# KECK TELESCOPE CONTROL SYSTEM UPGRADE

K. Tsubota, J. A. Mader, W. M. Keck Observatory, Kamuela, Hawaii

*Abstract*

The Keck telescopes, located at one of the world's premier sites for astronomy, were the first of a new generation of very large ground-based optical/infrared telescopes with the first Keck telescope beginning science operations in May of 1993, and the second in October of 1996. The components of the telescopes and control systems are more than 15 years old. The upgrade to the control systems of the telescopes consists of mechanical, electrical, software and network components with the overall goals of improving performance, increasing reliability, addressing serious obsolescence issues and providing a knowledge refresh. This paper is a continuation of one published at the 2013 conference [1] and will describe the current status of the control systems upgrade. It will detail the implementation and testing for the Keck II telescope, including successes and challenges met to date. Transitioning to night time operations will be discussed, as will implementation on the Keck I telescope. Throughout this paper the telescope control system will be referred to as TCS.

## TCS OVERVIEW AND CONTEXT

Each of the Keck telescopes is over 8 stories tall, weighs in excess of 300 tons, uses an alt-az mount and has the equivalent of a 10meter mirror which is comprised of 36 individual segments. A general diagram is shown in Fig. 1. The telescope supports a wide range of instruments at various focal locations in addition to providing both a natural guide star and laser guide star adaptive optics.

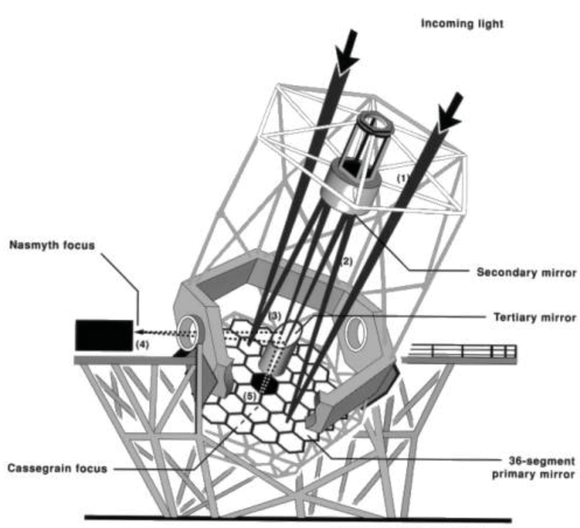


Figure 1: Keck Telescope.

TCS consists of a supervisor and set of subsystems that work together to provide Status and Control of:

- Telescope mounts
- Dome and shutter positions
- Facility rotators
- The secondary mirror

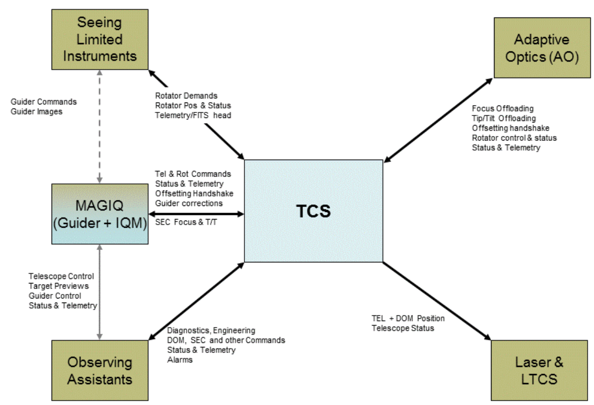


Figure 2: TCS System Context.

Figure 2 shows a high level context diagram for the Telescope Control System (TCS). It and the other Observatory principal systems interact through well-defined interfaces to accomplish the desired behaviour. Systems are tied together by the use of an Ethernet Bus. The main purpose of the TCS software is to accept the target position of a celestial object (which can be given in a variety of coordinate systems) and then calculate the mount, rotator and dome/shutter positions, so that the target is imaged perfectly at a given point in the focal plane. Furthermore, the TCS is characterized by the need to integrate a number of heterogeneous subsystems, which exhibit complex interactions. These interactions, although not hard real-time bounded, need a high level of synchronization. All this has to be done in a manner that protects the staff and equipment.

TCS operates the mechanical components of the telescope through a number of computer subsystems which control the telescope mount assembly, the dome enclosure, secondary and tertiary mirrors and facility rotators. The subsystems are responsible for the actual servo or hardware control, while the TCS coordinates their activities.

- The Telescope Axes (AXE) subsystem controls the telescope mount assembly, including the elevation and azimuth drives and other components associated with the mount operation.
- The Dome subsystem (DOM) operates the enclosure, which includes the dome carousel, dome lights and shutters, and other auxiliary equipment.



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- The Secondary (SEC) subsystem controls the secondary mirror, including its tip-tilt-focus and thermal requirements. It also handles the monitoring of thermistors placed around the telescope tube which is used for focus compensation.
- The Rotator (ROT) subsystem controls the cassegrain, forward cassegrain, bent cassegrain and nasmyth facility rotators and positions the tertiary.
- The Telescope Safety System (TSS) handles the safety interlock system. It includes items such as Estop, limit switches and interlock processing and is implemented using a PLC. There are multiple interlocks including module handler deployed, crane deployed, horizon lock deployed, and so on.
- The Timing subsystem (TIM) handles time synchronization for each subsystem in addition to providing accurate triggers and time conversion routines

## PROJECT OVERVIEW

Keck follows a standard development process that includes concept, preliminary and detailed design, full scale development, followed by integration and test, and commissioning. The TCS Upgrade project is at the end of the integration and test phase for the Keck II telescope and working towards commissioning. This will be followed up with integration and test of the Keck I telescope

A philosophy for the TCS upgrade project was to remain backwards compatible with the existing system. This was particularly critical for instruments and clients that were expected to communicate with TCS. As a result of this philosophy the project chose an architecture that uses proven hardware and software, is primarily COTS, leverages the open source community, is inherently backwards compatible, is viable for 10+ years and allows the subsystem controllers to be upgraded without affecting I/O. It was a conservative approach; all existing top level EPICS records can be reused, there is 100% reuse of the Keck Task Library and, if necessary, all existing UIs and tools can continue to operate.

Another key philosophy was to minimize the need for any telescope down time and to allow continuous night time observing. This meant allowing the use of both systems in parallel and to provide a failsafe fall back to the old system during commissioning. The overall approach taken to minimize telescope downtime was to implement a physical switching solution.

## IMPLEMENTATION

The new redesigned telescope axis encoder systems have been successfully implemented and tested on Keck II and are currently being installed on Keck I. The EL design uses existing surfaces for mounting two read heads to a rigid yoke main triangle structure. The AZ design uses a compact, on-axis annular design with four read heads mounted to rigid and fixed structure at the center of the telescope structure. This second generation simplified encoder design has saved the project considerably in cost and effort by being easier to fabricate and install with no telescope downtime as compared to our original design. It also allows the new encoding system to run in parallel with the operational encoding system for a side by side comparison.

From the beginning TCS had a requirement to minimize operational downtime. This led to the design and implementation of a switching solution [2] to allow quick and easy switching between the operational system, referred to as Drive and Control System (DCS), and TCS. The switching solution and all significant preparation work such as cable pulls was performed well before summit I&T.

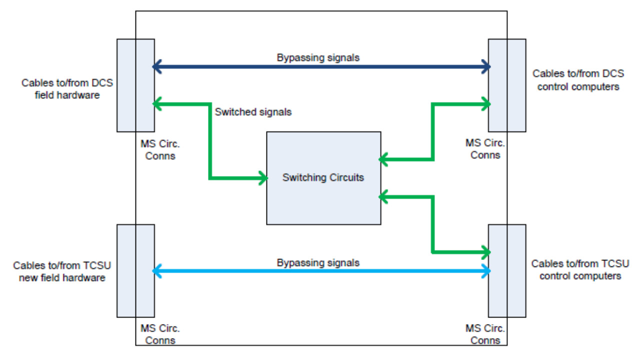


Figure 3: Switching Solution.

Figure 3 shows the basic switching implementation. The switching solution was very easy for the secondary and basically consists of cutting the existing cables and terminating them with connectors so that they can be switched between DCS and TCS with the addition of relay switches. The solution for AXE and ROT was a bit more complicated and relied on banked sets of DIN mounted relays to be switched. Switching occurs at the subsystem level. The number of switch points was reduced by utilizing the ability to simply run signals such as limit switches etc. in parallel between DCS and TCS. This not only reduced cost but also reduced implementation complexity.

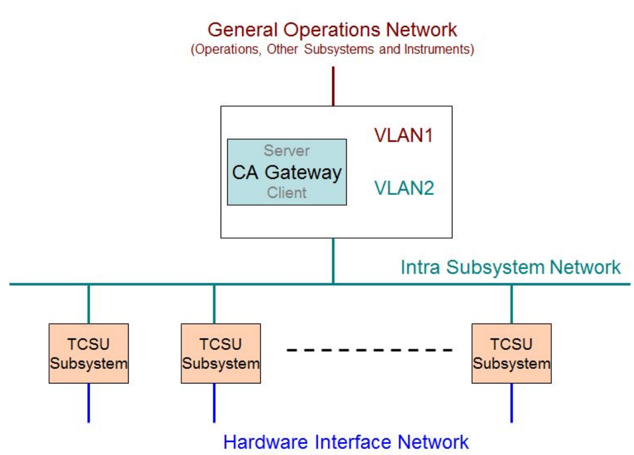


Figure 4: Network Layout.

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Software also has a similar switchover concept. Fig. 4 above shows the basic network layout. TCS is implemented on a separate network and tied to the operational network by a single supervisory server with dual network interface cards (NIC). One of the NICs is on the operational network and the other on the TCS network. During standalone TCS testing all subsystem EPICS IOCs communicate through an EPICS gateway with a non-standard EPICS channel access server port running on the dual NIC server. When switching the software over to operations, the operational VxWorks control systems are halted and the TCS EPICS gateway changed to to communicate on the standard port. This allows all existing operational clients access to the new TCS control systems.

## TESTING

Testing is a critical aspect of system development. Once components have been built and unit-tested, they must be tested in relation to the system as a whole. Two general principles were followed: test functionality and performance at the lowest level possible. When it could be avoided no hardware or software whose functionality and performance had not been verified was integrated. Of course it wasn't always possible to follow these principles, e.g. sometimes software must be integrated with hardware before either can be meaningfully tested.

TCS identified various levels of testing and are briefly described here.

- Developer testing
- Hardware Checkout
- Unit Testing
- Functional Unit / Subsystem Testing
- System/Acceptance Testing

Starting from developer testing and hardware checkout, each subsequent layer essentially builds on the last providing more complete and encompassing testing. Initial testing took place at our HQ lab environment where the basic hardware was installed with minimal functionality followed by summit testing after everything was installed in its final configuration.

An official deliverable of the testing phase is the documentation of the requirements acceptance testing. For each requirement the project developed a standard test acceptance form and sorted them by subsystems. In cases where one requirement spanned multiple subsystems, each subsystem had a copy of the test acceptance to complete. The major sections of the test acceptance form are the requirement to be tested, the test procedure, the test results and disposition, the test conductor name, and the date of the test. As the tests are completed and documented, they are checked off in the requirements matrix and the individual sheets are compiled into a system notebook.

## SUCCESSES

The TCS Upgrade project has had a number of successes that has proven invaluable. The implementation of the hardware switching solution allows quick and easy switchovers during the day and at night. Since switchover involves three switches and a couple of cable moves and a simple procedure, anyone not familiar with the system can do it.

Implementing the switching solution on a subsystem by subsystem basis also gave more freedom in testing. It allowed TCS to selectively switchover a single subsystem as needed, especially if another subsystem was not available because of operational needs.

From the software perspective the use of a separate network and EPICS gateway implementation to isolate the software and make it public only when needed by switching the port number allows the project to run the software in parallel day and night.

Insisting on software backwards compatibility freed the project from having to change and re-validate existing client applications, of which there are many.

All these have led to successfully integrating and testing the full TCS system prior to on-sky engineering.

## CHALLENGES

During the integration phase on the summit, considerable planning and coordination with operational tasks and projects as well as for personnel support was involved. There are processes in place for this but it still took a more time and effort than originally planned. Understandably, operations are the highest priority and could bump anything on the schedule for preparation of the nights observing. Also the longer it took for integration the more TCS had to deal with competing projects for telescope access.

Another challenge was getting on-sky test time. These nights are scheduled months in advance and you need to ensure you will be ready for the testing. Missing a night of testing could mean a month or more delay. Not being fully ready but going on-sky is also a waste of resources. There was one night where the project team thought they were prepared but failed to fully test all interfaces to the existing system and the project ended up dead in the water when a part our target selection tool interface failed after it had to be restarted and it was too late to give back for other projects to make better use of the time. The interface issue was eventually resolved the next day but it had already prevented the project from doing the tests that were originally planned. There is also the weather for which we don't have much control over and that the project has experienced this first hand. Just recently this past August, two scheduled partial back to back nights where weathered out preventing any TCS upgrade on-sky validation. To compensate for weather delays, this the project has requested contingency nights.

Another challenge the project ran into and is still dealing with is the tuning of our telescope axis closed loop servo performance. By design, the internal velocity loop was digitized with a FPGA which allow for much more freedom and sensitivity and driven with a 100Hz position loop. While attempting to tune the servo loop, an intermittent timing issue with our 100Hz event trigger



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would crop up. This was eventually traced down to a termination issue in the initial signal generator setup. This was difficult to trace because whenever probes were added to monitor the signal it would change the loading in a positive way and generate a solid 100Hz signal so the problem never occurred. It took nearly a full week to get to the bottom of the issue. The bad part was that this was not the final operational configuration. The signal generator was initially setup as a way to help facilitate testing but ultimately it costed the project more time. The final configuration was to have the timing card (Bancomm 635 with a crystallized oscillator) internally generate the 100Hz event signal. Another challenge was dealing with investigating and resolving a 1Hz period oscillation in our servo performance. The FPGA velocity loop has been looking at the tachometers as its feedback. These tachometers have been noisy in the past and cleaning them have helped. However, it was decided to add a derivative term to our servo loop to supplement the use the tachometers. Another option is being implemented to replace the tachometer feedback with an encoder velocity feedback calculated in software and feeding into the FPGA in place of the tachometer feedback.

## TRANSITION TO OPERATIONS

As the TCS Upgrade Project nears completion of its Keck II performance testing, a path for transitioning to operations is being actively developed. As part of this transition, Keck standards dictate that all projects undergo an Operational Readiness Review (ORR) prior to release. This is an external review of our readiness for operations by documenting that all requirements and performance specifications have been satisfied. It also verifies that all necessary as-built design documents, procedures is complete and in place for handing over to operations. The ORR also shows that all required training has been completed and that the project has proven that the system is stable and can be reliably operated by documenting the engineering and shared risk nights and results.

## CURRENT STATUS

Currently all Keck II telescope subsystems (AXE, ROT, SEC, DOM, TSS, TIM) have been fully integrated and tested as designed.

The full TCS system has been successfully run on-sky at night and the pointing model based on pointing data test results using actual stars was completed and updated.

Fine tuning our telescope axis servo performance continues as well as completion of all remaining test procedures. Completion of all as-built documentation and procedures continues as well as identification of and training preparation. The Keck II TCS Upgrade Project ORR is scheduled for December 2015 with plans to fully deploy the Keck II TCS upgrade in late January 2016.

### *Performance*

Some of the performance requirements are very tight and difficult to achieve, even if the system were to have been designed from scratch. As shown in Table 1, the current system does not meet the original settling time requirement for offset moves but has improved it over the current control system. With the TCS upgrade, the settling times for small moves in azimuth using the double path with feedforward turned on are nearing the original requirements and have met them in some cases. Double path means that the base position is separated from the offsets and the two are applied separately. In elevation, performance is close between the single path with feedforward and the double path with feedforward but both perform close to or better than the current system. With the continuing servo upgrades and tuning, TCS hopes to improve even more from the current system and get even closer to the original requirements.

Table 1: Keck II Offset Moves Settling Times

| Telescope moves (arcsec) | 1 | 5 | 10 | 50 | 100 | 1000 | 10000 |
|---|---|---|---|---|---|---|---|
| Time Requirement (sec) | 0.3 | 1 | 1 | 3 | 3 | 10 | 20 |
| **AZIMUTH** | | | | | | | |
| DCS System (2011) | 0.8 | 2.7 | 2.8 | - | 5 | 9.9 | 19.2 |
| TCS no feedforward | 1.8 | 2.4 | 2.5 | 3.9 | 4.8 | - | - |
| TCS one path w/FF | 1.1 | 1.2 | 1.5 | 2.7 | 3.3 | - | - |
| TCS two path w/FF | 0.7 | 0.9 | 1.2 | 2.4 | 5.8 | - | - |
| **ELEVATION** | | | | | | | |
| DCS System (2011) | 3.2 | 2.6 | 2.6 | - | 5.7 | 10.3 | 23.4 |
| TCS no feedforward | 2.7 | 4.2 | 5.1 | 6 | - | - | - |
| TCS one path w/FF | 0.9 | 2.6 | 3.1 | 3.7 | 5.2 | - | - |
| TCS two path w/FF | 2.1 | 2.9 | 2.6 | 3.8 | 5.1 | - | - |

## MOVING TO KECK I

As TCS nears completion of fine tuning the Keck II system, the necessary hardware upgrades to Keck I is being actively installed. To date the majority of the switching solution is installed. The dome, secondary, and rotator upgrades, which are fully installed, have been tied into the switching solution. The drive control and encoder system for the telescope axis are currently being tied in with the switching solution. All Keck I hardware installation will be complete by November this year with integration testing starting immediately after. The Keck I full system integration and validation completion is expected by the end of March 2016 followed by the Keck I TCS Upgrade Project ORR and handover in May 2016.

## ACKNOWLEDGEMENT

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[1] J. Johnson et al., "Keck Telescope Control System Upgrade Project Status", ICALEPCS 2013 MOCOAAB05

[2] K. Tsubota et al., "Switching Solution – Upgrading a Running System", ICALEPCS 2013 THCOBB05



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