Optimizing interactive performance for long-distance remote observing

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ABSTRACT

Remote observing is the dominant mode of operation for both Keck Telescopes and their associated instruments. Over 90% of all Keck observations are carried out remotely from the Keck Headquarters in Waimea, Hawaii (located 40 kilometers from the telescopes on the summit of Mauna Kea), and this year represents the tenth anniversary of the start of Keck remote observing from Waimea. In addition, an increasing number of observations are now conducted by geographically-dispersed observing teams, with some team members working from Waimea while others collaborate from Keck remote observing facilities located in California. Such facilities are now operational on four campuses of the University of California and at the California Institute of Technology.

Details of the motivation and planning for those facilities and the software architecture on which they were originally based are discussed in several previous reports.[1–5] The most recent of those papers reported the results of various measurements of interactive performance as a function of alternative networking protocols (e.g., *ssh*,[6] *X*,[7] VNC[8]) and software topologies.

This report updates those results to reflect performance improvements that have occurred over the past two years as a result of upgrades to hardware, software, and network configurations at the respective sites. It also explores how the Keck remote observing effort has evolved over the past decade in response to the increased number and diversity of Keck instruments and the growing number of mainland remote observing sites.

Keywords: remote observing, *X* protocol, VNC protocol, *ssh* protocol

1. INTRODUCTION

We provide here a brief overview of the Keck remote observing facilities in Waimea and California.

1.1. Remote Observing from Keck Headquarters in Waimea

Most observations with the Keck telescopes are now carried out from one of the two remote operations rooms located at Keck Headquarters in Waimea (see Fig. 1). The workstations in these rooms communicate with instrument and telescope control computers at the summit via a dedicated, 45 Mbit/sec fiber link (See Fig. 3).

The observer is supported by an observing assistant (OA), who operates the telescope, and a support astronomer (SA), who assists the observer in setting up and operating the instrument. During the first part of the night, an SA is present in the remote operations room and during the latter part an on-call SA 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 video-conferencing system links each remote operations room in Waimea with its corresponding telescope control room at the summit.

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Figure 1. Keck remote operations room in Waimea

Figure 2. Santa Cruz remote observing room

1.2. The Keck Remote Observing Facilities in California

The remote observing facilities in California (e.g., see Fig. 2) are primarily targeted towards observers scheduled for short-duration observing runs and who live within commuting distance of one of those facilities.[2] They are not intended to duplicate the Waimea facility nor to operate independently of it. Rather, each is an extension of the facility in Waimea. That facility and those on the mainland are intended to operate in collaboration, sharing resources where practical. We rely on the existing instrument support staff at Waimea and provide video-conferencing and shared software environments so that they can most effectively support the observers at the mainland sites.

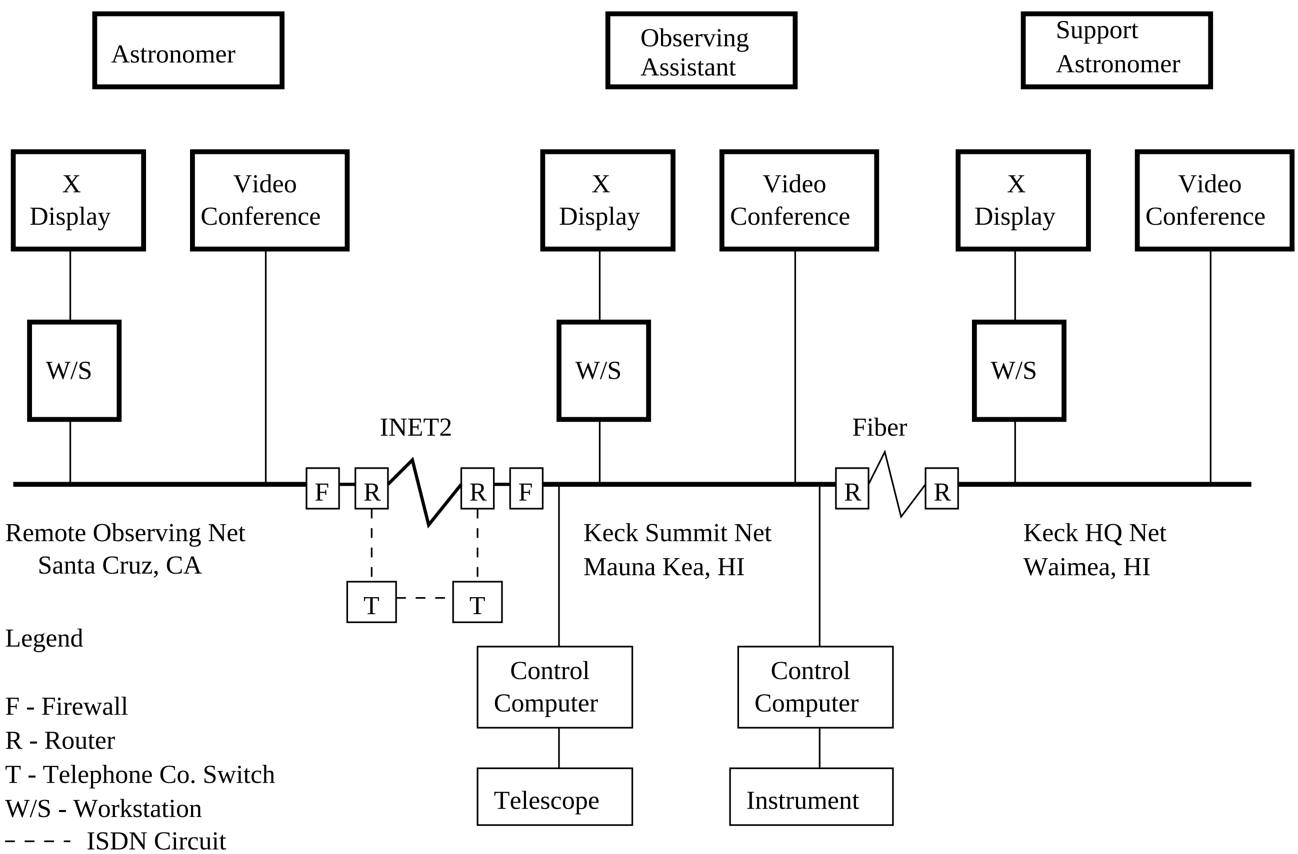

Figure 3. Global overview of connectivity between Santa Cruz, Mauna Kea, and Waimea

Communication between the sites is provided via the Internet-2 (INET2) network (see Fig. 3). However, each California remote observing site is also equipped with a series of dialed ISDN circuits that provide an alternate link to the Keck summit. In the event of a loss of Internet connectivity, remote observing traffic automatically fails over onto this ISDN backup path, and automatically falls back once Internet connectivity is restored.[3]

2. HISTORY

The objectives of the Keck remote observing effort have evolved gradually over the last decade in response to improvements in computing and networking technology and to the growing expectations of the Keck remote observing community.

Initial development efforts were undertaken by Keck Observatory staff and were primarily driven by the goal of moving observers off of the oxygen-starved Mauna Kea summit and enabling them to observe with greater safety and efficiency from a nearby facility located at a lower altitude.[9] The Keck I remote operations room in Waimea became operational in 1996, and the corresponding room for Keck II (see Fig. 1) came online the following year.

Subsequent efforts to extend this remote observing capability to mainland sites were undertaken by researchers at the University of California Santa Cruz (UCSC)[1] and the California Institute of Technology (CIT).[10] A key motivation for those efforts was to reduce the travel time and costs associated with short-duration observing runs.[2] The remote observing facility at UCSC became fully-operational in 2001, and served as the model for similar facilities that came online at CIT and at other UC campuses during the next five years (see Table 1).

Table 1. Keck Observatory remote observing sites

Number	Name	Location	First use
1	Remote ops 1	Waimea, Hawaii	1996
2	Remote ops 2	Waimea, Hawaii	1997
3	UCSC	Santa Cruz, California	2001
4	UCSD	San Diego, California	2003
5	CIT	Pasadena, California	2004
6	UCB (LBNL)	Berkeley, California	2005
7	UCLA	Los Angeles, California	2006

2.1. Administration

In terms of administration, Keck Observatory sets the overall policy under which remote observing from the mainland is permitted*, and Keck Observatory staff provide central coordination for the approval of remote observing requests and the scheduling of any needed facilities and resources. Otherwise, there is currently no other centralized management of the mainland remote observing facilities; rather, they are only loosely bound together into an informal collaborative enterprise.

Each site has its own independent computer system and network management, and local administrative policies vary between sites. For the most part, the mainland remote observing sites do not have any local staff that are specifically allocated to provide operational support for those facilities, but instead rely on departmental staff to pitch in as needed. While these arrangements are not ideal and have increased the difficulty of bringing each new mainland remote observing site online, they reflect current realities and impose significant design constraints which are reflected in our model for remote observing. That model attempts to minimize the amount of non-generic software that needs to be installed and maintained at each remote site and to minimize the overall level of local support that is needed for each such site to operate.

*For details, please see: http://www2.keck.hawaii.edu/inst/common/mainland_observing.html

2.2. The Keck Remote Observing Model

Keck adopted its existing remote observing model[1] in 1996, and for the past decade it has provided the foundation for all of the Observatory's remote observing efforts. The model is based on two fundamental principles:

1. All instrument control applications (including user interfaces) run on summit control computers
2. The displays generated by those applications are re-directed to the remote observing sites (See Fig. 3).

Although the specific mix of protocols used to provide that re-direction has evolved over the past ten years, the basic structure of that model remains unchanged.

2.3. Performance Goals and Progress

For both the remote observing facilities in Waimea and those in California, a primary goal is to provide the observer with a similar range of observing capabilities, a similar "look and feel", and a comparable level of interactive performance to what was provided at the Keck Telescope control rooms on the Mauna Kea summit. (A related goal for the mainland observing sites is to minimize any negative impact that such mainland operations might impose on the efficiency of operations in Hawaii, either in Waimea or at the summit.)

While the Waimea facility was able to achieve that primary goal early on, meeting that goal from the facilities in California has proved much more challenging, primarily due to network latency and tuning issues.[5] It is only in the past year that both the "look and feel" and the level of interactive performance provided at the mainland sites have become nearly comparable to what is provided in Waimea.

Our current operational approach for conducting remote observations from California is the result of an iterative evolutionary process. Initial strategies provided inadequate performance with the then-available computer and networking technology. When tested a year or two later using more advanced hardware and software the same strategies delivered satisfactory results.

3. CURRENT DIRECTIONS AND STATUS

Our 2004 paper[5] compared measurements of the interactive performance delivered by the *X* and VNC protocols for typical remote observing functions. At that time, we determined that neither protocol, by itself, provided a satisfactory solution for all Keck observing applications displayed to remote observing sites in California. In particular, while the *X* protocol delivered significantly better interactive response for most functions provided by image display applications such as *ds9*, VNC protocol delivered superior response for those applications that either create many new windows or which perform other window operations that are sensitive to high latencies between the *X* client application and the *X* server on which the output from that application is displayed. Based on those results, our earlier procedures for Keck remote observing from the mainland sites have employed a somewhat cumbersome mix of both protocols.

In the intervening two years, the Keck remote observing landscape has changed significantly with regard to the hardware and software now in place. Much faster computers (e.g., 1.28 GHz UltraSPARC-IIIi vs. 400 MHz UltraSPARC-II processors) have been installed at the Keck summit, where both the observing client applications and VNC servers are run, as well as at many of the remote observing sites. Over the same period, newer versions of both *ssh* (*OpenSSH* version 4.2p1) and VNC software (version 3.3.7) have been installed, and tuning of TCP window size parameters has been optimized (e.g., increased by factors of 8 to 32) for the high latency of the Mauna Kea to California network path. In addition, network bandwith on the limiting segment (Mauna Kea to Honolulu) has been increased. Together, these changes have significantly improved the interactive performance that the VNC protocol provides for Keck observing applications so that it now equals or exceeds the performance provided by the *X* protocol.

As a result, we are now in the process of migrating our mainland remote observing procedures towards the exclusive use of the VNC protocol (encapsulated within *ssh* tunnels) to provide remote access to the observing application software that runs at the Keck summit. This not only provides improved interactive performance over our previous approach, but also enables the mainland sites to approximate more closely the "look and feel" of remote observing from Waimea. In addition, it helps address other operational concerns (see Sect. 4.3).

4. A VNC-BASED APPROACH

Regardless of whether they are observing from the Keck summit, from Waimea, or from a remote observing facility on the mainland, observers are accustomed to operating Keck instruments while seated at a local workstation equipped with at least three monitors (see Figs. 1 and 2). Typically, these monitors are allocated to displaying the user interfaces and image displays associated with the selected instrument, and a fourth monitor (usually attached to a second workstation) is used to display the real-time images from the guide camera, plus the status and meteorological displays provided by the Observatory's telescope and dome control systems.

4.1. Observing only from Waimea

Currently, if the entire observing team is working from Waimea, then the *X* displays generated by the observing client applications (running on the given instrument's control computer located at the summit) will be re-directed to the *X* servers associated with the three monitors where the observers are seated. At present, after logging into the local workstation, a member of the observing team starts up the instrument software by selecting entries from pull-down menus that are served by the local virtual desktop. Each entry in those desktop-level menus remotely invokes a corresponding startup script on the relevant instrument control computer on the summit.

For its remote operation rooms, Keck has standardized on Sun/SPARC workstations running the Solaris operating system and using Sun's OpenLook virtual window manager (*olvwm*) to manage the desktop. At present, observers start and stop the various components of the instrument software using the desktop-level pull-down menus that are served by *olvwm* and are defined within its .openwin-menu file. However, since Sun no longer supports *olvwm*, Keck will soon be replacing it with the *fvwm2* virtual window manager.[11]

As part of that conversion, these instrument-related menus will no longer be served by the window manager (even though *fvwm2* is capable of doing so), but will instead be served by the *instr_menu* widget, a *Tcl*-based GUI which runs on the instrument control computer and which parses menu configuration files similar in format to those currently used by *olvwm*. This GUI, served by the instrument host, will launch on the local desktop upon login to the workstation[†]. Only generic functions (e.g., opening local xterms or manipulating the window manager) will remain within the pull-down menus served by the window manager.

4.2. Shared observing between Waimea and mainland site(s) using VNC

If some or all of the members of the observing team will be working from a mainland remote observing site, then an additional step is inserted in the process of starting up the instrument software. After logging into the local workstation in Waimea, a member of the observing team (or the Keck support astronomer, if all observing team members are working from a mainland site) invokes a VNC[‡] startup script on the local workstation which:

1. Remotely starts up on a VNC server host located at the Keck summit:
   - (a) Three 8-bit VNC servers (e.g., :1, :2, :3) and three 24-bit servers (:6, :7, :8) for instrument displays
   - (b) One 8-bit and one 24-bit VNC server (e.g., :4 and :9) for guider, telescope/dome, weather, and adaptive optics displays
2. Starts on the local workstation six VNC viewers such that:
   - (a) On each of the three local monitors, one 8-bit and one 24-bit VNC viewer is displayed, with each viewer residing within a separate window pane of the local virtual desktop
   - (b) Each VNC viewer connects to its respective VNC server on the VNC server host at the summit

[†]Once the conversion from *olvwm* (and the use of its desktop-based menus) to *fvwm2* (and the *instr_menu*-based menus) is completed on the workstations in Waimea, the *xstartup* script for these VNC servers will be updated to replace *olvwm* with *fvwm2* and to launch an *instr_menu* widget on the VNC shared desktop when each VNC server is started.

[‡]Virtual Network Computing (VNC[8]) is a thin-client system in which a generic VNC client (the VNC viewer, with which the user interacts) offers remote access to a sharable virtual desktop provided by a VNC server; multiple VNC viewers can connect to a single, shared VNC server, and all such viewers provide comparable views of and access to that desktop. VNC servers can offer either 8-bit of 24-bit *X* visuals, but unlike modern X servers, cannot offer both simultaneously.

At the end of this process, each of the VNC viewers that appear on the three local monitors in Waimea will be displaying the shared VNC desktop that is served by the respective VNC server to which that VNC viewer is connected. Since we require those VNC servers to run the same window manager (either *olvwm* or *fvwm2*) and use the same desktop (or *instr_menu*) menu-definition file as is used on the local workstation in Waimea, the shared VNC desktop and the desktop-level (or *instr_menu*) menus that each VNC server presents to the user will appear the same as those provided by the local desktop in Waimea. Accordingly, from this point on, the user can start up the instrument software using the appropriate entries from the desktop-level (or *instr_menu*) pull-down menus (i.e., the ones provided by the VNC shared desktop) using the same procedure as described in Sect. 4.1 above. The only difference is that on each screen, the 8-bit X applications will be displayed in the virtual window pane holding the 8-bit VNC viewer and any 24-bit applications in the pane holding the 24-bit VNC viewer.

The members of the observing team on the mainland follow a similar process to the one used in Waimea. After logging into the local workstation at the mainland remote observing facility, a member of the observing team there invokes a script on the local workstation that functions much the same as the one just described. The only difference is that the script at the mainland site contains an additional step that establishes, for each VNC viewer at the mainland site, an *ssh*[6] port-forwarding tunnel. Those tunnels enable each VNC viewer to connect (across the various network firewalls) to its respective VNC server on the Keck summit VNC server host. At the end of that process, each of the VNC viewers that appear on the local monitors at the mainland site will be displaying the same shared VNC desktop as displayed on the corresponding monitor of the local workstation in Waimea.

This same process can be repeated at additional mainland sites as needed to support multi-site observing teams. All members of the observing team who are working from any mainland remote observing facility have the same view of and access to these six shared VNC desktops as do the Keck support astronomer in Waimea and any members of the observing team who are working from Waimea. A similar set of scripts is provided on the second workstation (the one whose monitors are used to display guider images, telescope/dome status, etc.) at each site. Those scripts start up a pair of VNC viewers on the monitor attached to that workstation and connect those viewers to the shared VNC desktops (:4 or :9) on which these telescope-related applications are displayed.

4.3. Advantages

There are a number of advantages to this VNC-based mode of remote observing. First, because all sites share the same virtual desktops, more effective collaboration is possible, both between the observing team members at each site, and between the team and the Keck support astronomer in Waimea. The shared desktops enable all members of the observing team, regardless of where they are located, to have an identical view of the instrument status and the data it produces. In addition, it enables the observers at each site to see the actions taken by the observing team members at all of the other sites. In particular, it greatly facilitates the ability of the support astronomer in Waimea to provide remote support to observing team members operating from the mainland. It also enables a support astronomer to troubleshoot problems more effectively from home.

Second, it simplifies training, because observers interact with the Observatory's software and with the instrument in much the same manner, regardless of whether they are observing from Waimea or from the mainland. Third, it provides the observers on the mainland a more unified and less confusing operating environment as compared to our prior mix of VNC viewers and remote X displays. Fourth, it provides much more rapid startup of remotely-displayed applications, reducing the startup time for applications such as *ds9* from over a minute to just a few seconds. Fifth, it provides efficient shared access to all applications, including those legacy applications which permit only a single instance to be run. Sixth, it eliminates font mismatch problems between sites, since all fonts are served from the hosts at Keck, and that is especially important given the decentralized nature of the systems administration of our mainland remote observing sites. Lastly, because VNC viewers can be switched into and out of a *viewonly*[§] mode, and because each monitor runs its own VNC viewer, that mode can be selected on a screen-by-screen basis, thus enabling sites to disable active control on some screens but not others.

[§] In *viewonly* mode, the VNC viewer displays all of the graphics and user activity that occurs within the shared VNC desktop served by the VNC server to which that VNC viewer is connected, but the viewer ignores any input from the local keyboard and mouse and does not relay any such input to that VNC server. Thus, when operated in this mode, the VNC viewer can display the shared desktop but cannot alter it.

4.4. Disadvantages

While the shared virtual desktops that VNC provides promote collaboration between sites, they also have the potential to create confusion and conflict between those sites if they aren't working in close communication with each other. This potential for conflict exists whenever multiple sites have a VNC viewer connected to a common VNC server and more than one site is operating their respective VNC viewer with the *viewonly* option disabled. In such cases, if observers at two (or more) sites attempt to enter keyboard input at the same time, their respective keystrokes will be interleaved if the local window focus at each of those two sites is currently selecting the same shared desktop. Similar problems can arise if observers at multiple sites simultaneously attempt to move their respective mice when such mice are both pointing within the same shared desktop.

In practice, observers appear to adapt their behavior rather quickly so as to avoid such conflicts. The fact that all of our remote observing sites are linked together via video-conferencing systems is of critical importance in enabling observers to closely coordinate their activities via both verbal and visual cues. In addition, observers who are primarily interested in passively watching the observing activity (rather than actively controlling it) can switch their VNC viewers to *viewonly* mode and thus avoid any unintended interference (e.g., as might occur if they accidentally bump their mouse) with the actions being commanded from the other sites.

Because each monitor of our multiple-monitor arrangement runs a separate VNC viewer that is connected to a distinct VNC server, the various sites are sharing multiple desktops rather than a single one. Accordingly, conflicting keyboard and mouse actions are avoided so long as multiple sites are not attempting to work within the same shared desktop at the same time. Thus, an observer at one site might be responsible for instrument configuration activities that are carried out via the shared desktop that is displayed on the leftmost of the three monitors, while an observer at another site would be responsible for image processing activities that are performed via a different shared desktop that is displayed on the rightmost monitor. So long as both observers work within their respective shared desktops, both can work at the same time without interfering with the other, yet both can watch in real-time what the other is doing.

A separate concern that some observers have raised with this VNC-based approach is that each VNC viewer fills each screen, thus hiding the local desktop and making it less convenient to access resources (e.g., reading email) from the local workstation. This concern is addressed by running a virtual window manager for the local desktop, configuring it so that its pager window is always displayed on top, and then locating the VNC viewer (and hence the shared virtual desktop that it displays) within one virtual window pane of that local virtual window manager. This arrangement enables an observer to switch rapidly between the shared virtual desktop and the local desktop simply by switching between the virtual window panes served by the local virtual window manager. Different background colors are used for the local desktop and the shared virtual desktop so that the observer is given a very strong visual cue as to which desktop is currently selected. An alternative solution is to operate the frame buffer and monitor at a higher resolution than that of the shared desktop so that it no longer fills the screen, thus enabling access to the shared desktop and a portion of the underlying local desktop at the same time.

4.5. Bit-depth complications

The X-based applications used at Keck Observatory to control both the instruments and the telescopes to which they are attached were developed, over a period of 15 years, by different groups at several different institutions using a variety of different software tools. Accordingly, there is significant variation in the graphics capabilities that these applications require. Much of the legacy X-based software used to operate the telescopes and the first generation instruments was developed with earlier versions of the X protocol. As a result, such applications can only be displayed on an X server (and associated frame buffer) that offers an 8-bit pseudocolor visual as the default visual; however, much of the software for the second generation Keck instruments requires X servers (and frame buffers) that offer 24-bit truecolor visuals. Since the legacy software is unlikely to replaced or upgraded in the foreseeable future, support for both visual classes will continue to be needed for quite some time.

Similarly, some of the older frame buffer hardware installed in workstations at the Keck summit, in Waimea, or at the mainland remote observing sites only offer 8-bit pseudocolor visuals, while others offer only 24-bit truecolor. Fortunately, more modern frame buffers and X servers are able to offer both types of visuals at the same time.

As a result, depending on the characteristics of the currently-installed frame buffers (and the corresponding configurations of the *X* servers) used to drive each of the three monitors at a given site, it may only be possible to display some *X*-based Keck observing applications on certain screens and not on others. To eliminate that restriction, the frame buffer hardware and *X* server configurations at several sites needs to be upgraded so that all three monitors will be capable of simultaneously offering both 8-bit pseudocolor and 24-bit truecolor visuals, and will offer the former as the default visual class. Unfortunately, it will likely take many months for that upgrade to be completed at all sites where it is needed.

The VNC server contains a virtual *X* server, i.e., an *X* server that is not attached to any hardware frame buffer. Unfortunately, that virtual *X* server is unable to offer simultaneously both 8-bit pseudocolor and 24-bit truecolor visuals, but it can offer either type of visual individually. As a result, for this VNC-based mode of remote observing, we provide both an 8-bit and a 24-bit VNC desktop on each physical screen, using different background colors to tell them apart, and locating these two VNC desktops in separate window panes of the local virtual desktop. Using the pager panel of that local desktop (which is always visible, regardless of which pane is selected), users can quickly switch between that local desktop, the 8-bit VNC desktop, or the 24-bit VNC desktop with a single click of the mouse (or via function keys defined to provide that operation).

For example, most first-generation instruments will only utilize the three 8-bit VNC desktops, while second-generation instruments will utilize a mix of 8-bit and 24-bit VNC desktops. Similarly, first-generation telescope-related applications (e.g., the displays for the guide camera image, telescope status, etc.) will utilize an 8-bit VNC desktop, while second-generation applications (e.g., adaptive optics control) may utilize a 24-bit VNC desktop.

While it is possible to connect an 8-bit VNC viewer to a 24-bit VNC server (and vice versa), doing so will result in a significant loss in interactive performance (and loss of color resolution) as the viewer is forced to translate between the two formats for every pixel displayed. Optimal interactive and color performance is achieved when the bit-depth (8 or 24) and class of the VNC viewer is matched to those of the VNC server to which it is connected, as well as to the capabilities of the frame buffer and local *X* server through which that VNC viewer is displayed.

Thus, the remote observing scripts that are developed to enable operation of each of Keck instrument from the various remote observing sites need to ensure that the characteristics of the VNC servers, VNC viewers, and frame buffers associated with each of the three monitors at each site are appropriately matched in order to both meet the graphics requirements of that instrument and deliver optimal performance to each site. Given the existing variations in graphics hardware between the various remote observing sites, coupled with hardware upgrades that will occur at different sites at different times, it is clear that the maintenance of the remote observing scripts at each site is an ongoing challenge.

4.6. Other approaches

Before settling on the current VNC-based approach (in which each screen of a multi-screen configuration is mapped to a separate pair of VNC servers), we considered several other options. First, we explored using the *xinerama*¶ extension with the local *X* server to enable all three screens to function as if they were a single large screen. *Xinerama* enables the user to drag windows from one screen to another or to have a large window that spans multiple screens. However, for our application, *xinerama* has more disadvantages than advantages because it eliminates much of the flexibility afforded by having separate *X* servers (and hence separate VNC servers and VNC viewers) for each screen, as described in Secs. 4.3 and 4.4 above. For example, with *xinerama* enabled, it would no longer be possible to enable or disable the *viewonly* option of VNC on a screen-by-screen basis. Similarly, since *xinerama* requires all screens to operate at the same bit depth, it would no longer be possible to configure some screens to be 8-bit and others 24-bit.

We also explored using a commercial product, the *GO Global* remote access system from GraphON Corporation‖ in place of VNC. Like VNC, this product provides its own virtual *X* server which can be remotely accessed via its own viewer. (The *GO Global* server is a licensed product while the viewer is available for free, and both are supported across a wide range of platforms.) This product uses its own proprietary protocol to provide extremely efficient transport of graphical content between its server and viewer.

¶For details, see http://sourceforge.net/projects/xinerama/

‖For details, see http://www.graphon.com/

However, the version we evaluated did not provide sufficient advantages over VNC. First, unlike VNC, it did not provide any support for shared virtual desktops. While it did provide more efficient transport than VNC for certain classes of graphical objects, it did not perform as well as VNC for various interactive functions, such as drawing a projection across an image displayed with the *ds9* image display. Furthermore, while it could enable various window managers (e.g., *olvwm* or *fvwm*) to be run within the virtual desktop provided by its virtual *X* server, that capability is only provided in 24-bit and not 8-bit mode. While an 8-bit virtual *X* server is provided, that server can only run GraphOn's own proprietary window manager, and not the window managers that we want to run. In addition, installation and configuration of both the server and viewer components of this product are considerably more involved than for VNC, and would thus add significantly to the systems administration support burden at the various remote sites.

We also investigated the possibility of using *x11vnc*[**], a program that enables VNC viewers to connect remotely to a real *X* server (i.e., one attached to a physical monitor, keyboard, and mouse) instead of to a virtual *X* server, such as the one contained within the VNC server. This would enable mainland sites to have VNC-based remote shared access to ordinary *X* sessions running on the workstations in Waimea but without the need to start up those Waimea *X* sessions within the context of a VNC server.

While this approach would simplify session startup in Waimea, it does not provide any other significant advantages over running a VNC server in terms of enabling remote shared access from the mainland, and it is not yet a mature product[††]. Also, because *x11vnc* relies on periodic polling of the physical frame buffer memory, it must be run on the workstation in Waimea at which the observer (or support astronomer) is seated, and there are several disadvantages to doing so. First, this polling activity imposes significant computational overhead on that workstation. Second, because the memories in video frame buffers are typically optimized for writing speed versus reading speed, this polling activity is usually not very efficient, and can lead to significant delays in generating the graphical updates that *x11vnc* sends to the remote VNC viewers, thus resulting in degraded interactive performance for the observers at the mainland sites. Third, this approach results in additional traffic on the summit-to-Waimea network (and additional latencies for the graphical updates sent to the mainland) because the nexus for the shared VNC traffic (i.e., the *x11vnc* program) is located in Waimea rather than at the summit (as is the case under our current VNC-based approach). Given the topology of the Keck wide area network (see Fig. 3) in which the summit is located in between the mainland and Waimea, routing of VNC-based traffic is most efficient if the nexus for that traffic is located at the summit.

5. OPERATIONAL EXPERIENCE TO DATE

When the mainland remote observing facilities were first conceived, two distinct modes of operation were envisioned and subsequently articulated in Keck's formal policy:

1. Remote eavesdropping:
   - (a) At least one member of the observing team observes from Waimea, while the other members of the team observe from the mainland.
   - (b) Observer(s) in Waimea have primary responsibility for instrument operation, but observers on the mainland are able to operate the instrument if desired.
2. Mainland only:
   - (a) All members of the observing team observe from California site(s).
   - (b) California observer(s) have sole responsibility for instrument operation.

[**] For details, see http://www.karlrunge.com/x11vnc/

[††] However, while *x11vnc* does not appear to be an appropriate option for supporting remote observing from mainland sites, it may still prove to be a useful tool for enabling Keck support astronomers or technical staff working from home to provide remote support to observers working in Waimea or to observing assistants working at the summit when those users are running software outside of a shared VNC desktop.

In reviewing the use of the mainland remote observing facilities over the last two years, several trends become apparent. First, the majority of observing teams that have utilized the mainland facilities have employed the first mode of operation. While the "mainland only" mode has been used from three of the five mainland sites (UCSC, UCSD, and CIT), to date such usage accounts for less than 10% of mainland remote observing activity.

Second, some observers utilize only a subset of the capabilities provided by the mainland facilities. For a few, all they require is access to the video-conferencing system, so that they can answer questions or provide advice to the other members of the observing team in Waimea. For others, their only interest is real-time access to the guide camera display, so that they can assist their colleagues in Waimea with target identification. In addition, some users of the mainland facilities prefer to have only passive access to the observing client applications, enabling them to watch (without any risk on inadvertently interfering with) instrument operations commanded by their colleagues in Waimea; this option is particularly useful when a student or other new user of an instrument wants to become familiar with the operation of that instrument by passively eavesdropping on an observing run from one of the mainland sites.

Third, as expected, the number of nights per month that involve Keck remote observing from the mainland has grown significantly as more mainland sites have come online. For example, during the first 3 months of 2006, remote observing from mainland sites was conducted an average of 7 nights each month, and included operations from four of the five mainland sites.

Fourth, an increasing fraction of those nights involved operations conducted from two different mainland sites on the same night. Such operations have come about in several different ways. Since there are two Keck Telescopes, two distinct observing programs can take place each night, and each such program could involve observer(s) located at a distinct mainland site. Alternatively, a single observing program involving only one instrument and telescope may involve a multi-institution observing team in which team members participate from more than one mainland site. In addition, for a given instrument on a given telescope, some nights are scheduled as "split nights", where the observing time is split between two different programs, each with their own observing team; in such cases, each of the two remote sites would operate the instrument for only half the night.

6. SCHEDULING ISSUES

Unlike Waimea, which has two separate remote observing rooms (one for each of the two Keck Telescopes), each mainland facility is currently equipped to support only a single telescope/instrument at any given time, and that is unlikely to change. In most cases this is not an issue, because on most nights the observing teams using the Keck I Telescope and those using Keck II are not associated with the same mainland site. However, on a small fraction of the nights, the observing teams on both telescopes are from the same mainland site.

For example, during the 181 nights of the Keck Telescope scheduling semester that spans February through July 2006, on 20 (or 11%) of those nights members of the observing teams scheduled on both Keck I and Keck II are associated with the same mainland site. Thus, a conflict could potentially arise if both such teams requested use of their institution's mainland remote observing facility for the same night[‡‡]. To date, no such conflicts over the use of a given institution's mainland facility have arisen, and should any occur, current policy would allocate use of that facility to whichever team asked first.

A separate scheduling constraint is currently imposed by the number of ISDN circuits installed at the Keck summit. As noted in Sec. 1.2, these circuits are used to provide an alternate link between the summit and the mainland sites in the event of a loss of Internet connectivity. While the underlying topology and routing capabilities of our ISDN backup method can support multiple mainland sites simultaneously, at present there are only enough ISDN circuits installed at the summit to provide a functioning backup path to a single mainland site at a time. While the availability of such a backup path is not required (although it is highly recommended) for the remote eavesdropping mode of remote observing, Keck will not approve requests for the mainland-only mode unless such a backup path is available. Until such time as additional ISDN circuits are installed at the summit, the mainland-only mode of observing can only be provided to a single mainland site on any given night.

[‡‡]During this semester, such potential conflicts were not evenly distributed between the five mainland sites. Of the 20 nights on which such conflicts could potentially arise, 55% were at CIT, 30% at UCB, 10% at UCLA, and 5% at UCSC.

7. FUTURE PLANS

Plans are currently underway to increase the number of ISDN circuits to the summit, either by adding additional Basic Rate Interface (BRI) circuits to the three already installed, or by replacing those circuits with a single, higher capacity Primary Rate Interface (PRI) circuit that exceeds the bandwidth provided by 11 BRI interfaces. Along with this upgrade to the ISDN service, the existing Cisco 2621 ISDN router at the summit will be upgraded to a newer router capable of providing higher aggregate throughput. Together, these changes should enable ISDN-based backup paths to be provided simultaneously to multiple mainland remote observing sites.

We are also considering plans to install at both Keck I and Keck II separate server hosts that will be dedicated solely to running VNC servers to support remote observing. As an interim measure, we are running VNC servers directly on some of the newer instrument control computers, but overall administration and access control issues will be simplified once the VNC servers can be relocated to dedicated hosts at each telescope.

Work will continue on optimizing the performance of the VNC-based mode of remote observing, through continued testing and evaluation of alternative versions of VNC. At present, we are also using the open source edition of VNC, which has been freely available since 1998. Commercially-licensed versions of VNC (e.g., *RealVNC*) providing greater functionality than the open source edition are now available, and we may test such products as time and resources permit.

Also, additional mainland remote observing facilities may be implemented at other campuses of the University of California system (e.g., Davis, Santa Barbara, or Irvine), or at the sites of other institutions affiliated with Keck Observatory, if there is sufficient interest from the community of Keck observers at those locations.

Managing the configuration of the various remote observing sites will remain an ongoing challenge, as new sites are added and as existing sites upgrade their hardware and software. Even within our single vendor (Sun Microsystems), every year there are new graphics cards, new hardware drivers, new versions of the operating system (including new hardware configuration utilities), and new versions of the X server. In addition, there are new versions of the window manager, of VNC, and *ssh*. Each system presents new challenges for determining the characteristics and possible ways in which it can be configured. The options are not always well documented, and we have encountered several instances of vendor-supplied software with bugs. With each new system we have resorted to experimentation for determining the usable capabilities and optimum configuration of each component.

8. CONCLUSION

Over the past decade, remote observing at Keck Observatory has expanded significantly, from its initial support of a small number of instruments on a single telescope (Keck I) operated from a single, nearby site (Waimea), to its current support of three times as many instruments spread across two telescopes and operated from six sites, five of which are in California. While the Keck remote observing model has remained unchanged, the mix of software protocols used to support that model has evolved over the years, and will likely continue to evolve in the future. We expect that in addition to the *ssh*, *X*, and VNC protocols that have been used to date, next-generation instruments may employ web-browser-based protocols (e.g., AJAX[12]) to extend that model.

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