Report from the Keck Time Domain Working Group (TDAWG)

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A Working Group Created by the
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Executive Summmary

Keck Observatory, for a modest investment, will be able to supply the tools necessary to remain competitive in the next decade in the realm of **Time Domain Astronomy** (TDA). This report describes the scientific motivation for TDA at Keck, evaluates the current Keck capabilities for TDA science, and proposes new hardware, software, and logistical improvements to enhance Keck Observatory's competitive position in the TDA realm. Our primary conclusions and recommendations are summarized here:

1. Technical improvements with the greatest impact are centered around software projects. As our highest priorities, we recommend that the Observatory take the following steps:
    - Create a Data Access Project at the Observatory, to oversee the construction of a suite of software tools for facilitating data flow of TDA science.
    - Facilitate intranight communication between observers and TD scientists through informational websites
    - Create of one-stop shop (real-time) website for potential TDA observers
2. All instruments that are possibly available for TDA science should be readied to the extent possible given resources
3. Begin to advertise TDA science and associated Observatory projects as a funding opportunity for private donor institutions.

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CHAPTER 1

Time Domain Astronomy

SECTION 1.1

Introduction

While time domain astronomy (TDA) implies unplanned observations of sources with temporal brightness variability on short timescales, the broader scope of TDA includes the observations of *any* observable property of an astrophysical source that changes with time. TDA science, then, can make use of observed changes in **brightness**, **location** (through astrometry), **velocity** (through, e.g., spectroscopic Doppler shifts), and **source size** to infer the basic physical parameters of the system of interest. In this respect, from the discovery of massive bodies in the Solar System and exoplanets, to physical measurements of the black hole at the center of the Galaxy, to the measurement of the acceleration of the Universe with supernovae, it is clear that TDA is a central pursuit of modern astrophysics.

How TDA observations are conducted falls largely into two categories:

1. **Target of Opportunity** (ToO) where the position and epoch (and perhaps mode) of observation is not known with sufficient warning to allow such observations to be scheduled in advance. ToO observations are not necessarily of rapidly (<day) changing, singular events (such as a cosmic explosion), but simply observations that could not be prescribed in advance.

2. **Monitoring** where the parameters of the observations are known with sufficient lead time to allow for scheduling.[1] A Monitoring program consists of at least two (likely similar) observations spaced in time (*synoptic* observing).

The distinction between these two categories is essentially driven by the timescale of change of the system of interest and the way in which telescope time is scheduled.

Keck Observatory, by virtue of its world-renowned user community, aperture size, and instrument suite has been a leader in TDA discoveries. We highlight some of the many TDA results here (instruments used are in brackets):

[1] We do not distinguish here between those monitoring programs where the user can specify all the parameters of the observations in a following observing semester (e.g., transit of moon of a dwarf planet) versus those where there are some unknowns at the start of the observing season (e.g., supernovae spectroscopic monitoring).

- Inference of a cosmological constant with photometry and spectroscopy of supernovae [LRIS] (Riess et al. 1998; Perlmutter et al. 1999)
- Measurement of the orbits of stars around Sgr A*, providing the location and mass of the black hole at the center of the Milky Way [LGS-AO, NGS-AO; NIRC/NIRSPEC] (Ghez et al. 2005)
- Discovery of more than 100 exoplanets [HIRES] (Marcy et al. 2005)
- Discovery of Dysomnia, a moon with common proper motion with Eris, the largest dwarf planet. This will lead to the measurement of the mass of Eris [LGS-AO] (Brown et al. 2006)
- Discovery of the cosmological nature of cosmic gamma-ray bursts of the long (Metzger et al. 1997) and short (Bloom et al. 2006) variety [LRIS; DEIMOS]
- Discovery of the largest volcanic eruption in the Solar System on Io and the first spectrum of an Io eruption [NGS-AO; NIRC2, OSIRIS] (Marchis et al. 2002)

Despite the successes it is clear that Keck is facing increased competition in TDA science from other large-aperture telescopes for a variety of reasons. First, Keck is no longer the only functioning observatory in the 8-m class domain, implying increased competition with similarly sized aperture. Second, most new 8-m class telescopes are fully or partially queue-scheduled allowing for greater flexibility for time-domain science. Third, some 8-m telescopes are designed to provide rapid instrument switches, allowing other observatories to facilitate and accommodate a greater diversity of TDA programs. In §3.2.2 we review in detail the current capabilities of other large-aperture telescope programs for TDA science.

When evaluating future steps that the Observatory can take to ensure competitiveness, it is important to get a sense of potential science drivers for TDA work (§2). Understanding the current capabilities of Keck in relation to other observatories is another important ingredient towards accessing and prioritizing the steps that can be taken to ensure Keck's future competitiveness in TDA current and future science endeavors. In many instances, Keck TDA observations represent the culmination of programs on smaller-aperture telescopes[2] and it seems plausible that Keck TDA science will continue to operate in such a manner. However, in the decade hence, Keck will become more and more of a follow-up tool (likely of transients found with wide-field surveys such as LSST), and act as a feeder to the Thirty-meter Telescope (TMT), much as the Palomar 200-inch is to Keck today.

SECTION 1.2

Time Domain Astronomy Working Group (TDAWG)

At the 2005 Keck Strategic Planning meeting, the Keck community articulated the need to better facilitate Time Domain Astronomy. In response to this, the SSC, in

[2] This is especially true for non-TDA work, but often true for TDA astronomy — for example, programs to study the nature of abnormal supernovae are most efficient by first recognizing outlier properties through smaller-aperture telescope programs and then using Keck for detailed follow up when appropriate.

Fall 2005, initiated the creation of a working group dedicated to these considerations. The **Keck Time Domain Astronomy Working Group** ("TDAWG") was officially impanelled by an email from Fred Chaffee, then WMKO Director, on 30 December 2005 with a charter stating that the goals of TDAWG would be:

1. To provide clear, science-driven strategic guidance for the development of facilities that will enhance Keck's capability in time-domain astronomy.

2. To assist in prioritization of short-term activities that will optimize the Observatory's ability to respond to time-dependent astronomical events. (See §4.8)

J. Bloom was named chairman of TDAWG and R. Goodrich was named as Observatory liason. TDAWG's identified responsibilities were "to assist the Observatory and the SSC in understanding the requirements for improved time domain astronomy at Keck" and to "define the priorities, resources and consequences required to establish the capability for synoptic and rapid time-response observations with the Keck telescopes." These goals and responsibilities were to be met in the form of a presentation to the SSC and Observatory Director as well as a "written assessment of the Observatory's current and desired future capability for responding to time-dependent astrophysical phenomena," including:

- the establishment of the scientific case (See §2)

- an assessment of the time and resource (manpower and equipment) requirements for existing facility instruments to be made available in a timely/flexible way to respond to such phenomena. (See §4.1 – 4.3).

- An assessment of possible modifications to the telescopes and/or instruments that would improve the scientific effectiveness of the observation of such phenomena (See §4.1 – 4.3).

The TDAWG committee met via teleconference on six occasions in 2006 (28 February, 28 March, May 9, May 23, 29 August, 29 September), all via teleconference. In addition, members of the committee gave formal progress reports to the SSC on two occasions (17 April – Goodrich, Bloom, SSC meeting; 15 Sept – Bloom, Keck Science Meeting). This document represents the results of those meetings as well as numerous other smaller discussions with TDAWG members and with members of the Keck observing community.

CHAPTER 2

Science Drivers

SECTION 2.1

Overview

This section provides several representative cases for Keck time domain science. While the cases presented span subjects from the inner Solar System to high redshift, we have made no attempt to submit an exhaustive list of science drivers. High impact science is a necessary ingredient for inclusion herein but it is not sufficient; we have focused on cases where Keck, by virtue of its size and instrument suite, could play a pivotal role. A few of the identified science projects are being conducted already but are not making most efficient use of the facilities because the instrument-switching capabilities are not in place or are not well known. No attempt is made here to discuss the *mechanics* of how the projects will be implemented.

Most projects are *forward looking* in that they could not been done today for two reasons. First, the capabilities may not yet be in place (e.g., rapid switching to HIRES). Indeed, as new capabilities of the Observatory come on line, the nature of inquires will evolve and the timescales over which observations become interesting will, generally, shorten. For instance, as the astrometric accuracy of KI improves[1] from 1 milliarcsecond to 30 μarcsecond (1 σ), significant astrometric motions can be detected 33 times more quickly: testing for the common proper motion of two sources could then be done over nights instead of months. Also, with improved precision, the Galactic center becomes a General Relativistic testing ground for frame-dragging (§2.2.7). Second, the discovery rate of targets for Keck TDA follow-up might be, at present, low. For example, a few tidal-disruption events around supermassive black holes have been discovered in archival data, but future surveys starting as earlier as 2007 are expected to yield near real-time discovery of dozens per year (§2.3.6). TDAWG believes that Keck, over the next decade, can be positioned to capitalize on the "needles in a haystack" found by Next Generation Imaging Surveys (NGISs). NGISs such as Pan-STARRS[2] and LSST[3] will image much deeper ($\sim$24th mag)

[1] Through the funded program "Development of the Keck Interferometer with Laser Guide Star Adaptive Optics for Microarcsecond Astrometry - from Exoplanets to Black Holes," PI Peter Wizinowich.

[2] `http://pan-starrs.ifa.hawaii.edu/`

[3] `http://www.lsst.org`

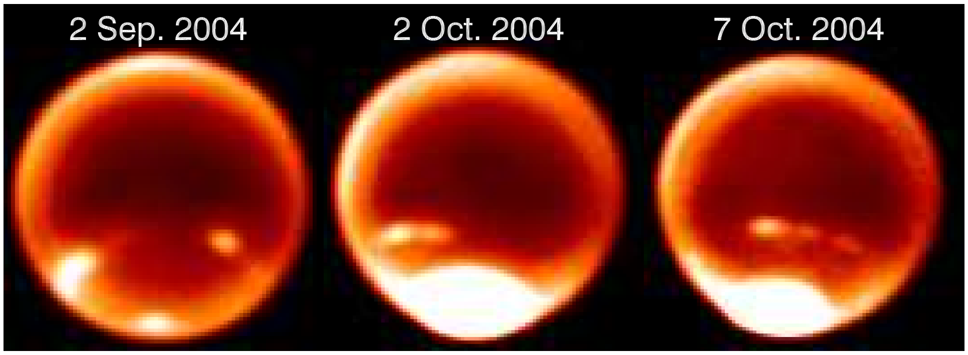

Figure 2.1 Shown is the evolution of massive south polar storm on Titan evolving during late 2004 and several eruptions of the mid-latitude clouds that we have now linked to a single geographic region on Titan's surface that is the best candidate location of currently active cryovolcanism. The discovery and understanding of both of these features has been made possible with Keck NGS-AO in modes that allow gathering small amounts of data (15–20 min) over 41 nights. From Roe et al. (2005)

than contemporary sky surveys and, important for TDA science, repeat coverage of the entire sky with cadences of weeks or less. The deep synoptic imaging will be a major discovery engine for "known unknowns"[4] and explore large enough regions of new parameter space to allow discovery of as yet unknown phenomena.

SECTION 2.2

Monitoring Science

Topics outlined here are both time-sensitive in nature and require observations that have some degree of forewarning. The observer could be looking for a rare event by monitoring many fields, have scheduled with other facilities simultaneous monitoring across the electromagnetic spectrum, or could require regular observations of a source that changes with time.

2.2.1 Titan Meteorology and Hydrology

Titan's methane weather (see Figure 2.1) is in a period of significant seasonal change with the south polar clouds nearly having disappeared and the expectation that equatorial clouds should emerge in the next few years. Astronomers have now linked the mid-latitude clouds to a region on the surface that is likely geologically active and controlling cloud formation. With continued monitoring it will be possible to identify other localized regions of cloud formation from geologic activity. This is primarily a monitoring project, requiring only 15–20 min per snapshot (either using a single OSIRIS setting, or images in 3 filters from NIRC2.)

[4] Pan-STARRS1, slated to begin in 2007, will, for example, allow for the identification of more asteroids in a single lunation than are currently known ($\sim 3 \times 10^5$) and on a nightly basis find more Near Earth Objects (NEO) and Potentially Hazardous Objects (PHO) than all existing surveys combined.

2.2.2 Single apparition Potentially Hazardous Objects (PHO) followup

Some objects will be identified by NGISs for which the derived orbit indicate the object is a PHO. Most of these objects will be recovered by the NGIS in subsequent (or precovered in previous) lunations or even in later (and earlier) apparitions. Some small subset will turn out to be dangerous and unlikely to be recovered. While other smaller telescopes can obtain followup as long as possible, the extra arc length afforded by astrometric measurements by a 10-m class telescope when the object is too faint for all other systems could be critical to an impact risk determination. Only those objects that fall into this category need be passed on to the Keck Monitoring or ToO pipelines.

2.2.3 Close Approach Opportunities

The Keck LGSAO system[5] can provide seeing FWHM at R=19 mag of about 0.1 arcsec (and much better for brighter objects but we use the worst case scenario here). The 0.1 arcsec-resolution corresponds to about 10 m at a distance of 20,000 km. Asteroid Apophis will approach the Earth to about this distance in 2029 and 2036 and it is about 300–400 m diameter. At that time it will actually be a naked-eye object. Thus, LGSAO could be an important tool for understanding this object's shape especially in combination with simultaneous radar measurements. We expect that the NGIS will provide more opportunities for this kind of science.

2.2.4 Probing the Fundamental Parameters of Dwarf and Sub-stellar Systems

Combining[6] visual and radial velocity (RV) orbits of binary and multiple star systems provides measure of component masses and the distance to the system (allowing determination of the intrinsic stellar luminosities). However, until recently the number of systems for which such combined models were possible was severely limited by the conflicting observational biases for visual and RV measurements; visual orbits are more sensitive to long-period, widely separated systems, whereas velocities are largest in short-period systems.

The gap between visual and RV measurements has been bridged by the maturation of long baseline optical interferometry, which has been used to obtain high resolution measurements of the visual orbits of spectroscopic binaries (see, for example, Boden et al. 1999; Armstrong et al. 2006; Boden et al. 2005). Additionally, the high resolution observations in several instances determine additional fundamental properties of the system such as the component sizes and luminosity ratios. While the properties of sunlike main-sequence stars are relatively well established, those at the extremes of stellar types still require observational support. In particular, low mass, young, and evolved systems lack many direct measurements of their physical properties. The improved sensitivity of the KI allow many more of these (often very red) targets

[5] http://www2.keck.hawaii.edu/optics/lgsaoperformance.html

[6] TDAWG thanks M. Muterspaugh and J. Eisner for contributions to this and other KI science drivers

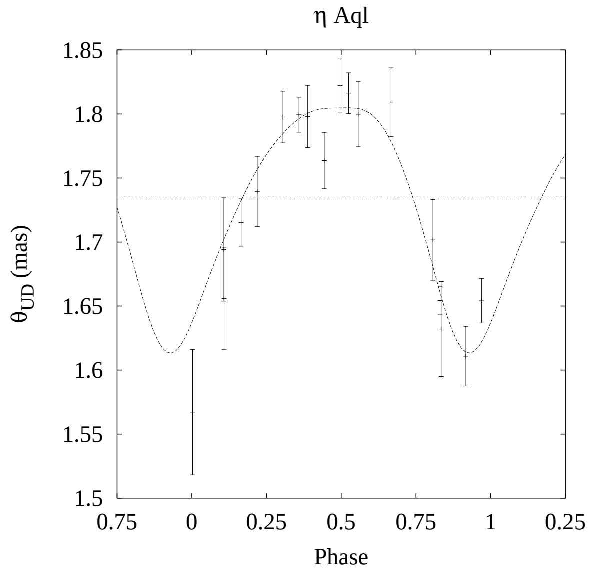

Figure 2.2 Variations in the apparent diameter of η Aql caused by radial pulsations in the Cepheid (figure from Lane et al. 2002). When combined with spectroscopic observations of the line-of-sight velocity variations of the stellar surface, the Cepheid's distance can be determined. This calibrates the Cepheid Period-Luminosity relationship, a key part of the astrophysical distance scale.

to be studied. The differential astrometric orbits of binaries can also be used to as distance measures. An important recent result in this field concerns the distance to the Pleiades, as measured by observations of the binary system Atlas. By combining interferometric observations with simple models (Pan et al. 2004) or radial velocity data (Zwahlen et al. 2004), the distance to the system was find to disagree with the controversial result from *Hipparcos* while agreeing with other results.

2.2.5 Cepheid Distance Scale

The relationship between intrinsic luminosity and pulsation period in Cepheids has long been recognized as an important tool for measuring astrophysical distances. Accurate calibration of this relationship affects a vast number of astrophysics programs. Combined studies of the angular size and line-of-sight velocity pulsations allows determination of the distances to nearby Cepheids, see Figure 2.2.

As relatively early type stars, Cepheids have high surface brightnesses. Given the limited (5 mas) resolution of the KI, Cepheids large enough to be resolved by KI are bright enough to be observed by other systems (e.g. PTI and the CHARA Array), and those too faint for other observatories are unresolved by the KI baseline. However, in phase-referenced astrometric mode, the relative parallaxes of some Cepheids might be measured directly, to establish their distances.

2.2.6 Investigating the Nature of Relativistic Outflow Physics

Relativistic astrophysical outflows are ubiquitous yet the detailed nature of the evolution and emission mechanisms (particularly in the presence of magnetic fields) is far from well understood. The Crab pulsar represents an excellent nearby laboratory

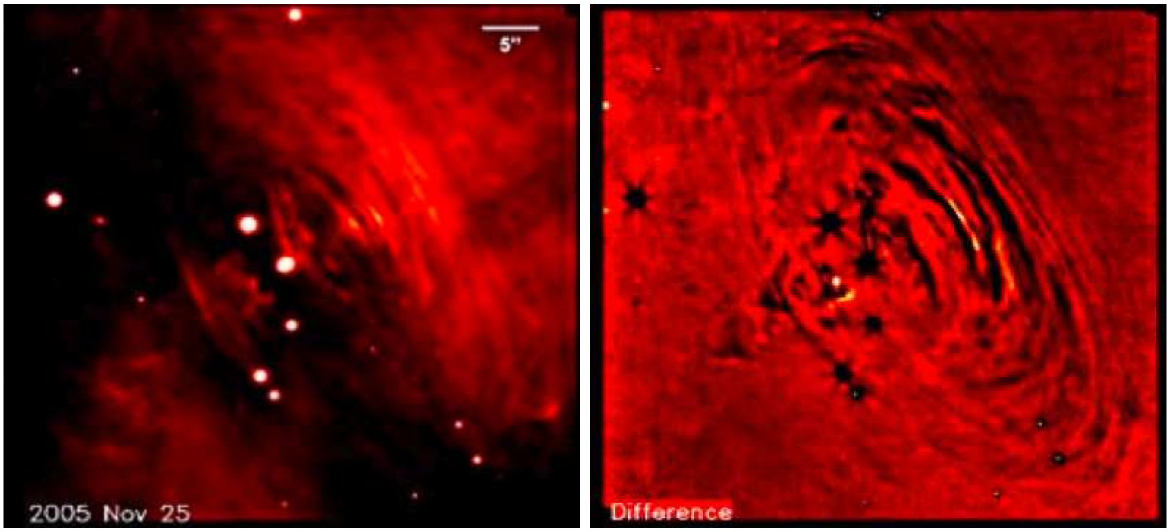

Figure 2.3 Keck LGS-AO observation (left) of the Crab Nebula by Max & Graham. At right, a difference image from a previous epoch. Brightness variations of the wisps are apparent. Long term monitoring with LGS-AO of this field over years timescale will allow for the detailed measurement of secular changes in the wisp and knot structure providing a detailed picture of the physics of pulsar winds.

for the study of relativistic winds from pulsars. How is the pulsar wind launched? How and where is the rotational energy of the neutron star transformed into the synchrotron-emitting plasma that fills the Crab Nebula? What mechanisms accelerate particles at the wind termination shock? At optical and X-ray wavelengths the wisps appear to propagate outward like wave crests. However it is unclear whether old wisps propagate outwards and are replaced by newly formed wisps close to the pulsar, or whether the wisps undergo an oscillatory "limit cycle". Close to the pulsar (50 light days), and interior to the wisps is a polar sprite that fluctuates violently in both location and brightness.

A unique aspect of Keck LGS-AO – one that has just begun to be exploited by C. Max and J. Graham – is the potential for relatively easy access to time-series imaging, to measure timescales for changes in the wisps and knots as a function of distance from the pulsar, and hence constrain the ion mass–to–charge ratio and the Lorentz factor in the inner regions of the pulsar wind nebula. Typical observations would be conducted in a series of 1.5-hour observations of the Crab at H band on a variety of timescales (days, months, years) sampling changes in the large wisps, and with a time baseline long enough to characterize the slower secular behavior of the overall wisp and knot pattern[7] .

2.2.7 The Galactic Center

The Galactic Center (GC) has been monitored for over a decade with Keck, first using speckle, then with NGS-AO, and now with LGS-AO (Ghez et al. 2005). The transition to each new technique saw an improvement in the astrometric accuracy of

[7] This section is summarized from the work and Keck proposal of C. Max & J. Graham; TDAWG thanks them for their assistance

stellar positions, solidying precise location and mass of the black hole at the center of the Galaxy (Figure 2.4). A major leap in the accuracy of stellar orbits in the GC is on the horizon thanks to the successful proposal by Wizinowich et al. to introduce a phase referencing mode which will lead 30 μarcsecond rms positional accuracies. With the more than factor of 30 improvement over LGS-AO, continued monitoring of stellar orbits will open up new vistas: "parametrized post-Newtonian" General Relativity effects in the strong-field limit and "extended matter" effects are easily detectable (at the $>$ 5-σ level in several years of monitoring). The detection of BH spin via frame-dragging is also a possibility with this new capability (based on Weinberg et al. 2005).

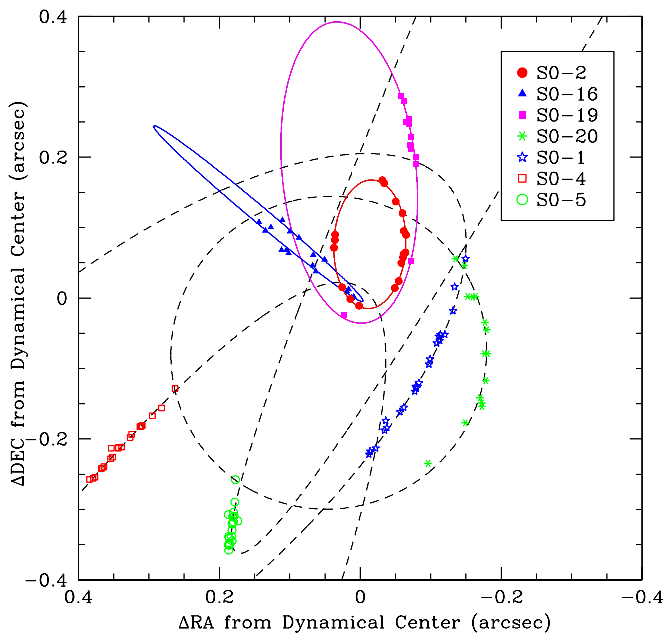

Figure 2.4 (left) Remarkable astrometric monitoring of the stars near the Galactic Center with Keck have demonstrated the existence of the $2.6 \times 10^6 M_\odot$ supermassive black hole (Ghez et al. 2005). As the KI capabilities improve, astrometric monitoring may be sufficient pin down the black hole spin.

2.2.8 Supernovae – Diversity & High redshift observations

The meticulous spectroscopic and imaging observations (with Keck, in part) of supernovae (SNe) out to redshifts of order unity, led to one of the most dramatic and unexpected discoveries of the 20th century: the universe is accelerating due to the presence of a non-zero cosmological constant (Riess et al. 1998; Perlmutter et al. 1999). Observing campaigns for the discovery of high redshift SNe ($0.5 < z < 2$) continue to be organized. Few-epoch spectroscopy of the highest redshift sources, for type confirmation and for searches of diversity relative to the low z sample is of critical importance to the precision cosmology work. Some targets will be found serendipitously, necessitating a ToO, but most will be discovered with enough regularity to allow a Monitoring campaign. *Ad hoc* multi-epoch Monitoring of individual objects may also be triggered with increasing regularity as the higher rate of SN discovery (with, e.g., the NGISs) will increase the possibilites of finding anomolous sources. The recent discovery of a bright Type Ia supernova (SNLS-03D3bb), inferred to have arisen from super-Chandrasekhar-mass white dwarf (Howell et al. 2006), is a reasonable example of the need for Keck Observatory to facilitate intra-semester Monitoring campaigns to observe watershed events.

SECTION 2.3

Target of Opportunity Science

Topics outlined here are time-sensitive but observations are required with little or no warning. New transients in the night sky found by small-aperture telescopes might serve as the feeder to Keck ToO spectroscopic observations.

2.3.1 Comets

The NGISs will find more comets in a year than are currently known. One of the big questions in cometary science is the size-frequency distribution (SFD) of cometary nuclei. There are a few techniques used to measure the SFD but one of the most obvious is imaging of the comet when it is still coming into the solar system before a coma has time to appear or long after it has passed the Sun. The NGISs could feed lists of these faint, distant comets to the Keck for followup within a few months.

2.3.2 High impact risk PHO characterization

Some objects will be identified by the NGISs for which the derived orbit indicates a high future risk of impact. Most of these objects will be very faint and have little or no time in the future when they will be bright enough for smaller telescopes to obtain spectra or even colors that would provide a much better indication of the objects' diameter and compositions (both affecting the risk characterization). In some instances a 10-m class telescope will be the only option for obtaining the colors and/or spectra of the object. Further characterization would involve obtaining high S/N fast time-resolved photometry in order to invert the light curve and determine the objects' rotation period, pole orientation and rough shape. These parameters are necessary to quantify the Yarkovsky effect (the force due to anisotropic emission of thermal photons) on the asteroid. For well determined orbits, the Yarkovsky effect is usually the largest remaining uncertainty in the impact risk calculation. Low resolution IR spectra would provide even better information on the objects' composition allowing a better density determination.

2.3.3 Unusual Solar System Objects

The list of unusual objects that the NGISs may identify in the next 10–15 years is very exciting and include distant planets (e.g., Eris), extra-solar objects passing through our Solar System, Main Belt asteroid collisions in progress, tumbling (non-principal axis rotation) and fast-rotating (near their mechanical strength limit) asteroids, strangely colored objects (many NGIS surveys will obtain measurements in multiple bandpasses as well), and multiple asteroid systems. Most of these strange detections will benefit dramatically from followup by a 10-m class telescope. The distant planets will likely be faint and the only way to obtain good S/N measurements of their color and visible/NIR spectra will be with a giant telescope. While the odds of detecting an extra-solar object passing through our Solar System are low, the opportunity to physically characterize it with good visible/NIR spectra and determine the chemistry of another solar system is priceless. A main belt asteroid collision would be identified by the NGIS as a high S/N moving object with main belt-like rates that is not identified on subsequent or previous images or that has a dramatic change in brightness. They will continue to fade fast and immediate followup by any telescope capable of characterizing the aftermath of the expanding dust cloud is critical. Tumbling, fast-rotating, strange color and multiple object systems will often be detectable by other smaller systems. But a 10-m class telescope will allow fast time-resolved photometry and spectroscopy to characterize the rotation state and physical properties of the objects. Objects that approach close to the Earth on their first apparition may never be in reach of ground-based telescopes for decades and fast followup is necessary. Some of these objects will fall under the monitoring category while others will be ToO.

2.3.4 Microlensing

High-magnification[8] gravitational microlensing events provide a unique opportunity to acquire high signal-to-noise spectra of distant (lensed) stars. Heyrovský et al. (2000) showed how spectra at both high- and low-resolution of lensed red giants could provide meaningful tests of atmospheric models. Since giants are efficient at mixing heavy elements, observations of lensed dwarf offer a more accurate measure of initial gas content. Recently, Johnson et al. (2006) presented an R = 45,000 Keck spectrum of the microlensed Galactic bulge G-dwarf OGLE-2006-BLG-265, which has a high (~ 60; Fig. 1) signal-to-noise ratio despite its short (15 min) exposure time because the source was magnified by $A \sim 135$. At the time of observations, Keck had an effective aperture of > 100m, so these results indeed provide a taste of future TMT science. Similar high resolution spectra could be obtained for about a dozen bulge dwarf stars per year[9] (or more, if Pan-STARRS opts to focus on microlensing in the buldge) by means of well-designed ToO observations with HIRES.

2.3.5 Interferometric Imaging of Explosive Outbursts

Recently, eruptive transients such as Novae have been successfully resolved by interferometers as ToO events. The high resolution observations provide a new window into the sequences of events occurring in these systems. Figure 2.6 shows observations from the Palomar Testbed Interferometer (PTI) which measure the linear growth of Nova Aql 2005 during the week after its detection (Lane et al. 2006). Later, the growth appears to stop, perhaps as the ejected material becomes optically thin. Con-

[8] TDAWG thanks A. Gal-Yam for his contribution to this section.

[9] By monitoring more than a hundred million bulge stars, the Optical Gravitational Lens Experiment (OGLE-III) Early Warning System (EWS; Udalski 2003) has been finding about 600 microlensing events in each of the last four years, of which about a dozen per year have $A_{max} > 100$.

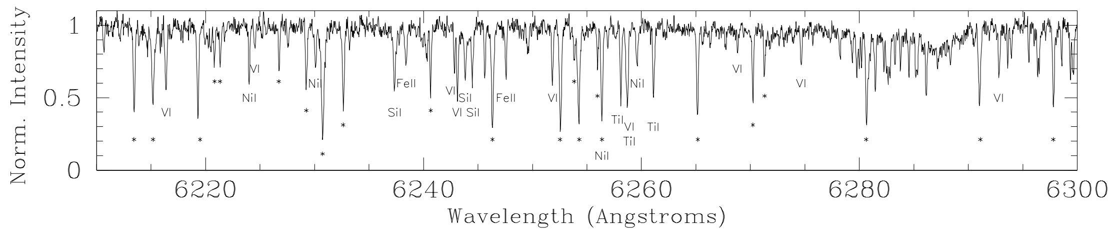

Figure 2.5 A portion of the HIRES spectrum of OGLE-2006-BLG-265. This bulge dwarf star was magnified by $A \sim 135$ during the observations, so a high (~ 60) signal–to–noise was achieved in just 15 minutes of observing time. This bulge dwarf is apparently the most metal-rich star known ($[Fe/H] = 0.56$), but the higher temperature of this star compared with the luminous red giants usually measured in the bulge gives its spectrum many unblended atomic lines. Johnson et al. (2006) measure the abundances of 17 elements, including the first abundances for S and Cu in a bulge star. Because the star is a dwarf, the [O/Fe], [Na/Fe], and [Al/Fe] ratios cannot be attributed to internal mixing, as is sometimes claimed for giants. The unpredictable nature and short duration of such high magnification events requires a ToO program to take advantage of these rare opportunities.

versely, little size change is seen in the recurrent Nova RS Oph, which had an outburst in 2006 (Monnier et al. 2006). Clearly, nova phenomena are varied and much is yet to be understood. The improved sensitivity of KI will allow many more of these to be observed; as nova are often very red, these fainter targets will still be resolvable by KI. As a ToO, some Novae may be missed when not in interferometry mode; however, it is noted that a KI measurement of RS Oph was made within days of its outburst, and contributes to the study of that system.

Supernovae tend to be much more distant, and thus fainter, than Novae. KI, particularly in phase-referencing mode, will be the first interferometry with the sensitivity to probe these phenomena at high spatial resolutions. It will have a several year advantage in development over the VLTI, the only other system that might have the sensitivity to target these objects.

2.3.6 Black Hole Tidal Disruption Events

It is widely expected that black holes smaller than about $10^8 M_\odot$ can tidally disrupt stars that pass sufficiently close to them. Above this mass, the disruption occurs within the Schwarzchild radius and is thus unobservable. Part of the material from the disrupted star would settle into an accretion disk, igniting a short-lived active nucleus. Determining the rates of such events is important as they may be significant contributors to the cosmological growth of black holes. Only a few candidate events have previously been detected in X-ray (Komossa et al. 2004) and optical (Stern et al. 2004) surveys, and little observational data exists yet to constrain the event rates or optical luminosities. NGISs are likely to find large numbers of candidate events[10] , en-

[10] E. Quartert has looked at the Pan-STARRS1 rate in detail and finds that roughly 30–100 events will be found out to $z < 0.1$ per year. The precise peak magnitude ($R \sim 20$) is uncertain because

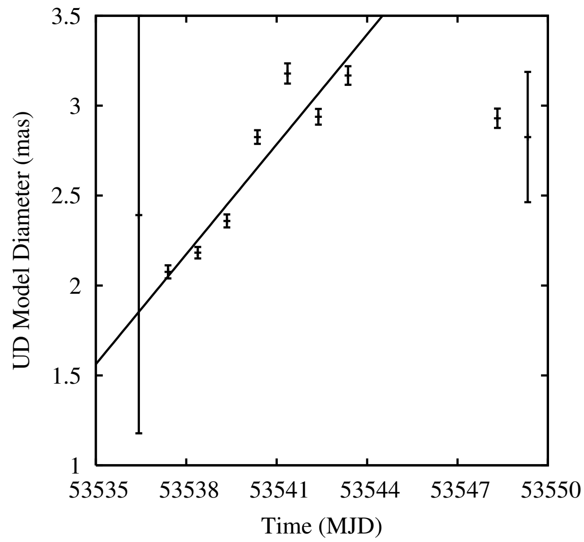

Figure 2.6 The linear growth of Nova Aql 2005 in the week after its outburst (figure is from Lane et al. 2006). In later weeks, the growth appears to stop.

abling the first opportunities for "real-time" monitoring. A major challenge will be to distinguish tidal disruptions from normal AGN variability or SNe, prior to conducting follow-up observations on Keck and other large telescopes. If good candidates can be found, Keck observations could provide crucial spectroscopic confirmation, redshifts, and monitoring of emission-line diagnostics and variability over timescales of weeks to months. Low to moderate resolution optical spectroscopy (LRIS, DEIMOS, ESI) would be ideal for emission-line diagnostics and variability monitoring.

2.3.7 Supernovae

Identification[11] and study of the progenitor systems of supernovae (SNe) provide a key clue to understanding SN physics, still far from being understood. Different explosion mechanisms predict unique mappings between progenitors and the resulting SNe (e.g., Heger et al. 2003). However, we still do not know how the observed SN properties (brightness, light curve shape, spectroscopic abundances of H, He and other elements) relate to the putative progenitor (age, initial mass, mass loss history, binarity). There are two promising directions in the context of Keck TDA: studying with spectrographs the shock breakout hours after the explosions and obtaining with AO imaging constraints on the progenitors. Both will leverage off of increased detection rates of (young) supernovae with NGISs.

Young supernovae: shock break-out

The models of Ensman & Burrows (1992) show that shock breakout occurs roughly 1–2 hours after core collapse, brightening many magnitudes to a maximum brightness

the total amount of energy released at optical wavelengths is highly uncertain. Pan-STARRS4 and LSST will increase the detection rate by a factor of 4 and > 20, respectively. We thank him for this calculation.

[11] TDAWG thanks R. Foley & A. Gal-Yam for their contributions to this section.

in a few minutes, dimming after a few minutes, and fading for approximately one day before the normal SN light dominates. The rise/decline as well as peak luminosity allow for the determination of many aspects of the progenitor (radius, whether it had a wind) and SN explosion (energetics, heavy-element creation). Furthermore, changing densities and ionizations determined from multiple spectra during this phase will tell us about the circumstellar environment of the progenitor. Spectropolarimetry (with LRIS-p) would probe the asymmetry of the different layers/stages of the explosion as well as possibly the circumstellar environment.

A single data set would be incredibly useful in understanding both the progenitors and explosions associated with SNe. Observations of many shock breakouts would lead to the categorization of progenitors by radius, allowing for a better understand stellar evolution (what portion of blue supergiants explode as SNe, etc.) and death (associating progenitors with SN spectral types).

Progenitors

Direct observations of massive stars — before they explode — provide a model free identification of SN progenitors. Such studies require the combination of a deep, high-resolution image of the SN location, serendipitously obtained before it exploded, with a precise localization of the SN (after it exploded) to enable the correct selection of the progenitor from among the stars in the pre-explosion SN images. After decades of effort, *only seven SN progenitors* have so far been detected. The use of Keck LGS-AO represents a promising direction for such studies (Figure 2.7). A minimal ToO allocation leveraged by superb archival *HST* data provides exciting results. Each trigger requires $\sim 600s$ total integration, or ~ 30 min of clock time, including typical LGS-AO overheads. With each additional progenitor identified and studied, we move closer to a robust mapping of specific progenitors to each SN class, a key to understand the physics of these powerful cosmic explosions.

2.3.8 Gamma-Ray Bursts

The gamma-ray burst (GRB) field, a natural driver for ToO observations, is rapidly evolving. Whereas a few years ago the state-of-the-art was in the discovery of redshifts through absorption line spectroscopy (something at which Keck was a world leader until Gemini and the VLT came on-line), most of the science drivers now call for repeated deep imaging, low-resolution spectroscopic monitoring, and synoptic high-resolution spectroscopy. Deep imaging on timescales of minutes to days after a short duration GRB will be required to search for and characterize any thermal emission (Li-Paczyński "mini-supernova") of non-relativistic ejecta (Li & Paczyński 1998) from degenerate merger products (such as neutron star–neutron star mergers).

Low-resolution (especially polarimetric) spectroscopy campaigns on low-redshift GRBs (such as GRB 031203 and GRB 060218) will be required to study in detail the supernovae which are thought to accompany long-duration GRBs and provide constraints on the nature of the progenitor[12] . Changes of absorption line properties, seen only once (Figure 2.8), are predicted to occur in the first several minutes after a

[12] Such a campaign should start within one day after a GRB and obtain data approximately every day for two months. In this sense, this project is a triggered *Monitoring*

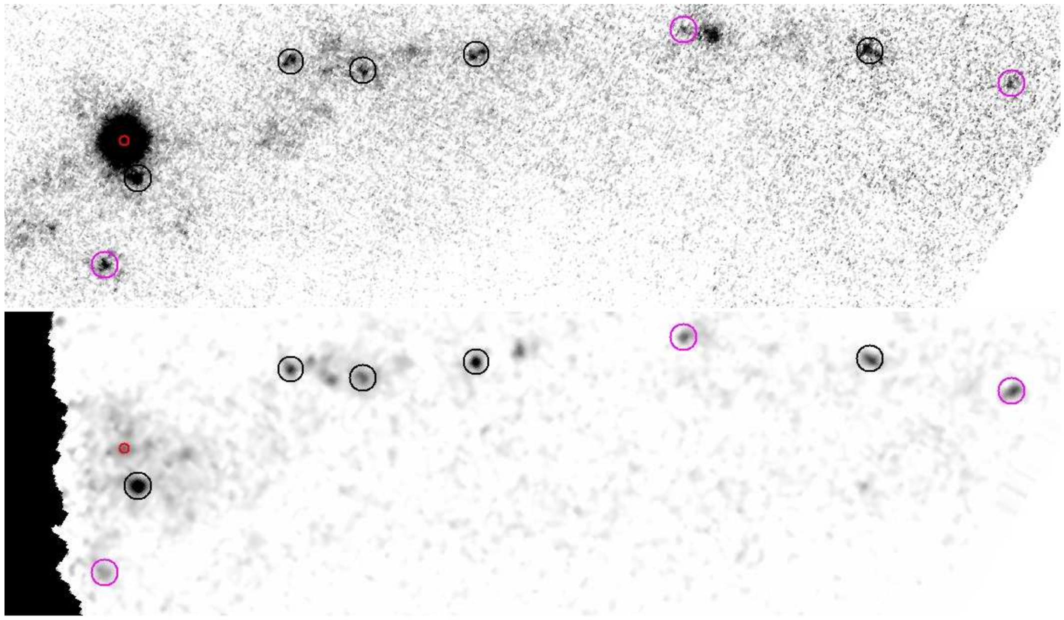

Figure 2.7 Accurate registration of an LGS K'-band image of SN 2005gl (top) onto pre-explosion *HST* V-band image of this location (bottom) using common sources (green circles). A point source ($M_V = -10.3 \pm 0.2$ mag) at the SN location (red circle; 5σ localization) is tentatively identified as the progenitor, a luminous blue variable (LBV). Gal-Yam et al. (2005) placed the best constraints on the luminosity of the progenitor of type Ic SN 2004gt, excluding a large fraction of Wolf-Rayet stars as possible progenitors.

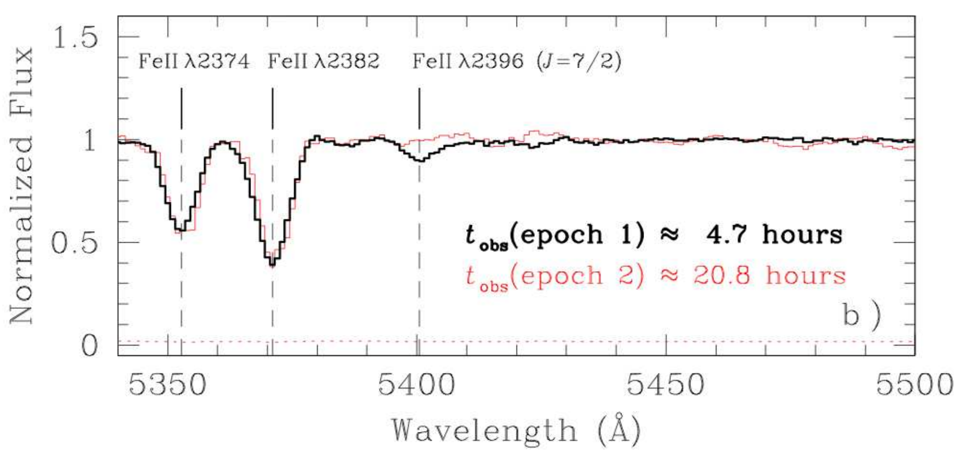

Figure 2.8 First detection of line-strength variability in a GRB afterglow, a critical diagnostic of the progenitor wind (Dessauges-Zavadsky et al. 2006). Shown is the re-binned and smoothed VLT-UVES spectrum (thin red curve) to the spectral resolution of the LRIS spectrum (thick black curve) with its corresponding 1-σ error spectrum. FeII $\lambda2396$ is clearly detected in the epoch 1 LRIS spectrum, but is not observed in the epoch 2 UVES spectrum. Synoptic ToO observations of new GRB afterglows with HIRES will undoubtedly reveal the detailed geometry and composition of progenitor winds.

GRB. As such, high-resolution spectroscopy (HIRES) in the first hour after a GRB has the potential to reveal details of the progenitor through studies of the gas in the circumburst wind.

As bright lighthouses, GRB afterglows for hours can outshine the brightest quasars in the sky. This has allowed several groups in the past to use GRBs as unique probes of the gas and dust in distant galaxies. With "easy access" to moderate- to high-resolution optical spectroscopy, systematic programs could develop to use GRBs to understand the nature of Damped Lyman α (DLA) systems (e.g., Chen et al. 2005) and non-continuum features extragalactic extinction curves. Evidenced by the Subaru spectrum of a GRB at $z = 6.295$ (Kawai et al. 2006), GRB afterglows will also soon provide probes of the early universe (in to the Epoch of Reionization), before the assembly of supermassive could produce bright quasars. In this respect, rapid access to low- to moderate-resolution IR spectroscopic capabilities with Keck must be cultivated.

CHAPTER 3

A Current Assessment

Before detailing our recommendations (§4), we provide an overview of the current capabilities from both a software and hardware perspective. That is, how do TDA scientists currently make use of Keck?

SECTION 3.1

Overview of Current TDA Capabilities at Keck

As highlighted in the *Introduction* (§1.1), Keck Observatory has played a leading role in TDA science, having leveraged the large aperture, large and experienced user base, and instrument suite. Clearly the advent of half-night scheduling has allowed for increased flexibility, allowing the user base to better optimize their classically scheduled time (for instance, for Galactic Center monitoring). Moreover, TDAWG did learn of several TDA monitoring projects that obtained observations at or near desired intervals by a series of informal trades between many observers. Logistically, then, Keck observers are making adequate use of Keck facilities for TDA science (through the TAC process or by other means).

We learned of no instance at Keck Observatory where an instrument change was performed during the night for TDA science on Keck; all TDA science has been performed using either a mounted instrument (for a ToO) or through obtaining regularly scheduled synoptic observations through the TAC process. Still, we feel it is crucial for the Observatory to provide the functionality of intranight instrument switches as well as assurances to the community that the instrument switches (and switch back) will be smooth and robust. In the following, we highlight the current and planned capabilities of Keck with particular attention to time-domain related issues. How does the TDA scientist get TDA science data? How rapidly could different instruments or different configurations be put into the optical path?

3.1.1 Hardware and Instrumentation

Currently, on Keck I, HIRES, LRIS, and NIRC are the primary science instruments. NGS-AO is the only available adaptive optics but an NSF-funded project for a laser and next-generation wave front sensor (NGWFC) will shortly allow LGS-AO on Keck

I. NIRES[1] and MOSFIRE[2] are expected to enter regular operations in semester 2008A and semester 2010A respectively. On Keck II, DEIMOS, ESI, NIRC2, NIRSPEC, and OSIRIS are in operation. A graphic giving the total number of nights scheduled on each instrument over the past three years is given in Figure 3.1. The Keck interferometer (KI), making use of both telescopes, was scheduled 10 nights in 2006 and will likely see increasing usage. We will address the specific mapping of instrumentation to TDA *Science drivers* in the *Recommendations* section (§4).

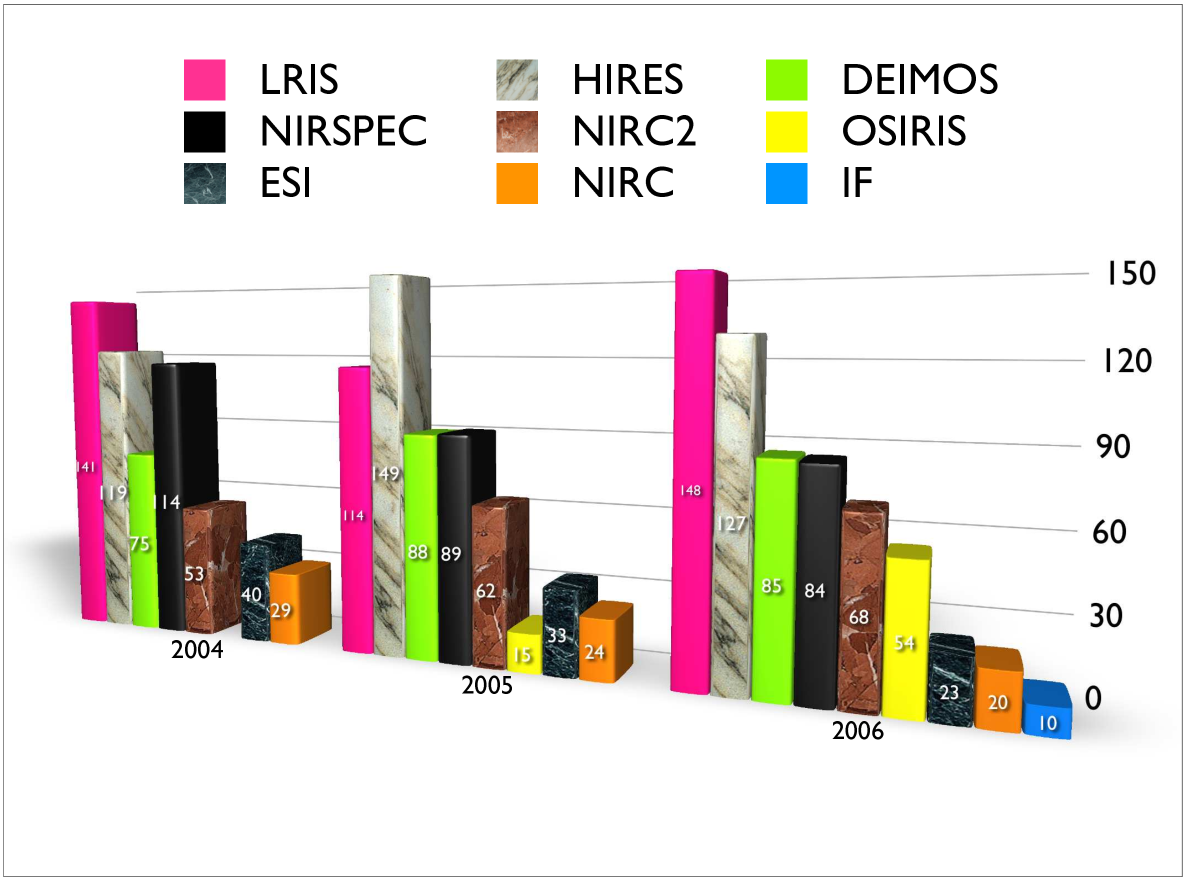

Figure 3.1 Total number of nights scheduled on each instrument over the past three years. Reproduced from a graphic provided to TDAWG by WMKO Director, Taft Armandroff.

As noted in §3.1, when planning TDA science, there are three choices with respect to instruments. The TDA scientist:

1. obtains a series of nights (or partial nights) on a specific instrument of choice for a monitoring campaign[3]

2. utilizes whatever instrument is in the optical beam at the time of a ToO,

[1] Near InfraRed Echelette Spectrograph
[2] Multi-Object Spectrometer for Infra-Red Exploration: http://www.astro.ucla.edu/~irlab/mosfire/
[3] While not addressing specific issues related to scheduling and the efficacy of the scheduling for TDA science, we do note here that nightly or half-nightly schedules for campaign on a single high-impact target is clearly not the most efficient use of Keck.

3. does not perform a TDA observation because of the lack of accessibility of the instrument of choice.

Relevant to item #2, figure 3.2 shows a typical timeline for a TDA science observation from the time that the observation is requested of the OA to the time that the science data acquisition begins. Assuming that the telescope is focused and that the instrument for TDA science does not require on-the-fly setup (such as wavelength calibration), a TDA science observation can usually begin 5 – 6 minutes after requested, depending mostly on the length of the slew and the time to setup on the target. Time to switch back to the previous configuration and slew to the next non-TDA target should take a similar amount of time.

TDAWG has considered means of alleviating the impediment in item #3 to increase the chance of availability of a given instrument for TDA science. Clearly, for instrument switches during the night both **time** and **robustness** is of the essence. During a night, a change from any instrument at a bent position (bent Cassegrain or Nasmyth) to any other instrument at a bent position is possible. On Keck I, this list includes IF (interferometry), HIRES, and soon, NIRES. It also includes the engineering imaging cameras PCS and SSC, which have limited use for TDA science. On Keck II, the list includes NIRC-2, OSIRIS, and IF (all three behind AO), and NIRSPEC and DEIMOS. Only one of NIRSPEC and DEIMOS are in beam at any given time, and only one of OSIRIS and IF are in beam. NIRC-2 is always in beam. IF and LGS-AO nights require large support crews, so there is inertia against using those. In particular, since NASA owns most of the IF nights, there would be the greatest political pressure against not interrupting them for non-IF ToOs. To be sure, it is not possible to rapidly mobilize the large crews required in order to do ToOs using IF or LGS-AO. It is relatively easier to go from IF or LGS-AO to another instrument.

3.1.2 Software Infrastructure

There are no TDA-specific software suites in place at the Observatory. All software-related interactions of TDA scientists, observers, and OA take place through normal channels, which are generally designed for a static target list and single instrument on a given night. For instance, if a new target is to be observed through a ToO, the target name and position are often communicated to the OA through the Polycom system. The Sky tool, used for planning observations and checking telescope limits on individual targets, is not available to people outside the CARA intranet (and the new Java-based "Target Visibility Tool"[4] is not well known) adding to the overhead of obtaining rapid observations. There is no communal repository to house scripted observations for a monitoring campaign (for instance, if a TDA monitoring campaign requires 10 minutes per night for 2 weeks with the same instrument). Once a TDA observation has taken place, due to security restrictions on outside logins, there is no way for remote scientists to pull their data back (or even know, robustly what to pull back). Needless to note, the observers, many of whom have had their science interrupted, are not excited about dealing with TDA data management after their science observations resume.

[4] http://www2.keck.hawaii.edu/software/obsplan/obsplan.php

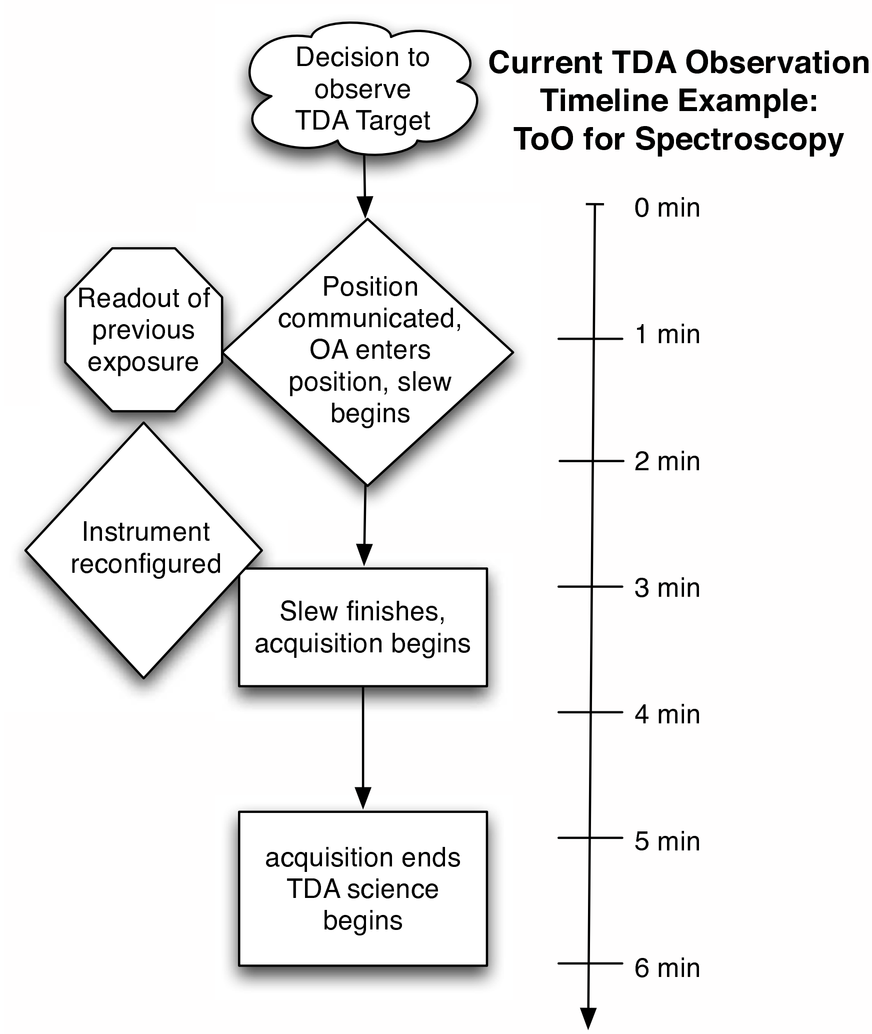

Figure 3.2 Example TDA timeline with no instrument change. There are no elements that can be skipped and only a few elements here can be shortened in time. A monitoring project, for instance, might already exist in the current starlist saving roughly 30 seconds from the pre-slew time and likely ∼1 minute off of the slew time (if the previous target is positioned near the TDA target). There is thus a "5 minute minimum" rule of thumb for TDA spectroscopic observations.

SECTION 3.2

Current TDA Policies and Procedures

In this section, we briefly review the current situation regarding TDA observing at Keck and at other observatories. Most large telescopes now have ToO policies in place, although specific rules and the level of detail in the official policies vary widely among institutions. Some relevant ToO policy issues include the following questions:

- Is it mandatory that interrupt requests be honored, or does the scheduled observer retain the right of refusal?
- How much time per night may be claimed by an interrupt?
- At observatories shared by multiple institutions, can a PI from one partner institution request a ToO interrupt during a night belonging to another partner?
- How do astronomers communicate ToO requests to the observatory?
- What happens if multiple ToO teams request the same observation simultaneously?
- Can observers who lose time to ToO programs request future observing time as compensation?
- Are ToO programs required to offer co-authorship or some other form of reward to scheduled observers whose time is taken?
- Is there Director's Discretionary Time that can be allocated for ToO programs?
- Who is responsible for keeping track of the amount of time taken by ToO programs?

Addressing these time-allocation issues is beyond the scope of the TDAWG charter. However, we would urge the SSC to strongly encourage the respective Keck institutions to redress their TDA approach in light of the new functionalities for TDA that are being recommended in this document.

3.2.1 Keck Community

Each institutional partner within the Keck community — each with varying degrees of access and TDA user base — approaches TDA science differently in allocation. We summarize the current policies and procedures below.

California Institute of Technology (Caltech)

Caltech allows ToO programs and allocates time for ToOs where no more than 2 hours per night may be used for override. For monitoring programs, time is scheduled in hour-long intervals. Programs with a faculty member as PI are required to give up time when an interrupt is requested by an approved ToO program. Proposals with a postdoc as PI are required to specify whether or not they are willing to accept ToO interrupts, and the TAC may use this information as part of its selection process. Interrupt requests are communicated directly to the night's scheduled observer, and the PI of the ToO program is responsible for accounting for the total amount of interrupt time used during the semester. There is no provision to compensate observers for time lost to ToO programs. ToO programs are not required to offer co-authorship as a reward to scheduled observers whose time is taken, but in practice it is usually offered.

University of California

The UC TAC allows ToO proposals and allocates ToO time in hours. No time is allocated for monitoring projects that require less than half-nights. ToO interrupt requests are non-mandatory and the scheduled observer retains the right of refusal for any reason. The UC policy is that an interrupt should take up no more than 1 hour of the night, including overheads. Interrupt requests are communicated directly to the night's scheduled observer, and the PI of the ToO program is responsible for accounting for the total amount of interrupt time used during the semester. There is no provision to compensate observers for time lost to ToO programs. ToO programs are not required to offer co-authorship as a reward to scheduled observers whose time is taken, but in practice it is usually offered.

NASA

NASA does not offer a ToO program at Keck but it does allow for TAC override time. Observations of Jupiter's Little Red Spot (which was found during the previous semester) as it interacted with the Giant Red Spot, were obtained through this channel (I. de Pater).

University of Hawaii

The University of Hawaii does not have an official ToO policy for Keck, but observations can be made by informal arrangement.

NSF/TSIP

There is no provision for ToO interrupts during NSF/TSIP nights.

3.2.2 Other Observatories

Classically Scheduled Telescopes

Magellan I & II

As a classically scheduled observatory shared by multiple institutions, the situation for ToO programs at Magellan closely parallels that at Keck.

Astronomers at some partner institutions within the Magellan consortium are able to submit ToO proposals to their institutional TAC, but not all partner institutions have a formal ToO program in place. At Carnegie, ToO interrupts are mandatory and the scheduled observer is required to give up time when an interrupt is requested by a group with an approved ToO program. ToO interrupt requests are handled by email/phone contact between the ToO requester and the night's observer.

At present, Magellan has no formal mechanism for cross-institution ToO interrupts; that is, astronomers can only request interrupts during a night allocated to another astronomer from the same home institution. Cross-institution ToO requests are sometimes done by asking informally for an observation to be done as a favor.

Subaru

Subaru (8.2 m) allows ToO proposals, but does not give very specific policies or guidelines. A ToO proposal must include at least one member of the Subaru Telescope staff as Co-I. The Subaru Director can order an override of scheduled observations to carry out a ToO. Spectroscopic redshift discovery of the highest redshift GRB ($z = 6.295$) were obtained through this channel (Kawai et al. 2006).

Kitt Peak National Observatory (KPNO) and Cerro Tololo Inter-American Observatory (CTIO)

KPNO and CTIO allow ToO programs and interrupts, and a detailed set of policies and procedures is given on their web site:

`http://www.noao.edu/noaoprop/help/too.html`

For each approved ToO program, NOAO creates a web page describing which telescopes and instruments can be used for interrupts, how many interrupts are allowed during the semester, and how many hours are allowed per interrupt. When an interrupt is activated, the night's scheduled observer is responsible for taking the ToO data and any required calibrations.

Scheduled observers who give up time to a ToO interrupt may appeal to the site director for discretionary time as compensation, but there is no guarantee that compensation will be granted. ToO astronomers are not required to offer co-authorship to scheduled observers who obtain data for them.

Queue-Scheduled Telescopes

Gemini North and South

As a queue-scheduled system, monitoring campaigns can be efficiently scheduled with the cadences and instruments appropriate for the TDA science. The Gemini telescopes allow for ToO interrupts through the normal proposal cycle. There are two ToO trigger types[5] : "standard" (execution in no less than 24 hours – essentially enabling a monitoring campaign where the exact target location is not known in advance) and "rapid response" (minimum response time of 20 minutes, which will stop current observations). Observations are obtained after the TDA science uploads a revised script ("Phase II") to the Gemini Observing Database following a straightforward procedure[6] .

Given the selectable Cassegrain configuration of Gemini, in principle, many instruments are available on short notice for TDA science. To aid the potential TDA

[5] `http://www.gemini.edu/sciops/ObsProcess/ObsProcQRProcess.html`

[6] `http://www.gemini.edu/sciops/ObsProcess/ObsProcQRActivation.html`

scientist in making a decision to observe, an up-to-date availability website is made available[7] as are the specific gratings and slitmasks installed on GMOS (most equivalent to LRIS)[8] .

On the availability of TDA science data, the Gemini documentation states: "Raw data files usually arrive at the Gemini Science Archive within a few minutes of being taken and are accessible by the PIs. For Rapid Response programs the observer will send an e-mail to the PI contact announcing that data is available."

Very Large Telescope (VLT)

ESO has very detailed guidelines for ToO programs:
`http://www.eso.org/paranal/sciops/doc/ToO_policies.html`

During classically scheduled nights at the VLT, the decision on whether to override scheduled observations for a ToO interrupt is made by the Observatory Director. If the interrupt is made, service mode compensation time is offered to the scheduled observer. The VLT has Director's Discretionary Time that can be allocated with a turnaround of about 48 hours for urgent observations, or a shorter timescale for "emergency" observations.

For teams having approved ToO programs, there is a password-protected web form used to submit observation requests, including instrument details, calibrations, and requests for specific sky conditions (seeing, clouds, etc.). A special "Rapid-Response Mode" was created over the past several years to allow for almost humanless intervention in obtaining a ToO observation on high priority targets. The fastest-acquired (7.5 minutes after trigger) high-resolution (UVES instrument) spectrum of a GRB afterglow was obtained through this channel (Ledoux et al. 2006).

Hobby-Eberly Telescope (HET)

At HET, each partner institution's TAC assigns a priority level to each of their accepted programs. ToO programs are generally assigned the highest priority level, meaning that they can have interrupt authority over lower-priority programs. To activate a ToO observation, the requestor directly contacts the resident astronomer on duty at HET. Because of the pointing limitations of the HET, observations are then carried out once the target is accessible in the HET field of view. The observatory staff maintain records of how much ToO time is used by each program.

For ToO programs, if astronomers from multiple institutions request identical ToO programs, the policy is that they are forced into a collaboration; this has occurred specifically for GRB programs but it also happening with SDSS-II-discovered supernovae. The TAC chairs are charged with identifying potential conflicts between programs and forcing collaborations as needed, as well as negotiating how much of the time in a multi-institution ToO program is to be charged to each partner institution.

SOAR Telescope

SOAR is a 4-meter telescope on Cerro Pachon, Chile, operated by a consortium including NOAO, the University of North Carolina, Michigan State University, and

[7] `http://www.gemini.edu/sciops/schedules/obsStatus/GN_Instrument.html`
[8] `http://www.gemini.edu/sciops/schedules/obsStatus/gmosN.today`

the Brazilian Ministry of Science. It is set up to be operated in queue mode or remote observing mode, and is designed for fast switching between instruments. While the telescope has not fully begun operations, a detailed set of ToO policies is in place[9] , including rules for charging of ToO time to partner institutions. The SOAR policies will allow for approved ToO programs of one partner institution to interrupt regularly scheduled observations by another partner, although they will allow for some "protected" programs that cannot be interrupted.

[9] http://www.soartelescope.org/release/06observing/eng_observing/ToOPOLIC-2.pdf

CHAPTER 4

Recommendations

Driven by the exciting *Science* programs (§2) that are possible now, with current facilities, and in the future as new instruments and capabilities come on line, TDAWG sought to develop a detailed set of recommendations that the Observatory could undertake to improve and ensure TDA competitiveness. These are largely broken down between *Hardware* and *Software* work, though the distinction between these categories is blurred when discussing, for instance, instrument switches during the night.

There are overriding aspects to our recommendation: ready the telescope to direct the light to the new instrument, and to understand the respective instrument parameters (see §4.1.1); and ready the instrument software and hardware to take the observations and disseminate the data efficiently. Specifically, we suggest that the Observatory be operated with the **requirement that all instruments that are accessible on a given night are readied in advance**, requiring a minimum of startup time and with all observational parameters (including finding charts, instrument configuration, exposure times) readily available to observers.

We believe that software changes and improvements are likely to have the most impact on the the Observatory's functionality and competitiveness in TDA science. Moreover, when compared to some hardware projects, the costs are considerably lower and the lead times for completion significantly smaller. Some of the software projects listed are expected to have an impact beyond the realm of TDA and so these may be considered by the observatory as synergistic exercises, receiving a higher priority in budgetary planning. To be sure, the projects listed below are all of great utility for TDA and are relatively separate from each other in scope; a number of these projects could be undertaken simultaneously.

SECTION 4.1

New and Changes to Existing Instrumentation

Some of the identified TDA science drivers require a specific instrument (and setup) that may not always be in the optical path. It is thus important to understand what needs to be done to complete an **instrument switch** in the middle of the night. Briefly, the OA selects the new instrument, new parameters are read into the Drive Control System (DCS), and if necessary optics are repositioned (usually only the tertiary mirror). This normally takes about 8 minutes, dominated by the time to slew the tertiary mirror, but because of a software bug that has not been tracked down, can take close to 20 minutes (requiring a reboot of a low-level crate to recover from the bug; see §4.1.1). The instrument can be prepared at the same time. This could include logging into the instrument host, starting the software, and setting instrument parameters for the specific ToO which is being invoked. This can typically take 10–15 minutes though we do make recommendations for significant improvements to the instrument switch time at the user end (§4.3). Figure 4.1 shows an idealized instrument switch timeline after some of the improvements we suggest are adopted.

Some instrument changes are currently possible in the middle of the night. The cost in time is approximately ten minutes to move the tertiary into position and set the telescope parameters for the new instrument, and an additional zero to 20 minutes to set up the new instrument. The latter can often be done ahead of time if the transition can be anticipated by 30 minutes or more. Again, changes recommended in §4.3–4.4 are meant to significantly improve the instrument timeline.

The following figures 4.2 and 4.3 show the available science and engineering instruments, and indicate which ones are readily accessible at night from another.

4.1.1 Optimize Instrument Switches and ensure readiness

We suggest instituting a *requirement that the Observatory optimize switches between instruments*. Specifically, this will entail, at minimum:

- **Focus.** Ensuring that the optimal relative positions of the secondary between instruments are regularly measured and stored in the case that instruments are switched during the night.
- **Pointing** Calibrating the pointing origin offsets between every possible instrument combination.
- Encoding the most recent pointing origin and focus offsets in the tools seen by the OA, to ensure minimal start up time after an instrument change.

Telescope Control Software

There is currently a bug in the software that switches between instruments that causes incomplete loading of the new instrument's parameters and a subsequent failure of a process on one of the crates. (see also §3.1.1.) We strongly recommend that this problem be addressed as it will facilitate and make more robust instrument switches that will be required for TDA science.

4.1.2 Fiber Feed to HIRES

Some of the current and future TDA science (§2) would be aided by the rapid availability of a high-resolution optical spectrograph. At the present time, HIRES, which would be ideal to support this science, is only available for limited periods. Even though it is easy to keep HIRES in a state of readiness, the fact that it needs the

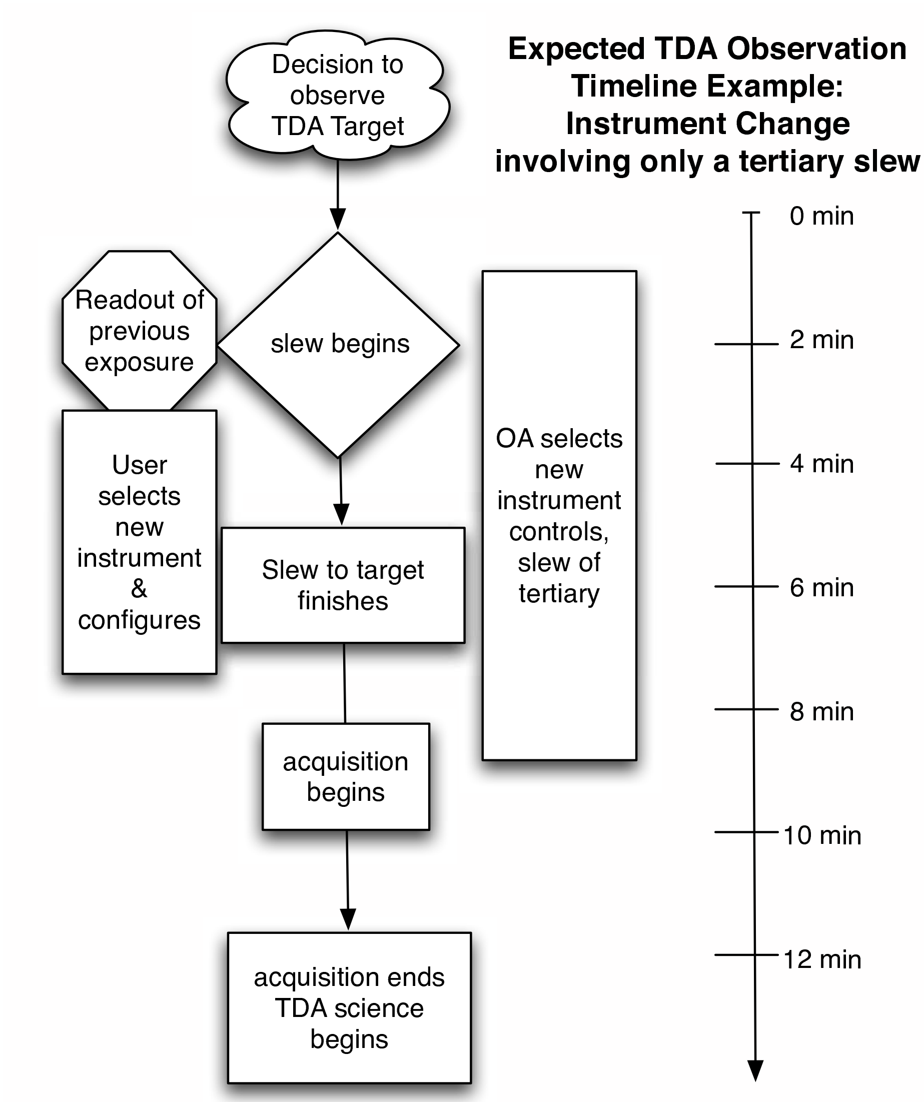

Figure 4.1 Example TDA timeline with an instrument change involving only the slew of the tertiary mirror . This is a target timeline (of less than 15 minutes between switches), one that can be achieved following our recommendations. Currently an instrument switch would require more than 40 minutes.

Keck I		To:						
		HIRES	IF	LRIS	LRISp	NIRC	NIRES	PCS/SSC
From:	HIRES	OK	OK	no	no	no	OK	OK
	IF	OK	OK	no	no	no	OK	OK
	LRIS	no	no	OK	OK (I)	no	no	no
	LRISp	no	no	OK (I)	OK	no	no	no
	NIRC	no	no	no	no	OK	no	no
	NIRES	OK	OK	no	no	no	OK	OK
	PCS/SSC	OK	OK	no	no	no	OK	OK

Figure 4.2 Instrument switch matrix for Keck I. A "no" indicates that no switch at night is possible. (I) The change from LRIS to LRISp usually is done as a daytime-only job, but could be done in a half-hour (possibly less) at night.

- Interferometry is shown as "IF" below, but on the telescope is shown as either "V2" for visibility science or engineering, or "Nuller" for Nuller science or engineering.

- PCS/SSC are engineering cameras that are often shown on the telescope schedule together, but could be shown individually on some nights. Neither is very suitable for TDA science.

Keck II		To:						
		DEIMOS	ESI	IF	NIRC2	NIRSPEC	OSIRIS	PCS/SSC
From:	DEIMOS	OK	no	sometimes (3)	OK	no	sometimes (2)	OK
	ESI	no	OK	no	no	no	no	no
	IF	sometimes (1)	no	OK	OK	sometimes (1)	no	OK
	NIRC2	sometimes (1)	no	sometimes (3)	OK	sometimes (1)	sometimes (2)	OK
	NIRSPEC	no	no	sometimes (3)	OK	OK	sometimes (2)	OK
	OSIRIS	sometimes (1)	no	no	OK	sometimes (1)	OK	OK
	PCS/SSC	sometimes (1)	no	sometimes (3)	OK	sometimes (1)	sometimes (2)	OK

Figure 4.3 Instrument switch matrix for Keck II. A "no" indicates that no switch at night is possible. (I) Either DEIMOS or NIRSPEC might be in-beam on Right Nasmyth, but not both. (II) Either OSIRIS or IF (the DSM) might be in-beam on Left Nasmyth, but not both.

- There is a separate, not readily-accessed schedule that shows when the DSM module (for IF) or the OSIRIS module are in-beam at the Left Nasmyth focus. This focus is behind AO. NIRC2 is always available at this focus behind AO (assuming that the tertiary mirror is installed).

- IF and LGS-AO require small armies to operate, and these cannot be mobilized on short notice. Further, IF requires significant daytime alignment. LGS-AO requires target lists to be approved in advance by U.S. Space Command , and requires notification of an intent to use the laser.

tertiary mirror to feed it precludes its use during both LRIS and NIRC runs. When MOSFIRE comes on line toward the end of the decade, it will also displace the tertiary. With this in mind, a feed to HIRES that circumvents the tertiary could provide an almost "on-demand" use of HIRES.

The most logical way to create such a feed would be to use a fiber, since imaging is not required. The f/15 (f/25 in the case of the forward Cass) would be converted to a fast beam to feed the fiber and then back to f/15 to feed the HIRES slit. Two difficulties present themselves: the loss of efficiency and the loss of the HIRES guider. The loss of efficiency probably is inevitable and must be accepted in order to have continuous availability of the spectrograph. The guiding most likely can be accomplished using the guider on the Cass instrument. The most difficult problem might well be finding a location to attach the fiber feed head to the Cass instrument. If a small ADC was included, the difficulty would be increased.

Though this approach to making HIRES available is certainly feasible, the cost and difficulty in implementing it has not been studied; a cost of half a million dollars or more is not out of the question. If it is decided that there is an advantage in going in this direction, the proposed method would have to studied and its cost estimated.

4.1.3 Considered, but Not Recommended

We do wish to note briefly a few hardware upgrades that were considered by TDAWG but ultimately did not make our list of recommended changes. Despite reasonable science drivers, these projects were deemed not worth the expense or risk.

Improving the Slew Rate

Observations of new targets in less than a 5-minute time window is clearly advantageous for both high priority ToO and improving the efficiency of Keck observing in general. With the advent of the MAGIQ guider, *acquisition* of targets will become increasing easier and so a critical bottleneck is in the slew rate to target – now typically 0.5 degrees per second. For a rather major cost (including major upgrades to the dome) the slew rate could be increased to a few degrees per second, which could shave ∼1–2 minutes off of a typical TDA observation. However, the main impediment for TDA science, we believe, will continue to be overhead in instrument switching and target setup, so slew-rate improvements are unlikely to have a significant return on investment. Since the lion's share of TDA science does not demand rapid slew, TDAWG feels that this is not worth pursuing for TDA science alone.

Considerations for MAGIQ (Guider)

The new MAGIQ guider facility will use a significantly better and more sensitive CCD than currently available guiders for Keck instruments. It is therefore tempting to consider MAGIQ as an "always mounted" instrument, capable, in principle, of allowing for faint object photometry with minimal overhead and impact to the primary instrument. While the photometric stability of MAGIQ in standard passbands is not a design requirement we consider this a reasonable avenue to test as MAGIQ is commissioned. However, TDAWG does not believe that the use of MAGIQ as a science instrument for TDA is an efficient use of Keck. Smaller aperture telescopes, especially those that are designed for frequent interrupts, with wider fields of view, and more rapid slew rates, are better suited than using Keck guiders for TDA science.

SECTION 4.2

Policy Changes

4.2.1 NIRSPEC as a backup instrument for NGS-AO

On Keck II, the current general policy that, barring necessary servicing work on NIRSPEC, it will be in beam on the Right Nasmyth platform during LGS-AO nights. Given the committee's finding that access to Near IR spectroscopy takes higher precedence over optical spectroscopy (long or multislit), this policy should be extended to NGS-AO nights (the alternative would be that DEIMOS is in-beam).

4.2.2 Consideration for Future Instrument Suites on Keck I & II

There almost certainly will be shuffling of instruments between telescopes (e.g., in the short term, OSIRIS is likely to move to Keck I after the Keck I LGS system begins regular operations) to help balance demand load and make way for future generations of instruments. Recognizing this, and noting that there will be future generations of instruments for both Kecks that are not already considered in this document, it is imperative that some consideration for time-domain science be given as such configurations are planned. In particular, given the science cases currently envisioned, TDAWG recommends that **quick and ready access to near IR spectroscopy and high-resolution spectroscopy** be maintained, all other considerations being equal. Not only should the locations of instruments on both telescopes be a consideration but also the general policies of which backup instruments are placed in which beam (e.g. §4.2.1). This could affect the decision of whether NIRES moves to Keck II after OSIRIS moves to Keck I, or after MOSFIRE commissions.

SECTION 4.3

Improve Instrument Readiness: Minimize Setup Time

Each instrument, to the extent possible, should reside in a state of readiness, living within it's own set of Virtual Network Computing (VNC) terminals at all times that the instruments is in science position. This removes the "login" and "startup" steps described above. All instruments support "setup scripts" so that proper planning for a ToO could allow simply selecting the appropriate setup file in order to configure the instrument. This should cut down the time from invocation of a ToO to instrument-ready to roughly 5 minutes. While we envision the Remote Ops observer performing the TDA observation, the multiple VNC paradigm will also allow mainland observers to easily perform, or at least monitor, the observing, should that be agreeable to all parties (and provided sufficient bandwidth is available, etc.). To this end, we suggest[1]

, that the **necessary software and hardware be procured to allow for this new paradigm**. We believe that the Keck staff has the expertise to perform the necessary work. Many of the startup tasks, such as setting up directories, configurations, and homing the instrument components can be done as a matter of course during daytime operations with default values. For all instruments sitting ready in their own VNC windows, the instrument shall be placed in a state such that a minimal number of user steps are required to begin observing.

SECTION 4.4

Create Software for Seamless Observations

We suggest that CARA provide a mechanism for collecting and organizing observing details for TDA observations. The information should be available both to the observers in Waimea and at mainland remote observing sites. A suggested short-term implementation is to **leverage existing scripting capabilities** and ensure that the **documentation for using these capabilities is up-to-date**.

4.4.1 Enable One-Stop Scripting for All Instruments

We recommend that a software tool to generate observing scripts for any instrument be made available for TDA observations. Most instruments are keyword based, meaning that scripting, even if not used as the norm in current operations, is a rather straightforward process to implement. The scripting tool should:

- GUI-based
- (optional) capable of being run through a webpage maintained by CARA
- capable of being run from the command line to enable auto-generation of scripts on the client side.
- useable outside of the Keck network (unlike, for instance, *Sky* program[2]).
- compatible with a number of popular platforms (Mac OS, Linux, Solaris)

Depending on the wishes of the various Observatory Councils, monitoring projects could be required to have the scripts pre-compiled and pre-vetted (similar to a Phase II proposal on some other telescopes) and ToO projects would strongly benefit from having scripts ready made. For instruments where certain critical observing functions have not been implemented in the scripting language we recommend that such capabilities be retrofitted. The Observatory may choose to require that new instruments conform to a series of protocols developed for scripting.

[1] We note that this proposal might dovetail well with the currently proposed VNC project at the Observatory

[2] http://www2.keck.hawaii.edu/inst/common/sky.html

4.4.2 Manage observing details: Repository for Observation-Specific Data

We recommend the creation of a repository with specialized clients and transaction agents where observing script and configurations can be uploaded, deleted, and viewed, with appropriate access restrictions. The idea is to allow one-stop shopping for observers to implement a TDA project: each VNC window would have access to a client of the database. A ToO could be implemented by simply clicking on the appropriate project or observation. After observing is completed, there would be the ability for the observer to add comments to be stored in the database. This will help the respective Observatory Councils with bookkeeping and manage *Monitoring* projects.

SECTION 4.5

Improve Access to Observation and Calibration Data

Transfer of the science data and calibration data back to the TDA scientists is a critical pathway. For ToOs, getting the data back to the scientists can mean the difference between *discovery* or simply *confirmation* of a potentially major result. Many in the Keck community have already felt the agony caused by the difficulties of getting time-critical data back to the mainland. A elegant solution is to create a robust archive for **all** Keck data, which are made securely accessible in (near) real-time. If the archive is robust, it would also provide a level of assurance that the TDA data are not only accessible without the aid of the current observer but would be backed up for a long time hence. Already, with HIRES, there is a capability of passing data back to the community by making use of the NASA Keck Observatory Archive (KOA).

The requirements of a TDA-related data access facility are as follows:

- data must flow quickly back to the TD scientist
- proprietary access rights must be preserved
- data transfer should have no or little impact on the observers
- transfer of the data should happen transparently without having to require Hawaii observers/staff to move data around by hand
- transfer rate should be controlled so as not to impair the operations of the instrument

Additionally, a complete archive suite could facilitate the need for a proper accounting of the time used for TDA science by the community. Here we will not consider further infrastructure that directly addresses the need for *bookkeeping*, but we do realize that some of the proposed solutions may also be useful such a purpose should the TACs require such a functionality.

4.5.1 Suggested Implementation

The onus should be on the remote TDA scientists to pull the data (rather than having the on-site observers push). We see three tiers of implementation ordered from less time-to-implement to longer.

- **Data Staging & Observer Push**. Build a data staging machine which could be a single, cheap workstation. Each approved TDA program PI would receive a password each semester in order to download data by `scp` from this one specific machine. Upon completion of an observation, the scheduled observer or support astronomer would bring up a GUI tool to select which images to send, and select the TDA project PI from a drop-down list of approved known TDA projects, and just hit a "send" button. The data would then be copied to the appropriate TDA PI's directory on the staging machine, an email would be sent to the TDA PI, and then the data would be ready for secure download. Other TDA groups would not have access to this directory with their own passwords. This solution cheap (<5k in hardware cost) and quick, and would be relatively easy to set up (we estimate 50 person-hours) and maintain. The downside is that there is no long-term archiving and no easy way to control data flow rates to protect the instrument response time.

- **Construction of a custom database/archive for TDA data**. The advantages are that this would be a highly customized data serving and access system specifically for TDA science, providing high levels of security and proprietary access. The disadvantages are that such a system would involve a long (>2 year) development and could come at a significant cost (at least $200 k).

- **Recycle the KOA to accommodate other instruments**. This implementation would make use of the codes already written for the NASA KOA archive. The advantages of such an approach is that the existence proof that such an archive is useful and secure is already in place. The disadvantages are that 1) there could be a significant cost in costing our the implementation 2) this is not an obvious choice for rapid deployment and 3) current data keywords do not distinguish between TD projects and normal science data so some work be needed to automate the data sweeping and archiving.

Costing and Lead times: We suggest that the Observatory **create an exploratory group to cost out various solutions** proposed above and that a **Data Access Project be started** at the Observatory. The ESO Data Archive for the VLT[3] and the Gemini Data Archive[4] can be seen a reasonable starting points for a Keck TDA data access solution. As a benchmark, we note that TDA data – and associated calibrations – now flows to the Gemini archive within minutes after the data has been obtained.

Regardless of the specifics of the solution, funds will need to be invested in procurement of disk space to house TDA data. Disk space costs and associated networking costs could be subsumed into larger observatory project, such as the construction of

[3] `http://archive.eso.org/wdb/wdb/eso/observations/form`
[4] `http://www1.cadc-ccda.hia-iha.nrc-cnrc.gc.ca/gsa/`

global Keck archive. However, for rapid deployment (by the end of 2007), we suggest that a separate TD-specific archive should be purchased, set up, and maintained. There is a modest cost for hardware associated with this (<$2k for 1 TB of space). The dominant cost will be software engineering time.

SECTION 4.6

Create a One-Stop Shop Website for TDA Scientists

Potential TDA scientists who are considering "calling in"[5] a ToO should be able to make an informed decision about the viability of their science goals *without* having the confer with Keck observers. Is their instrument of choice mounted? If not, can it be put in the optical path? How long will such a process take (ie., what would be the overhead for calling in a ToO)? Is the weather good? What is the current seeing? Is there staff on hand (or on call[6]) to perform instrument switches?

To this end, we suggest that the Observatory build a website – some static pages with general information, and some dynamic pages based on specifics for that night – to facilitate the potential TD scientist in answering these questions and taking the guesswork out of ToO data acquisition.

4.6.1 Suggested Implementation

- Provide an overview of the instrument mounting schedule and possibilities of using the instrument on a single page. Gemini Observatory has such page, which is reproduced in Figure 4.4. The page could be made interactive (a "mouseover" on each day could provide a summary of which instruments are available for exchange, who the observers are, etc.)

- Provide a set of links to relevant instrument pages, phone numbers for the remote observing rooms, and links to ToO policies of various institutions, etc.

- A detailed summary page for the current night should be provided. How long will it take to switch towards a new instrument? How long will it take to switch back? Is there the staff on hand to do this? If not, can they be called in? Ephemeris data (lunar phase, twilight) and links from the DIMM (for seeing and transmission) will also aid the potential TDA astronomer. An example is shown in Figure 4.5.

Though this website will be useful on a daily basis, maintenance would be minimal, except at the beginning of the semester when schedules could be encoded in an XML format. Most instrument switches will be static and will not change on a nightly basis. However, night-specific information could be easily encoded (in XML) and the pages could use all available information when generated on-the-fly.

[5] We are not considering here issues of *permission/rights* issues for calling in a ToO. We do consider, however, ideas for smoothing the logistics of doing so

[6] Where there is a 2-hour minimum time for staff to get to summit, clearly some TDA science might warrant such an impact to personnel.

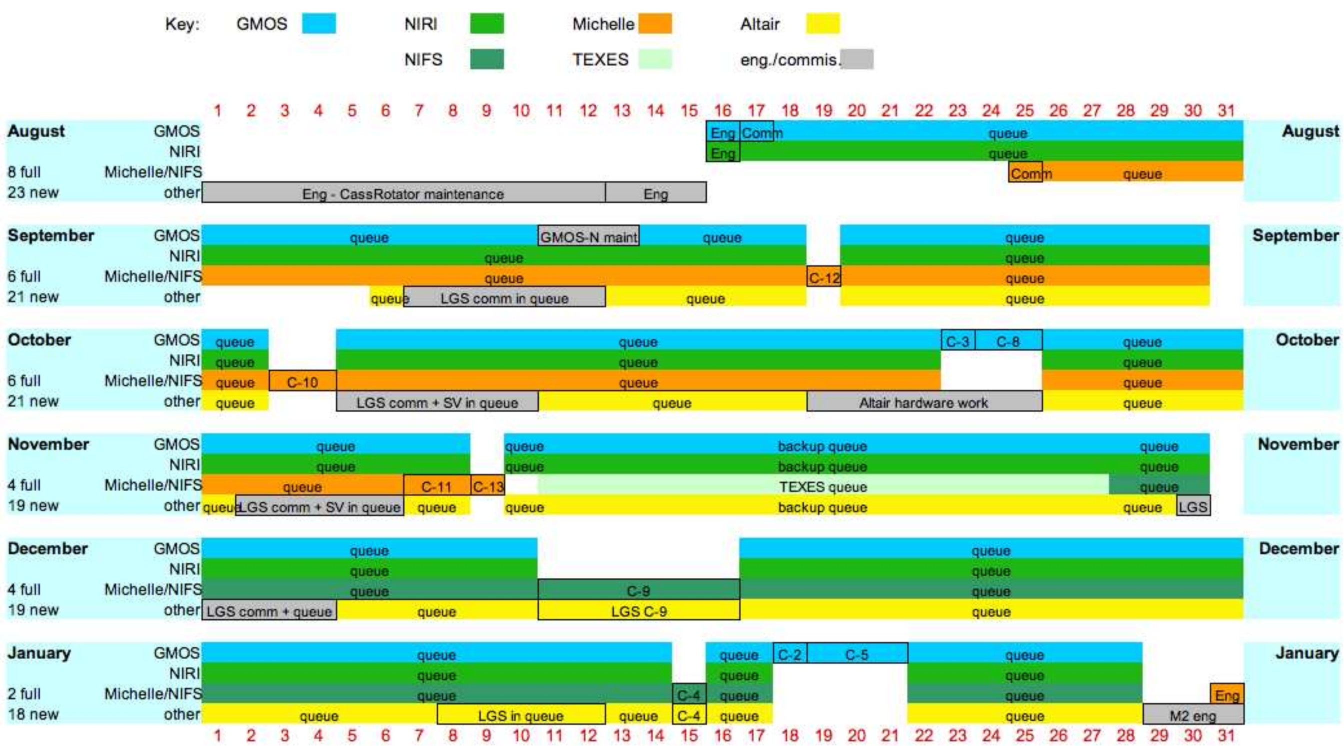

Figure 4.4 Example of an Overview of instrument availability throughout the semester (from Gemini Observatory). Instruments potentially usable are indicated by the colored-horizontal bands. Engineering or commissioning runs are shown as well. New and full moon dates are shown.

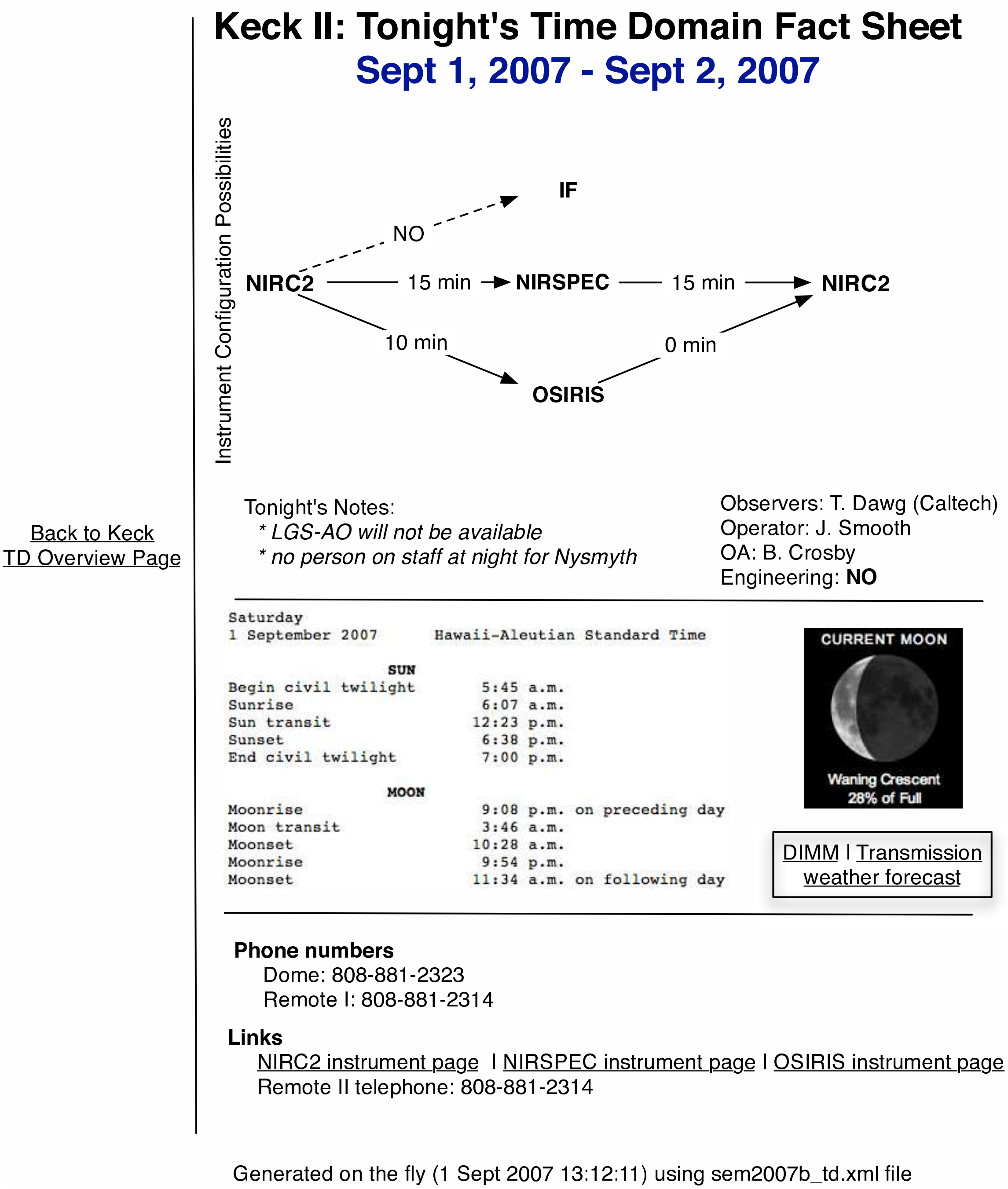

Figure 4.5 Example informational page for potential TDA scientists. This page will greatly aid the decision process for calling in a ToO.

SECTION 4.7

General Considerations

We have considered some representative science cases which could drive the Observatory's consideration of an investment towards improving Keck's functionality in the time domain.

4.7.1 Consideration of TDA as a Funding Opportunity

Most of our recommendations have been made with an understanding that TD-related improvements to the observatory will have an impact on the financial and personnel resources. As such, we have prioritized our recommendations as follows

1. Create a small informational document for potential funding bodies. This should include highlights of potential science projects and a brief listing of the larger-scale projects for TDA science that are included in this document.

2. Add TDA to the current list of funding opportunities at Keck Observatory and begin to shop TDA recommendations as a necessary improvement for the observatory.

3. Encourage TDA scientists, having made use of Keck for noteworthy ToOs or monitoring campaigns, to issue press releases through the Keck press office

4.7.2 Laser Guide Star Considerations

As Keck I begins laser operations and the efficiency of LGS improves toward shorter and shorter wavelengths (with Next-generation AO: NGAO), there will be a growing call to put more instruments behind the laser system. Furthermore, improvements in PSF and Strehl stability — leading to improved photometric stability — will likely lead to increased demand for LGS nights at Keck both in the classical schedule and for TDA programs. The Observatory should consider ensuring that LGS nights are as amenable as possible to TDA science.

One particular consideration involves target position clearance. As is current policy, targets for LGS runs must be cleared more than 48 hour in advance with US Space Command in Cheyenne Mountain in Colorado. The lasers used for LGS can be a hazard to astronauts and satellites, so coordination of LGS targets is critical. While 48 hour is an acceptable time for long-timescale monitoring campaigns (where the target positions will be known well in advance), TDA science concerning targets with more rapid timescales clearly is hampered. While, in principle, clearance of a position can be obtained with "a phone call" to Space Command, there needs to be a formal procedure in place to gain rapid clearance. TDAWG recommends that a dialog be started with those involved in Space Command with the aim of **decreasing the minimum time limit** for space command target approval. Such a dialog could be initiated in conjunction with other Mauna Kea observatories.

4.7.3 Creation of a TDA Oversight Group (TDOG)

As our recommendations are assimilated into the operations of the Observatory, the SSC may wish to create a **TDA Oversight Group** to help direct the TDA-related activities at the Observatory and ensure that the SSC-sanctioned priorities are being adequately addressed. Several other suggested functions for this group include:

- helping to create TDA as a funding opportunity (following §4.7.1)
- interacting with the Keck community user base to raise awareness about new TDA opportunities.
- producing, biyearly, a "Guideline for TACs" document to advise of new functionalities as implemented.

SECTION 4.8

Prioritized Summary, With Approximate Costing

In prioritizing our recommendations, we have considered 1) the rate of return of the recommended work for both TDA science and the Observatory in general 2) anticipated costs, labor, and lead time (given the current funding landscape, we are partial to smaller projects with high impact), and 3) importance for TDA science. We break our recommendations down into two categories – those activities that will occur at the Observatory and those for the SSC. Many of these activities a can occur in parallel.

4.8.1 For the Observatory

1. Improve intranight instrument switching
    - Fix the motor crate bug (§4.1). *Anticipated Costs*: 80 person hours
    - institute the NIRSPEC backup policy on Keck II (§4.2.1). *Anticipated Costs:* $0.
    - create specialized tools for observers (software, checklists) (§)4.2.1). *Anticipated Costs*: 100 person hour (software)
    - institute the policy that every instrument which can be deployed in a given night, be readied. *Anticipated Costs*: small overhead for daycrew each shift.
    - The Observatory, commensurate with the other TDA-related improvements, should define policies and periodically revisit such policies on when and under what circumstances instrument changes will be allowed and supported
2. Develop a TDA archiving mechanism with a **Data Access Project**. We suggest opting for a quick fix solution immediately (§4.5) with eventual deployment of a robust archiving suite. *Anticipated Costs*: Simple solutions will cost roughly $5k for hardware and could require less than 50 person-hours for software development. Fully robust solutions (§4.5.1) will be a major undertaking for the

Observatory, costing ∼$150k over a one year period (including hardware and software engineering time).

3. Deploy the TDA website (§4.6). *Anticipated Costs*: Creation of the site is a small project, likely costing less than 2 person months. Small overhead (5 person-hours) at the beginning of each semester to marshall schedule into metadata for the website.

4. Deploy the One-stop instrument scripting (§4.4.1) and a scripting repository (§4.4.2). *Anticipated Costs*: This can be deployed in steps as old instruments are retrofitted and new instruments come on-line. All the costs will be in software development, which we believe could be completed in 6 person-months.

5. Deploy the Multiple VNC paradigm (§4.3). *Anticipated Costs*: This is a large project, which may be joined with current efforts to improve VNC operations for Mainland observing. Alone, given the possible need to update instrument data-taking software to work with new versions of Solaris, we estimate that hardware and software (labor) costs will exceed $50k. Testing of such a system will require a few engineering nights (most can be done during the daytime)

6. Upgrade Mainland remote observing site to coincide with the VNC improvements. *Anticipated Costs*: We expect that roughly $15k per site will be required to upgrade the computers and monitors.

7. Begin construction of fiber feed to HIRES project (§4.1.2). *Anticipated Costs*: $3M over 5 years. Not recommended without outside funding.

4.8.2 For the SSC

1. Discussion and consideration of the TDAWG recommendations in this document. This may involve advertising the identified priorities (and this document) to the Keck community to gain feedback.

2. Communication of the SSC TDA priorities in advance of the budgeting in Spring 2007.

3. Creation of a TDA Oversight Committee (§4.7.3)

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Glossary

$M_\odot$	One solar mass unit	13
ADC	Atmospheric dispersion corrector	34
Caltech	California Institute of Technology	23
CARA	California Association for Research in Astronomy	36
DCS	Drive Control System	29
DIMM	Differential Image Motion Monitor	39
KOA	Keck Observatory Archive	37
MAGIQ	A next-generation guider facility for most Keck instruments	35
NASA	National Aeronautics and Space Administration	37
NEO	Near Earth Asteroids	5
NGIS	Next Generation Imaging Surveys	5
PHO	Potentially Hazardous Objects	5
PI	Principal Investigator	23
RV	radial velocity	7
scp	secure copy – UNIX command	38
SFD	size-frequency distribution	11
TAC	Time Allocation Committee	37
TDA	Time domain astronomy	1
TDAWG	(Keck) Time Domain Astronomy Working Group	2
TDOG	TDA Oversight Group	42
ToO	Target of Opportunity	1
VNC	Virtual Network Computing	35
WMKO	W. M. Keck Observatory	2

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