Enhanced Laser Traffic Control System Operation Mode

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ABSTRACT

The proportion of telescopes using Laser Guide Star (LGS) systems is increasing worldwide. LGS systems generally use either "pulsed lasers" (at 532 nm), creating an LGS in the upper troposphere by means of molecular scattering of light, or "sodium lasers" (at 589 nm), creating an LGS by means of excitation and spontaneous emission of sodium atoms in the mesosphere. Adequate coordination of observations involving non-laser and laser-assisted telescopes is necessary to prevent the laser beams from contaminating the field of view of telescopes operating in the visible. This coordination is done using a Laser Traffic Control System (LTCS).

A key aspect of the LTCS is the implementation of a set of policies defining the pointing priorities of all telescopes during LGS assisted observations. A simple policy, "lasers always yield", was to assign the lowest operational priority to the lasing telescope. This basic scheme evolved into the "first-on-target" policy, giving priority to the first telescope pointing in a given direction. Here we propose an evolution of these policies, the "enhanced LTCS", which defines pointing privileges according to the scientific priority of the observing programs.

This study was made in the context of the Observatorio Roque de Los Muchachos (ORM), the location of the Cherenkov Telescope Array North (CTA-N). The interest has been triggered by the fact that the CTA-N includes multiple elements (telescopes) and all of them are of large field of view, and on the other hand, the Thirty-Meter Telescope (TMT) has selected ORM as its alternate site, and it is also the location of the Gran Telescopio de Canarias (GTC). This study was conducted to assess the operational impact of LGS-equipped telescopes on all existing and future ORM telescopes (the CTA-N included).

Our results show that implementing an enhanced LTCS Mode, based on the scientific priorities of the executed programs, minimizes the disruption imposed on high-priority science programs, maximizing the science impact of all telescopes operating at a given site.

Keywords: LTCS, Laser Guide Star, Enhanced LTCS Mode

1. INTRODUCTION

Modern astronomical telescopes are including technology to enable diffraction limited imaging and spectroscopy, the so-called adaptive optics (AO) systems. As a result of this, astronomical facilities capable of both seeing limited and

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diffraction limited observations are co-existing, at the same observatory site, with other telescopes only intended for seeing limited instruments for visible and near-infrared (NIR) observations. The telescopes including diffraction limited instrumentation are increasingly making use of laser systems as to create one or more reference stars (laser guide stars, LGS) in the mid (~ 12 km) and upper levels (~ 90 km) in the atmosphere. These LGS(s) help to compute the magnitude of wavefront aberrations, at various spatial frequencies, introduced by the fluctuations in the air index of refraction along the path of the light from the astronomical sources through the atmosphere. The fluctuations in the index of refraction are the result of various atmospheric processes inducing turbulent mixing of air masses of different properties (mainly temperature and absolute humidity).

Achieving diffraction-limited imaging/spectroscopy capability is a must as to exploit the angular resolution that is possible to obtain with existing medium-size aperture telescopes and new generation large aperture telescopes. There are multiple scientific goals that can only be possible to pursue with the use of diffraction limited telescopes/instruments.

However, co-existing seeing limited and diffraction limited telescopes assisted by laser systems (a lasing telescope) may enter in a conflict when the laser beams (most of them in the visible at 532 nm or 589 nm) crosses the field of view (FOV) of another telescope conducting observations in a spectral band prone to be affected by the laser light. This is understood as a collision of the laser beam and the FOV of one or more telescopes. The number of collisions and their duration is highly variable at a given observatory site, and they also depend on the proximity of the lasing telescope to those passive (non-lasing) telescopes operating in optical bands susceptible to laser light contamination as well as the FOV of the telescopes.

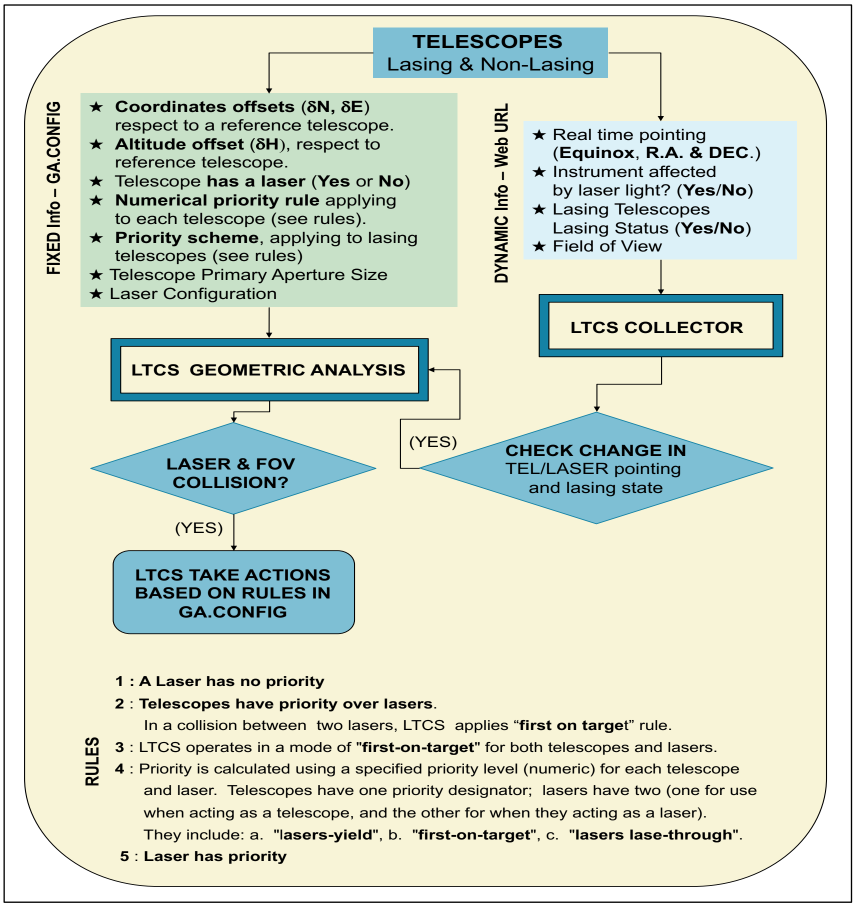
Fortunately, the time and duration of a laser beam collision with the field of view of another telescope can be successfully predicted and anticipated. The collision depends on the position on the sky where the lasing and non-lasing telescopes are aiming, as well as the size of their respective field of view. The possibility of having a collision can be computed using accurate information on the plane coordinates (northing, easting), height of the optical axis (above ground level), the angular size of the field of view of the telescopes involved and their respective pointing information. A tool that does exactly this work was made available to the astronomy community as a contribution from the Maunakea Observatories, this is the Laser Traffic Control System (Summers et al., 2002).

The successful co-existence and operations of lasing and non-lasing telescopes at a given observatory site also depends on the policy, agreed among all stakeholders, consisting of the procedures to decide the priority of the various telescopes to gain access to an unaffected field of view. Therefore, a successful observatory site-wide operation needs not only of having the right software tools (such as LTCS) but also of a set of policies that will decide which telescope have priority in the event of a conflict. So far one policy, that arguably can be considered a fair policy, is that of giving the priority to the telescope that has reached its current astronomical observing target position first. Therefore, if a non-lasing telescope currently observing its scientific target is foreseeing to become affected by the laser beam of a lasing-telescope, then that telescope that was first on its target will have the right to continue with its current observing mode. If the priority is to the non-lasing telescope then the lasing-telescope is expected to shut off its laser(s) for the period of time the collision is expected to last. In the contrary, the non-lasing telescope shall follow a procedure to avoid the laser beam altogether (if saturation and CCD persistence is a problem, for instance) or stay put and resume observations once the collision with the laser beam is over.

Detailed studies carried out, both by the CTA-N and the TMT teams, have consistently shown that such a “first-on-target” policy leads to the loss of several science cases per year, particularly those that cannot be re-scheduled to later times, e.g. fast target of opportunity alerts, such as Gamma-Ray Bursts, or Gravitational Wave alerts. Such cases can be recovered, without loss of the science by either of the involved installations, if the “first-on-target” policy gets modified to account for the science programs scheduling priorities. Such priorities need to take into account the urgency of an observation and the general easiness with which a given observation can be re-scheduled to later times, without loss of the science case. Interestingly, the afore-mentioned studies predict that the simultaneous observation of a same target (e.g. a same Gamma-Ray Burst) does not create a conflict, at least not between the CTA-N and another lasing-telescope. “A common misconception is that, if two telescopes point to the same target, there is necessarily a collision — this is not always the case.” (Amico et al., 2015). Only the need for a fast target-of-opportunity observation by the CTA-N and simultaneous observation of a target by the lasing-telescope crossing the field-of-view of the CTA-N needs to be avoided.

The flexibility of the queue observing mode at the various telescopes is key to avoid conflicts between lasing and non-lasing telescopes. At the ORM site, a prime site for modern astronomy, the co-existence of various lasing and non-lasing astronomical facilities is expected. In here, the modelling work as to predict the probability of laser beams collision (of TMT and GTC) with the field of view of other telescopes at the ORM site is explained, and results from simulations are summarized. This information can be used to derive a policy that can consider the flexibility of the observing mode at the various telescopes, as well as the priority of the scheduled observations, as a way to avoid conflicts between lasing and non-lasing telescopes, and implement those policies as integral part of an enhanced operation mode of the LTCS system.

2. LTCS METHODOLOGY



1 : **A Laser has no priority**

2 : **Telescopes have priority over lasers**.
In a collision between two lasers, LTCS applies "**first on target**" rule.

3 : LTCS operates in a mode of "**first-on-target**" for both telescopes and lasers.

4 : Priority is calculated using a specified priority level (numeric) for each telescope and laser. Telescopes have one priority designator; lasers have two (one for use when acting as a telescope, and the other for when they acting as a laser). They include: a. "**lasers-yield**", b. "**first-on-target**", c. "**lasers lase-through**".

5 : **Laser has priority**

Figure 1. Diagram that shows the Laser Traffic Control System information needed and the decision making process.

The LTCS design, as well as its implementation and operation experience at various astronomical observatories has been extensively documented. For those readers interested in the very details of the logic of operations and the implementation of LTCS the following are key references to look at (Summers et al., 2002; Summers at al., 2006; Summers et al., 2012; Amico et al., 2015; Santos et al., 2016). Here, we limit ourselves to show in a more concise way how the way LTCS works. First, in order for LTCS to determine if a collision between a laser beam propagated from a given telescope will cross the field of view of another, it requires to know: a) The respective geographic location of all telescopes subscribing to the LTCS, from which the offsets in their plane coordinates (δN, δE) are calculated, as well as the difference (in altitude, δH) of their respective optical axes. b) Whether the telescopes are equipped with a laser, c) As well as, the policy agreed at the observatory site for handling collisions between laser(s) and telescopes. This information is kept in a configuration file and is considered as fixed inputs. Besides, the LTCS needs to know the dynamic information associated to the programs under observation by the telescopes subscribing to it, including: i) The real-time pointing (Right Ascension and Declination of the source under observation), ii) Whether the telescope is prone to be affected by laser light or not (this will depend on the instrument/spectral-band currently in use), iii) The field-of-view of the instruments being used, and importantly for the telescopes equipped with lasers, the LTCS needs to know the lasing-status (is the laser active and propagating through the atmosphere or not).

The LTCS includes two main modules. One, the LTCS Collector, receives the dynamically changing information (based on a Web URL database form), this checks whether there are any changes in pointing of the telescopes and laser's lasing status. If there are any changes, it will provide the information to the LTCS Geometric Analysis Module, which is based on the static information (telescopes coordinates) and dynamic information (current pointing of the telescopes), will compute if a collision of the laser beam(s) and fields of view will happen (including the time when the event will occur and its duration). If a collision is predicted, then the LTCS will make a decision based on the policies agreed and implemented at the observatory sites. If the laser has no priority, the LTCS will automatically shut off the offending laser. On the other hand, if the non-lasing telescope has no priority it will receive an alert to let the operators/observers know of the impending collision for them to plan for it and make a decision. Figure 1 shows the methodology of LTCS, as described in here, and also include a set of rules that define the way priorities are handled.

3. THE ENHANCED LTCS OPERATION MODE AT THE OBSERVATORIO DEL ROQUE DE LOS MUCHACHOS

3.1 LTCS Setup

The LTCS code has already been implemented at the ORM observatory site, and a configuration (*ga.config*) file was prepared during the setup of LTCS. The configuration files uses as reference point the location of the William Herschel Telescope (WHT), and its northing (N), easting (E) and height (H) offset are listed as (0, 0, 12.25 m), where the 12.25 m is the vertical distance from ground level to the intersection of the azimuth/elevation axes of this telescope. The northing and easting coordinates for all the other telescopes included in the configuration files are given relative to the WHT. For this study, we modified the original *ga.config* file as to include the position of all of the telescopes part of the Cherenkov Telescope Array (CTA-N), as well as of the candidate location for the TMT, relative to the position of the WHT.

The LTCS allows the possibility to be used in planning mode. I.e. if the HA/DEC and time of the observations for the sources to be observed by the lasing and non-lasing telescopes are known in advance. This information can be run through the Geometric Analysis Tool (GAT) and determine if a collision is expected. We are thankful to Doug Summer, the software engineer behind the development of the LTCS code, for having provided us with a modified version of the GAT that can handle the large field of view of the CTA-N elements. We have used that tool to run a Monte Carlo simulation with the goal to predict the likelihood of collision between the TMT (and GTC) laser beams and a the telescopes part of the CTA-N as well as other telescope facilities at the ORM site. This modified version of the GTA is the *ha_dec_collision* tool and has been compiled to run under a 64-bit linux environment. The format for using this tool us show below:

ha_dec_collision <laser_telescope_name> <ha(hrs)> <dec(deg)> <FOV(deg)> <tel_name> <ha(hrs)> <dec(deg)> <FOV(deg)> <observe_duration(secs)>

Where;

<laser_telescope_name>	Is the acronym (in the ga.config file) used for the lasing telescope of interest (ex. TMT).
<ha(hrs)> <dec(deg)>	Hour-angle and declination of the source to be observed by the lasing telescope.
<FOV(deg)>	Field-of-view of the lasing telescope.
<tel_name>	Is the acronym (in the ga.config file) used for the non-lasing telescope of interest.
<ha(hrs)> <dec(deg)>	Hour-angle and declination of the source to be observed by the non-lasing telescope.
<FOV(deg)>	Field-of-view of the non-lasing telescope (changes from instrument to instrument).
<observe_duration(secs)>	Time window (in seconds) to check for possible collisions (ex. 3600 secs).

3.2 Monte Carlo Approach for LTCS simulations

A single simulation, as shown in the parameters listed for the *ha_dec_collision* tool, requires the celestial coordinates of the sources observed by the telescopes. Specifically, the tool uses as inputs the hour-angle (HA) and declination (DEC) of the sources to be observed by a lasing telescope, and the other telescope using an instrument sensitive to laser light beam contamination and for which it is desirable to check for possible collision of the laser beam and the instrument field of view. Therefore, we used a Monte Carlo approach where HA and DEC for both, lasing and non-lasing telescopes, were selected randomly for each simulated observation-night.

The exact procedure followed is listed below:

★For every simulated night: the hour-angle and declination of a random number of sources (minimum: 6, maximum : 24, sources per night,) where prepared for each telescope (a lasing, and a non-lasing telescope).

★ For each simulated astronomical source, the hour-angle was picked randomly in the range -3h – +3h. The declination angle was picked randomly in the range -30^{o} – +80^{o} (i.e. limiting the zenith angles to 60 degrees maximum).

★ The night observing time, taken as 12 hours, was split evenly among all the sources to be scheduled in a given night at each telescope.

★ Priorities were randomly assigned (to each obs.) based on SCHEMES 1 and 2 (see Section 3.3).

3.3 Schemes for assigning a priority to astronomical observations

In the enhanced-LTCS mode the goal is to provide additional information to the LTCS so that it will make a decision based also on the priority of the science programs under observation by the telescopes (lasing and non-lasing, respectively). LTCS, in case a collision is foreseen, will then allow the program/telescope of highest reported priority to continue uninterrupted. For the lowest priority telescope, LTCS will issue a collision warning (if using an instrument in a spectral band potentially affected by laser light). Alternatively, it will shut-off the laser(s) of the lasing telescope.

In a real application of the enhanced-LTCS mode, each telescope operator (understood as the agency responsible for the operation of a given telescope subscribing to the LTCS ruling) will have to assign a priority to each of the observing programs intended to be observe. This needs to be done beforehand, with anticipation to the scheduling of the observing programs for a given observing night. We foresee two ways that may be suitable for assigning a priority to a science program (the reader may think of other possible ways). For the purpose of this study, the following two schemes were foreseen as possible:

SCHEME 1: The priority of the observing programs are pre-assigned by each telescope team based on categorization of the programs. For instance: 15% are priority 1 (top priority), 20% priority 2, 30% priority 3 and 35% priority 4 (the lowest priority).

SCHEME 2: The priority of an observing program gets calculated [by a piece of software independent of the LTCS] based on information known for each program, such as: Time Critical Observation (Yes/No), Observing Mode (Visitor/Service), Program Completion (near completion, Yes/No), Flexible Adaptive Queue Status (Best atmospheric conditions / Standard Atmospheric Conditions), others. A weight can be assigned to each parameter included for consideration, and a total priority is computed for each observation. The programs are ranked then according to their overall evaluation and categorized in priority ranges.

In the course of this study we checked with telescope operators at the ORM observatory site, and we concluded that about 15% of the observations scheduled in a given year may meet the merits as to be considered top priority. This was used as a guideline, in collaboration with the CTA-N team, for the determination of the ranges shown in the SCHEME 1 above. In the case of the CTA-N top priority is essentially synonymous with "highest time criticality."

Figure 2 shows in a graphic way the procedure followed in our simulations.

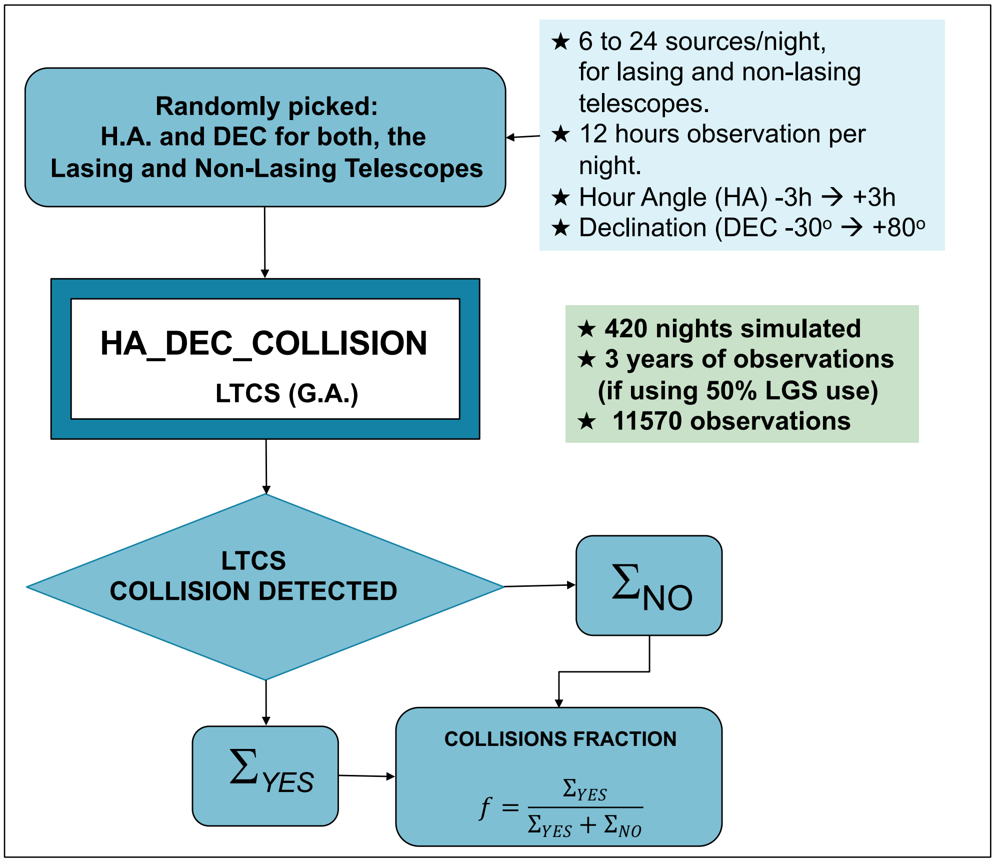


Figure 2. Simulations of the LTCS Enhanced Operation Mode, a Monte Carlo Approach.

4. MONTECARLO SIMULATIONS OF ENHANCED-LTCS OPERATION MODE

4.1 Simulations: some considerations

Using the criteria detailed in Section 3, a total of 11570 pair of observations, each for the lasing and non-lasing telescopes, each with their own observing time duration, were lined up. In the case a telescope was expected to run an observation longer than the other one (either the lasing, or no-lasing telescopes), then LTCS's *ha_dec_collision* tool was run only for the fraction of the time the observations were to be running simultaneously. Then, a new run of the LTCS's *ha_dec_collision* tool was done, this time for the remainder of the observing time of a given telescope, but checked against the new source position assigned (in the random process) to the other telescope. Considering the fact that we assumed a number between 6 and 24 sources to be observed each night, then 11570 simulations correspond to about 3 years of operations.

As the lasing telescopes we considered the TMT and GTC, and as non-lasing telescopes we took the CTA, GTC, William Herschel Telescope (WHT), Isaac Newton Telescope (INT) and the Nordic Optical Telescope (NOT). When checking for laser beam collisions between a lasing telescope and the field of view of a non-lasing one, we used the same set of sources randomly picked, only attributing the observations of the non-lasing telescope, as if those were to be observed by CTA, GTC, WHT, INT, or the NOT telescope, respectively. In other words, our results reflect the effect of distance to the lasing telescope as well as the varying field of view of the instruments considered in the non-lasing telescopes.

4.2 Simulations: Number of collisions predicted and annual probability of collision

Table 1, shows the number of collisions that the LTCS’s *ha_dec_collision* tool predicted for the TMT and GTC (as lasing telescopes) when checked against simultaneous observations with the CTA, GTC (for the case of TMT), WHT, INT and NOT telescopes. For instance, out of 11570 simultaneous observations of the TMT and the CTA-N, we predicted 720 collisions. In other words 6.2% of the time we expected a collision. However, TMT is expected to schedule LGS assisted observations (as to achieve diffraction limited imaging/spectroscopy) only 50% of the science observing nights in a year. Therefore, the annual probability of a collision between the TMT and a CTA-N telescope element, will be 3.1% (i.e. out of 100 simultaneous observations, we may expect that 3 times a collision of the TMT laser beam and the field of view of a CTA-N telescope may occur). Similarly, if we compare the case of GTC and the CTA-N, the number of collisions predicted increases to 900, this is due to the fact the GTC is closer to the CTA-N than is TMT. However, the annual use of lasers expected for the GTC is only 15% (compared to the TMT 50%) and this reduces the probability that a collision will occur to an annual probability of 1.2%. The likelihood of a collision between the TMT or GTC lasers beams and the other telescopes, located further away at the ORM site and using instruments of smaller fields of view than the CTA-N, is at or below 0.7% (for the case of TMT), and expected to be below 0.35% for the case of GTC because of the their use of laser is less frequent.

The 3.1% (TMT/CTA-N) and 1.2% (GTC/CTA-N) annual collision probability, we have obtained from our analysis, agree well with the collision probability estimated from the combined pointing distribution computed using 10 years of the MAGIC (Major Atmospheric Imaging Cherenkov) telescope pointing and one year from the GTC, as shown in the study of Gaug & Doro, 2018. *“We find no conflict expected for the use of lasers [at the ORM site]. However, 1%* (**3%**) *of extra-galactic and 1%* ***(5%)*** *of galactic observations with the CTA-N may be affected by the GTC (**TMT**) LGS lasers, unless an enhanced version of a laser tracking control system gets implemented.”*(Gaug & Doro, 2018).

Table 1. Results of the modeling and simulations of collisions between laser beams and the field of view of selected telescopes at the Observatorio del Roque de Los Muchachos (ORM). The results of number of collisions predicted (in an annual basis) and the probability of collisions are for when the lasing telescope is the TMT, and GTC (only for the case of GTC lasing affecting the CTA-N). The simulations assume that 50% of the year, TMT will be using laser assisted (LGS) observations, and for the case of the GTC that a maximum of 15%, of the annual observing programs, will make use of laser to achieve diffraction limited capability. Results for the case of the GTC, as lasing telescope, are highlighted.

Lasing Telescope	**Telescope (using an instrument sensitive to laser light contamination)**				
TMT / GTC	CTA-N	GTC	WHT	INT	NOT
Total Simulations	11570	11570	11570	11570	11570
Field of view	5° and 8°	10 arcmin	2°	20 arcmin	10 arcmin
Number of collisions predicted out of 11570 simulations	720 / 900	103	154	57	55
Collision probability based on 50% / 15% annual use of LGS	3.1% / 1.2%	0.50%	0.70%	0.25%	0.20%
Duration of collisions **[mean**, mean+1sigma] (seconds)	[**760** , 1520] **[622 , 1601]**	[**511** , 1095]	[**700** , 1612]	[**401** , 877]	[**310** , 743]

4.3 Simulations: Regarding the duration of the collisions

Table 1 lists the mean and mean + 1-standard deviation of the predicted duration of the TMT laser beams affecting the field of view of various telescopes. The statistical distribution of the duration of the collisions is not normal distribution. In the case of the TMT and the CTA telescope elements, out of the 720 collisions predicted by the LTCS in this simulation exercise, the average duration of a collision is of about 760 seconds (12 min, 40 sec). However, in 65% of the cases the collision duration is below 220 seconds (i.e. shorter than 3.6 minutes). The median collision duration was of about 60 seconds (1 min) duration. If the time duration of the predicted collision is short, perhaps interrupting the program for that period of time and resuming the same observation afterwards is the best course of action. In the contrary, when the observations gets impacted beyond a reasonable waiting time, a telescope running a flexible queue scheduling of the observations, may consider that the best course of action is moving to different science object for observations. We have used the example of the CTA-N telescope elements because these are the instruments with the larger field of view (as shown in Table 1), and there are cases when the duration of the collisions are long and of order 15-60 minutes.

4.4 Simulations: Does the Enhanced-LTCS mode help?

In a final step, we looked at the priority of the observing programs of both, lasing and non-lasing telescopes, involved in a collision. Such priority was assigned randomly to all of the observations based on the schemes shown in Section 3.3.

If the First-On-Target LTCS rule were to be applied, for the case of the TMT/GTC and the field of view of the elements in the Cherenkov Telescope Array, we learned that:

★ Out of the 100% of collisions detected (720 collisions), it is expected (and so it is confirmed by the Monte Carlo Simulations) that 50% of the time the LTCS will rule in favor of the non-lasing telescope (i.e. CTA-N) and 50% of the time in favor of the lasing telescope (i.e. GTC or TMT).

★ Out of all the times that either telescope (non-lasing or lasing) was asked to yield by the LTCS (because such telescope was last in moving to its current pointing target), 25% of those occasions (180 times out of 720 collisions predicted) the telescopes were engaged in high-priority observations and had to abandon those high-priority observations in favor of the other telescope.

★ In the case of collisions with the large field of view of the CTA-N telescope elements, this potentially implies a long disruption in these high priority observations.

If LTCS-Enhanced Mode was set to check the priority flag of the programs as to make a decision, we learned:

★ 73% of the time (523 cases out of 720 collisions), LTCS was able to rule in favor of the telescope that was engaged in a science observation previously classified as of high priority. The rule splits the decision in half between the two telescopes, i.e. there is no bias in favor of either, lasing / non-lasing type of telescopes.

★ 27% of the time (181 cases out of 720 collisions), LTCS was not able to make a decision because both telescopes (lasing and non-lasing) were engaged in an observation of equal priority. In those cases LTCS can default to the First-On-Target policy.

★ However and importantly, only 4% of those cases (~ 8 cases, corresponding to about 1% of all the collisions detected by the LTCS) a given telescope was engaged in the upmost high priority. This needs to be compared against the 25% of the occasions of high-priority programs affected when simply applying the First-On-Target rule. An alternate share of the risk (night observing coordination) can help make a fair decision in those few cases (the operators could agree to default to First-On-Target rule too).

5. CONCLUSIONS

Modern astronomical telescopes are including technology to enable diffraction limited imaging and spectroscopy, the so-called adaptive optics (AO) systems. As a result of this, astronomical facilities capable of both seeing limited and diffraction limited observations are co-existing, at the same observatory site. The telescopes including diffraction limited instrumentation are increasingly making use of laser systems as to create one or more reference stars (laser guide stars, LGS) in the mid (~ 12 km) and upper levels (~ 90 km) in the atmosphere. Co-existing seeing limited and diffraction limited telescopes assisted by laser systems (a lasing telescope) may enter in a conflict when the laser beams (most of them in the visible at 532 nm or 589 nm) crosses the FOV of another telescope conducting observations in a spectral band affected by the laser light. This is understood as a collision of the laser beam and the FOV of one or more telescopes.

The Laser Traffic Control System (LTCS) uses accurate information on the geographic coordinates, height of the optical axis (above ground level), the real-time pointing, and the angular size of the field of view of the telescopes, to calculate the projection of a laser beam and the projection of the field of view of a telescope potentially affected by laser light. The LTCS tool, based on a previously agreed policy, makes a decision through which telescope involved in a collision will have the privilege to continue its observation uninterrupted.

Monte Carlo approach simulations conducted to understand the fraction of the time the CTA-N may be affected by laser beam propagating from the TMT telescope estimated that the annual probability of the CTA-N to be affected by the TMT lasers is of 3.1%. If applying the First-On-Target rule, our simulations show that up to 25% of the time, a telescope asked to yield (until the collision is adverted) was engaged in high priority observation. Implementing a LTCS rule policy that is based on the priority of the scientific observation decreased the high-priority programs affected by a collision to only 1%. Therefore, the LTCS enhanced-operation mode, allows the telescope engaged in the highest priority to continue uninterrupted.

Our simulations, with results listed in Table 1, show that in the case of other telescopes, located further away from the TMT, or GTC, and using instruments of relatively smaller field of view (a few tens of arcmin), the percentage of the time in a year that they will experience a collision is relatively low. In these cases, perhaps the First-On-Target rule (as already implemented at the ORM site) is good enough for making decisions on which telescope will be granted the privilege to keep going with its observations uninterrupted.

The results presented in this study were focused on understanding the case of TMT/GTC co-existing with the CTA-N at the ORM site. However and for completeness, simulations have also been done, using the same approach detailed in this study, for understanding the case of TMT operating in the context of the various observatories at the Maunakea site. At Maunakea, the TMT site is further away from the ridge at which most of the telescopes are located, lower in altitude, and there are no telescopes using instrumentation with such large field of view as the Cherenkov Telescope Array does at the ORM site. In this case, our results show that the annual probability of collision between the TMT lasers and the field of view of telescopes at Maunakea (including the Keck Telescopes, Gemini-North, Subaru, and CFHT) is of order 0.2% — 0.5%. The 0.5% probability is for the case of TMT and the CFHT/MegaCAM, this is due to the relatively larger field of view of MegaCAM.

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