Operational Concept of the VLT's Adaptive Optics Facility and its instruments

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ABSTRACT

The ESO Adaptive Optics Facility (AOF) will transform UT4 of the VLT into a laser driven adaptive telescope in which the corrective optics, specifically the deformable secondary mirror, and the four Laser Guide Star units are integrated. Three instruments, with their own AO modules to provide field selection capabilities and wavefront sensing, will make use of this system to provide a variety of observing modes that span from large field IR imaging with GLAO, to integral field visible spectroscopy with both GLAO and LTAO, to SCAO high Strehl imaging and spectroscopy. Each of these observing modes carries its specific demands on observing conditions. Optimal use of telescope night-time, with such a high in demand and versatile instruments suite, is mandatory to maintain and even improve upon the scientific output of the facility. This implies that the standard VLT model for operations must be updated to cover these partly new demands. In particular, we discuss three key aspects: (1) the need for an upgrade of the site monitoring facilities to provide the operators with real-time information on the environmental conditions, including the ground layer strength, and their evolution throughout the night; (2) a set of tools and procedures to effectively use these data to optimize the short-term scheduling (i.e. with granularity of one night) of the telescope and (3) the upgrade of the current laser beam avoidance software to better cope with the AOF operational scheme, where the four laser units are continuously operated as long as the atmospheric conditions allow.

Keywords: laser guide star, adaptive optics, laser traffic control, laser beam avoidance, LTCS, adaptive optics, GLAO, LTAO, deformable secondary mirror, sodium laser

1. INTRODUCTION

The ESO Adaptive Optics Facility (AOF) project [1] has been launched in early 2006 after completion of a number of feasibility studies and formal approval by ESO Council. It constitutes a major evolution of one of the VLT unit telescopes (UT4) to transform it into a laser driven, adaptive telescope in which the corrective optics and the LGS Units are integrated. To this purpose the conventional Dornier M2 Unit is replaced by a Deformable Secondary Mirror (DSM) with 1170 actuators, and 4 LGS Units are assembled on the telescope Center-Piece to focus 4 laser beams in the Na-layer at approximately 90km and create 4 bright artificial star-like sources. For the telescope Nasmyth foci two adaptive optics modules, GRAAL [2] and GALACSI [3], are currently being integrated at ESO Germany and will implement ground layer adaptive optics (GLAO) and laser tomography adaptive optics (LTAO) correction to feed the science instruments HAWK-I, a wide field infrared imager and MUSE, an integral field visible spectrograph, respectively. The AOF will offer a very large (7'x7') field-of-view (FOV) GLAO correction in J, H and K bands (GRAAL+HAWK-I), and for the visible integral field spectrograph a 1'x1' GLAO corrected FOV (GALACSI-MUSE wide field mode) in addition to a LTAO 7.5" FOV (GALACSI-MUSE NFM) mode. All sub-systems are in the manufacturing and/or integration phase with intense system testing foreseen for 2012/13 in Germany. Thereafter, the complete system will be shipped to Paranal (Chile) for installation in the course of 2014. A dedicated branch of the AOF project takes care of organizing and implementing the telescope modifications required for accommodating the new facility. The first of these interventions was successfully completed in April 2012. The completion of the complex commissioning of the AOF with its science instruments is planed for the end of 2015 and thus availability to the scientific community is foreseen for the beginning of 2016.

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The Cassegrain focus of UT4, which is currently occupied by SINFONI, an integral field near-IR spectrograph, is also foreseen to be used with the AOF. To this extent ESO is carrying out a Phase A study for the new SCAO high-Strehl imaging and spectroscopy instrument ERIS [4], which will re-use the spectrograph of SINFONI called SPIFFI.

In this contribution we describe selected aspects of the operational concept for the AOF and more specifically the ones, which require an update of the current operational scheme and operational support tools at the Very Large Telescope (VLT).

2. SUMMARY OF AOF INSTRUMENT MODES

The instrumentation suite at UT4 will offer a wide range of laser driven adaptive optics observation capabilities in imaging as well as spectroscopy (see Table 1). The instruments MUSE and HAWK-I with their adaptive optics modules use GLAO to provide more often seeing conditions matching the best to median natural conditions. At the same time these basic instrument modes remain operational in seeing limited conditions allowing use of the telescope, for example, when site conditions are not favorable for laser driven adaptive optics (e.g. thin cirrus). Also poor seeing conditions (e.g. seeing > 1.5"), typically not used for AO assisted observations can be exploited if appropriate observing programs are available. The LTAO mode of MUSE and the SCAO modes of ERIS require typically good seeing conditions (e.g. seeing ≤1.2 arcsec at 500nm) in addition to good coherence times τ_0 (e.g. > 2ms).

Table 1: Summary of foreseen observing modes at UT4 with the AOF

Instrument	**Mode**	**Wavelength**	**Observing conditions**
MUSE (Nasmyth B)	Wide Field Mode (WFM) - IFU	480-930nm	Seeing limited
MUSE	"	"	GLAO
MUSE	Narrow Field Mode (NFM) - IFU	480-930nm	LTAO
HAWK-I (Nasmyth A)	Imaging	J, H, K	Seeing limited
HAWK-I	"	"	GLAO
ERIS* (Cassegrain)	Imaging, pupil plane coronagraphy & SAM	J, H, K, L, M	SCAO
ERIS*	IFU	J, H, K	SCAO

* ERIS is currently completing its Phase A. If approved, it will replace SINFONI at the Cassegrain focus on UT4.

Service mode observing at the VLT has several general goals including to (i) maximize the science efficiency by executing the programmes with the highest scientific priority first and under the required observing conditions; and (ii) to maximize the scientific use of the telescope time by having appropriate programmes ready for execution under a broad range of observing conditions. Optimally matching the available observing programmes to the current weather conditions is a well-known challenge for all observatories offering service mode. A pre-requisite for efficient operations, also in visitor mode, is knowledge of the current observing conditions. Besides the classical information on seeing, typically provided by a DIMM, the AOF in GLAO mode requires information on the turbulence content in the ground layer (≤ 500m). In Section 3 we briefly describe our first steps towards providing real time information for the ground layer and provide examples of how this information could be used for AOF instrumentation thus ensuring the specified image quality in Section 4.

A further noteworthy challenge in the operation scheme of the AOF will be the potential collision of the back-scattering beams and artificial guide stars of the four lasers with other (laser light sensitive; 589nm) observations on the mountain. First steps towards providing largely automated collision prevention on Paranal have been taken and are described in Section 5.

3. UPGRADE OF SITE MONITORING FACILITIES

Measurements of the vertical profile of atmospheric turbulence, $Cn^2(h)$, can be obtained from site monitoring sensors such as the "Slope Detection and Ranging" (SLODAR) technique and the "Multi-Aperture Scintillation Sensor" (MASS). SLODAR determines the profile from the spatial covariance of the slope of the wavefront phase aberration at the ground for the two different paths through the atmosphere defined by a "double star" target [5]. It gives the $Cn^2(h)$ for 8 layers starting from the ground up to about 100m depending on the separation of the observed binary system and its zenithal distance. MASS provides continuous measurements in 6 vertical resolution elements via optical scintillation measurements of a single star. The latter measurements are not sensitive to the turbulence in the first ~350m above the site, which does not contribute to the scintillation. These techniques have been extensively used to characterize astronomical sites and it is now foreseen to make them available for operations on Paranal. To this effect ESO has started an upgrade programme for the automated surface layer SLODAR instrument to Paranal operational standards including hardware and software standards. As part of the upgrade programme the maximum sensing altitude will be extended to about 300m thereby closing the gap to the MASS sensor.

The combination of measurements from the MASS and SLODAR sensors allows deriving estimates of the image quality at various altitudes. For example, SLODAR measurements can be used to estimate and remove the turbulence contribution of the first meters from the ground, which is not seen by the ATs (~5m height) and UTs (~30m height) due to shielding by their respective dome structures (see Figure 1). Estimates on the image quality, which the AOF will provide in GLAO mode to the instruments, can be similarly achieved by inclusion of MASS data.

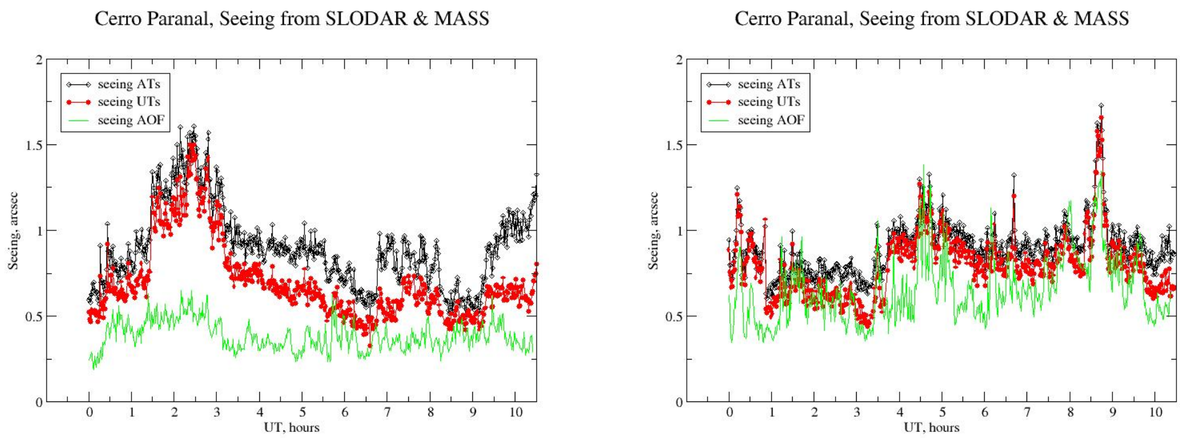

Figure 1. Examples of seeing estimates for selected altitudes above the Paranal platform derived from SLODAR and MASS measurements on June 1, 2012 (left) and May 21, 2012 (right). The green (light grey) line reflects the free atmosphere seeing of MASS and therefore is a measure of the seeing above ~350m which can be used as a guideline for the image quality the AOF will deliver to the instruments. The black and red (dark grey) lines reflect SLODAR measurements, where the contribution from the first 5m and 30m, respectively, is removed. These numbers provide a guideline on the image quality for the ATs and UTs, respectively (source Marc Sarazin).

Preliminary usage of test data from the current SLODAR and MASS instruments indicates that the turbulence ground layer on Paranal is often well developed and thus provides excellent conditions to operate the AOF in GLAO mode (see Figure 1, left panel). However, there are also atmospheric conditions where the turbulence is dominating at higher (above

~350m) altitudes (see Figure 1, right panel) and therefore a balance has to be made between the expected image quality gains and the operational overheads caused by the laser and adaptive optics setup time for the AOF.

The provision of real-time general site monitoring information and the overall seeing, the ground layer strength and the coherence time (for LTAO & SCAO) promises to bring a significant contribution to the operational efficiency on Paranal (see also Section 4). Further effort is needed to make the AOF relevant site monitoring information available in the control room as well as in the ESO dataflow and to calibrate the measurements with respect to the AOF performance parameters.

4. PROCEDURES

With the additional information on the vertical turbulence profile outlined in Section 3 and performance predictions for the individual observing modes of the instruments, the telescope operator or night astronomer at UT4 can make a quantitative evaluation for which observing programs the specified image quality can be achieved. Simulations show that the image quality, which the AOF delivers in GLAO mode to the instruments HAWK-I and MUSE, is determined (only) by the overall seeing and the turbulence strength in the ground layer (see Figure 2).

Using this information (and other parameters such as scientific priority and e.g. moon illumination) the operator can make a clear decision on which observation to start. The provisions of real-time atmospheric parameters including the ground layer strength, allows for monitoring of the performance during the execution and also for final data quality control should there be a lack of point source objects in the final data product.

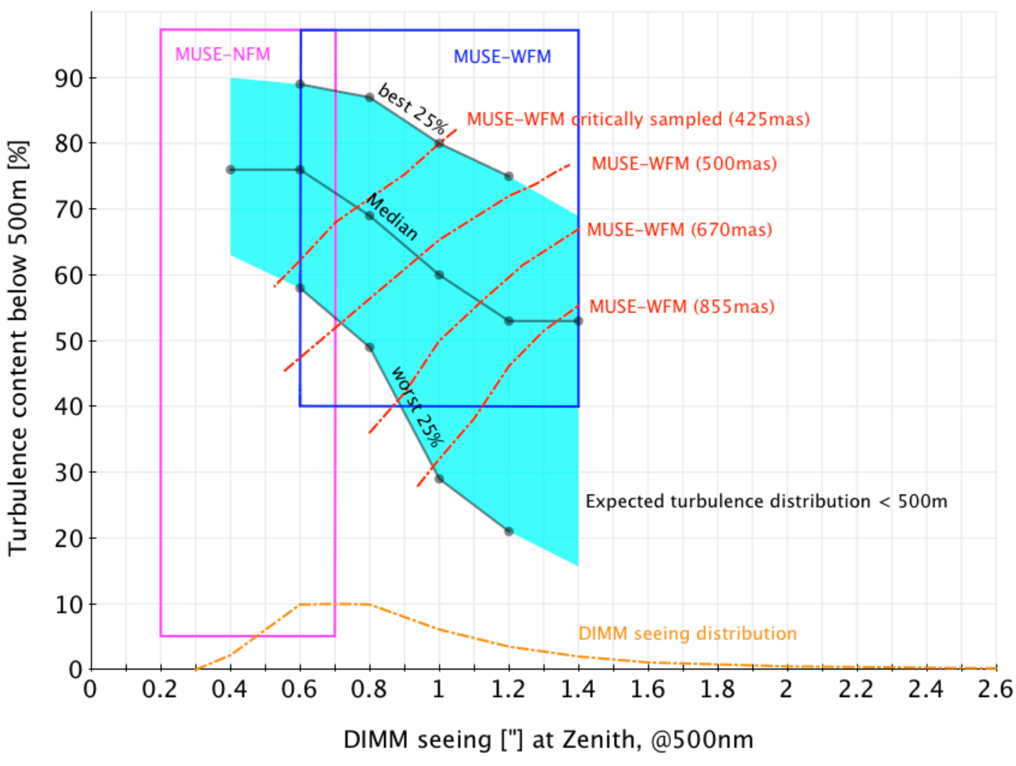

Figure 2. MUSE-WFM estimated image quality (650nm, red dash-dot lines) as function of DIMM seeing and turbulence content below 500m. The image quality is assumed to be the quadratic sum of the MUSE internal PSF (300mas for >650nm) and the image quality delivered by GALACSI, the adaptive optics module for MUSE. The distribution of the Paranal seeing (over 9 years) is indicated as orange dot-dashed line just above the x-axis and the expected distribution of the median, best and worst 25% distribution of the turbulence content below 500m is indicated in as shaded region. Observing conditions which are suitable for MUSE-NFM (LTAO) and MUSE-WFM (GLAO) are indicated by the purple (light grey) and blue (dark grey) boxes, respectively.

5. UPGRADE OF LASER BEAM AVOIDANCE SYSTEM

Adaptive Optics in astronomy has become a routine observing technique allowing improved image quality via GLAO techniques and diffraction limited observations via LTAO and SCAO modes at many astronomical observatories. All AO modes rely on the availability of a relatively bright "AO reference" source to measure the atmospheric turbulence and remove its effects from the scientific observations. If the target itself cannot serve this purpose, then a natural guide star (NGS) is needed (or even multiple NGS). The requirement to provide a relatively bright (V~12-16) reference star, and close to the science target in order to limit angular anisoplanatism effects, results in a very limited fraction of the sky that can be observed with classical NGS AO. In order to mitigate this restriction, the use of artificial Laser Guide Stars (LGS) has been developed. At ESO we use a sodium (Na) laser which is tuned to a wavelength of 589.2 nm to energize a layer of Na atoms which are naturally present in the mesosphere at an altitude of about 90 km. The Na atoms then re-emit the laser light producing a glowing artificial star of V~10 for an input power of about 10W [6].

Compared to NGS-only AO observations, the use of LGS has enabled a large increase in sky coverage. However, this comes at the price of a significantly more complex operation of the system. For example, the technical as well as "weather" downtime of LGS operation is in practice larger than that of normal or NGS-AO observations [6]. Furthermore, the propagation of a Laser beam from one telescope can negatively affect the observations at other telescopes on the same site if that instrumentation is sensitive to the laser light. In general, two sources of contamination are to be considered: the LGS generated in the sodium layer at an altitude of ~90 km and the Rayleigh and Mie scattered light from the laser beacon typically reaching up to about 15 km altitude or above (see Figure 3).

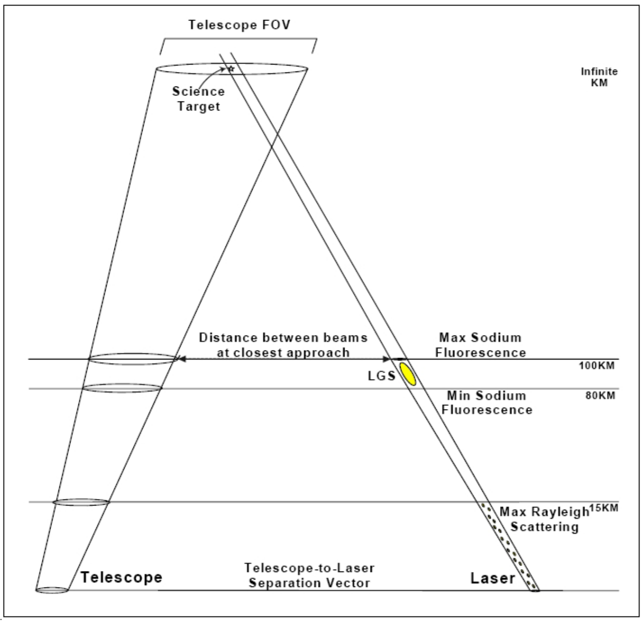

Figure 3. Example of telescope and laser geometry (for details see [7]). Note, that while the laser and the telescope point at the same science target there would not be a collision for the illustrated situation.

The artificial laser guide star or scattering cone can be seen by any optical (i.e. sensitive to 589.5nm) instrument and wave front sensor when their field of view intersects the relevant area of the sky. This artificial light contamination may cause increased sky background and even saturated images in sufficiently long exposures. Examples of this type of collision for the VLT instrument VIMOS and the VST with the Laser operated on UT4 are shown in Figure 4. Although there is no risk of permanent damage to the detectors, these short exposures clearly demonstrate the severe negative impact on the science quality of the images. It is therefore of paramount importance to avoid these collisions in normal science operation of the telescopes.

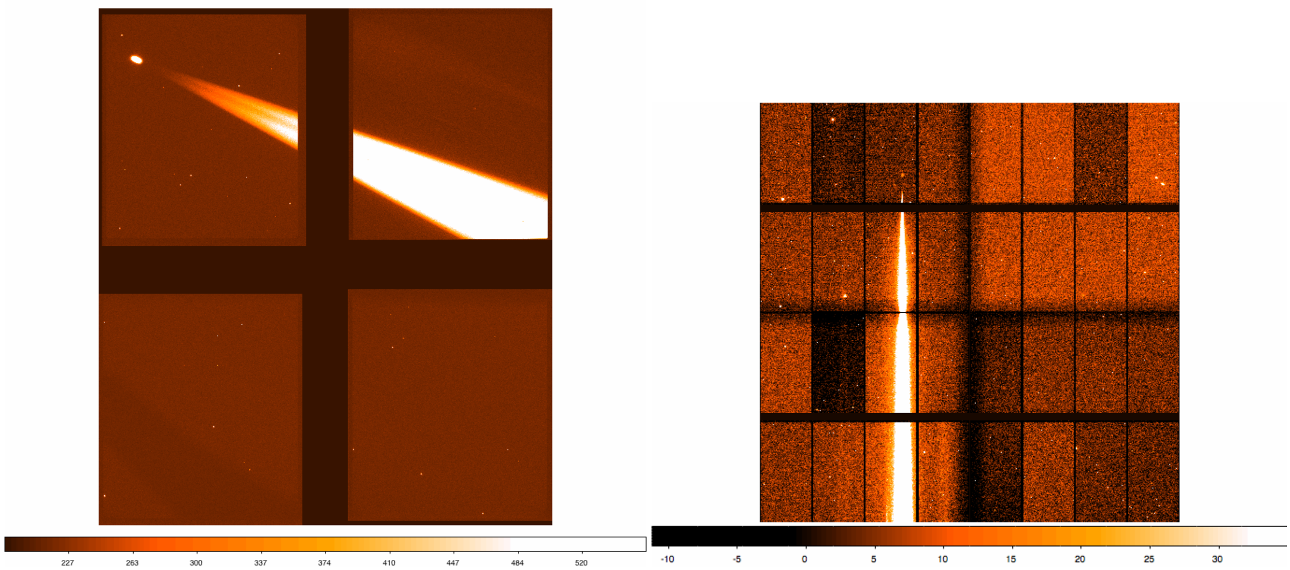

Figure 4. **Left:** ESO/VIMOS V-band image of the UT4 laser for an exposure time of 0.5 sec. The image shows the laser guide star in the upper left corner as well as the Rayleigh scattering beam. In imaging mode, VIMOS features 4 independent channels (each 7'x8') separated by ~2' gaps shown as dark regions in the above image. VIMOS is mounted on UT3, which is about 62m away from UT4. **Right:** ESO/VST V-band image of the UT4 laser for an exposure time of 10 sec. Both Rayleigh scattering beam and laser spot are visible in the FoV (1x1 degree). The distance between VST and UT4 is about 75m.

Presently, the Laser Guide Star Facility (LGSF) operated on UT4, serving the instruments NaCo and SINFONI is scheduled in pre-arranged observing blocks of about one week every four weeks. This limits the time when observatory staff needs to be vigilant about potential Laser collisions and a simple visual display is used to indicate the most obvious collisions in target coordinate space with observations at the non-lasing UTs. This Laser collision prevention tool relies on visual inspection by the night astronomers or TIOs and communication between UTs is carried out via verbal agreements. When the AOF with its 4 Lasers becomes available, on demand use of the facility depending only on observing conditions (e.g. seeing, ground layer turbulence content) is foreseen. This operation mode is distinctly different from the current operation scheme and most importantly connects the observations of different telescopes at the site via potential collisions for all laser suitable observing conditions. This requires a continuous monitoring and accurate prediction of collisions with precise calculations in 3D (i.e. science target at infinite distance, Laser spots at ~90km height and Rayleigh beam scattering below ~15km; see Figure 3). Potential collisions with VST and the auxiliary telescopes (and VISTA if it would be upgraded with optical capabilities) also need to be added to the monitoring system.

Such a system (Laser Traffic Control System or “LTCS”) is currently in operation on Mauna Kea, Gemini South and La Palma [7]. A key ingredient for the software are the precise locations of the individual telescopes (i.e. UTs, VST, auxiliary telescope at their various possible positions and VISTA), only then one can quantitatively judge the impact of the Lasers on other observations at the observatory and prevent any unforeseen collisions. A demonstration version of the LTCS software, with a realistic Paranal telescope geometry setup, has been developed as part of the AOF project and delivered to ESO in 2011. After a positive evaluation it was decided to develop the software further and provide the needed interfaces to the Paranal telescope suite for a test run in June 3-11, 2012. All UTs, the ATs, VST and VISTA are now included in the Paranal LTCS software and thus available for collision monitoring.

LTCS [7] offers automatic retrieval of telescope/laser pointing and configuration information via URL feeds. Various configurable priority resolution rule “schemes”, including “lasers-yield”, “first-on-target” and numeric priority levels for each telescope and laser are supported. Furthermore, laser “Preview” simulations (for avoiding “immediate” collisions upon opening laser or instrument shutter) are supported. Fast (sub-second) query server response times offer the opportunity to preplan observations for all telescopes. Site-specific atmospheric parameters can be conveniently adjusted in a configuration file. Critical information for all telescopes is contained in one simple web-based server GUI, the “Status and Alarms Summary” (see Figure 5).

Unfortunately, during the June 2012 test run the UT4 Laser was not available due to technical problems. However, using the true telescope pointings during the test and simulating Laser propagation on the software side, an extensive verification of the Paranal LTCS version was carried out. A snapshot of the main “Status and Alarms Summary” Web page is shown in Figure 5. The tests clearly demonstrated that the LTCS software is capable of monitor the complete telescope suite on Paranal for laser collisions. Over the course of the test, real time collision control, predictions for collisions with information on start and end time, as well as access to the query server was exercised. Simulating continuous laser propagation on UT4 but using true pointing information for all telescopes between 0 and 7 collisions were detected per night.

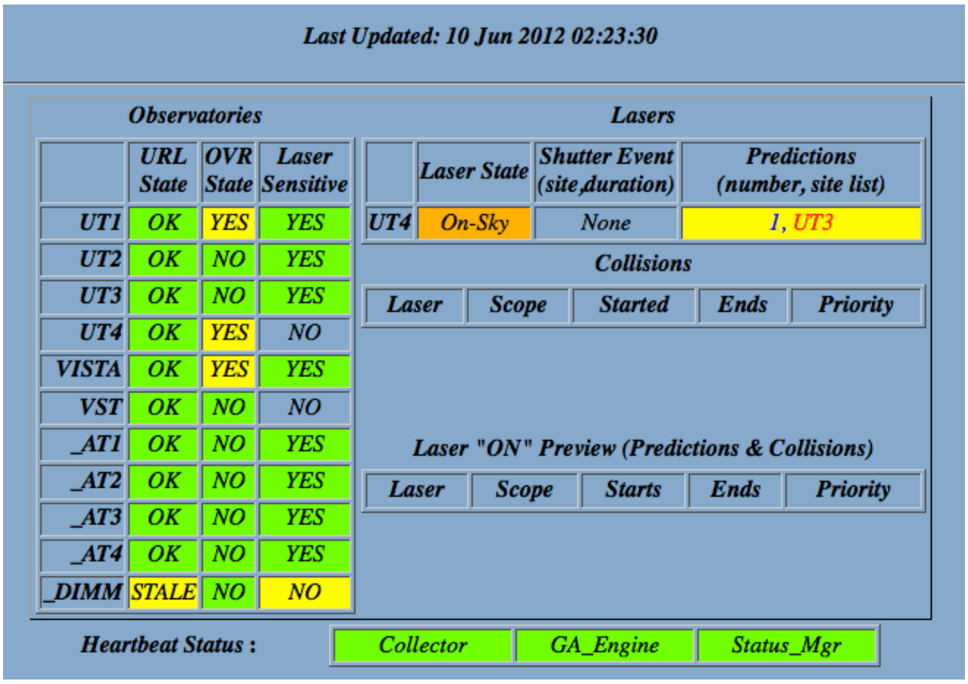

Figure 5. LTCS-Paranal “Status and Alarms Summary” Webpage showing a collision prediction between UT4 and UT3 (yellow box, top left). Due to technical problems the Laser was not operational and therefore the Laser on UT4 was “turned on” only in the software (see OVR status) but using the true pointings of UT4 and other telescopes. Furthermore, VISTA and UT1 were forced to be “Laser Sensitive” for testing purposes in this example.

In conclusion, it was shown that the use of laser beam avoidance software such as LTCS can efficiently avoid collisions and provides convenient information to the operational staff. Further software interfaces need to be developed to fully incorporate LTCS into the Paranal operational model. For example, an automatic check for collisions needs to be incorporated into the Observing Tool (OT), which provides the operator with a list of queue-scheduled observing programs, which are suitable for the current conditions.

6. CONCLUSIONS

With the advent of AOF science operations it will be necessary to efficiently select and execute the most suitable observing programs given the current atmospheric conditions. The real-time provision of estimates on the turbulence content in the ground layer in combination with a good understating of instrument performance as function thereof is a key ingredient to enable an efficient operational model. Furthermore, the AOF will significantly enhance the use of laser-time at UT4, therefore laser collision prevention for observations at other telescopes on Paranal is of paramount importance. The AOF project has taken first steps towards the provision of suitable tools (LTCS) and site sensors (SLODAR, MASS) to be incorporated into the Paranal operation scheme by the onset of AOF science operations.

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