by Joseph Jensen

New Instrumentation for the Gemini Telescopes

To produce forefront science and continue to compete in the global marketplace of astronomy, Gemini Observatory must constantly update its instrument suite. A new generation of instruments is now nearing completion. The Near-Infrared Coronagraphic Imager (NICI) was recently delivered to Gemini South, and the near-infrared multi-object spectrograph FLAMINGOS-2 should arrive at Cerro Pachón later this year. Gemini staff members are integrating the Multi-Conjugate Adaptive Optics (MCAO) system in Chile now, and the Gemini South Adaptive Optics Imager (GSAOI) is already there, waiting to sample the exquisite images MCAO will deliver. At Gemini North, the visiting mid-infrared echelle spectrograph TEXES will join the Gemini collection again for a few weeks in semester 2007B as a guest instrument. The new instruments, along with the existing collection of facility instruments, will propel Gemini towards the lofty science goals outlined in Aspen, Colorado nearly four years ago.

Gemini is now beginning construction of the next generation of instrumentation that will help answer profound questions about the universe and our place in it. Many of these questions relate directly to the formation of planets, their physical characteristics, and their prevalence. Others address the most fundamental questions about the nature of the matter (baryonic and dark) and dark energy that make up the universe. Two of the new Aspen instruments–the Gemini Planet Imager, (GPI), and the Precision Radial Velocity Spectrometer, (PRVS)–have been designed explicitly to find and study extrasolar planets. The Wide-field Fiber Multi-Object Spectrometer (WFMOS) will provide a revolutionary new capability to study the formation and evolution of the Milky Way Galaxy and millions of others like it, reaching back to the earliest times of galaxy formation. WFMOS will also shed light on the mysterious dark energy that is responsible for the accelerating expansion of the universe, counteracting the force of gravity on the largest scales. Finally, the Ground-Layer Adaptive Optics (GLAO) capability being explored for Gemini North will improve our vision across a large enough field of view to explore the first luminous objects in the universe, along with practically everything else as well.

The Aspen instruments build on pathfinding projects being started now using existing Gemini instruments like the Near-InfraRed Imager (NIRI) and Near-Infrared Coronagraphic Imager (NICI). The promise of the new Aspen instrument projects will only be fully realized if they are built in a timely fashion and are allocated large amounts of telescope time for appropriate surveys, with well-supported teams to conduct them.

The Gemini telescopes are unique among the family of large 8- to 10-meter-class telescopes because they are optimized for maximum performance at infrared wavelengths. They were designed and built to: 1) deliver the finest image quality allowed by the excellent site conditions, 2) deliver diffraction-limited images, and 3) have the greatest thermal infrared sensitivities achievable from the ground. Adaptive optics (AO) is a key technology installed on both telescopes to achieve this goal (see the December 2006 special AO issue of *GeminiFocus*). Gemini is also unique in that the two telescopes provide astronomers with complete sky coverage, an important advantage in the field of exoplanet research. Gemini's search for extrasolar planets using imaging techniques has been ongoing since late 2000. During the same period, astronomers using Gemini have worked at the forefront of research at the highest redshifts. Several teams have used the Gemini telescopes to search for the first luminous objects that reionized the hydrogen throughout the early universe. Other astronomers using Gemini have observed fleeting supernovae and gamma-ray bursts to better understand these violent explosions early in cosmic history, and how the universe has changed since then. This is transformational science that is uniquely enabled by the cutting-edge tools (sensitive detectors, AO and laser guide stars) now available at Gemini.

With the discovery of more than two hundred planets around other stars, we now stand on the brink of a new understanding of the universe and our place in it. After centuries of debate, speculation, and many false starts and erroneous claims, a growing population of extrasolar planets has finally been conclusively identified in the last decade. In addition to these exciting and fundamental discoveries, we have obtained a few glimpses into the intermediate stages that link the births of stars to the formation of planetary systems. We are now poised for the transition from discovery of these systems to their characterization. At Gemini we have telescopes and instrumentation optimized for exoplanet detection, and a fully integrated program to strategically explore a range of planetary masses and semi-major axes around nearby stars. Figure 1 illustrates the projects and related instruments discussed in the next sections.

The Gemini Near-Infrared Coronagraphic Imager (NICI)

Gemini's latest addition to its instrument arsenal is the Near-Infrared Coronagraphic Imager (NICI) at Gemini South. NICI is the first Gemini instrument designed specifically to search for and analyze the properties of planets orbiting other stars, and one of the first in the world optimized to image the light from the planets directly. With its own custom AO system, dual imaging cameras, and specialized coronagraph, NICI is designed to be a significantly more capable planet-finder than existing instruments. Each camera has its own detector and set of filters, so two wavelengths can be sampled at the same time. Giant planets that contain methane will appear dark in some narrowband infrared filters and brighter in others. The contrast between the two simultaneous images will help astronomers to distinguish methane-rich giant planets from background stars and residual diffracted starlight.

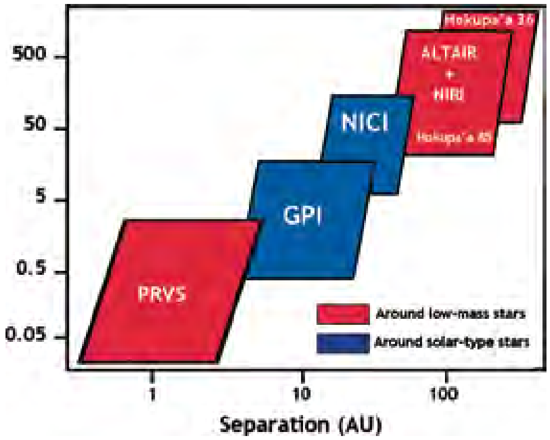

Figure 1. *Some of the new instruments planned for Gemini are key components of strategic development within the observatory. These will enable astronomers to systematically probe lower-mass regimes in the quest to find extrasolar planets.*

NICI passed acceptance testing in Hilo in October 2006, and was shipped to Cerro Pachón at the beginning of 2007. The Gemini and Mauna Kea Infrared (MKIR) team, under the leadership of Doug Toomey, Mark Chun, Tom Hayward, and Manuel Lazo, assembled NICI and tested it in the lab at Gemini South. NICI was installed on the telescope in mid-February, and saw first light on the night of February 20, 2007. The very successful first commissioning run results are shown in the box on page 13.

Figure 2. *NICI installed on the Gemini South telescope, getting ready for its first commissioning night on the sky.*

The NICI team is actively working through a number of issues to prepare it for regular science operations, and for the NICI planet search campaign in particular (for more information see page 63 of the special December 2006 AO issue of *GeminiFocus*). Perhaps the most important issue with NICI that must be corrected has to do with the deformable mirror (DM) in the NICI AO system. The current DM lacks the stroke needed to achieve the desired Strehl ratios because of a relatively large minimum radius of curvature, low resonant frequencies, and two damaged actuators. We plan to fix the two actuators prior to the next NICI commissioning run. We are also exploring the possibility of acquiring a new DM with a smaller minimum radius of curvature and higher resonant frequencies than the existing DM. Testing of the existing and new DMs will be conducted in June and July of this year, hopefully leading to better performance in poorer-than-average seeing conditions. If NICI's AO system can be made to work in a wider range of natural seeing conditions the survey observations will be much easier to integrate into Gemini's multi-instrument queue observing system.

Once NICI's AO performance is fine-tuned with a better DM, and other minor problems solved, the planet search observing procedures and software will be tested. Some test data will be taken on targets that are known from past planet searches to have faint background objects near them. These observations will demonstrate the ability to subtract the point-spread function and distinguish real targets from speckles. Methane-rich brown dwarfs will also be imaged to demonstrate the ability to distinguish such objects using the two narrow-band filters. Giant planets should have methane in their atmospheres, making them easier to find with NICI's dual imaging channels (for more information see page 66 of the December 2006 issue of *GeminiFocus*). The test data will be released with the call for proposals when NICI is offered for regular observing for the first time. When the test observations have shown that all is ready, both with the instrument and software, the NICI planet search campaign will begin.

NICI is the most specialized of Gemini's instruments thus far, and meeting its science goals requires a large survey of nearby stars conducted over several years. This will hopefully find a few needles in a very large haystack. In 2005, Gemini awarded approximately 500 hours to a team led by Michael Liu, Laird Close, and Mark Chun to conduct the NICI planet search survey. The experience acquired with ALTAIR and other exoplanet research projects will be crucial to the success of the NICI campaign.

The 500-hour NICI planet survey will search for massive planets (like Jupiter) around young, nearby stars. With a census of young planets, the NICI campaign team will address three important questions:

- What is the distribution of masses and separations of planets in the outer regions of other planetary systems?

- How does the mass of the parent star affect the chances of planetary formation?

- What are the properties and compositions of the young extrasolar giant planets?

Most planets that have been discovered around other stars are detected only indirectly via their gravitational influence on their parent stars (the radial velocity technique). NICI will find a very different class of planets than the radial velocity searches do. This is because it will preferentially find the giant planets orbiting farther out in regions of their planetary systems comparable to those occupied by the giant planets in our own solar system. Unlike the radial velocity instruments, NICI will be able to detect the infrared light from the planets directly, revealing much about their masses, compositions, and temperatures.

NICI is unique among Gemini instruments in that it was funded by a NASA grant as part of the agency's mission to explore extrasolar planets. This independent funding made it possible to design a specialized AO instrument that might not have otherwise been built because of tight funding within the Gemini partnership. NICI is a pioneering instrument that is blazing a trail for the future Gemini Planet Imager (GPI).

FLAMINGOS-2

While their basketball and football teams have been attracting national attention, our colleagues at the University of Florida at Gainesville have been working feverishly to complete FLAMINGOS-2 and get it ready for delivery later this year. FLAMINGOS-2 will provide wide-field imaging and multi-object spectroscopy across a field of view six arcminutes in diameter. When used with MCAO, FLAMINGOS-2 will provide an AO-corrected multi-object spectroscopic capability across more than an arcminute (more details may be found in the December 2006 issue of *GeminiFocus*, page 69). In the past few months, the team has integrated all of the optics, electronics, mechanisms, and detectors in FLAMINGOS-2 in their lab in Gainesville. All the optics are now installed, including the low-resolution grisms. The high resolution (R=3000) grating was received in February 2007, after years of effort by the University of Florida team working closely with the vendor. It will be integrated with its prism and installed in the instrument shortly. Having all the optics installed, aligned, and tested cold is an important milestone in the integration and testing of FLAMINGOS-2.

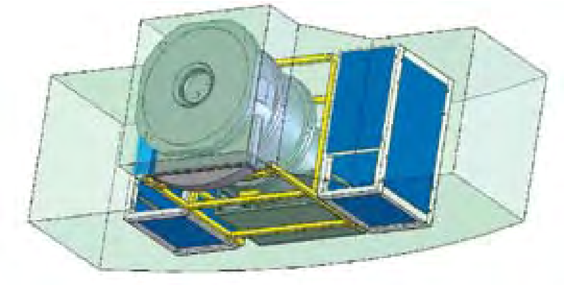

Figure 3. *A schematic of FLAMINGOS-2 shows the dewars and electronics enclosures inside the instrument space envelope.*

During the recent cold tests, the mechanisms were also tested and a number of minor problems were fixed. All the mechanisms are now working reliably.

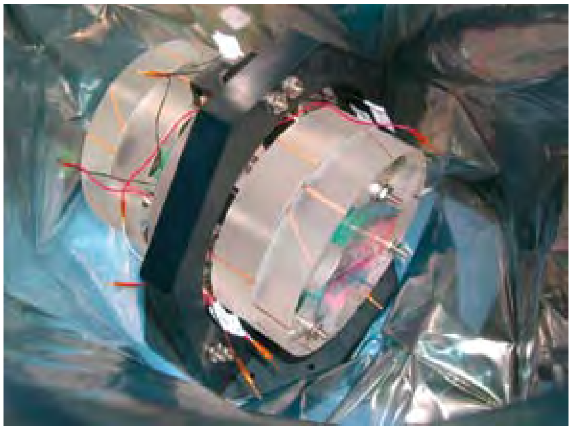

Figure 4. *The dual etalons of the tunable narrow-band filter are currently being integrated and tested in Canada.*

One of the key science questions that FLAMINGOS-2 will address is how the first luminous objects formed and how they ionized the neutral hydrogen in the universe less than a billion years after the Big Bang. At redshifts greater than z = 6 the Lyman-alpha emission from hydrogen is shifted into the near-infrared J and H bands (1.1 and 1.6 microns, respectively). To find these objects, special narrow-band filters are being procured for FLAMINGOS-2. In one experiment, very narrow filters are being designed to take advantage of the dark gaps between bright atmospheric OH emission lines. In another experiment, a team led by Roberto Abraham at the University of Toronto is building a special tunable filter composed of two Fabry-Perot etalons in series. The etalons have been built and are now being tested in Canada (Figure 4). They will be installed in the FLAMINGOS-2 mask foredewar for dedicated observing campaigns.

The Gemini Planet Imager (GPI)

The Gemini Planet Imager (GPI), currently being designed and built by a collaboration led by Bruce Macintosh at Lawrence Livermore National Laboratory, follows directly in the tradition of NICI, both scientifically and technologically. A large consortium of institutions in the U.S. (Lawrence Livermore, the University of California at Los Angeles, the University of California at Santa Cruz and Berkeley, the American Museum of Natural History and the Jet Propulsion Laboratory) and Canada (the Herzberg Institute of Astrophysics and the Université de Montréal) is involved in what is one of the most ambitious instruments ever built for a ground-based telescope. GPI is described in more detail in the December 2006 issue of *GeminiFocus*, starting on page 73.

Like NICI, GPI is a specialized coronagraph designed to see planets around young, nearby stars. However, GPI has a couple of new tricks up its sleeve to improve on NICI's performance. GPI is a coronagraphic instrument with its own sophisticated on-board AO system and apodized masks. GPI will have a much higher order AO system to achieve higher Strehl ratios than possible with NICI or ALTAIR. GPI will also have an advanced interferometer incorporated into the AO system to further reduce wavefront errors. Finally, GPI will have a unique low-resolution (R = 45) integral field spectrograph to help identify planets and characterize their atmospheres (Figure 5).

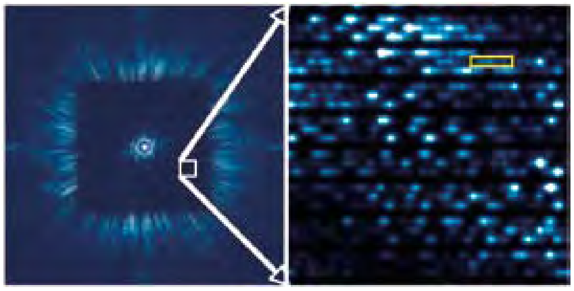

Figure 5. *Simulated GPI data (left) shows the dark square hole created by the calibration wavefront sensor. The expanded image on the right shows the individual spectra created by the integral field spectrometer for each point in the field of view.*

GPI represents the natural progression of high resolution and coronagraphic imaging that has been developed through Gemini's instrument program, consistent with the intrinsic strengths of the Gemini telescopes. This progression started with Hokupa'a and ALTAIR at Gemini North, continues with the deployment of NICI at Gemini South, and ultimately will be defined by the capabilities of GPI. The NICI instrument will be an important pathfinder to test observing schemes, quantify in real terms the coronagraphic performance on Gemini, and experiment with different apodization techniques, all of which can be fed into the GPI design, reduction pipeline, and science program.

GPI is the first of the Aspen instruments to advance beyond the conceptual design phase. After completing a conceptual design study, the GPI team won the competition to build what was then known as the "Extreme AO Coronagraph." The project was started in June 2006, and the team quickly came up to speed, making several key design decisions. The GPI team is now (as of this writing) in the final stages of preparation for their preliminary design review, to be held in Santa Cruz, California in May. If all goes according to schedule, GPI will be completed and ready for testing on the telescope toward the end of 2010. The campaign to survey hundreds of southern stars to find young giant planets will begin shortly thereafter. The science goals of the survey are being developed along with the instrument, and the design decisions made thus far are tightly coupled to the requirements of the science case.

The Precision Radial Velocity Spectrometer (PRVS)

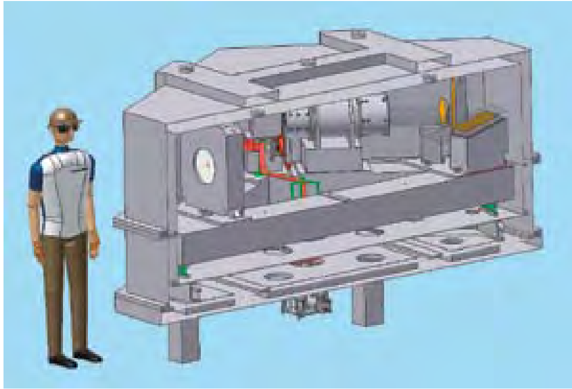

Figure 6. *The UK ATC conceptual design of the PRVS spectrograph shows it mounted on a vibration isolation bench and located inside a vacuum jacket and radiation shield. The spectrograph will be located in the pier lab and fed with a fiber running up through the ceiling to the telescope's cassegrain focus*

Last year, Gemini Observatory commissioned two conceptual design studies for a Precision Radial Velocity Spectrograph (PRVS). PRVS is the offspring of the High-Resolution Near-Infrared Spectrograph (HRNIRS), a multi-purpose instrument that went through the Conceptual Design phase following Aspen, but was not built due to limited funding. One of the Aspen science goals that motivated HRNIRS was to detect planets down to a few earth-masses around low-mass stars by measuring the radial velocity reflex motions of stars. By making PRVS a bench-mounted fiber-fed spectrograph sensitive from 1 to 1.6 microns, high stability can be achieved. PRVS will open up the radial velocity planet search to low-mass M-dwarf stars, which are very numerous in the solar neighborhood and brightest at near-infrared wavelengths. Planets in the "habitable zones" of M-dwarf stars have short-period orbits, and the low-mass stars will wobble more due to the influence of such planets. PRVS will find lower-mass planets around the most common stars in our galaxy, and therefore answer important questions about how common terrestrial-class planets may be in the universe. The parameter space probed by PRVS is highly complementary to that sampled by optical radial velocity searches and the imaging surveys described above. PRVS therefore represents an essential part of Gemini's overall strategy to answer the fundamental questions posed at the Aspen meeting. PRVS can also provide a sample of terrestrial-mass planets for follow-up imaging by the James Webb Space Telescope (JWST).

The PRVS conceptual design studies were completed in October 2006 and the team lead by the United Kingdom Astronomy Technology Centre (UK ATC) was chosen to build PRVS. The team includes the University of Hawai'i Institute for Astronomy, Pennsylvania State University, and the University of Hertfordshire. The Gemini Board will meet in May 2007 to decide whether or not to proceed with the design and construction of PRVS.

The Wide-field Fiber Multi-Object Spectrometer (WFMOS)

The scientifically highest-ranked instrument to emerge from the Aspen process was WFMOS. It would permit about 4,500 spectra to be taken simultaneously across approximately a 1.5-degree field of view. This multiplex gain makes WFMOS a truly transformational instrument, enabling exciting science projects that were nearly unfathomable with the current generation of instruments.

During the WFMOS Feasibility Study two years ago, Gemini and Subaru Observatory (of the National Astronomical Observatory of Japan) agreed to explore the possibility of a collaboration on WFMOS. The Japanese would share the cost of building WFMOS and it would be installed on the Subaru telescope, a more appropriate platform than Gemini for such a massive, wide-field prime focus instrument. In exchange for observing time on Subaru, Japanese astronomers would have access to observing time on Gemini.

The agreement is still in the early phases of development. Subaru's new wide field imager, HyperSuprime, is now being designed, and it would be developed in parallel with WFMOS. They would share a common wide-field corrector, and the science goals of the two instruments, to measure the acceleration of the expansion of the universe, are highly complementary.

In October 2005, the Gemini Board agreed to begin competitive conceptual design studies for WFMOS. In May 2006, while contract negotiations were still in progress with two teams, the Gemini Board decided to suspend the studies until adequate funding could be secured. A few months later, in September, the funding for the design studies was committed, and Gemini began the challenging process of re-engaging the two teams, a process that is still underway. Gemini is exploring possible organizational models that will be needed to coordinate WFMOS construction across a number of institutions around the world and to include Subaru in the overall management of the project. An instrument as expensive and complex as WFMOS will demand new ways of working together within the Gemini partnership and around the world.

Ground Layer Adaptive Optics (GLAO)

The final Aspen capability that is being considered will improve telescope image quality and performance for almost all instruments. GLAO is a specialized AO system using five laser beacons and an adaptive secondary mirror to correct the turbulence very near the ground on Mauna Kea (see the December 2006 issue of *GeminiFocus*, page 77 for more information). Since the targeted turbulence is close to the telescope pupil, the corrected field of view on the sky is quite large. GLAO will be able to feed an instrument with a field of view of several arcminutes across, providing images with 0.2 to 0.3 arcsecond resolution (FWHM) across the field. The effect of improving image quality is to reduce integration times, making the telescope more efficient and productive. Some science projects that would otherwise require prohibitively long exposures, such as deep imaging of very faint, distant galaxies, will become possible with GLAO. As an additional benefit, the Strehl ratio and system emissivity in the mid-infrared will be significantly improved using the adaptive secondary mirror.

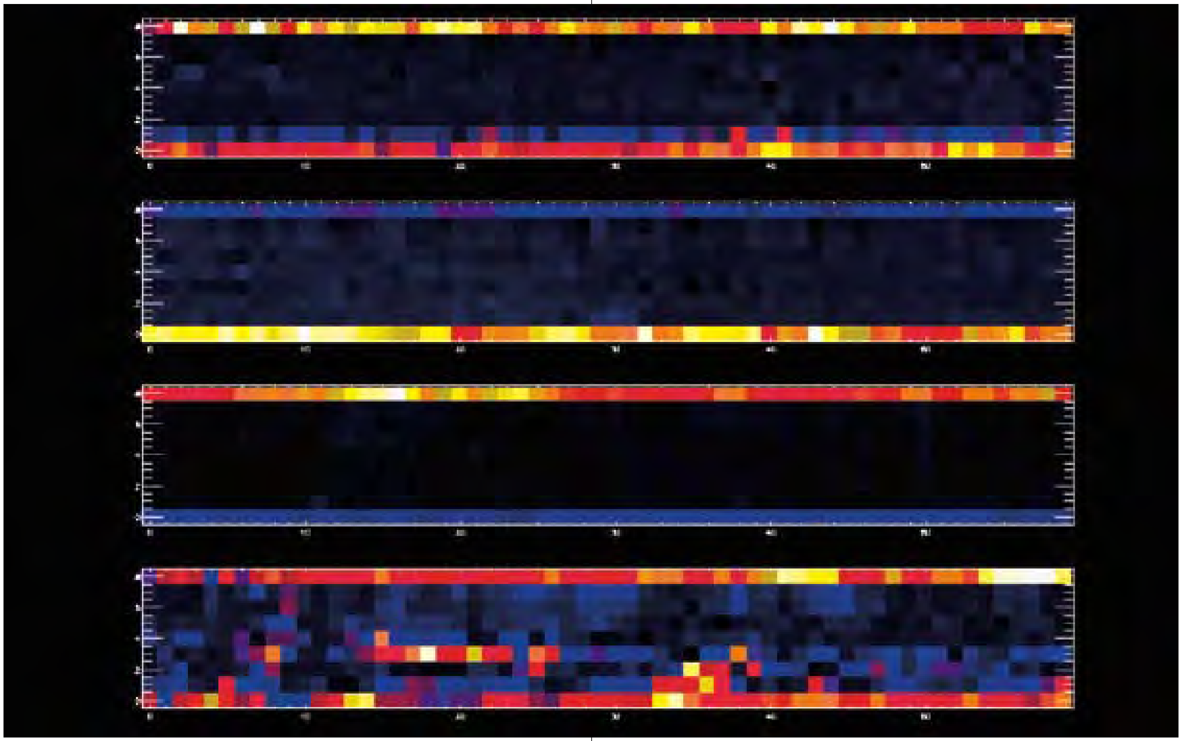

Figure 7.
A sample of turbulence data from the MKSM project illustrating four different types of turbulence profiles. In each box, time progresses along the x-axis. Height above the ground is represented on the vertical axis (the uppermost row represents all of the turbulence above roughly 500-1,000 meters). The brighter colors indicate stronger turbulence. There is often a strong layer of turbulence in the lowest 100 meters.

After the Aspen meeting identified the potential of GLAO, a feasibility study was performed by our colleagues at the Hertzberg Institute for Astrophysics (in Victoria, British Columbia), Durham University (in the United Kingdom), and the University of Arizona, (in the U.S.). It showed that GLAO would indeed be very effective at improving observing efficiency, almost like having a third Gemini telescope when GLAO is in use. The baseline GLAO system calls for an adaptive secondary mirror, a laser guide star constellation comparable to the MCAO system at Gemini South, and new wavefront sensors in a new acquisition and guidance system (which are already scheduled for replacement in a couple of years). No new instruments have yet been proposed to take full advantage GLAO, but the conceptual design was made to be compatible with the existing suite of instruments.

The feasibility study results were based on atmospheric data from Cerro Pachón. Since the ground layer turbulence on Mauna Kea may not be as significant as at Gemini South, the next step in the GLAO development is to make a detailed measurement of the ground layer turbulence on Mauna Kea. The Mauna Kea Site Monitoring (MKSM) project is now under way, under the direction of Mark Chun at the University of Hawai'i. The MKSM project runs two specialized instruments on a small telescope, temporarily installed on the roof of the University of Hawaii's 88-inch Observatory building. They are collecting data for approximately 1,000 hours spread throughout the year to sample a variety of weather conditions during all seasons (see Figure 7, previous page).

When the project is complete, the MKSM data will be fed into the numerical models constructed during the feasibility study. The model results will indicate the efficiency gain likely to be achieved with a GLAO system for a variety of conditions. The results will be used to decide whether or not to conduct a conceptual design study for GLAO in 2008.

Summary

With the existing and future instruments that are being designed, constructed, and commissioned now, astronomers using the Gemini telescopes will be able to detect new and different types of planets than have been found to date. Through dedicated surveys, these will help determine the abundance of planetary systems like our own. We will find the first galaxies to form after the Big Bang and chart the expansion history of the universe. Astronomers will examine the relationships between millions of stars in the Milky Way by reading their compositions and motions. Through international cooperation in constructing these new instruments (which are designed and built by institutions in our partner countries), and by conducting dedicated surveys, the Gemini partnership will contribute fundamentally to our understanding of planetary systems, the formation and evolution of galaxies, and the nature and composition of the universe.

Joseph Jensen is the Head of Instrumentation for the Gemini Observatory and can be reached at: jjensen@gemini.edu