their respective instruments) without some loss of observing efficiency. For example, certain pan and zoom operations on image displays would complete almost instantly if performed at the summit but would require several seconds when run remotely from Waimea. Such sluggish performance often increased the likelihood of operator error, effectively magnifying the loss in observing efficiency.[8] Despite such losses, the percentage of remote observations from Waimea grew steadily. Once the summit to Waimea link was upgraded to 45 Mbits/sec in 1997, these observing efficiency differences were essentially erased. As a result, remote operation from Waimea became the dominant mode of observing.

While the overall reliability and bandwidth of the Internet-2 path between Mauna Kea and the mainland is expected to be quite high and should approach the performance afforded by the Mauna Kea to Waimea link, the overall length, complexity, and security of these two paths is fundamentally different. The summit-to-Waimea path consists of a single segment that spans only a few tens of kilometers. It involves only a single provider (GTE/Hawaiian Telephone), and Keck directly controls the active network gear at each end. The entire link is private and therefore secure. If a connectivity problem develops, it should be relatively straightforward to isolate the source and assign responsibility for repair. If the failure is at the summit, there are already staff on site who can quickly swap in spare hardware, and if it is in Waimea, there are on-call staff who can respond.

4.2.2. Concerns regarding the wide area link

The Mauna Kea to mainland link is much longer and complex. It consists of several dozen segments that span three thousand kilometers, and few segments are backed up by redundant paths. It involves seven different network organizations, including UCO/Lick Observatory, UCSC Communications and Technology Services, CalREN-2, Abilene, DREN, UH, and Keck Observatory. If a connectivity problem develops, trouble shooting requires isolating the source, assigning responsibility, and correcting the fault. In the middle of the night, this could be a lengthy and difficult process.

While interruptions of the network between Mauna Kea and the mainland are likely to be very infrequent, given the length of the path and total number of active components involved, occasional interruptions are almost a certainty. The consequences of such interruptions for observers working from a mainland remote observing site can be severe, especially if the interruption lasts more than a few tens of seconds. Observers will be unable to operate the instrument or receive any telemetry from it or the telescope. They will also lose their video-conferencing connection to the summit and to Waimea. If the outage persists, network connections will time out and sessions will be disconnected. In the meantime, the remote observers will have little or no information regarding the source of the interruption or how long it will take to repair.

4.2.3. A backup data path

To protect against such interruptions, we are planning to install a backup data path between the remote observing room in Santa Cruz and the Keck Telescopes using dialed ISDN telephone lines. Network routers (Cisco 2600-series) containing both conventional ethernet and ISDN BRI interfaces will be installed at both sites. These routers will provide both inverse multiplexing and dial-on-demand capabilities for the ISDN lines. A generic routing encapsulation (GRE) [¶] tunnel will be established via the Internet-2 path between the two sites and will allow rapid detection of a loss of connectivity across that path. Such a loss will cause the tunnel to collapse, triggering the router in Santa Cruz to initiate ISDN connections to the companion router at the Mauna Kea summit. Once those connections are established, traffic between the two sites will be temporarily re-routed via the ISDN path. This entire process will occur automatically without any manual intervention required by staff at either site. Based on preliminary laboratory tests conducted by Cisco Systems, we estimate that traffic will be re-routed to the ISDN path within 15 seconds. Once connectivity via the Internet-2 path is restored, the routers will automatically re-establish the GRE tunnel and re-route traffic back to that path. The routers can be tuned to provide appropriate hysteresis so as to avoid excessive route switching in cases where the Internet-2 path is unstable.

While the backup ISDN pathway will provide significantly less bandwidth than the Internet-2 path, it will allow the remote observer to continue observing, albeit with significantly reduced efficiency. It will prevent the severe consequences and the feelings of helplessness and panic that observers would likely experience from a complete loss of network connectivity. We expect that most network interruptions will be relatively brief (e.g., comparable to the time required for a router reboot).

By providing a backup ISDN pathway directly between the remote observing room and the Keck summit, we hope to bypass outages that might occur anywhere along the Internet-2 path, including even those within our own building or the UCSC campus. Both the computing and video-conferencing equipment and the ISDN routers will be powered by an uninterruptible power supply to ensure that a loss of utility power does not interrupt remote observing.

We are currently planning to install three ISDN lines at each site, yielding an aggregate bandwidth of 384 Kbits/sec. Should it prove necessary, additional lines could be added. During normal remote observing, these lines

[¶] See RFC-1701 and RFC-1702 at http://www.faqs.org/rfcs would not be used, and would accrue long distance toll charges only during those times when Internet-2 connectivity was interrupted. The ISDN routers will attempt to minimize those charges by maintaining only as many connections as are needed to sustain the demanded bandwidth. During the daytime, these ISDN lines will be available to support ISDN-based video-conferencing to any sites to which IP-based conferencing is not available or practical. The fixed lease charges for the three ISDN lines at each site will cost about $4,000/year.

The ISDN backup data path also raises security issues. At the Keck summit, the ISDN router will be located outside the Keck summit firewall. The routers are equipped to utilize the caller I.D. feature provided by the telephone lines and will only accept ISDN connections from known sites. Calls will be initiated from the mainland to Mauna Kea. Under normal operation, the ISDN routers in Santa Cruz will not accept incoming ISDN calls.

5. SOFTWARE ISSUES

The software for remote observing can be organized in a number of different ways. Several different models have been explored to date:

1. All observing software runs at summit with X11 displays routed to Waimea and remote data access via NFS;
2. All observing software runs at summit but image data is relayed to remote site;
3. Components of the observing software are run both at the summit and the remote site

5.1. The Waimea model: remote X displays and NFS data access

The first model parallels the current mode of remote observing from Waimea. With this approach, the software applications used to conduct observations all run on summit machines, just as they would for observing at the summit. Because nearly all of the user interfaces for these applications are client applications of the X11 window system, their respective X displays can be re-directed to workstations anywhere on the network. In the infrequent case when observing is conducted on the summit, those X displays are directed to workstations in the summit control rooms. In the more common case of remote observing from Waimea, those same X displays are redirected to workstations in the appropriate remote operations room (See Fig. 1). Because a dedicated display host is used in either case, there is no significant difference between the summit and remote configurations and no noticeable difference in interactive performance when the remote site is nearby and connected via a high speed link.

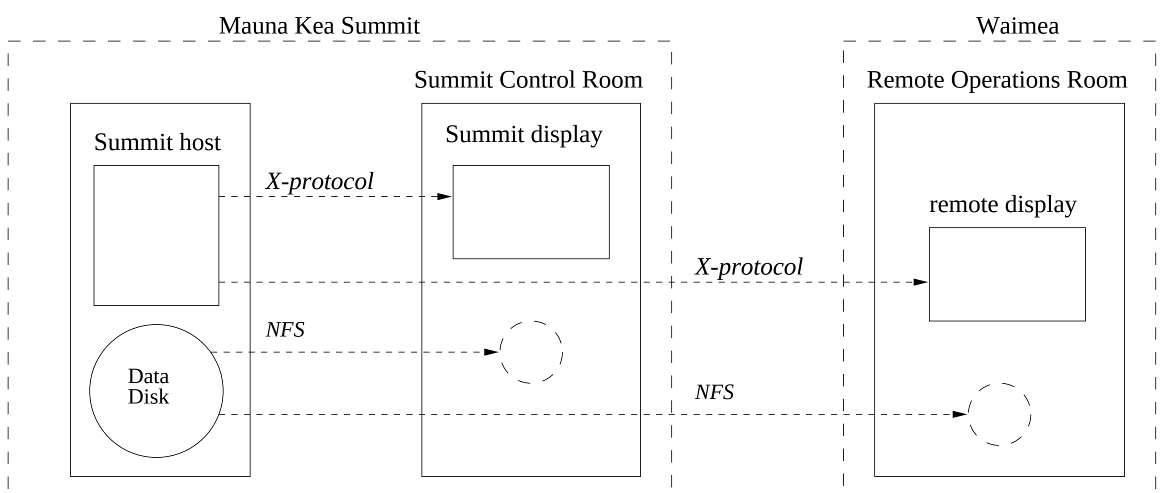

Figure 1. Summit/Waimea Configurations

The primary advantage of this approach is simplicity. No configuration changes or redistribution of software is needed to switch between summit versus remote observing. This approach also works equivalently well for all existing Keck instruments. Under this model, observational data is captured to disks on the summit. The contents of those disks are NFS-exported to the display workstations on the summit and in Waimea. Administration of these NFS-exports is straightforward because both the summit and Waimea workstations share the same set of user accounts and are centrally managed by the same staff.

5.1.1. Extending the Waimea model to the mainland

Based on the successful use of this model in Waimea over the last 3 years, one might reasonably imagine extending it to support remote operation from the mainland. While this can be done in theory, there are several practical problems that need to be addressed: bandwidth, propagation delays, security, and coordinated system management. Specific observing software applications are impacted by these problems in varying degrees.

The Keck autoguider software provides an excellent example of the range of problems that can arise when trying to extend the Waimea model of remote observing to the mainland. This software is used to display in real-time the images from an instrument's guide camera. It can also be commanded to save a guide camera image to disk to permit more detailed analysis. Depending on the binning, the size of the readout window and the integration time, the guide camera generates new images for display every 1 to 2 seconds. When an observer is acquiring an object and aligning it to the entrance aperture of an instrument, it is essential that the autoguider software updates its display at the same rate as the guide camera generates new images. Currently, when the X display for this software is directed to workstations on the summit or in Waimea, the display keeps pace with the camera. But when the X display is redirected to a workstation in California, an update typically requires between 8 and 9 seconds and the software quickly falls behind the camera.

5.1.2. Interaction of bandwidth and propagation delay

The magnitude of this degradation in performance could not be fully accounted for by the bandwidth of the existing link. At present, the link from Mauna Kea to the mainland is constrained by its narrowest segment, the 1.5 Mbit/sec link from Mauna Kea to Oahu. Under normal nighttime conditions, the bandwidth typically observed between Santa Cruz and Mauna Kea is approximately 55 Kbytes/sec (or 0.44 Mbits/sec). Each autoguider display update requires transmission of approximately 256 Kbytes of image data (uncompressed) and would thus require about 4.8 seconds to transmit to Santa Cruz given the typical link bandwidth. Yet the observed autoguider update rate was nearly twice as slow.

Analysis of the actual packet traffic confirmed that nearly half of the performance degradation was due to a series of 38 separate X transactions between the X client software in Hawaii and the X server in Santa Cruz. These transactions, which involved unnecessary queries of the X server rather than transfer of the image, each required a separate round-trip between the client and server software. When the client and server are both running on machines on the summit, this round-trip time is 1 millisecond or less, so that the total time for all the transactions is at most a few tenths of a second. This is also true when the X server is running in Waimea, because the round-trip time only increases to between 1 to 2 milliseconds. But when the X server is running in California, due to the increased path length and increased number of nodes through which the packets flow, the round-trip time increases nearly 100-fold to about 100 milliseconds. As a result, those same 38 transactions now consume 3.8 seconds of time per update, which accounts for the remainder of the performance degradation.

Thus, it is important to consider both link bandwidth and propagation delay in determining whether an existing X application will perform adequately if its X display is redirected to the mainland. While the bandwidth of the overall link will improve when the Oahu to Mauna Kea link speed is increased to 45 Mbits/sec later this year, the propagation delay will remain essentially unchanged. In order for the guider software to perform adequately even over the higher speed link, it will need to be revised so as to eliminate all unneeded round trip transactions between the X client and server. Because of the large, fixed propagation delays between Hawaii and the mainland, one cannot assume that an existing summit application that performs well when its X display is directed to Waimea will perform adequately when displayed to an X server on the mainland, even if a high speed link connects the two sites.

Large propagation delays can also degrade performance for other types of TCP-based applications running over high speed networks. This degradation can be particularly acute over links employing geostationary communications satellites where the end-to-end paths between ground stations via the satellite may exceed 70,000 kilometers. For some types of applications (e.g., bulk transfer of large files), such degradation can be reduced or eliminated by appropriate tuning of TCP-protocol parameters such as the TCP window size.[9]

5.1.3. Security and systems-related issues

Security is another problem that arises when trying to extend the existing Waimea remote observing model to the mainland. Because mainland machines are not under the same system management nor within the same security domain as the machines at Keck, the mechanisms currently employed at Keck to allow shared NFS access between the disks on the summit and those in Waimea cannot be used for shared access with the mainland. While distributed file systems and virtual private networks address many of these concerns, both require a high level of investment, system support, and coordination.

Fortunately, some of these security issues can be addressed rather inexpensively using the secure shell (ssh) protocols.[12] The ssh protocols provide a secure and transparent mechanism that permits forwarding of X protocol traffic to and from the remote site via the same secure connection over which the remote login connection was established. This secure login mechanism relieves the user of the need to manually reset their X display variable and also secures the X protocol transmissions. These secure shell methods have been used extensively for these purposes between the summit and Santa Cruz. During our mainland remote observing experiments of the past year, ssh has provided a secure means for redirecting X displays and copying image data to mainland sites. When invoked with its compression option enabled, ssh has also allowed more effective utilization of the currently limited link bandwidth. For typical autoguider camera images, ssh compression yields nearly a 3-to-1 compression of the image sent to the remote X display, thus reducing the transmission time by a factor of 3.

The workstations at Keck and on the mainland are separately managed by different staffs with only minimal coordination between sites. As a result, the X servers, font servers, and window managers running at each site are likely to be at different revision levels and may thus exhibit subtle differences in how a particular display is rendered. While closer coordination between sites would certainly be advantageous, resource limitations at both currently preclude this.

In summary, while the Waimea software model of remote observing can in principle be extended to the mainland, it will require more than just the currently planned upgrades to link bandwidth. A mechanism such as secure copy (scp) will need to be used as an alternative to NFS for shared data files. Software applications (such as the autoguider display software) which are sensitive to propagation delays will need to be modified so as to eliminate any unnecessary round trips between X client and server.

5.2. Relay of image data files to remote site

In a number of cases a mainland remote observer has simply wanted to collaborate with other observing team members who are conducting observations from Waimea. Rather than needing to control the instrument remotely, the mainland observer simply wishes to eavesdrop on the progress of the observations by reviewing the data as it is collected. To support this "eavesdrop" mode of operation, a software suite known as *shadowmon* was developed in 1996 at Santa Cruz.[5] It has been used successfully from several sites across the U.S. While this method has proven effective, it requires deployment of custom software to remote sites, which can be problematic.

Under this model, a client program running on the summit automatically detects whenever new image data is written to disk by either the instrument software or the autoguider software. The client copies any new images to a local spool area, compresses them using *fcompress*,[13] and queues them for TCP-based transmission to a server program running at the mainland site. The server program receives the compressed data, decompresses it into a disk file at the remote site, and alerts the remote observer about its arrival. Given the existing constraints on bandwidth between Mauna Kea and Oahu, this entire process typically takes 3 minutes or less (from the time the image is written to disk on the summit) to transfer to the remote site the 8 to 9 Mbyte images produced by the first generation Keck optical instruments.

In 1999, an alternate version of *shadowmon* suite was implemented using the compression-enabled secure copy (scp) component of the ssh software suite. This version results in even more efficient transfer of images over the existing network since the compression and decompression of the image occurs on the fly and is thus overlapped with transmission. Under equivalent network conditions, total transfer time for comparable sized images is reduced by up to a factor of three.

5.3. Running observing software components at both sites

The user interface and image display clients for the Keck Telescopes and instruments are separate X client applications that could be run directly on hosts at the mainland site. In some cases this may provide more rapid interactive response since both the X client and server run on the same host. Software support staff in Santa Cruz find this mode of operation to be invaluable for impromptu instrument engineering and troubleshooting from home over 56 Kbaud modem lines. Unfortunately, these applications use many different communications protocols (e.g., channel access, remote procedure call, etc.) to exchange control, status, and image traffic with the telescope and instrument control software that runs at the Keck summit. As a result, redirecting this traffic to the mainland requires different solutions for different instruments and is significantly more complex and less general than the redirection of X displays employed under the Waimea software model. This approach creates additional software configuration management tasks, since client software at the mainland site must be kept in sync with the versions run at Keck. It also raises additional security concerns that currently make this mode of operation infeasible for anything other than engineering or trouble shooting purposes. In the future, once a more widely-deployed public key infrastructure is in place, this mode of operation could be made more generally available by re-implementing the underlying communications protocols using Transport Layer Security (TLS) as outlined in RFC 2246.

6. RECENT OPERATIONAL EXPERIENCE

Our partially-completed Keck remote observing facility in Santa Cruz was used for remote engineering and commissioning of the Echellette Spectrograph and Imager (ESI) on Keck II.[3] IP-based video conferencing was successfully used between Waimea and Santa Cruz to coordinate between the commissioning team members at each site. We ran most observing software clients at the summit with X displays redirected both to Waimea and to the mainland via a compression-enabled ssh tunnel. Automated relaying of image data to the mainland site via the compression-enabled scp version of shadowmon proved to be an effective and secure alternative to NFS (See Fig. 2).

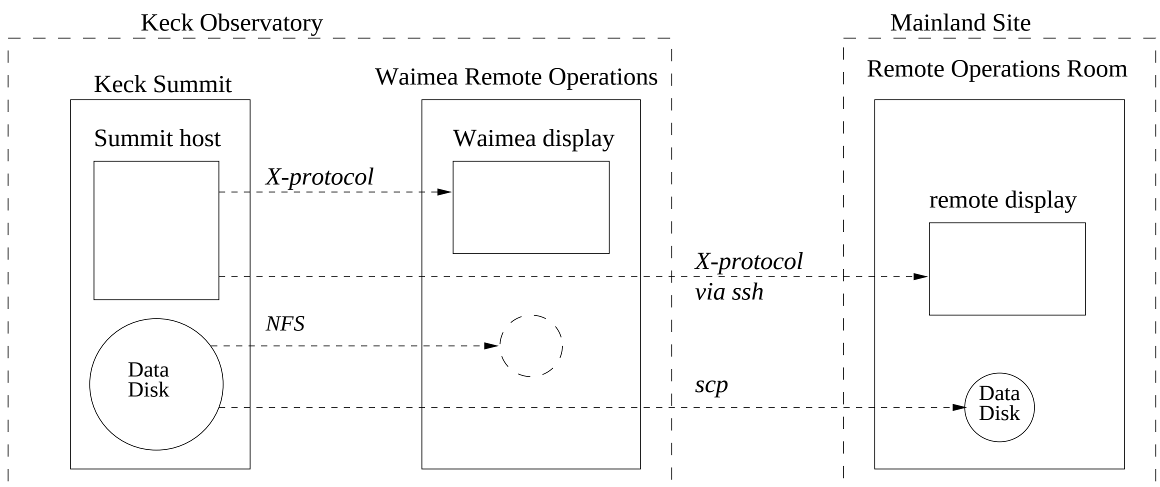

Figure 2. Summit/Waimea/Mainland configurations

The one area in which the mainland operation was noticeably slower than operating from Waimea was during the initial start up. When the X displays of summit clients were directed to the mainland, software start up took several minutes longer than when they were directed to Waimea. Since this start up is performed several hours before observing commences, this was not a serious problem. Once the start up was complete, subsequent interactive performance was quite good. Although we have not yet analyzed packet traffic to confirm this, it appears that the initial instantiation of X displays involves a significant number of round trip exchanges between the X client and server.

7. REMAINING CHALLENGES

Within the next few months, the Santa Cruz facility will begin supporting Keck remote observing as an extension of the Waimea facility. While most of the technical hurdles involving software and high speed networks have been overcome, significant administrative, operational, procedural, and policy issues remain to be worked out. The resolution of these issues will require significant collaboration, cooperation, and negotiation between Keck and the respective mainland institutions. Several months of trial operations will be needed to identify the most critical operational issues and evolve optimal solutions. During this period, the Santa Cruz facility will be operated on a shared-risk basis.

In order for our proposed model for mainland remote operations to succeed, we must ensure that the astronomer on the mainland, the instrument specialist in Waimea, and the observing assistant on the Mauna Kea summit all have a consistent and sufficiently complete view of the instrument, the telescope, and each other. Ideally, we would like them to be able to collaborate as effectively and efficiently as if they were in the same room. While that is probably not possible, we need to provide cost-effective tools that will enable them to approach that ideal.

Accordingly, we need to optimize the video conferencing arrangements to ensure that communication is clear and convenient. As enhanced Internet capabilities such as quality of service (QoS) become more widely supported, we need to apply these to our IP-based video conferencing systems to optimize performance. While we have considerable experience with dedicated point-to-point video conferencing between Mauna Kea and Waimea and more limited experience with IP-based video conferencing between Waimea and the mainland, we do not yet have the hardware to explore the capabilities and limitations of multi-site conferencing via multi-point controllers (MCU). Determining the optimal arrangements for MCU configuration, operation and management will require further study and experimentation.

In the interim, we have successfully used a low-tech, low-budget solution to the problem of multi-point conferencing between Mauna Kea, Waimea, and a mainland site. Currently, a separate, dedicated, point-to-point video conferencing system connects each Waimea remote operations room with its corresponding summit control room. A different, portable, IP-based video conferencing system has been used to link Waimea to the mainland. Thus, there can be two separate video conferencing systems (one for the summit, one for the mainland) in a given Waimea control room, each with its own camera and monitor. By remotely steering the camera from one system so that it points at the monitor from the other (and vice versa), the mainland observer can conference with the observing assistant at the summit. At the same time, the instrument scientist in Waimea can both watch and listen to their exchange, and can be heard (although not directly seen) by the other two participants. Although not ideal, this daisy-chained mode of operation has proven quite effective, and was used extensively during ESI instrument commissioning.

We also need to provide software tools so that the instrument scientists in Waimea and the observing assistants on the summit can best support the remote observer on the mainland. Fortunately, nearly all of the user interfaces for Keck telescope and instrument software allow copies to be run simultaneously from multiple sites, so that the observer, OA, and IS all have a consistent view of and similar abilities to operate the instruments. However, when a mainland observer encounters difficulties in operating the instrument, it is often helpful if the support staff in Hawaii can see precisely what is being displayed on the observer's workstation monitor and observe what sequence of operations is being attempted. In many cases, we have been able to accomplish this by remotely steering the video conferencing camera to peer at the observer's monitor.

The use of collaborative software environments, such as Virtual Network Computing (VNC) [‖], provides a more precise and effective method of remotely observing the remote observer's interactions with the observing software. VNC allow users at different sites to share a common, virtual software desktop. All users connected to that virtual desktop see the identical environment, and can interact with it equally via their respective keyboards and mice. VNC will allow support staff in Hawaii to not only observe the remote observer's interactions but to help guide them by example. Using VNC, support staff can effectively type and move the mouse on the remote observer's screen so as to illustrate the correct procedures for operating an instrument. However, running VNC involves considerable computational and network overhead, so it will most likely be used for remote teaching and troubleshooting rather than for routine operations. Because of the nature of the virtual desktop, the native VNC applications represent a potential security hole. However, with appropriate ssh encapsulation, VNC can be run securely.

8. CONCLUSION

While operation from Waimea will continue to provide advantages for longer duration observing runs, remote operation from the mainland should provide significant reductions in travel costs and travel time for short-duration runs. The extent to which it reduces overall costs remains to be seen. In the case of telescopes and instruments in Chile that were remotely operated from a European Southern Observatory (ESO) facility in Germany, the costs of a dedicated satellite communications channel plus the costs of providing on-site instrument specialists at the remote facility effectively cancelled out any savings in travel costs.[14] By avoiding the high costs of a dedicated communications channel and leveraging the existing investment in Waimea facilities and staff, the Santa Cruz facility should yield a net reduction in overall costs. Over the long term, oil prices and travel costs are likely to continue to climb, while advances in optical communications technologies should cause communications costs to fall. Those trends should make mainland remote observing an increasingly cost-effective option.

[‖] See http://www.uk.research.att.com/vnc/index.html and http://www.uk.research.att.com/vnc/sshvnc.html

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REFERENCES

1. P. J. G. Forster, "Health and work at high altitude: a study at the Mauna Kea observatories," *Publications of the Astronomical Society of the Pacific* **96**, pp. 478–487, 1984.
2. T. Boroson, J. Davies, and I. Robson, eds., *New Observing Modes for the Next Century*, vol. CS-87, Astronomical Society of the Pacific, San Francisco, 1996.
3. R. I. Kibrick, J. S. Miller, J. E. Nelson, M. V. Radovan, A. I. Sheinis, and B. Sutin, "Active flexure compensation software for the Echellette spectrograph and imager on Keck II," in *Advanced Telescope and Instrumentation Control Software*, H. Lewis, ed., *Proc. SPIE* **4009**, 2000.
4. S. S. Vogt *et al.*, "HIRES: The High Resolution Echelle Spectrometer on the Keck Ten-Meter Telescope," in *Instrumentation in Astronomy VIII*, D. L. Crawford, ed., *Proc. SPIE* **2198**, pp. 362–375, 1994.
5. R. Kibrick, A. Conrad, J. Gathright, and D. Tucker, "User Interface and Control Software for the HIRES Image Rotator on Keck-1," in *Telescope Control Systems II*, H. Lewis, ed., *Proc. SPIE* **3112**, pp. 187–198, 1997.
6. R. Kibrick, A. Conrad, and A. Perala, "Through the Far Looking Glass: Collaborative Remote observing With the W. M. Keck Observatory," *ACM Interactions* **5**(3), pp. 32–39, May-June 1998.
7. J. B. Oke *et al.*, "The Low Resolution Imaging Spectrometer for the Keck Telescope," in *Instrumentation in Astronomy VIII*, D. L. Crawford, ed., *Proc. SPIE* **2198**, pp. 178–184, 1994.
8. A. R. Conrad, R. Kibrick, and J. Gathright, "Remote Observing with the Keck Telescopes," in *Telescope Control Systems II*, H. Lewis, ed., *Proc. SPIE* **3112**, pp. 99–110, 1997.
9. J. Cohen, P. Shopbell, and L. Bergman, "Remote Observing with the Keck Telescope Using the ACTS Satellite," in *Final Report for NASA Grant BK-509-20-42-00-00*, pp. 1–22, March 1, 1998.
10. D. Lassner, "Hawaii High Performance Internet Connection," in *NSF Award ANI-9876406*, pp. 1–15, March 15, 1999.
11. D. Lassner, "Revised Engineering Plan Hawaii High Performance Internet Connection University of Hawaii," in *NSF Award ANI-9876406*, pp. 1–4, May 31, 1999.
12. A. Carasik, *UNIX Secure Shell*, Osborne McGraw Hill, Berkeley, 1999.
13. J. Percival and R. L. White, "Efficient Transfer of Images over Networks," in *Astronomical Data Analysis and Software Systems II*, R. J. Hanisch, R. J. V. Brissenden, and J. Barnes, eds., *ASP Conference Series* **52**, pp. 321–325, 1993.
14. A. A. Zijlstra, A. Wallander, L. Kaper, and J. A. Rodriguez, "Remote Observing at the ESO NTT and CAT Telescopes," *Publ. Astro. Soc. of the Pacific* **109**, pp. 1256–1263, November 1997.