

KECK TELESCOPE CONTROL SYSTEM UPGRADE PROJECT STATUS

J. Johnson, K. Tsubota, J. Mader, W.K. Keck Observatory, Kamuela, HI, USA

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. The first Keck telescope began science operations in May of 1993, and the second in October of 1996 making the components of the telescopes and control systems 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, providing a knowledge refresh and having the ability to better adapt to new requirements. The telescope encoder systems will be replaced to fully meet demanding science requirements and electronics and software will be upgraded to meet the needs of modern instrumentation. The upgrade will remain backwards compatible with the remaining Observatory systems to allow for a phased migration to the new system. This paper describes the stage the team is at in the development processes and key decisions that have been made. It also covers successes and challenges to date and presents an overview of future plans. Throughout this paper the Telescope Control System Upgrade will be referred to as TSCU.

TCS OVERVIEW AND CONTEXT

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

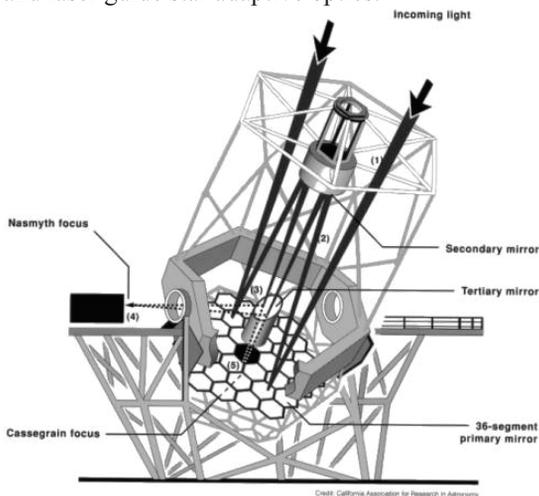


Figure 1: Keck Telescope.

TCS Subsystems

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

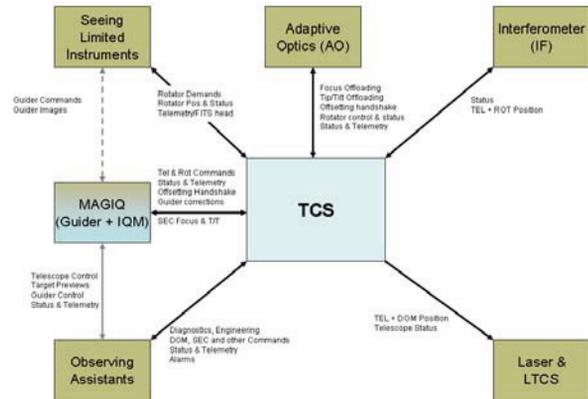


Figure 2: TCS System Context.

Fig. 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.

At the heart of the system lies the pointing kernel, a key part of the pointing subsystem (PNT). In order to accurately follow the current science target and guide object, the pointing kernel produces a stream of demands directed toward the tracking mechanisms of the telescope. The exact value of the demands produced will depend on how TCS is configured. The demands will not be directly supplied to the subsystems but will have trajectory adjustments and shaping applied, clamped (if necessary) and will honour selected cable wrap selections and so forth.

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 altitude 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.
- 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

What is Being Reused

The current TCS system, known as DCS, is based on the following platforms / architectures

- VME based MVME-2304 PPC processor
- VxWorks V5.3.1 operating system
- EPICS R3.13.10 framework and tools
 - Display manager (dm)
 - Schematic capture tool (xschedit)
 - Alarm handler (alh)
- Sun Workstations, X11/Motif
- A broad range of custom electronics

Where possible the existing infrastructure from the current solution is being reused. This includes all custom EPICS records (though underlying algorithm are updated in some cases), all top level database records, many subroutines, and all of the existing DOM software with the exception of device interfacing. In addition the following field hardware is being reused: drive amplifiers, drive motors, tachometers, rotator encoders, brakes, limit switches, interlocks switches and e-stops, manual control panels and hydraulics. New hardware includes a number of 19-inch 2U rack controllers, Symmetricom PCIe timing boards, RocketPort serial extenders, Delta Tau

Brick Controllers, National Instruments RIO and C Series IO, Heidenhain tape, read heads with encoder interface boxes and Rockwell PLCs with FLEX IO. New software includes the use of RT Linux, EPICS revision updates, use of TDCT as a schematic editor, use of BEAUTY and BEAST, use of ASYN, CA gateway and caQTDM.

PROJECT OVERVIEW

Keck follows a standard development process that includes concept, preliminary and detailed design, full scale development followed by integration/test and commissioning. TCSU is currently in the full scale development phase.

Trade Studies

Numerous trade studies were carried out to determine the software platform selection, the general I/O electronics, the motion control solution, the PLC selection and also included a tape mounting study and prototype to determine the ideal encoder locations. These were aided in part by discussions with members of the ITER CODAC team, Thirty Meter Telescope (TMT), Advanced Technology Solar Telescope (ATST), Australian Square Kilometre Array Pathfinder (ASKAP) and others and by having a number of formal reviews with members of various external institutes.

Philosophy

A key philosophy for the upgrade was to remain backwards compatible with the existing system and the instruments and other clients that connect to TCS. In addition the approach taken was to eliminate or minimize the need for any down time during observing. The overall approach taken to achieve this is discussed in THCOB05 [1].

As a result of this philosophy an architecture has been defined that meets TCSU requirements, uses proven hardware and software, is primarily COTS, leverages the open source community (and hopefully gives something back), is inherently backwards compatible, is viable for 10+ years and allows the subsystem controllers to be upgraded without affecting I/O.

It is 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 should continue to operate.

The approach taken will minimize telescope down time, allows the use of both systems in parallel, and provides a failsafe fall back to the old system during commissioning.

Best Practices

This is a short summary of some overall observatory best practices we have followed. It is critical to have an adequate lab available early, to involve the operations group early, to have good team communication, perform early prototyping, to hold frequent mini-reviews and to give sufficient time and attention to summit planning.

SOFTWARE

This section briefly describes the changes to the TCS software. The VxWorks 5.3.1 OS has been changed to RHEL 64 bit running the RT Patch. EPICS was migrated from R3.10 to R3.14.12, EPICS records have been tidied up and all MOSUBS replaced with aSub. We have moved from CAPFAST to TDCT [2] as our graphical hierarchical database editor. There are a number of new drivers (see THPPC067 [3]) based on ASYN. There is a new database-backed runtime configuration service (see TUPPC032 [4]). In addition to the EPICS development there is some LVFPGA and RSLOGIX PLC code. The end user UIs is being redeveloped using QT and the engineering UIs have migrated from DM to caQtDM.

In terms of the application software the current pointing kernel is being replaced with a design based on Pat Wallace's TCSpk [5]. In addition, PNT will get many new features such as orbital element support, an improved pointing model, and separate data streams for tracking vs. offsetting and various user requested enhancements. The ROT and SEC subsystems will now use a common motion control solution and the current serial communication with the motion controllers located at the secondary top socket is being replaced with Ethernet. SEC is also getting coordinated moves, new load-side encoder monitoring and coning to achieve zero coma at the instrument detector and vacuum monitoring. There is little change to the DOM software other than the general EPICS and driver updates described earlier, though the interface to the Dome PLC is being improved. Changes to AXE are mainly related to the encoders and to the servo and are discussed below. TCS introduces a new subsystem called TSS that monitors and integrates all fault and interlock information into EPICS. The TSS IOC is for monitoring only and does not play a part in processing the data but provides a single viewpoint into the TCS interlock logic with dedicated displays and alarm integration. Faults and interlocks are processed by a PLC and subsystem hardware.

ELECTRONICS/CONTROL

The existing control system has a significant amount of VME-based hardware and external interface boxes that are custom-made solutions. The primary logic boards housed within the amplifier assemblies are custom CMOS based boards. Some boards are actually wire wrapped solutions and some analogue boards contain a significant amount of red line changes, making these difficult to maintain and update. Previously, due to space limitations in the relay logic, interlocks were daisy-chained together and inputs were wired together to generate a single limit or fault preventing us from easily determining which fault or which interlock has triggered. The same holds true for all the emergency stop switches. The update is addressing these items by utilizing newer larger capacity COTS hardware, removing the daisy-chaining and replacing the physical relay logic with a PLC based solution. The PLC

will have an associated PanelView Graphic Terminal to allow fault visibility without the need for EPICS to be running. This replaces the existing colour coded LED scheme embedded in the CMOS logic cards.

All of the drive hardware for the secondary mirrors is obsolete and this is being replaced by a DeltaTau PMAC and Parker Zeta4 drive amplifiers. In addition new Sony Magnescale load-side encoders and home switches are being added to the secondary mirror to provide better trouble shooting capabilities.

These address the obsolescence and maintenance issues but it is the upgrades to the servo loop, coupled with the encoder upgrade that will bring the performance benefits. Servo analysis showed that the linear performance of the system is similar to when it was commissioned but that the coulombic friction is substantially higher. Over the years more instrumentation has been added to the telescope and the increased weight corresponds to a decrease in azimuth response. Overall the settling time is affecting performance. The servo design has benefited greatly from work done by Peter Thompson of STI. It has evolved from the current PI solution to a faster closed-loop PID with FF solution with the ability to differentiate between tracking demands and offsets in order to fine tune performance. The response time can be improved with the new architecture. The servo design is expected to reduce overshoot and jerk for small position changes. Parts of the new servo design have been successfully prototyped on the telescope and have shown the expected improvement. Work includes changes to the structural filter and inclusion of the fee-forward.

MECHANICAL

The azimuth and elevation axes of the telescope rotate on hydraulic bearings. The telescope tube rotates on four hydraulic pads, with two mounted on a journal on each side of the tube. The yoke rotates in azimuth on a journal on four horizontal hydraulic pads at the corners of the square yoke base. The yoke is constrained radially by vertical hydraulic pads on the side of the journal. For azimuth, the elevation pads are further constrained by axial pads to keep the telescope from shifting (left to right). The telescope is driven by eight friction-coupled drives in azimuth and four in elevation. There are shaft-mounted tachometers for each motor to regulate velocity and recognize when friction rollers slip.

The current encoder systems are a combination of high resolution incremental encoders, low resolution barcodes, and high precision reference marks known as PRMs. These three systems work in concert to provide the Keck telescopes with their absolute and high precision pointing needs. This type of solution was necessary because the friction-driven encoder has limitations due to its linear drift error and non-reproducible errors with elevation angle. Angular positions are measured by friction-coupled, incremental encoders: one for elevation and an average of two for azimuth. The encoders are intended to measure position changes continuously over small intervals. Angular positions are marked at specific

reference positions, separated by about a degree, for both elevation and azimuth by a system of tabs that interrupt light switches (sensors). For azimuth, the tabs are fixed to the journal (ground) and the sensors are fixed on the yoke. For elevation, the tabs are fixed to the tube and the sensors to the yoke. The incremental azimuth encoders used in the current system are the Heidenhain ROD800C rotary encoders. This encoder system is prone to both calibration errors and run-time errors primarily from the PRM switch/tab repeatability and frictional encoder slippage. In addition to the performance-related issues the system is maintenance intensive and the PRMs are prone to damage.

The TCSU project plans to encode the azimuth and elevation axis of both Keck telescopes with Heidenhain tape encoders. The components of each encoder can be broken down into four categories: the Heidenhain tape; multiple Heidenhain scanning read heads; a mounting surface for the tape; and hardware to position and protect the scanning read head above the tape scales. The TCS upgrade project selected Heidenhain ERA8400C tape scales to encode both the elevation and azimuth axes. These scales are manufactured using photolithography to produce precision graduations with a grating period of 40 microns. In addition to the incremental signal there is also distance-coded reference marks at 1000 period spacing that provide the ability to determine absolute position as soon as two adjacent reference marks are crossed.

Four read heads will be used for azimuth and three read heads for elevation. The azimuth read heads are separated by 90° for full 360° coverage and the configuration provides for full translation error rejection. The elevation read heads are oriented to provide continuous coverage over the elevation range from -8° to +94°. The new solution does not require barcodes or PRMS so there will be no PRM calibration or PRM induced errors nor roller slippage, the PRMS tabs can be removed, and more read heads should provide for better translation rejection and redundancy. The solution also lends itself to automated PM diagnostic based on read head signal strength.

WHERE WE ARE

At the DDR the encoder design had some issues and an additional follow-up delta review was required. As a result the encoder design went through a major overhaul and changed as follows: The original EL design called for a separate segmented ring structure, which would hold the tape, mounted off of the yoke main triangle with three read heads mounted to the elevation journal. The original AZ design called for a very large separate segmented ring structure mounted off of azimuth axial journal bearing with one read head mounted at each of four yoke base corners. The revised EL design, which has been successfully prototyped on Keck II, consisted of a variation of the originally proposed barcode surface mounted encoder system using existing surfaces for mounting where three read heads are mounted to rigid

yoke main triangle structure. The revised AZ design moved to a compact, on-axis annular design with the read heads mounted to rigid and fixed structure. These changes were mechanical and physical and resulted in no changes to the software or electronics. The electronic, software and control design has remained unchanged since preliminary design and has progressed without technical issues.

The entire software infrastructure is in place. The infrastructure was tested with 32-bit and then 64-bit Linux. This includes running EPICS 3.14.12 over RHEL 6.3 with RT MRG, porting of the custom records, migrating the CapFast schematics to TDCT, integrating the TCSpk pointing kernel into EPICS, testing all new drivers, implementing and testing the new TIM subsystem and the configuration service, and performing proof of concepts with the PLCs and motion controllers. Development is ongoing at the application level for each of the subsystems and includes SNL, DB configuration, C/C++ code, PLC and LVFPGA.

A representative amount of hardware is staged at the HQ lab including all subsystem controllers, motion controllers, PLC and RIO configurations. A complete elevation encoder prototype has been deployed and tested on the summit. In addition to the mechanical components this includes a subsystem (AXE) controller with BC635, EIB, RHEL 6, EPICS and AXE Encoder Processing running on the summit. There is also a PNT controller providing test AZ, EL demands. Analysis of this is aided by the use of BEAUTY and the dedicated data server.

HQ integration and test is scheduled to complete mid next year at which time we will start subsystem deployment to Keck II followed approximately a year later by Keck I.

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