A Decade of Operations with the Laser Traffic Control System; Paradigm Shift and Implied Development Directions

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ABSTRACT

The Laser Traffic Control System (LTCS) is a software solution to the problem of laser beam avoidance, using priority based collision resolution and an optional built-in laser shutter command interface. LTCS uses static site survey information, dynamic telescope pointing and control data, and a configurable "rules" scheme, to monitor laser beam geometry (Rayleigh and LGS) and warn or prevent undesired emission at participating institutions. LTCS was developed for use on Mauna Kea in 2001, but through collaborative efforts with multiple institutions, has since been enhanced and installed at several sites around the world. Functional implementations, either operational or in prototype form, exist for Mauna Kea, La Palma, Cerro Pachon, Cerro Paranal, and Haleakala. Since the last LTCS SPIE update in 2006, many important features have been added. There has also been some new site testing activity that has resulted in lessons learned and the development of new analysis/test tools. Finally, an important lasing operations paradigm shift has emerged on Mauna Kea and is anticipated for Paranal. The trend is clearly away from static collision priority rule determination, toward dynamic "negotiated" priority determination. The implications of this paradigm shift, discussion of forced collision test results and lessons learned, and a status update on development activities since the last update will be presented in the paper.

Keywords: laser guide star, adaptive optics, laser traffic control, laser beam avoidance, LTCS

1. INTRODUCTION

The operations concept for a laser beam avoidance system to avoid LGS and/or Rayleigh "collisions" between laser equipped telescopes and collocated non-lasing telescopes, was originally envisioned by Wizinowich et. al[1]. A "first generation" LTCS system was developed in 2001, and has been in continuous use on Mauna Kea since 2002. A detailed description of the initial LTCS implementation was provided by Summers et al[2].

1.1 LTCS Concepts Overview

The core function of LTCS is determination of laser beam collision geometry via geometric analysis of static site geometry, and dynamic telescope and laser pointing information. A secondary function is to determine priority during collision conditions, and where appropriate, warn and/or command shuttering of an involved laser. Site survey information is stored in a configuration file. The dynamic pointing and control data is obtained via URLs. Figure 1 illustrates the atmospheric effects of a telescope pointing FOV compared against laser beam emission for the same observation target. Note that in the given case, although the telescope and laser are viewing the same object, there is no collision between Rayleigh or LGS with the telescope FOV.

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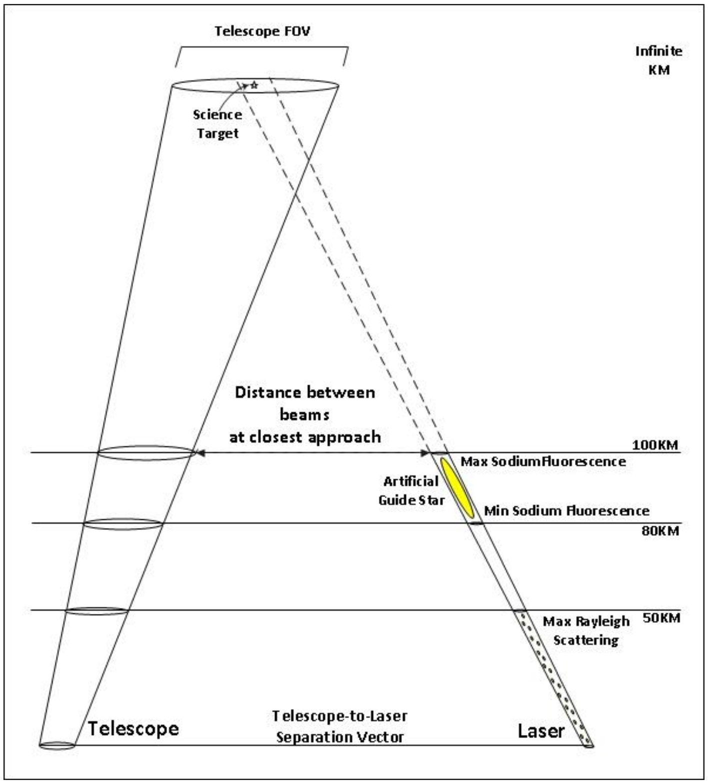

Figure 1 – Example telescope and laser geometry

The geometric crossing algorithm is centered on the optical axis vector. Figure 2 illustrates the base vector approach. LTCS combines the vector analysis with laser beam and telescope aperture and FOV profile information to determine collision event predictions and entry/exit times. Figure 3 illustrates the overlay of laser and telescope profile information used in the calculations.

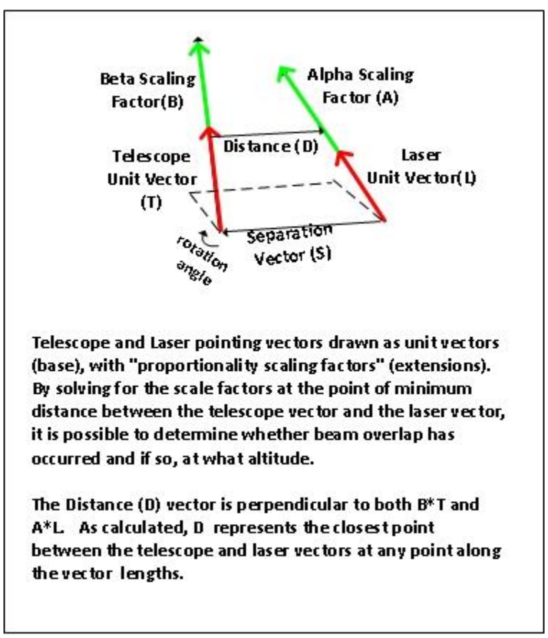

Figure 2 – Vector Analysis

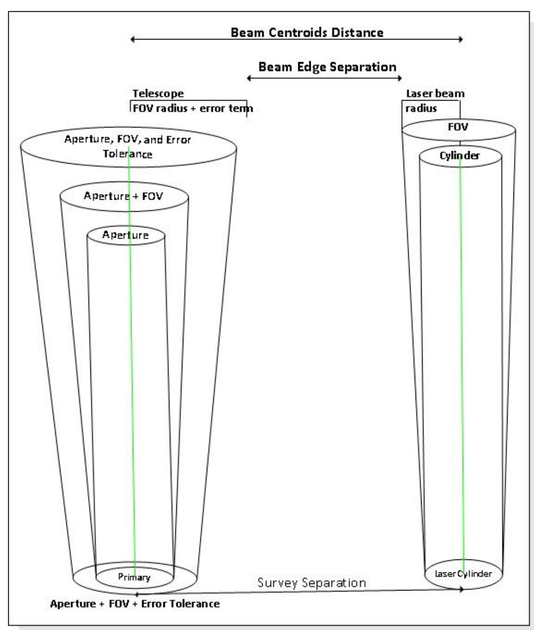

Figure 3 – Laser beam and FOV vector overlay

1.2 Software Architecture

LTCS core functions are implemented within four processes. Three of these processes act as a unit to monitor the flow of telescope pointing and state information, perform geometric laser beam calculations, and store results in a database. A fourth process is used independently to process collision query requests. Query requests can be used for pre-planning of future positions, or current (in-position) conditions. Queries can be performed via web-based forms or scripts. A centralized abstracted database interface, multiple operator GUIs, and some software administration tools are included in the base distribution. The LTCS software architecture is shown in Figure 4. For rough estimation purposes, LTCS consists of approximately 20K lines of Java, C, and PHP code running under Linux or Unix/Solaris architectures. The code requires some third party software prerequisites, including Slalib, Log4J, MySql (or Postgres), and Apache web services.

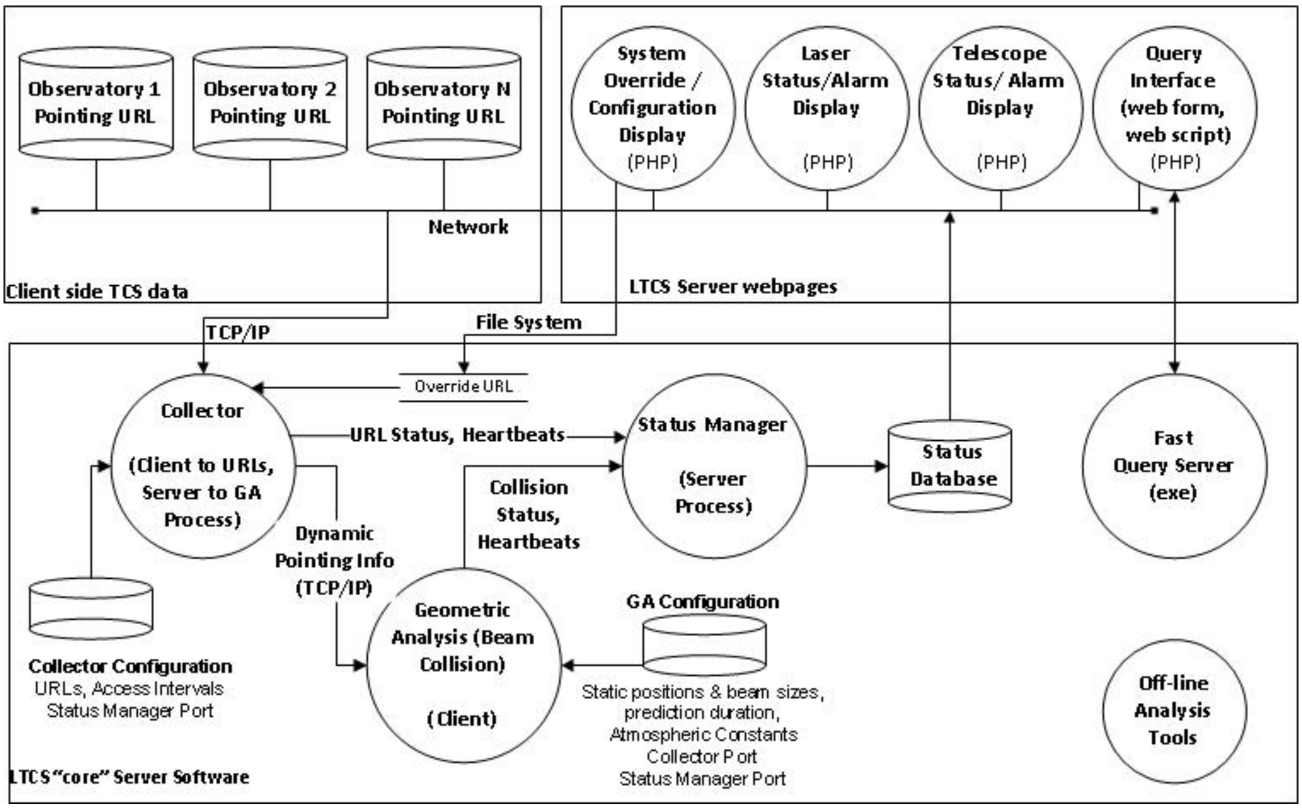

Figure 4 - LTCS Software Architecture

1.3 Basic Run-Time Capabilities and Features

LTCS features have evolved to incorporate diverse needs from several sites. The underlying geometric analysis calculations are essentially the same for all implementations. However, collision priority determination is configurable. Significant nuanced differences in operations are possible depending on how pointing URLs are implemented at the participating lasing and telescope facilities, and the configured rule scheme for resolving collision priority. The following list provides insight into current LTCS capabilities:

- Support for multiple lasers and telescopes on a site, with optional ability to direct-couple fast laser shutter control.
- Auto connection and retrieval of telescope/laser URL feeds, with configurable URL visit intervals, automatic stale data detection/filtering, and optional slew detection filtering.

- Five configurable priority resolution rule "schemes", including "lasers-yield", "first-on-target", and "lasers lase-through". Accommodation for hybrid site rule definitions, using different numeric priority levels for each telescope and laser are supported.
- Laser "Preview" simulation (for avoiding "immediate" collisions upon opening laser shutter).
- Fast (sub-second) query server collision "look-ahead" for preplanned object observations.
- Operator GUIs for server status (all telescopes/lasers), and client status (specific telescope).
- Individual telescope/laser control of calculations via dynamic URL control field settings.
- Configurable site survey, atmospheric parameters, and beam/FOV profile information, including provision for site survey x/y uncertainty.
- System level, GUI based URL override control and configuration.
- On or off-axis laser projection modeling for cylindrical or conical laser beam profiles.
- Configurable dithering distance and error tolerance for "base" position and time-on-target calculations.

Critical site status is contained in one simple web-based server GUI, the Status and Alarm Summary. The Mauna Kea version of this GUI, supporting 4 lasers, is shown in figure 5. A localized telescope GUI status page is available for telescopes interested only in a subset of the server data (local URL state and any collision predictions with lasers).

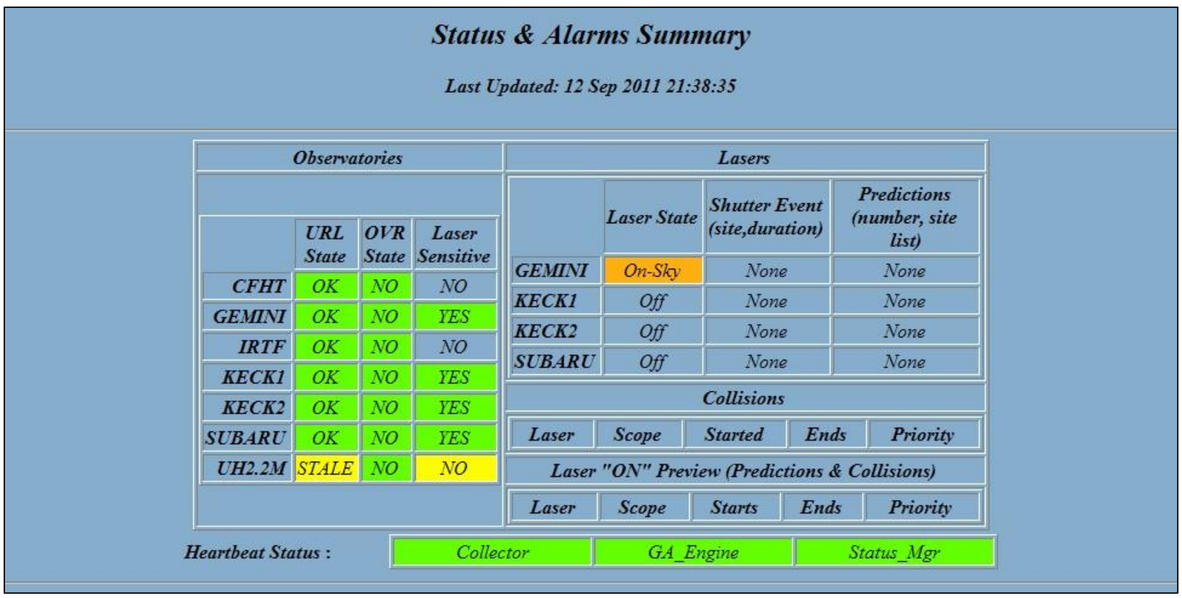

Figure 5 – Mauna Kea Status and Alarm Summary Webpage

2. FEATURES ADDED OR IMPROVED SINCE 2006

Since 2006, a variety of bug fixes and minor enhancements have occurred (as would be expected with any operational system). More significant enhancements include support for controlling multiple lasers from a single server instance, addition of conical laser beam profiles (to augment cylindrical modeling), and support for "first-on-target" and hybrid priority rule system configurations. In addition to run-time functionality, a variety of administration and test analysis/support tools have been created. Additional details for administrative and test support tools are given below.

2.1 Site Installation and Administration

Site Config Tool. The process of installing and configuring LTCS for a new site has traditionally been done by knowledgeable individuals. No installation document was originally developed for LTCS as the development was expected only for Mauna Kea. As part of preparatory work for ESO collaboration, some site installation documentation and automation was created. A site configuration tool now allows a user to auto-generate most internal files, and creates templates for URL and geometric calculator configuration. Along with reducing human errors, achieving a moderately complicated new site installation/configuration (e.g. ESO Paranal), has been reduced to approximately a day or two for an experienced developer, and 2-3 days for a non-experienced developer. Additional documentation on required 3rd party products and installation instructions are now provided in the LTCS baseline distribution.

Core Software Audit Tool. Given multiple LTCS implementations around the globe, some means of auditing source code baselines at sites was deemed desirable. A "core" software audit tool has been developed for this purpose. An audit tar file is now distributed with each LTCS release. The audit tool produces a difference report between the local source code and the distribution baseline. Although most sites will have minor site specific differences, the report is helpful to alert administrators to unexpected differences. Some code with site specific content (i.e. database account names, passwords, etc.) is not included in the audit, but having a majority of core software files included is still very helpful. Longer term, a fully automated audit tool, using site configuration tool enhancements, would be desirable.

2.2 Site Survey Analysis and forced Collision Test Support

Vincenty Site Survey Analysis Tools. In 2010, one of the LTCS functions for determining offset latitude and longitude (from the reference survey location) was found to be less accurate at large offset distances than an alternative calculation approach. The original home-grown calculation was replaced by a Vincenty geodesic algorithm[3]. Vincenty has centimeter accuracy potential for sites with 1-2 km baseline separations. During the regression testing for Mauna Kea, a tool to compare and analyze site survey definitions for internal consistency was developed. The tool compares known latitude and longitude for telescopes against the LTCS survey definition (reference latitude/longitude plus North, East, and Z offsets). The tool compares old and new algorithms, and reports errors. This tool has been helpful to verify the quality of Mauna Kea's survey definition, and was helpful in suggesting that further refinements were necessary in both the Cerro Pachon and Cerro Paranal LTCS survey definitions. The tool can also be used to generate the offsets from known lat/lon positions. The Vincenty algorithm requires an altitude scale factor, a tool for which has been developed using minimized error convergence from all positions in the site survey.

Forced Collision Tool. A highly desired tool for forced beam collisions has been created. The tool can be used to define the perspective pointing RA/DEC values needed for a telescope to image a laser beam at an intersect point some distance along the projected beam. This tool is based on simple vector centroids, so there are limits on fidelity (poor results for some circumstances such as off-axis laser projection in the near field, and inability to exclude the invisible "gap" between maximum Rayleigh height and lower end of the LGS). However, given the tool's limitations, it is still very helpful as an aid to guide telescopes into collision for studying emission impact on guiders and spectroscopic instruments.

Laser Zenith Pointing Error Analysis Tool. A typical forced collision test strategy is to position a laser at zenith, and then point one or more telescopes to intersect and image the beam. During collision tests between Keck and multiple other telescopes (Gemini, Subaru, and CFHT), unexpected position offsets were experienced while telescopes imaged the beam. Lessons learned are discussed in section 3. However, of note for this section is that an analysis tool was developed to quantify laser zenith pointing errors (assumes a trusted site survey) from image captures of the laser beam. Analysis of one imaged result will quantify the perspective pointing error (normal to the imaging telescope). Two observations (the second from a different telescope) are sufficient to solve the true laser zenith pointing error of the projection telescope. This tool can be used when access to pointing model expertise is unavailable, or when pointing errors are suspected but unconfirmed.

2.3 Audio Alert Scripts

LTCS audio alerts are routinely used in the Keck implementation to warn of impending or occurring collisions. The ways in which audio alerts can be used are highly subjective and vary between sites. Example audio alert scripts based upon Keck operations have been created and are now distributed with the software for optional use by sites that might desire to use or modify them for their own purposes.

3. LESSONS LEARNED FROM FORCED COLLISION TESTS

LTCS has been in continuous use on Mauna Kea since 2002. Although the number of lasing nights without incident is impressive and suggestive of an acceptable collision algorithm, explicit forced collision testing is always a good idea on new sites for multiple reasons. These include validation of telescope / laser profile configuration, verification of telescope/laser pointing URL data, laser shutter control verification, and a sanity check of site survey data.

On Mauna Kea, nighttime forced collision tests have occurred between Keck2 and Gemini, Keck2 and Subaru, and Keck1 and CFHT. The Subaru/Keck2 test was conducted in 2002, with results documented by Hayano et al[4]. Gemini/Keck2 tests have been conducted multiple times, first in 2005, and again during 2008-2010. Results were documented by Coulson and Roth[5]. The CFHT-Keck1 test results have not yet been published. While test results related to spectrographic impact have been relatively unambiguous, the early test results for LTCS algorithm verification were somewhat confused. Although there were suspicions of pointing errors in one or both telescopes in the first Keck/Gemini test, no conclusive evidence was immediately found. Most recently, in 2012, a problematic CFHT/Keck1 test elevated the probability of laser pointing error over other possible error sources (i.e. survey error, algorithm error). After further analysis, laser zenith pointing error was determined to be the problem in both the CFHT test and the early Gemini/Keck2 test.

As may be common with most large Az/Alt mounts operating in non-tracking mode at zenith, Keck pointing model error terms were not automatically applied, causing a zenith pointing error and LGS offset position from the expected location during imaging tests. Even a small pointing error can equate to an unexpectedly large Rayleigh and/or LGS offset position. As an example, the Keck2 zenith pointing error resulted in a 6 degree LGS azimuth position offset (as viewed from Gemini). In the CFHT test, less than an arcminute zenith pointing error resulted in a ~1 degree LGS azimuth position error. The test with Subaru only slightly suggested an offset of the LGS vs. expected location; this may have been simply due to the specific test geometry.

The major lessons learned are that site-level LTCS forced collision testing invokes interplay of laser and telescope pointing accuracy, site survey quality, telescope/laser beam/FOV profile setup, and the internal algorithm. De-convolving the error sources in cases of unexpected test results can be confusing. Some care in pre-planning of forced collision testing is well advised to limit the potential for confused results and avoidable error sources. Users are advised to approach forced collision testing first by planning to position the laser at zenith, with opt-axis (i.e. well centered) telescopic imaging of the Rayleigh or LGS. Users of lasing facilities should take care to pre-check pointing model error term inclusion, and are advised to pre-check the internal consistency of the LTCS site survey definition against known lat/lon information (using Vincenty analysis). If test results are unexpected, the magnitude of any error should help identify high probability causes. Although software algorithm errors are always possible, their probability should be considered low given the large operational nighttime experience on Mauna Kea. When position errors are large, laser pointing error may be likely. If the site survey is trusted, the laser zenith pointing error tool described above can be helpful to either partially describe the error (perspective pointing from one telescope), or fully define the error (two different imaging telescopes required). When errors are small, separating error source contributions may prove difficult.

A forced collision tool has been created to support testing at any geometry. The tool lacks fidelity to address some test cases of interest (edge capture, low elevation, off-axis projection cases), but can still be quite useful.

A lesson learned from experience setting up new LTCS sites is that site survey quality plays an important role in the eventual performance of the system. Some sites have considered using GPS in the absence of a professional survey. Commercial quality GPS has a typical accuracy of ~15 meters in the US, and degrades outside the U.S. Attempting to configure LTCS survey offsets using GPS (other than in precise differential mode) is ill-advised. A professional survey will result in much better operational efficiency. LTCS provides configuration parameters for site survey uncertainty, but configured uncertainty increases collision frequency and duration; it should be avoided if possible. While un-attempted to date, it should be possible to precisely define LTCS x,y site survey data using a combination of carefully calibrated pointing (including pointing model coefficients), imaged star fields, laser zenith pointing analysis, and Vincenty analysis. However, the effort to achieve this would be much greater than just procuring a professional survey.

4. LASER OPERATIONS PARADIGM SHIFT AND IMPLICATIONS

In 2006, in collaboration with the Isaac Newton Group, LTCS enhancements were made to support the William Herschel Telescope (WHT) Rayleigh laser AO system[6]. WHT requirements included a prescient laser operations paradigm shift toward a generalized "First-on-Target" priority mode. The Mauna Kea LTCS was originally implemented for passive laser operations (lasers-yield), with a notion for future support of an "active" first-on-target priority mode between two lasers. Operations requirements for achieving generalized active first-on-target operations mode with full pre-planning functions were not fully appreciated at the time of the ING/WHT site implementation. The "2nd generation" LTCS, supporting ING capabilities, was documented by Summers et al in 2006[7].

In the first era of LTCS development, the underlying geometric collision calculations for Mauna Kea were developed. The second generation LTCS began to expand the collision priority rules system for global use. Several new rules were added, including support for first-on-target mode and hybrid site configurations. In late 2006, Mauna Kea began transitioning from passive mode (lasers always yield) to the new first-on-target priority paradigm. Gemini, Keck1, and Keck2 were the initial first-on-target participants, with IRTF, UH2.2M, and Subaru remaining in "lasers-yield" mode. The hybrid site configuration allowed first-on-target lasing facilities to occasionally "lase-through" a participating telescope's FOV. The transition from a passive "lasers-yields" mode, to an active "first-on-target" mode on Mauna Kea, came with development implications and challenges. The active lasing paradigm required addition of logic in LTCS to determine time-on-target, base pointing position, and a maximum allowable dithering offset. To prevent gaming the system and to maintain query integrity (a foundation for observation pre-planning integrity), some constraints were placed on telescope and laser URL reporting parameters, with forced priority degradation in cases where states and/or positions were not maintained during observations.

Even after the first-on-target paradigm shift was implemented, operators showed clear preference for challenging priority determination when outcomes were unfavorable. Operators would attempt to dynamically negotiate priority in unfavorable cases, and when agreed, use LTCS system overrides (not intended for the purpose) to forcibly remove a participant from calculations. Most often, this tactic was used to allow a laser to lase through a telescope FOV when the rule system would have otherwise prevented this from occurring. Although effective, use of system overrides causes a loss of information by the removed participant. The removed participant often desires to know when a collision occurs, even if priority is willingly relinquished. However, this is prevented when system overrides are used in this manner. A third (future) era of LTCS development will be needed to fully develop tools supporting a transition from LTCS rules as hard convention, to a more advisory role, with tools for operators to dynamically adjust priority. Dynamic priority adjustment may serve as the foundation for more sophisticated concepts such as observation reservation blocks.

An effective active lasing paradigm requires support for pro-active (pre-planned) collision avoidance. This is accomplished with positional queries. Although a web-form query capability existed in LTCS prior to first-on-target mode, a more useful web script tool was developed by ING/WHT for use by remote observatories to help pre-plan and avoid collisions. This script tool was to be used primarily by telescopes to discover cases where a laser would have priority to "lase-through" their FOV. When Mauna Kea began transitioning to first-on-target mode, additional requirements were levied to support more robust pre-planning and warning functions. Query integrity and query performance are two critical system level requirements that were addressed. These are discussed further below.

4.1 Query Integrity and Performance

A foundational operational assumption about pre-planned observations is that once a proactive query has been executed while "in-position", the priority result should maintain integrity over time, no matter what other dynamic system changes might occur. Priority may be increased as a function of dynamic changes of other participants, but must not be degraded unless given up voluntarily. The operations concept is that once an observation has been pre-planned and determined to be unobstructed, the observation should be able to be completed unobstructed unless priority is voluntarily relinquished. For telescopes, this means no undesired laser emission, and for lasers it means no forced shuttering (i.e. ability to "lase-through" collisions). With an active lasing paradigm, query frequency and performance rise dramatically.

Prior to 2006, queries invoked an internal simulation thread for each defined telescope/laser. The pointing data for the simulation was obtained from the web-form (or web-script), and placed in a hidden URL. The visit interval for the simulated URL mimicked the visit interval for the real telescope URL. A handshake delay was required before retrieving the query result, constraining round-trip performance timing. The minimum query round-trip time was variable, but averaged 4 seconds on Mauna Kea. Prior to first-on-target operations, this wasn't considered a serious constraint, as the paradigm was passive and thus queries were infrequent. However, this performance was unacceptable following transition to the "active" pre-planning paradigm. In 2010, performance was dramatically improved by replacing the internal simulation threads with a dedicated external query server. The new query server typically achieves sub-second query performance, greatly increasing the number of queries that can be done per unit time. The new query capability is sufficient for a wide range of planning functions. New query performance using an old solaris host (Mauna Kea), configured for 6 impacted telescopes, 1 laser, and a 12 hour look-ahead, is shown in figure 6. Performance under Linux with newer processors is sufficiently fast to allow a wide range of possible query server uses.

- Best case is no laser or telescope impacted; Worst case is an active laser and all telescopes sensitive (impacted). Daytime testing shows:
- **Laser Impacted** **Calc Time (secs)**
  - 0 0.002 - 0.036 (Calculator not executed)
  - 1 0.199 - 0.234 (base case - calc call)
  - 2 0.330 - 0.380
  - 3 0.470 - 0.500
  - 4 0.790 - 0.822
  - 5 0.790 - 0.822
  - 6 0.922 - 0.987
- Network performance varied over multiple runs; some better, some worse, but all showed marked improvement over old query design.

Figure 6 – Typical Query Server Performance (slow Solaris Host)

4.2 URL Pointing and State Parameter Reporting Constraints

To maintain chronological query integrity, some reporting constraints on telescope URL parameters are required. A telescope wishing to operate in first-on-target mode must both maintain position (within dithering tolerance), and state (constantly reporting sensitivity to laser emission). A laser must remain in position and be operating under the rules for lasers (no switching between telescope/laser status during an observation). The reason for these constraints is to prevent a scenario whereby a laser or telescope alters priority determinations already reported by a prior query result to another participant. A change in status (increased priority), if allowed, would invalidate prior pre-planning by another participant. To avoid this confusing scenario, LTCS enforces query integrity via reset of time-on-target for state changes and dither/move distance threshold crossings.

5. DEVELOPMENT DIRECTIONS

Collaboration between ESO and Keck in 2011 identified several areas of mutual interest for potential new development. New concepts mostly mirror the experience on Mauna Kea and in the Canaries in regards to a paradigm shift towards more flexibility in the priority rule system. Some desired work is related to underlying geometric calculations (e.g. adding a non-sidereal model). Some new feature concept development work has subsequently occurred, but further development work is pending project schedules. Collaborating institutions should consider coordinating project schedules to effectively reduce development burdens for all involved. The current set of LTCS "wish list" items are defined further in the paragraphs below.

5.1 Current Development Items (funded/completed)

- URL Interface "hooks" for future high-priority development features. The underlying feature implementations are not yet funded, but updating the URL specification in preparation for future development has been funded. A draft LTCS URL specification upgrade to version 3.0 has been completed[8]. Support for the following concepts has been added:
    - Differentiated laser pointing from telescope pointing (for sites using off-axis laser dithers)
    - Non-sidereal pointing (multiple modes including az/el zenith pointing, and generalized velocity based AZ/EL and RA/DEC non-sidereal pointing)
    - Dynamic specification of dithering field size (per telescope)
    - Reporting of pre-planned observation end time (useful for optimizing first-on-target calculations)

- Pre-implementation Design Concept(s) Development
    - Dynamic Priority Adjustments – the ability to change from static (configuration based) collision priority to a GUI based operator tool "negotiated" priority adjustment.
    - Server synchronization – the ability to eliminate multiple LTCS servers on a multi-laser site. This will be accomplished by implementing LTCS server support for client connections to retrieve laser shutter commands on demand (thus allowing a single LTCS server to service multiple local and remote lasers on a site as opposed to having one copy of LTCS server software per lasing facility).

5.2 High Priority Future Development Items

Some development items will leverage and continue work completed in paragraph 5.1. For example, while a draft URL specification update (first bullet of 5.1) has been completed, the actual work to implement the 'hooks' and complete the underlying core functionality has not yet started. The desired high priority items include:

- Completion of all underlying feature sub-bullets in the 3.0 URL specification as defined in 5.1 above
- Reservation system – the ability to pre-reserve one or more pointing positions for a block of time at "super-priority" level, with TBD conflict resolution specification in case of conflicting reservations.
- Web-form GUI to integrate the forced collision tool for ease of use.

5.3 Lower Priority Future Development items

Many lower priority items have been on the "wish-list" for some time. These features include:

- Z-term (altitude) site survey uncertainty
- Modifications to the existing stand-alone geometric calculator to support backward time studies (the calculator already supports future time studies).
- Fully automated new site configuration (based on a simplified site definition file)
- Fully automated software audits (to include site-specific files altered for local configuration)
- Minor improvements to the forced collision tool (to address altitude vs. just distance along laser beam)
- Laser refraction modeling
- A beam geometry/collision visualization aid.

6. CONCLUSION

LTCS has experienced impressive reuse since inception in 2001. Several premier multi-telescope sites are using, or planning to use, LTCS for laser beam avoidance. Feature enhancements since the last SPIE LTCS update in 2006 have included support for controlling multiple lasers from a single server, conical laser beam profile support, some automation of new site configuration/installation, site survey validation/analysis tools, and forced collision test tools.

Long standing questions regarding laser/telescope forced collision tests on Mauna Kea have recently been resolved. The lessons learned from these tests, combined with experience configuring new sites, has resulted in better understanding of the interplay between several involved variables. Forced collision testing can be very helpful to verify laser/telescope beam/FOV profile information, site survey quality, URL reporting, and laser shuttering control. Although survey uncertainty may be configured into LTCS, a good site survey is crucial for efficient LTCS performance.

Collaborations between Keck, ING, and ESO have helped to confirm an LGS-AO operations paradigm shift affecting LTCS software. Early LTCS development was focused on solving geometric collision calculations for a passive (lasers-yield) lasing environment. Later development provided enhanced collision priority determination supporting "active" (lase-through) priority schemes. The latest paradigm shift is toward dynamic collision priority determination. In the new paradigm, a pre-configured collision priority rule is advisory and non-compulsory. This requires new operator tools to support dynamic priority adjustments coming from the rules system. Dynamic priority will be the foundation for more complicated concepts such as object reservations.

LTCS is currently well positioned for global use under a configurable compulsory priority rule convention. However, further feature development is needed to fully achieve non-compulsory system behavior supporting dynamic priority adjustments. To prevent feature stagnation, maintain development continuity, and avoid multiple "one-off" solutions, a global collaborative systems engineering approach should continue to be preferred.

LTCS software is generally available to the astronomical community with a simple academic licensing agreement. Contact the primary author for details.

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