Through the Far Looking Glass: Collaborative Remote Observing With the W.M. Keck Observatory

Robert Kibrick, Al Conrad, and Andrew Perala

In the past 2 decades, computing science has revolutionized astronomy. The cartoon image of an astronomer squinting through an eyepiece, twiddling dials, and taking photographs is as out of date as a bank of keypunch operators feeding stacks of paper cards into a vacuum-tube computer. Today's astronomer observes with giant telescopes and state-of-the-art instrumentation controlled by dedicated computer hardware and software. The light he or she gathers from the furthest reaches of the universe is transformed into a digital data stream.

Robert Kibrick
UCO/Lick Observatory
University of California
Santa Cruz, California
kibrick@ucolick.org
http://www.ucolick.org/
~ kibrick
+1-408-459-2262
Fax: +1-408-459-5244

Al Conrad and
Andrew Perala
California Association for
Research in Astronomy
W.M. Keck Observatory
Kamuela, Hawaii
aconrad@keck.hawaii.edu
aperala@keck.hawaii.edu

Atop Mauna Kea on the island of Hawaii, at an altitude of almost 14,000 feet, a dozen world-class telescopes peer nightly into the cosmos. The largest of these (in fact, the largest in the world) belongs to the W.M. Keck Observatory (see Figure 1). Home to twin 10-meter optical/infrared telescopes, Keck is pioneering the routine use of remote observing—controlling the telescope and its light-analyzing instruments—from its headquarters in the cattle-ranching town of Waimea, 32 kilometers distant.

Currently, virtually all astronomers work from a control room located immediately adjacent to the dome that houses the telescope, but at Keck, as at all other high-altitude observatories, this arrangement presents unique and potentially dangerous physical challenges. At Keck, these challenges have pushed astronomers toward observing remotely from control rooms located at observatory headquarters far down the mountain. Astronomers thus avoid the severe physical and mental stresses of working long nights at high altitude [2]. Currently, 90% of the observations performed with the Keck telescopes are conducted remotely from the headquarters facility.

For many astronomers, the ultimate goal is observing with the Keck telescopes from the mainland United States. “I’ve always wanted to observe from my kitchen table,” says University of California Santa Cruz (UCSC) astronomer and instrument builder Dr. Steve Vogt. Unfortunately, remote observing from the mainland is not yet routinely available because of the limited Internet bandwidth between Mauna Kea and California. In anticipation of improved bandwidth, however, software tools and methods to support mainland remote observing have been developed and tested.

When the bandwidth becomes available to support this observing mode, mainland astronomers will reap significant savings in travel costs and travel time. In addition, observing teams whose members reside at different sites will be able to observe jointly and simultaneously from their respective locations.

Observing time on the twin Keck Telescopes is shared by astronomers from four different institutions (see Figure 2): the California Institute of Technology (Caltech); the University of California, with nine campuses plus three research laboratories; the National Aeronautics and Space Administration (NASA), which sponsors qualified U.S. astronomers interested in planetary science; and the University of Hawaii.

Although these four institutions have not yet formally agreed to establish a “collaboratory,” the software tools for mainland remote observing described in this article represent the first step toward the formation of a Keck collaboratory.

Remote Observing From Keck Headquarters

Remote observing from Keck headquarters allows observers to think more clearly, function more efficiently, and avoid the hazards of the summit. At the summit of Mauna Kea, the ambient air pressure and oxygen level is only 60% of that found at sea level. Blood–oxygen

Figure 1. W.M Keck Observatory viewed from the north (Keck II, left; Keck I, right)

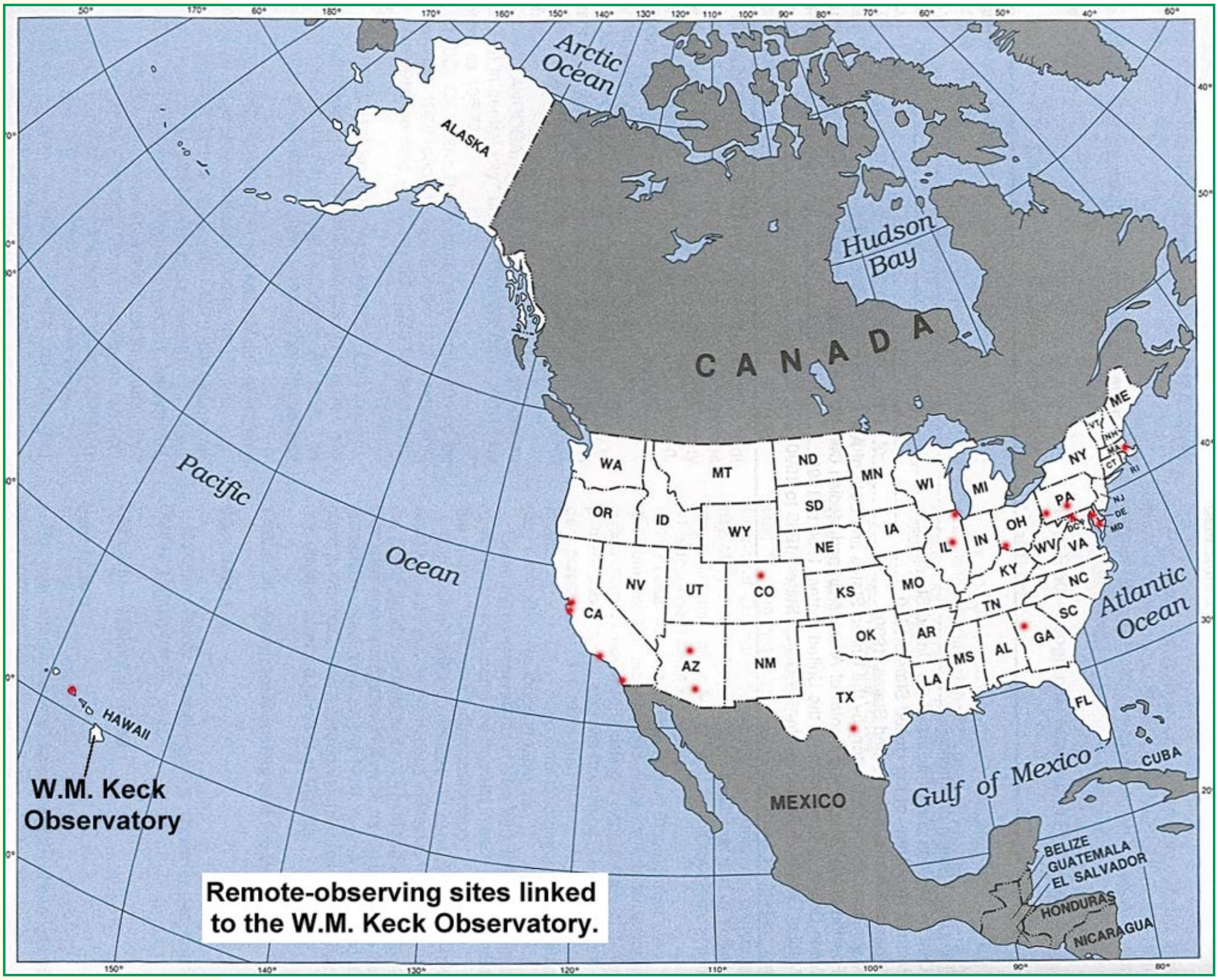

Figure 2.

levels at the summit drop precipitously in the first few hours and never completely recover, even for observatory employees, some of whom have made thousands of trips to the summit.

High-altitude sickness is not uncommon; pulmonary and cerebral edemas are real risks. Some observers, including pregnant women or those with chronic heart or lung conditions, cannot observe at the summit.

Acclimatization is key to performing well at altitude. Astronomers who observe at the summit are required to sleep at the 9,200-foot base camp and must arrive at least 24 hours before the start of observing to begin the acclimatization process; even with acclimatization, the dramatic physiological changes cause thought processes and mental acuity to suffer dramatically.

Some of the mistakes made at this altitude are comical. One of the world's most prominent astronomers was found midpoint in an observing run standing just 10 feet from the elevator door and was completely unable to find the elevator. Other mistakes made at that altitude, however, can be lethal. A misstep inside the dome could send a person tumbling 60 feet to a concrete floor.

Remote observing from the Waimea headquarters has proven hugely popular. From January to October 1997, the percentage of astronomers remotely observing jumped from 10% to 80%. Observers who opt to work from Waimea use one of two remote operations rooms located at Keck Headquarters (see Figure 3). The work stations in these rooms communicate with data-taking and telescope-control computers at the summit via a dedicated link. The original link, a 1.5-Mbit/sec T1, was upgraded to a 45-Mbit/sec DS3 in October 1997.

In addition, because Keck instrument specialists work primarily in Waimea and not at the summit, astronomers working from

Waimea are able to speak directly to these specialists regarding instrument performance and software improvements.

"We find it helpful to interact directly with the astronomers to improve the systems," said Hilton Lewis, software manager for the W.M. Keck Observatory. "By doing so, you'll notice little things that would never be reported but which may have a profound influence on observing."

X Protocol

All observing software runs on summit machines (just as it would for summit observing), but the X displays for the various software applications are redirected to Waimea and displayed on the workstation screens in the remote operations rooms. The primary advantage of the X protocol method is simplicity. No configuration changes or redistribution of software is needed to switch between summit and remote observing, and observers are presented with the identical user environment at both sites.

A major disadvantage of the X protocol method is performance. The throttling effect of the 1.5-Mbit T1 link on simple, text-only displays is negligible. For displays that require large bitmap transfers, however, the effect is glaringly noticeable. When observing remotely on both Keck-1 and Keck-2 over the single T1 circuit, a zoom/pan operation on a large bitmap image display may take as long as 5 seconds. Although this is marginally acceptable for viewing the result, the delayed response often causes impatient users to repeat requests. The subsequent buffering of these requests (e.g., mouse clicks and mouse motions) puts the observer out of synch with the application. The initial 5-second delay is magnified as the resulting disorientation experienced by the observer results in minutes of lost observing time.

Our experiments with remote observing from Waimea with a 45-Mbit link show little performance degradation with bitmap displays. This is not surprising, given that the 45-Mbit rate exceeds the 10-Mbit rate achieved on the LAN backbones in place at Waimea and the summit. Given the recent upgrade to a 45-Mbit link, we plan to continue with the X protocol approach when remote observing from Waimea.

Video Conferencing

Typically, the personnel involved in an observing run include the principal investigator (PI), a support team of graduate students and postdoctoral candidates, and the observing assistant (OA). The PI conducts the observation,

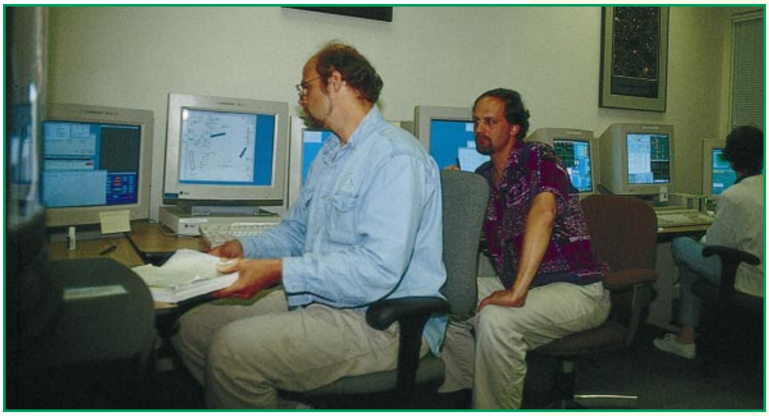

Figure 3. Paul Butler (foreground) and Geoff Marcy, planet hunting astronomers in the Keck I remote control-room

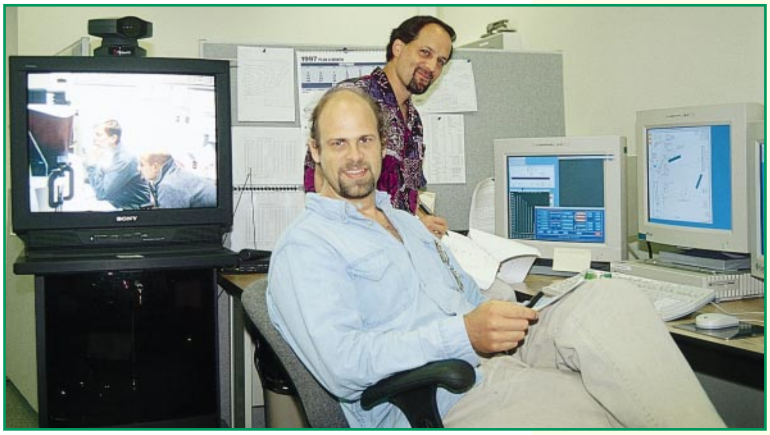

Figure 4. Picture-Tel Venue 2000 shows OA Ron Quick (left) and electronic technician Hector Rodriguez (right) at Keck I summit.

and the OA operates the telescope and assists the PI. Other astronomers, instrument specialists, engineers, and technicians often assist during the observation.

Personnel in the summit and remote control rooms communicate with one another via a dedicated video conferencing system (PictureTel Venue 2000, see Figure 4) running over a portion of a dedicated T1. In the cases where the PI and OA are separated, this system has proven critical for successful observing. Although the system is seldom used to actually view a diagram or hand-drawn pic-

Audio quality stands out as the most important factor favoring the dedicated system.

ture, we have discovered that the visual cues of body language and being aware of which other team members are listening are essential for two people collaborating on the operation of telescope and instrument [4].

Before acquiring the dedicated PictureTel system, we investigated generic systems that use TCP/IP and work-station technology to transmit audio and video over the network. Although such systems are less expensive and more flexible, we found that PictureTel provided superior performance.

Audio quality stands out as the most important factor favoring the dedicated system. Other features include better picture quality, preset camera positions, and a larger field of view. In addition, the dedicated video system isolates the link used for video conferencing from the link used for summit to Waimea computer network traffic, thus conserving network bandwidth and preventing the loss of audio and video contact should the computer network fail or become congested.

Hogging the Net

One of the greatest challenges for remote observing is determining which cooperating processes are consuming disproportionate amounts of the available bandwidth or, more simply stated, "Who is hogging the net?"

Although a 45-Mbit link accommodates normal traffic, we have found that a large block transfer, which is network limited (typically a tape backup of a cross-mounted file system), can effectively lock out communication between two event-limited processes. To date, we have not found a method of throttling these block transfers and rely on operational rules to prevent this type of transfer from interfering with observing.

Use of the World Wide Web

Although we have started using World Wide Web methods such as HTML, CGI, and Java to facilitate observing preparation (i.e., running planning tools, specifying instrument configurations, and scheduling the telescope), to date we have not experimented with these methods for real-time observing. Although Web technology may become the best method for remote observing, currently its inability to transmit data securely makes it inappropriate for this use.

Remote Observing From the Mainland

Despite the inadequate and unpredictable bandwidth of existing network links between Mauna Kea and the mainland and despite the lack of any formal collaboratory infrastructure, Keck observers have requested a variety of mainland remote observing capabilities. In response to these requests, researchers at UCSC and Caltech have informally collaborated with each other and with their counterparts at Keck on several different experiments to develop mainland remote observing capabilities. The experiments conducted from Caltech were funded by a NASA grant and investigated the use of dedicated, high-speed links provided by an experimental NASA geostationary communication satellite [1]. The experiments conducted from UCSC had no external funding and have explored various techniques to support mainland remote observing over existing public Internet links [3].

Mainland Remote Observing Over the Existing Internet

Internet bandwidth and reliability present the greatest challenges for mainland remote observing. As most observing teams are allocated only a small number of nights on the telescope each year, they understandably are unwilling to risk a significant loss of observing time caused by Internet outages or congestion. Similarly, because the cost of operating the Keck Telescopes is several thousand dollars an hour, the observatory cannot allow its telescopes to sit idle because a remote observer on the mainland has lost a network connection. As a result, until Internet bandwidth and reliability issues are resolved (or until a separate, reliable, dedicated link to the mainland becomes available), mainland remote observing via the Internet will require at least one member of the observing team to be in Hawaii, either at Waimea or at the Keck summit.

If the network connection to the mainland is interrupted, the on-site observer assumes responsibility for the observing program. Except for the Caltech experiments noted earlier here, all mainland remote observing conducted to date has included at least one member of the observing team located on-site in Hawaii. Coordination between the on-site observer and the observing team on the mainland is accomplished by keeping open a telephone line (often connected to speaker phones at each end) or by using digital audio tools to carry conversations over the Internet.

Conventional telephones provide superior audio quality, greater ease of use, and enhanced conferencing capabilities and are physically more portable than digital audio tools running on the work stations. The costs of all-night phone calls to Hawaii have proved minimal (less than $50 per night).

Internet network security presented an additional problem for mainland remote observing. Our experiments at UCSC addressed this problem in different ways, depending on the characteristics of the remote observing site. We investigated two separate approaches to mainland remote observing:

- "Eavesdropping" to arbitrary, nontrusted sites at low-to-moderate bandwidth.
- "Full-up" remote observing to a specific trusted site at moderate bandwidth.

Eavesdropping to Arbitrary Sites Over the Internet

While the on-site member of the observing team attends to local tasks (e.g., confirmation of target acquisition, instrument setup, and initiation of exposures), the mainland remote observers focus on quick-look data analysis and overall monitoring of the science program. Accordingly, a mainland remote observing system must at least provide remote observers with timely access to the science images from the telescope. We refer to this mode of operation as eavesdropping to distinguish it from the full-up remote observing currently provided at Waimea.

Network security measures in place at the Keck summit made implementation of eavesdropping difficult. The summit computers are protected by a firewall that rejects incoming connection requests. Thus, mainland remote observers cannot initiate file transfer protocol (FTP) or Web connections to collect images taken by their on-site colleagues. Although the on-site team members could initiate outgoing connections and could push these images to the mainland sites, they are usually too busy to do this.

Although technical solutions (e.g., distributed secure file systems) exist that address many of these security-related concerns, they require a significant level of coordinated system management between the participating sites. Although this level of coordination is possible within a heavily funded and centrally administered collaboratory, it was not feasible in our more diverse environment.

Often, the remote observer's workstation was located at some remote mainland institution that had no affiliation with Keck Observatory. Frequently, the machine had little system management support, and the astronomers who used it were not particularly skilled in installing, configuring, or maintaining complex system software. In addition, requests for mainland remote observing support often arose at the last minute, especially in cases where an observing team member had planned to go to Hawaii but suddenly could not because of illness or a family emergency.

For these reasons, we needed an application that made minimal assumptions about the system software already installed on the observer's machine, could be easily installed by a novice user, required no configuration nor intervention by local system management, and only relied on outbound connections from Keck to the remote site.

As a result, the "shadowmon" suite was developed at Lick Observatory/UCSC and was successfully used to support the automated relaying of compressed Keck images to a variety of California remote observing sites (i.e., Santa Cruz, Berkeley, San Diego, and Livermore), as well as to the Space Telescope Science Institute (STSci) in Baltimore, Maryland, and the Harvard Center for Astrophysics in Cambridge, Massachusetts.

This suite consists of a very small set of simple utility programs, some that run at the Keck summit and others that run at the mainland remote observing site. The remote observer simply downloads the software and

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starts it running on his or her machine. The software requires no further action for the remainder of the night. Once corresponding software is started at Keck, any subsequent images from the specified instrument will be automatically relayed to the remote observer's machine and recorded to its disk.

As each new image is received, several beeps are issued to announce its arrival. Barring network disruptions or congestion, the relayed compressed images, which are several megabytes in size and up to 10 megabytes uncompressed, are available for use at the remote site in under 3 minutes from the time they were written to disk at Keck.

On the Keck side, the corresponding software is invoked by Keck observatory staff, who specify as a parameter the location of the remote observer's computer. Because the network connection to that site is initiated from the Keck side of the link, there is no conflict with the firewall at the Keck summit. At the end of the observing session, Keck staff shut down the remote observing software at both sites. Remote observers cannot continue to obtain Keck images beyond the end of their observing run, even if they restart the remote-side software on their machine.

The shadowmon suite has proved to be a very effective, secure, and easy-to-use tool to support eavesdropping over low-to-moderate bandwidth public Internet links. Once started at the beginning of the night, it transparently relays images from Keck to the remote site without any intervention required from the observers at either site. Thus, observers at both sites can focus on their respective tasks of collecting and analyzing the data without having to waste any time on the transport mechanism.

Clever observers have found innovative uses for this suite that were not anticipated when first implemented several years ago. For example, an observing team may elect to leave shadowmon running even if the mainland remote observer has to retire early. The relayed data will accumulate on the remote observer's machine and will be waiting for analysis the next morning. Otherwise, the remote observer would face a several-hour delay trying to get the remaining data transferred from Keck during daytime hours when the Internet is congested. Although the on-site observer who collected the data is sleeping, the remote observer will be busy analyzing it and can report the results to the on-site colleague that evening. This multiplexing of activities between observers on different sleep schedules can provide an extremely efficient means of collecting and analyzing data.

Full-Up Mainland Remote Observing Over the Internet

This mode of observing requires a trusted machine at an affiliated site and usually demands close collaboration between the respective system management staffs at both sites. The trusted machine is allowed to make incoming connection requests to the summit computers and is thus able to run the full complement of observing software. Encryption mechanisms safeguard the security of these connections. Full-up remote observing over the Internet currently requires more bandwidth than is routinely available, and it is now possible only a few hours each night when the Internet is relatively idle.

We have tested two different models:

1. All observing software runs at Keck summit with X displays routed to the remote mainland site.
2. Components of the observing software are run both at the Keck summit and at one or more of the remote sites.

The first model parallels the current mode of remote observing from Waimea and thus shares all of its advantages and disadvantages. Because, in most cases, the bandwidth of the link between mainland sites and the Keck summit is significantly lower (and often less predictable) than that between the summit and Waimea, disadvantages that are bandwidth sensitive become more significant. Given the bandwidth of the existing Internet link, this model is extremely difficult to use at best and results in significantly reduced operating efficiency.

The second model allows the user interfaces, the image display, and the image recording software to be run locally at the remote site. This provides several advantages. First, interactive response is significantly improved, as mouse motions and button clicks are handled locally. Equally important, it allows the transmission of image data to be overlapped with readout of the image detector. This is a crucial point, as our current detectors require 1 to 2 minutes to read out each exposure. If we wait for the complete image to be read out before we begin transmitting it, we waste several minutes of network bandwidth that could have been used to transmit the image.

By overlapping image transmission to the remote site with image readout, overall utilization of the link bandwidth is significantly increased. Observing efficiency is also improved because the remote observer begins to see the displayed image data as soon as the detector readout commences. He or she can then contribute to team decisions about what to do next (e.g., continue observing the current object or begin moving the telescope to the next target) based on the data from the first part of the image. The remote observer is thus able to participate more actively in the observing process.

Once the image readout completes, the remote observer has a local copy (identical to the one recorded at the Keck summit) of the image data file on disk, allowing more efficient data reduction and analysis, as well as eliminating the need for repeated NFS or FTP access to the data files recorded at the Keck summit.

Another advantage of this model is that it allows the distribution of the image in real–time to multiple sites (e.g., Keck summit, Waimea, and California), protecting against a loss of data caused by hardware failure at one of the sites. This capability also greatly enhances the collaborative efforts of observing teams whose members are jointly observing from different sites, because all team members have simultaneous real-time access to the data as it is read out of the detector.

Conclusion

Our operational experience with full-up remote observing from Waimea and with eavesdropping from the mainland clearly demonstrates that both modes increase observing efficiency and enhance the ability of both astronomers and support staff to collaborate effectively in real time over long distances.

Our experiments with full-up remote observing from the mainland establish that observers will be able to conduct science almost as effectively from their home institutions as they now can from Waimea, once the necessary network infrastructure is in place.

Finally, Internet 2 holds the promise of solving most of the bandwidth and bandwidth management concerns that will prove critical for mainland remote observing with our next generation of Keck instruments. These new instruments have larger imaging detectors and faster readout rates and will require the significantly higher bandwidth that Internet 2 would provide. Because Internet 2's primary goals include the enhancement of collaboratory efforts, including remote operation of and access to major research facilities, it is essential that a path be found to extend Internet 2 connectivity to Keck and the other Hawaii observatories. Once that is done, full-up mainland remote observing may become commonplace.

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