VLT Unit Telescopes Performance Monitoring

Vittorio Nurzia

European Southern Observatory, Alonso de Cordova 3107, Vitacura, Chile

ABSTRACT

The Unit Telescopes (UT) at the Very Large Telescope (VLT), La Silla Paranal Observatory, are aging beautifully and delivering outstanding performances to the interfacing instruments.

Nevertheless, the introduction of 2nd and 3rd generation instruments comes with the demand of better, more continuous monitoring of key, high level performance.

While some of these demands cannot be met without restoring the commissioning configuration, a lot can be done by using the technical and science sensors distributed across the observatory for operational purposes.

This paper means to give an overview of the *status quo* and illustrate what developments are in sight for the mid-term future.

1. SCOPE

The VLT UTs have been designed to provide a great deal of diagnostics that have been used extensively and successfully during the first twenty years of their operations, proving to be an invaluable tool to assess daily the health status of the telescopes and it subsystems.

However, the very fact that the UTs keep delivering excellent results has allowed a continuous upgrade of the instrumentation placed at their focal stations and in the coherent and incoherent light combination facilities. Now, in some cases, the performance required by the instruments are met with margins that are not as large as they used to be, which leads to a remarkable increase of the level of attention to the matter.

A couple of examples might help:

- Sensitivity to the vibration environment of adaptive optics systems and interferometric instruments has increased remarkably, sometimes making the scientific instruments discover issues that the technical facilities are not equipped to measure
- The arrival of latest generation adaptive optics system and coronagraphs is revealing image quality issues (e.g. the so-called low-wind effect) that were once enveloped by the seeing disk, as good as it can be on Cerro Paranal.

Furthermore, while up to now, most frequently, the bottom-up approach seemed to satisfy the need of continued, well performing operations, currently the demand is for the direct availability of higher level performance indicators.

This somewhat changed scenario has triggered a debate about the subject, and an effort to investigate what affordable opportunities for improvement can be explored.

Engineers at the VLT, in synthesis, are aiming at:

- Collect all available data in a distributed data lake accessible by modern data processing and visualization tools (DataLab, currently in its advanced development phase)
- Choosing the most significant parameters and possible warning thresholds
- Identifying appropriate methods, statistical approaches and cross-correlations
- Selecting the most informative visualization techniques
- Make the outcome easily available to the observatory users.

The endeavor is articulated in three levels:

- Reproduce the currently available processing and visualizations in a more modern and customizable interface

- Expand the processing and visualization possibilities to allow more synthetic and informative data representations
- Expand the data lake and processing tools to include the possibility to analyze and correlate results from occasional tests, measurements taken manually and data obtained from instruments technical and science sensors.

2. MEASURING PERFORMANCE

For who, like the author, comes from a development environment, and a strictly regulated one like the aerospace industry, measuring the performance of a system pertains uniquely to a verification phase, before operations start or after a major intervention. Certainly, diagnostic provisions are almost always engineered into any system with complex functions and from which clear reliability and availability figures are expected. However, in most cases, those diagnostic features are unable to provide unequivocal information about the performance delivered by the system as specified at high level. Almost infallibly, an independent measuring system is needed, capable of recording data with an accuracy order of magnitudes higher than the maximum deviations allowed to the system under verification from the specified requirements.

That is to say, normally the UT is unable to measure its own performance by making use of its operational devices. A verification, or commissioning configuration is needed, with additional equipment and dedicated procedures. For instance, typically, such a device might be a test camera installed at a focal station, and, obviously, as far as the UTs are concerned, realizing such a configuration is utterly impossible without gravely impairing the science operations.

One shall therefore resort to alternative routes, e.g.:

- The bottom-up approach remains a key one. High-level performances can be, conceptually if not always quantitatively, broken-down in the contributions given by the underlying subsystems, allowing well-informed judgments about the possible cause of a degradation
- Some functions operate using sensors that might act as a quasi-independent, more accurate devices for measuring the performance of other functions
- Dedicated tests can be designed to allow the extraction of higher quality information from the available sensors
- The scientific instruments can become an excellent source of information about the telescopes, although one has to account for the increased complexity introduced in the chain, which implies larger uncertainty and difficulty in identifying the distinct contributions of the telescope and the instrument
- The four UTs are behave very similarly. Although this similarity is quite far from identity, the comparison between measurements taken on different UTs in comparable conditions can be a powerful way of identifying anomalies.

and so on.

3. DATA SOURCES

3.1 Network, workstations, local control units: the logs

The VLT operational facilities are controlled by a set of networked workstations (WS)[1] and real-time Local Control Units (LCU)[2]. The logical layout of a portion of such a network is shown in Figure 1.

The kernel of the VLT control system[3], known as Central Control Software (CCS), is a large set of functions and utilities developed for UNIX® and VITA™ VMEbus/VxWorksv® platforms, and covering mainly:

- Message handling
- On-line database
- Error and alarm handling
- Logging
- Process I/O
- Event monitoring

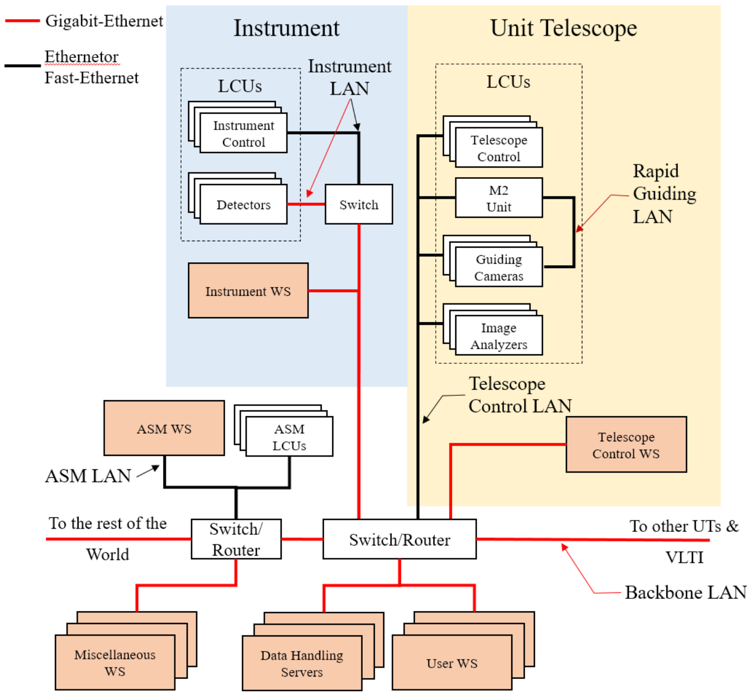

Figure 1: Network, workstations, LCUs: logical lay-out of the VLT LANs

– User Interface.

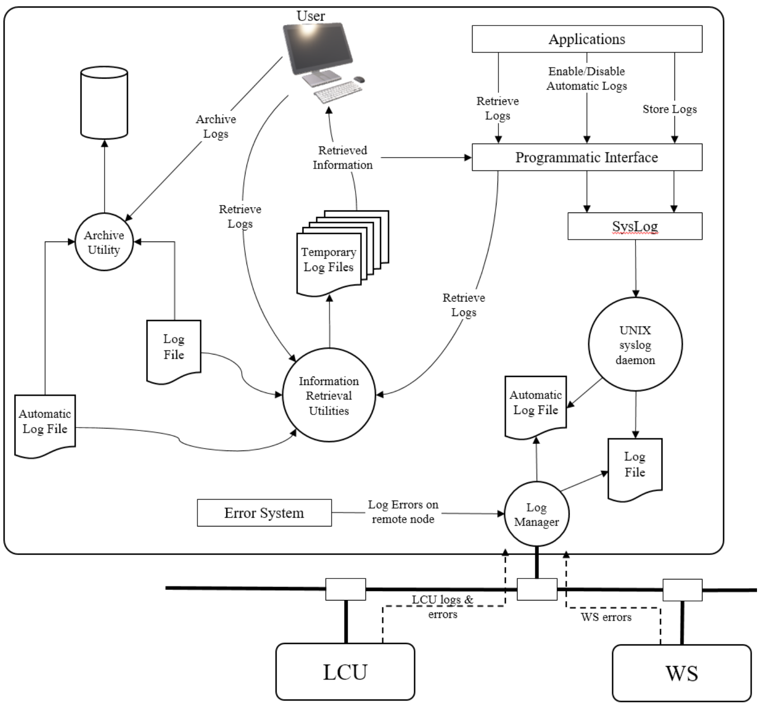

Figure 2: Logging system architecture

In particular, the logging system is implemented through the architecture shown in Figure 2 and supplies the users with a wealth of information for immediate use during operations, post-processing, troubleshooting.

The logs consist simply of lines of text, each line containing always a timestamp and a message, plus information about the provenance of the message itself.

A subset, known on site as OpsLogs, are made instead of the collection of a timestamp, a keyword and a value, and serve the purpose of recording parameters, mostly numerical, giving insight about the behavior of the telescope subsystems.

For instance, the following are a few occurrences as dropped by the logging system for UT4 on Christmas day in 2017:

```
logFile:Dec 25 06:13:49 wt4tcs logManager:  wt4tcs 06:13:49> TEL M1 X = -163.17566 / M1 X passive positions [wt4tcs]
logFile:Dec 25 06:13:49 wt4tcs logManager:  wt4tcs 06:13:49> TEL M1 Y = -10.71010 / M1 Y passive positions [wt4tcs]
logFile:Dec 25 06:13:49 wt4tcs logManager:  wt4tcs 06:13:49> TEL M1 Z = -8.54215 / M1 Z passive positions [wt4tcs]
logFile:Dec 25 06:13:49 wt4tcs logManager:  wt4tcs 06:13:49> TEL M1 A = 38.33758 / M1 A passive positions [wt4tcs]
logFile:Dec 25 06:13:49 wt4tcs logManager:  wt4tcs 06:13:49> TEL M1 B = -49.73456 / M1 B passive positions [wt4tcs]
logFile:Dec 25 06:13:49 wt4tcs logManager:  2017-12-25 06:13:49.542192 wt4tcs log logManager 8 61 Fits Keyword <TEL.M1.C> NOT FOUND in dictionary <ALL>
logFile:Dec 25 06:13:49 wt4tcs logManager:  wt4tcs 06:13:49> TEL M2 CEEPSILON = 7.90404 / [mm] Centering epsilon position of M2 [wt4tcs]
logFile:Dec 25 06:13:49 wt4tcs logManager:  wt4tcs 06:13:49> TEL M2 CEDELTA = -10.69218 / [mm] Centering delta position of M2 [wt4tcs]
logFile:Dec 25 06:13:51 wt4tcs logManager:  2017-12-25 06:13:49.804980 lt4m2 m2fo tm2foMRel 26 101 Wait DSM_SETFOC: HEX is RDY
logFile:Dec 25 06:13:51 wt4tcs logManager:  2017-12-25 06:13:30.450000 lt4m1m3 m1ps m1psMovMiAPos 33 110 PS Received cmd:  #1398 x=-163.18 y=0.00 z=-8.54 a=38.34 b=-49.73 c=-10.63
```

Since the control and the office networks are rigidly separated for security and safety reasons, access to the logs was, until recently, only possible by retrieving them at the user workstations, and one had to `grep` it's way through them to extract information.

Limited to the OpsLogs, a visualization and extraction tool named AutRep is available, with each night's data accessible from about 10AM of the following morning and a a year worth of data in local repository. A larger archive for historical trends assessment is available in a server at ESO Headquarters in Garching, Germany, but their gathering is pretty cumbersome from Cerro Paranal.

One important point, in particular about the OpsLogs, is that the frequency at which they are recorded is of the order of magnitude of the minute. Systems and functions with faster dynamics (e.g. axes control, field stabilization, active optics) are normally logged with statistics of representing parameters, typically a Root Mean Square (RMS) value. Some parameters, e.g. the telescope altitude and azimuth positions, are recorded at regular, minute-like intervals, others are logged when they are made available by the corresponding system WS/LCU or when they change.

Although the AutRep interface certainly shows its age (Figure 3), the tool offers standardized graphical reports (Figure 4), the possibility of visualizing time series of parameters of choice and a script language allowing more customized approaches. However, only time series can be visualized, further processing being possible only by extracting the data and using other means.

With the establishment of DataLab, the entire set of VLT logs since 2006 will be fully available, updated every few seconds, with evident advantages with respect to the original system. Furthermore, far more processing and visualization tools (Grafana®, ElasticSearch®/Kibana®, Jupyter®, Cassandra®/KairosDB®) will be available for standardized and customized monitoring.

3.2 Other sources

The logs are not the only source of information available to the users. The following, not exhaustive, list gives a panoramic view of what more is accessible, with different degrees of difficulty with regards to gathering and processing:

- The samplings: it is possible to select specific parameters from a broad choice available in the relevant database and sample them at a frequency higher than the logs. The outcome can be plotted for direct monitoring during operations, something that is done for example for the hydraulic bearings pressures, or for saving and post-processing. The CCS speed constraints the maximum frequency to a maximum of 200 Hz in the best case, and the sampled signals are not subject to analog filtering before sampling, therefore one has to be very confident that the dynamics of the sampled signal are slow enough for the sampling not to lose information contents
- The FITS (Flexible Image Transport System) files: cameras based on Charge-Coupled Devices (CCD), referred to as technical (TCCD), continuously analyze images of reference stars. As far as the UTs are concerned there are two TCCDs for each of the three focal station (the Coudé foci are not considered here as dedicated to interferometric and incoherent light combination instruments): one used by the field

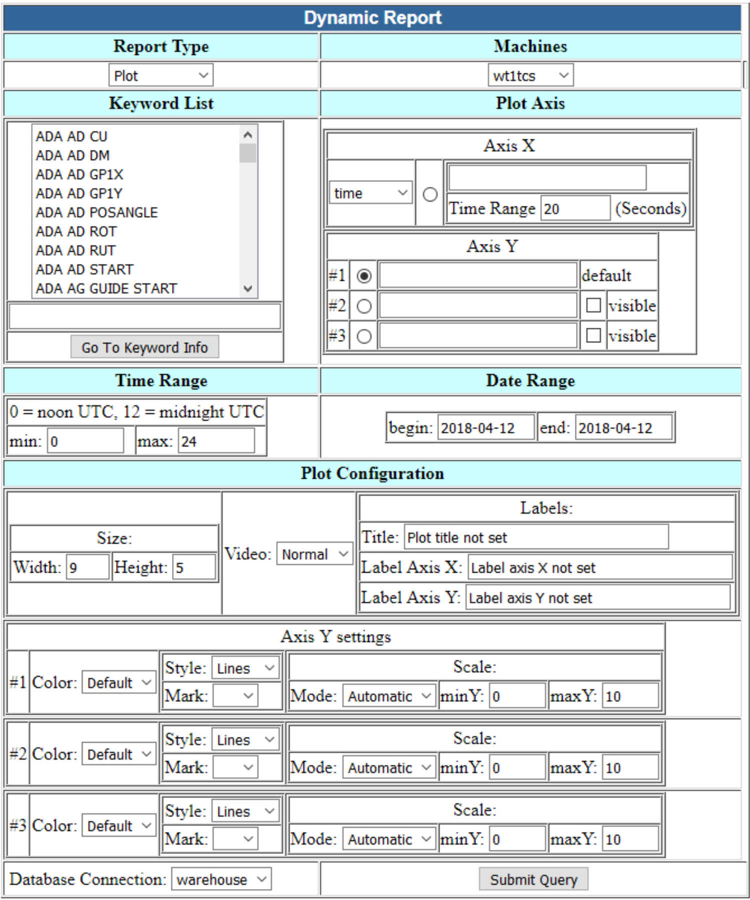

Figure 3: "AutRep: Dynamic Report" Interface

stabilization and auto-guiding functions and one by the Active Optics (ActO) image analyzer (IA). The latter are regularly recorded, while the periodic saving of the former is under investigation.

– The outcome of dedicated tests required for specific systems or in particular circumstances, for instance, after a new TCS software version deployment. The gathering of these data is not always very agile, and often the tests cannot be run during day-time, with obvious conflicts with the science operations.
– SPARTA (Standard Platform for Adaptive optics Real Time Applications) data logs. SPARTA is the system controlling adaptive optics systems, and logs, often at high sampling frequency, a remarkable amount of data which have proven already useful for troubleshooting telescope issues. The regular exploitation of these data is, however, part of future developments.
– Manually taken measurements. Lots of information is collected manually: for instance reflectance measurements after re-coating or cleaning of optical surfaces, or the oil film thickness between the hydraulic bearing pads and the support ring.

The above will be only partially considered in this paper, which tells about the early days in the effort to systematize performance monitoring, but all will certainly be considered in later developments.

4. A SELECTION OF DESIRED PERFORMANCE INDICATORS

The performance indicators discussed in the following paragraphs are at the center of the discussion currently on-going at Paranal. They are mostly high level indicators not directly measured or even measurable, which makes their monitoring quite a challenge.

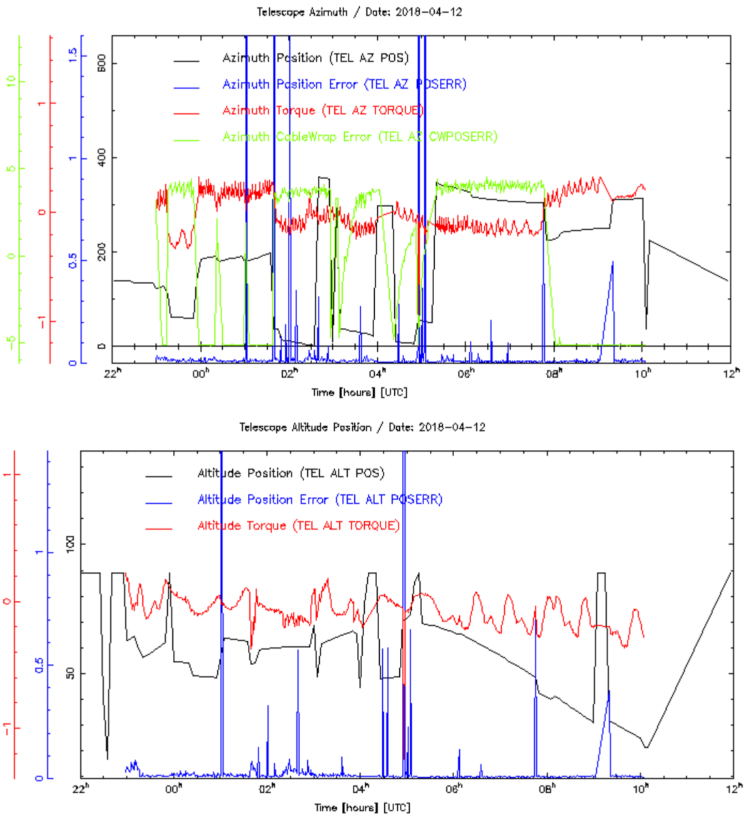

Figure 4: AutRep: charts in an "Automatic Report"

4.1 The `PRESET` command

To avoid misunderstanding, `PRESET` is the command by which the telescope is told to reach the science target position without a closed loop on a celestial object, i.e. based on catalog coordinates, the pointing model and the altitude and azimuth control systems. It does so as quickly as possible, realizing the highest slewing velocity allowed to the axes through appropriate position trajectories.

4.1.1 Pointing accuracy

The pointing error is the angular distance between the telescope pointing after a `PRESET` and the intended target position on the celestial sphere, and it cannot be assessed by the telescope alone.

What the telescope can measure is the guide star acquisition accuracy.

While quite demanding performance requirements were placed initially against this telescope function[4], what is actually required to the telescope is to reach its target position closely enough to allow the acquisition of the most adequate guide star.

How well that happens can be checked effectively by using the guiding function: once the telescope has achieved the target position, the first corrections after the guiding is engaged give a measure of the guide star acquisition accuracy, obviously neglecting in the first instance the astrometric errors of the guide star catalog coordinates and other possible sources of error in the guiding function.

This was also done at commissioning, which gives a term for comparison that should be taken quite loosely, and not as a strict reference performance. Figures 5 and 6 show, for UT1 and UT2 respectively, the comparison between data taken during the first quarter of 2018 and performance recorded during the commissioning phase[5,6]: the blue ellipse's semiaxes are 3σ values recorded during commissioning, while the red ellipse's semiaxes are 3σ values of the data being analyzed. The red arrows point from the corrections

RMS at commissioning to the current one. Corrections are computed based on data obtained from guiding cameras of all three focal stations.

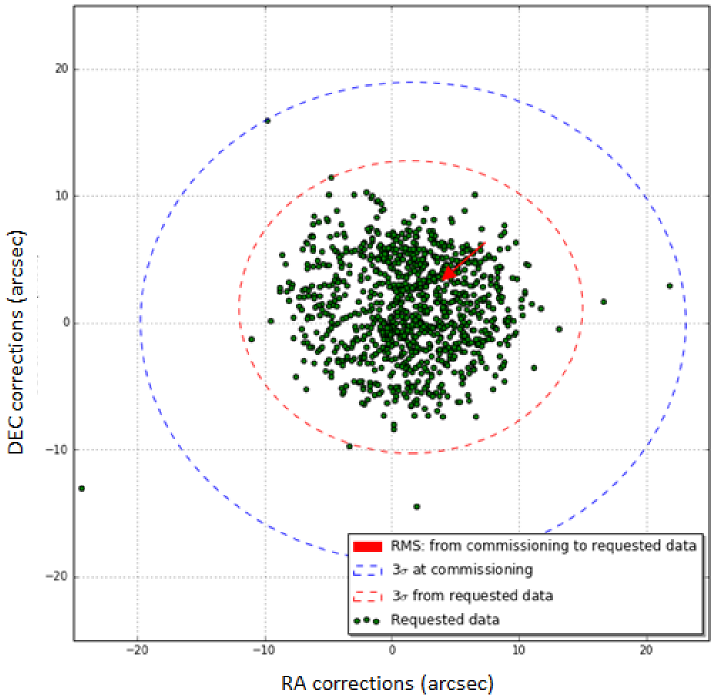

Figure 5: UT1 guide star acquisition accuracy, first quarter 2018

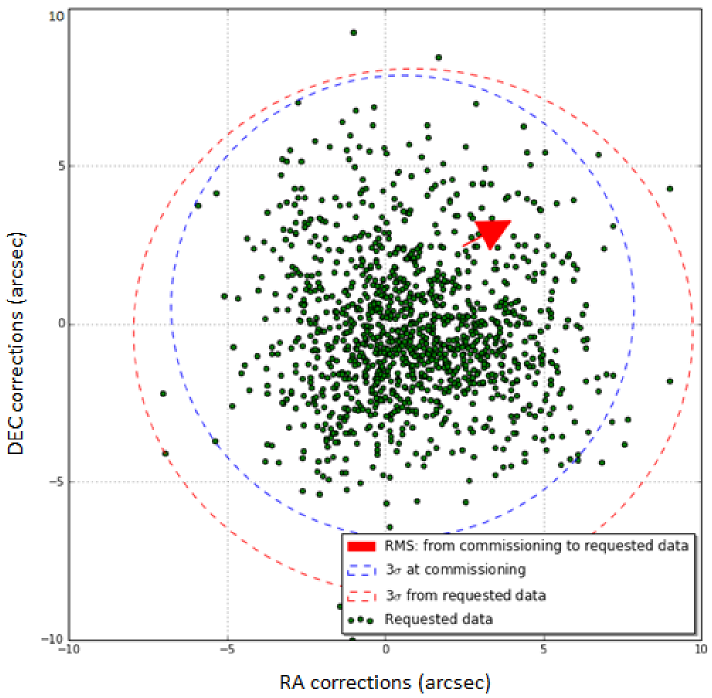

Figure 6: UT2 guide star acquisition accuracy, first quarter 2018

4.1.2 Time to guiding (TTG) on target

The target acquisition sequence involves several steps during which the telescope is moved to the required position and set in a status allowing science observation. The time to perform this sequence is an overhead limiting the operations efficiency and needs to be kept under control. The UTs are required, with high level confidence, to perform it within five minutes irrespective of the angular distance between the starting position and the target. Figure 7 shows the comparison of the time elapsed from when the `PRESET` command is given, until the telescope is guiding on the selected star.

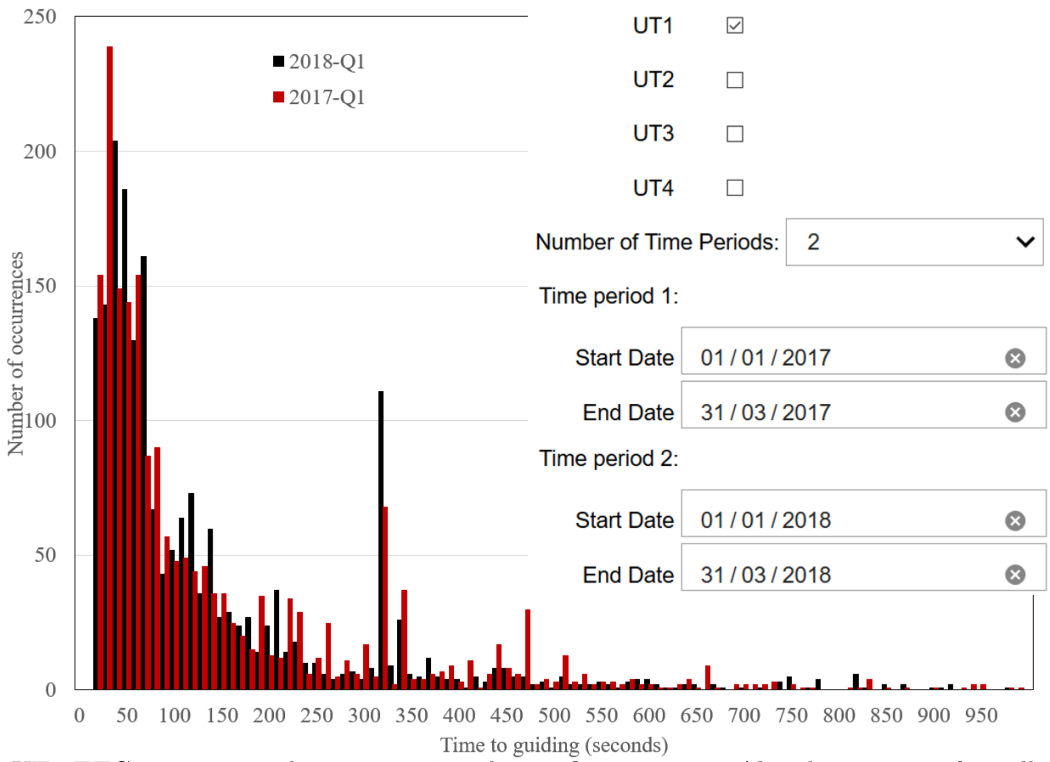

Figure 7: UT1 TTG: comparison between 2017 and 2018 first quarters. Also the user interface allowing easy comparisons between different telescopes and time periods is shown

The actual plan for a full monitoring of the overhead is to build the shown kind of statistics, or possibly even smarter and more synthetic representations, for a number of significant steps in the science target acquisition sequence: `PRESET` completion, application of look-up table corrections to mirrors position, start of guiding and ActO, first few ActO corrections, start of first science exposure. This would also allow to investigate the impacts of changes to the sequence on the `PRESET` overhead.

The time required by each step of the target acquisition sequence is not a performance of the telescope alone, since manual operations are intertwined with programmed ones. What certainly the telescope shall guarantee is to slew as quickly as allowed from the initial position to the target one. This can be monitored by correlating the time that elapses between the `PRESET` command acknowledgment and the message communicating the telescope is blind-tracking with the actual angular distance covered, either a reference one (e.g. measured on a great circle of the celestial sphere) or the actual one, which would require full knowledge of the actual trajectory.

4.1.3 Pointing model

More information about the pointing performance of the telescope can be obtained by looking at the long term evolution of the pointing model parameters, checking for anomalous drifts and by verifying regularly that, whenever required, the model fitting is performed adequately and the residual errors meet the prescribed criteria. This paper will not elaborate on this aspect.

4.2 Tracking & guiding

4.2.1 Tracking

Once the telescope has completed the PRESET command, it goes directly into blind-tracking, after which, either through manual or automatic operations, a guide star is selected and the guiding and ActO functions are engaged.

The tracking function operates by controlling the telescope axes to follow the sky motion based on the pointing model, which, correcting for numerous effects[7], transforms the desired coordinates on the celestial sphere, into altitude and azimuth time-changing set-points that the axes control system will pursue.

The tracking error is defined as the image drift when no guiding is active, without considering the fast motions corrected by field stabilization, which are more sensibly considered when addressing image quality.

No science operations are normally performed while blind-tracking, and to seriously affect those, the tracking should be poor enough to impair the ability to follow the guide star at the relatively slow sidereal rate.

However, the performance is checked regularly enough, to avoid its deterioration goes unnoticed. Typically, after a software upgrade or major maintenance interventions, a test is run consisting in having the telescope tracking while recording the corrections computed by the guiding function without applying them, and comparing these with the corrections computed while guiding (Figure 8). This measures the improvement provided by the guiding function and therefore the tracking performance.

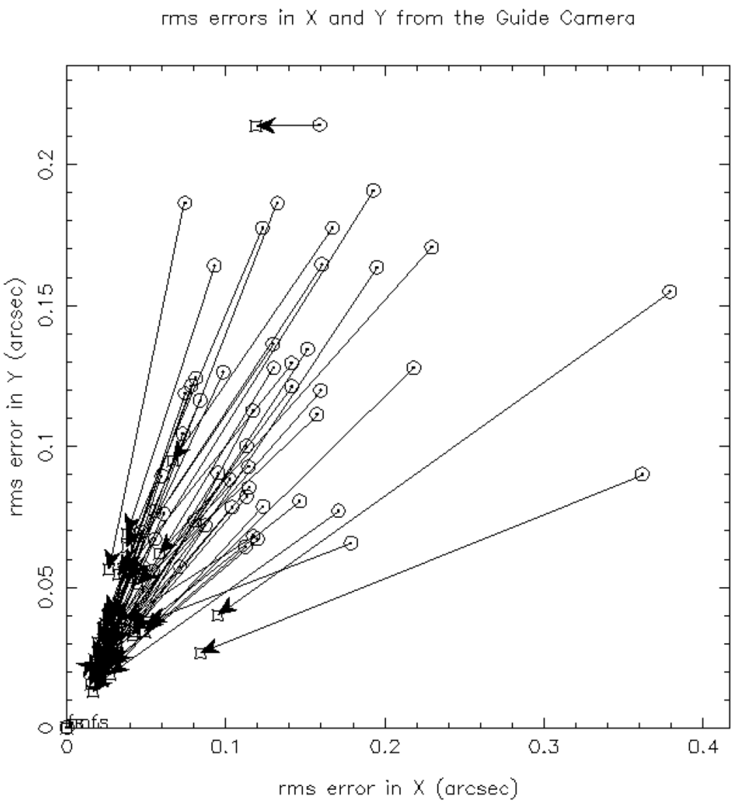

Figure 8: Measuring tracking performance using the guiding function

4.2.2 Guiding

The guiding function closes the axes control loop using a celestial object, the guide star.

Telescope axes and mechanisms are actuated in such a way that the guide star is seen in the same selected position on the guide camera. The UTs implement the function in several different ways, the main ones being:

– Auto-guiding (AG): corrections are sent directly to the axes control system roughly once per second
– Field Stabilization (FS): the secondary mirror is tipped and tilted at frequencies up to about 60 Hz, while cumulative corrections are still sent to the telescope axes once per second to keep the secondary mirror in the middle of its tip/tilt range.

Determining the performance of this function is not possible at telescope level. To commission the telescope in this respect:

– A star close to zenith was tracked through the meridian
– The position on the test camera was measured while the telescope was guiding
– The guiding error was inferred from the movement of the target on the test camera.

Unfortunately, as already said, test cameras are not an options during normal operations, and only partial information about this aspect can be obtained from the telescope without help from an instrument, which implies time subtracted to operations.

An attempt at building a meaningful budget would look at:

– Residual astrometric errors on actual guide star position
– Mirrors position errors, which determine the position of the optical axis
– Control system errors: azimuth, altitude, rotator, guide probe positioning (the last two including the set point calculation uncertainty, since there is no closed loop on a celestial object object)
– Guide camera detector errors

Of the above, the only contributions that are positively measured and logged are the axes position and velocity errors as detected by the relevant encoders. Figures 9 and 10 show respectively the altitude and azimuth axes error: the position of each point is the projection on the horizon plane of the tip of the normalized pointing vector while the color intensity is related to the error magnitude (a logarithmic scale is used to increase contrast). Two color-code scales are used to separate possible outliers beyond 3σ, which in most cases carry no significance. Similar charts can be easily obtained for the adapter/rotator assembly.

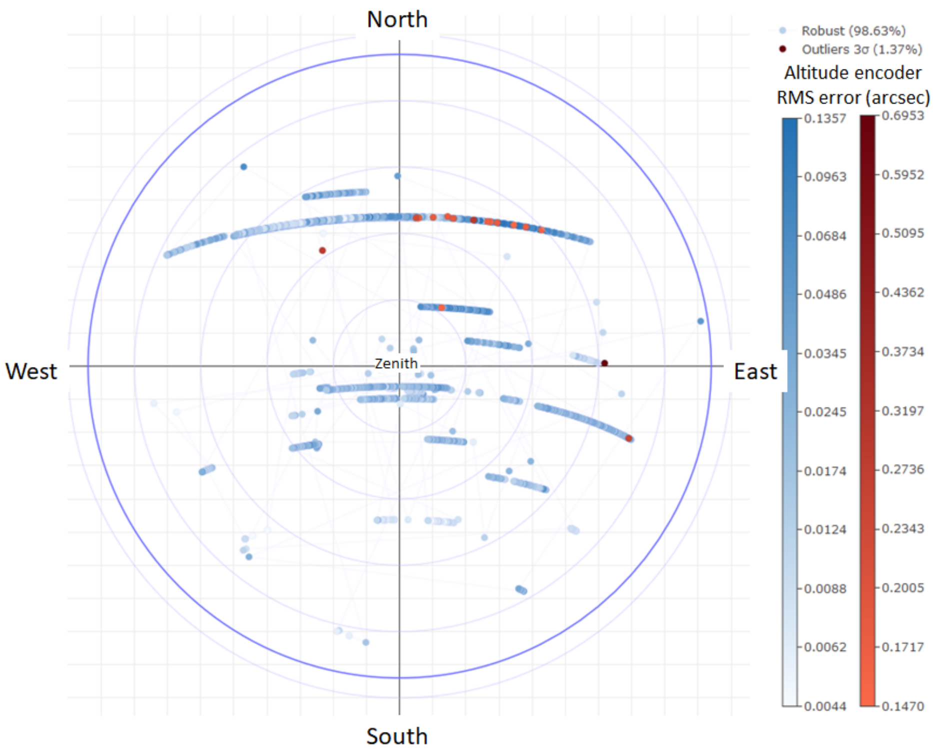

Figure 9: UT1 altitude axis encoder error

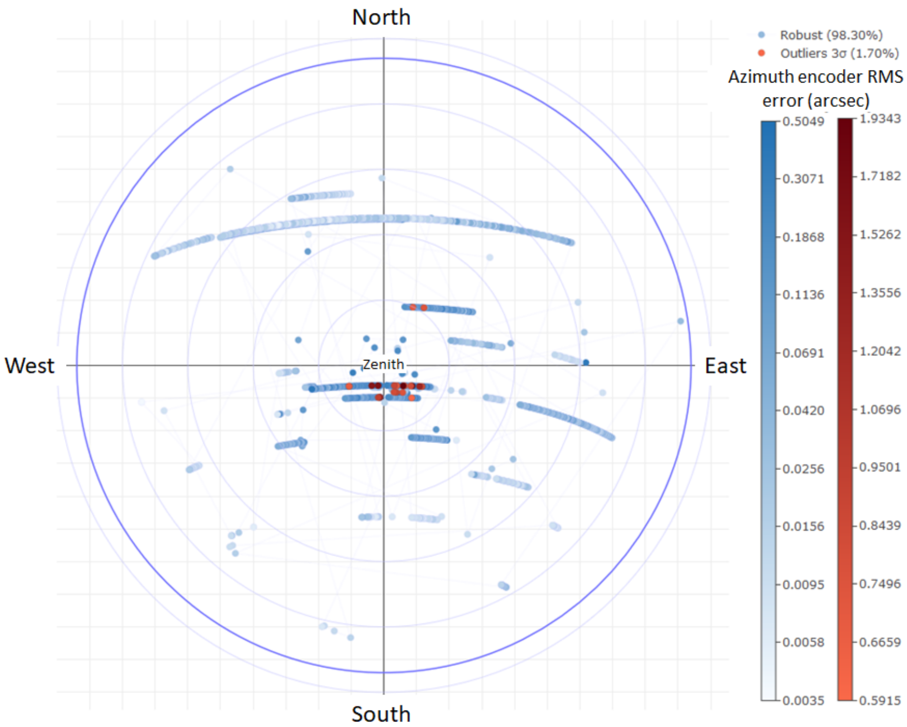

Figure 10: UT1 azimuth axis encoder error

These kind of visualizations allow zooming, and hovering with the mouse pointer over single data points will tell the user its details.

In judging the above one shall not forget to correlate axis errors with wind conditions (Figure 11) and atmospheric conditions.

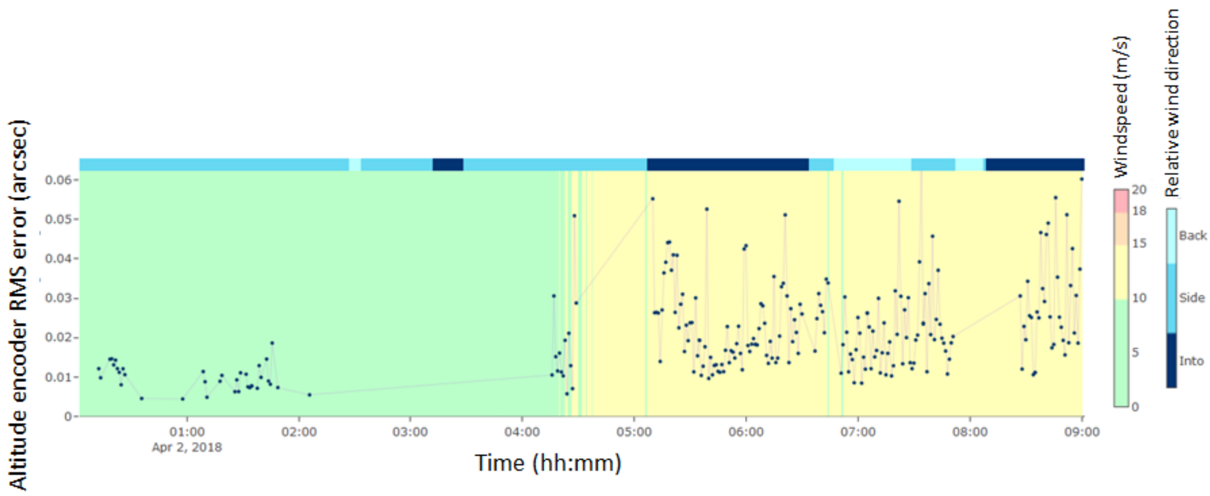

Figure 11: UT1 altitude axis encoder error versus wind speed and direction

Further to the above, one can look at the outcome of the guiding function, the corrections sent to the secondary mirror (in field stabilization mode) or the telescope axes (in auto-guiding mode). These are *not* a performance measure for the guiding function. However, it is unlikely that a misbehavior of the guiding would not lead to abnormalities in the behavior of these corrections, which is then good practice to monitor regularly (Figure 12)

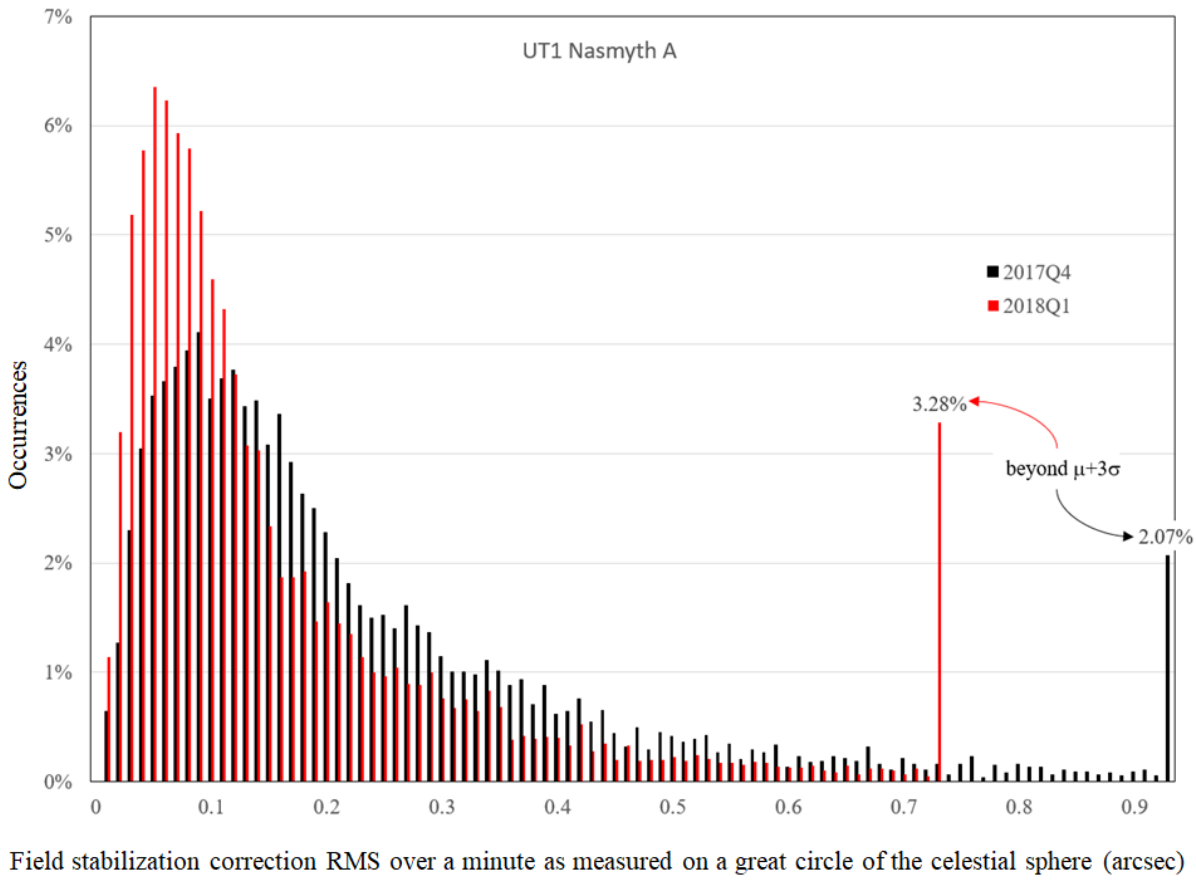

Figure 12: UT1 Nasmyth A: corrections sent by the guiding function in field stabilization mode during quarter 4 of 2017 and quarter 1 of 2018. The right ascension and declination corrections are combined in a single value as measured on a great circle of the celestial sphere

4.2.3 Guide star limiting magnitudes

One important indicator for science operations is how bright a star is needed for the guiding function to perform adequately. That is obviously a question with no single answer, since the required magnitude depends heavily on the environmental conditions. It is a sky coverage theme, i.e. the need for the operator to find a usable guide star wherever they need to point.

In general, with the fastest FS mode currently available (64 Hz, 14 ms integration), guiding has been found to be effective down to magnitude 13 (V) in most conditions.

Unfortunately, the stability of guiding cameras' counts is not sufficiently high to use them reliably for photometric purposes (Figure 13). Nevertheless, some statistics can be run in time to see what kind of accuracy can be achieved and in what conditions. This option might be considered further in the longer term.

Possibilities under investigation include:

– Correlating the magnitude of the guide star to the indicators mentioned in section 4.2.2 to judge the health of the guiding. Unfortunately, the magnitude of the guide star is not logged at the moment. A change to the logging system or some additional catalog manipulation software would be required

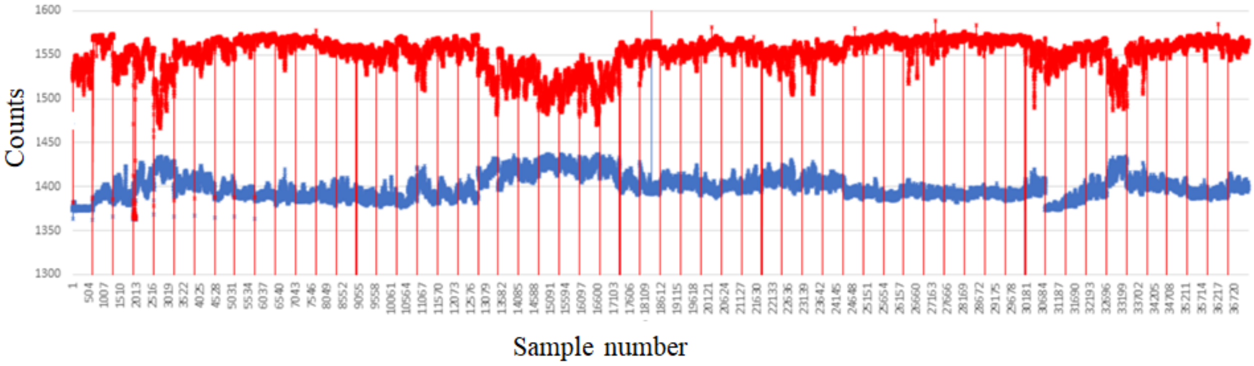

Figure 13: Typical behavior of a technical guiding camera counts over time

- Using the logged active optics IA camera 5th brightest pixel counts, which can be assumed to be a good representation of the flux coming from the guide star. Since the active optics integration time is known the relative brightness of the star can be loosely inferred and compared with the catalog one and the effectiveness of the guiding function.
- Designing dedicated tests during which guide stars of increasing magnitude are selected until the function is is lost. This has been done at commissioning resulting, at the time, in the telescope guiding down to the 15th magnitude.

In any case, at least the following parameters must be noted and delivered together with the detected limiting guide star magnitude:

- Wind speed
- Wind direction vs azimuth orientation
- Altitude orientation
- Environmental parameters (seeing, weather, etc.)
- Size of the guiding box
- Focus station.

There cannot be a single value of limiting magnitude irrespective of the mentioned parameters, which makes the reliability of this performance assessment very uncertain, since only values taken in very similar conditions can really be compared and making extrapolations from one set of conditions to the other is very risky to say the least.

4.3 Chopping: accuracy vs. parameters

The UTs currently provide a chopping function through the tipping and tilting of the secondary mirror. The hardware and software are the same implementing the field stabilization function.

At the moment there is nothing available in the regularly logged data to enable any monitoring, except its activation and deactivation.

There's a plan to introduce the chopping control loop error logging during tests performed for the verification of TCS software upgrades. Once planned for that purpose, this test can also be performed in other circumstances, though continuous logging is not possible for obvious reasons. The regular logging of a statistic value of the control loop error might be considered. However, the above is a subsystem performance and as such only contributes to a general health check of the chopping function, saying nothing conclusive about its performance.

Chopping performance is thus hardly a candidate for continuous monitoring, therefore dedicated tests are necessary.

A campaign in this sense took place recently, engaging the chopping function at different throws, angles and frequencies and recording low level data (tripod legs displacements, velocity and forces) and the pupil tip/tilt error as measured by instruments available in VLT Interferometer (VLTI) facility. The processing of the data is on-going at the time of writing of this paper. Nevertheless, this kind of activity is quite intensive in terms of technical time required and cannot be repeated very often.

4.4 Offset accuracy

The `OFFSET` command works by shifting the guide probe in the field and forcing thus the telescope to follow through, moving its axes so that the guide star is again seen on the camera's reference pixel.

Evidently its accuracy on sky is not measurable without external references very unlikely to be considered. A proper assessment would require the employment of a test camera or the instruments technical or science detectors.

Remembering that the guide probe is positioned without a closed loop on a celestial object, at the health check level, one can look at:

- The residual errors after the calibration adapter encoder
- The adapter positioning error and torque

In the longer term one might use standard stars from catalog of enhanced astrometric accuracy (e.g. from GAIA survey), provided such accuracy is at least one order of magnitude higher than what required to the offset function.

4.5 Image quality

ESO performance parameter of choice for the VLT as far as image quality is concerned is the Central Intensity Ratio (CIR), defined as the ratio between the actual Strehl ratio and the seeing-dependent Strehl Ratio of a perfect telescope in the same atmospheric conditions. It includes the effects of optical quality, telescope and enclosure seeing, wind buffeting of the mirrors and the telescope structure, tracking and differential seeing motions between the guide star and the science object.

It is required[8] that such parameter exceeds at all foci 80% for a 60 minutes exposure at 500 nm wavelength. The CIR criterion should be met for the 90-percentile wind velocity at 0.4 arcsec seeing for all usable wavelengths and zenith angles, with the appropriate adjustment for wavelength and zenith distance variation of the 5-percentile seeing Full Width at Half Maximum (FWHM).

That is clearly not a parameter that can be measured by available sensors installed on the UTs. The relevant error budget is very complex[9], and includes errors of the reflecting surfaces, errors due to misalignment and alignment stability, residual errors of the control systems.

The only ones one can try to measure in operation are the latter:

- The effectiveness of the compensation of "quasi-static" optical aberrations, i.e. the performance of the ActO system: it is regularly logged and the most apt parameters to monitor are the RMS value of estimated wavefront residual error of aberrations fit, which is expected to be reliably below 200 nm for normal operational conditions. (see Figure 14). More information about the UT active optics system performance can be found in Stephan et al.[10].
- The quality of the field stabilization, especially in the presence of windshake (see section 4.2.2).

On top of what stated above, some other indicators of image quality might be available from the geometrical evaluation of the images collected by the technical cameras (guiding and ActO):

- The guiding camera software does not provide information about the extension and the shape of the guide star image. A minimum reasonable approach would require to include a 2D Gaussian or Moffat fit of the recorded images. However, this would come at the cost of a reduction in the maximum FS frequency, and it is not a good practice to reduce performance to have more telemetry. It is under investigation whether the current hardware allow considering saving images at a sufficiently high frequency for post-processing.

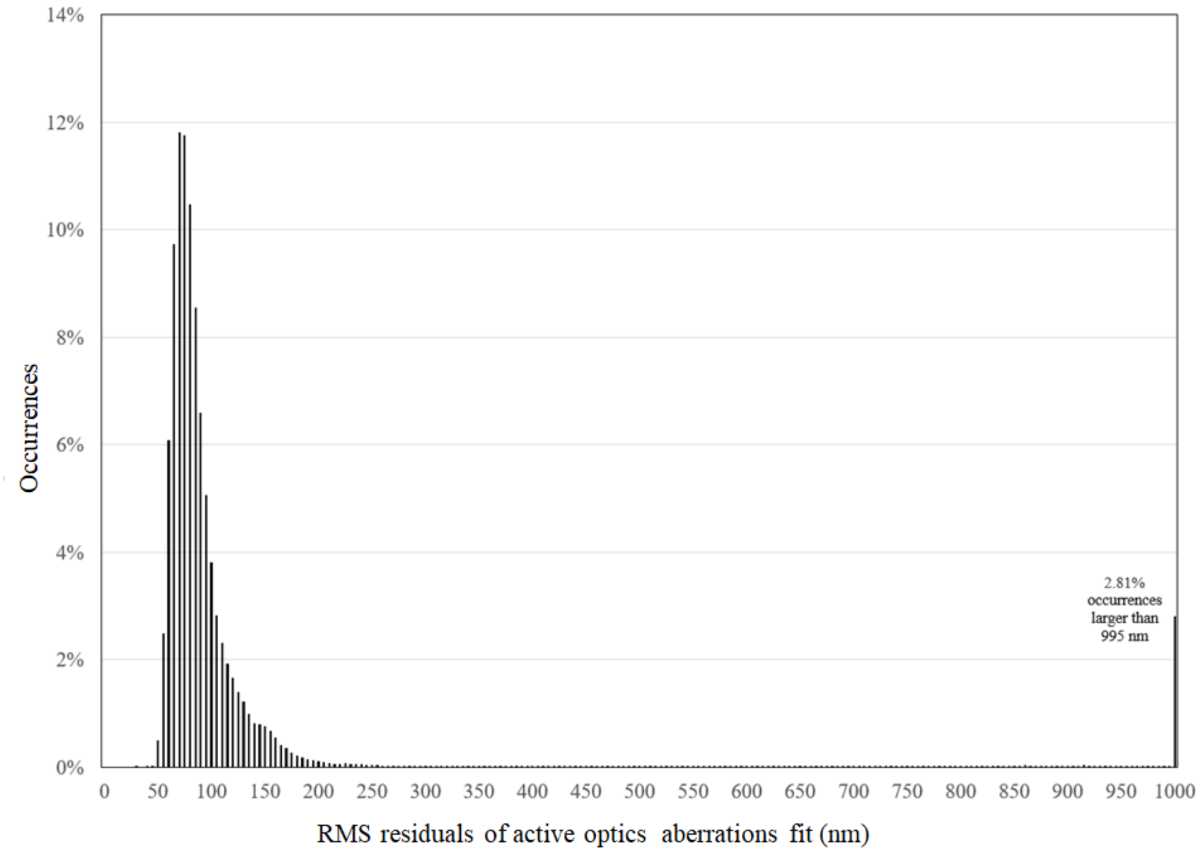

Figure 14: UT1 active optics performance between May 2017 and April 2018 (the widening of the main peak to the right is due to the use of a more roust but less accurate wavefront reconstruction algorithm sometime required by specific circumstances)

– The IA, based on a Shack-Hartmann sensor, provides the image's FWHM corrected for the observed airmass. However, this parameter does not seem to be a good indicator of image quality: the role of the Shack-Hartmann micro-lenses diffraction pattern is not clear and with the telescope field stabilizing at frequencies higher than 20 Hz the IA is integrating the effects of errors with frequency contents relatively high with respect to the active optics operating one (0.05 Hz). Currently, the UT4 IAs images of the last 2 years are being processed to assess whether this is a viable option.

Finally, the use of instruments' image quality checks should be considered to judge the quality delivered by the telescope. This seems obvious, and obviously more relevant, as in the end that's the quality the scientist is ultimately interested in. However, discriminating between effects produced by the telescope and effects produced by the instrument might prove very challenging, and that is critical if one intends to use monitoring to troubleshoot anomalies. Without considering that scientific data are more sensitive with regards to confidentiality, and not always easily accessible.

4.6 Throughput

At telescope level the quality of the coatings is the only source of throughput loss, if one does not consider occasional obstacles that are very unlikely to be found in the path between the aperture and the focal stations.

In fact, the overall telescope throughput cannot be measured without resorting to a photometric device covering the wavelength range of interest. At Paranal, only reflectance measurements are regularly performed in occasion of maintenance operations, either cleaning/washing or re-coating.

Figure 15 shows many years' worth of measurements for UT1s M1. One can note the reflectance restoration after re-coatings and the long period during which the coating facility was out of service.

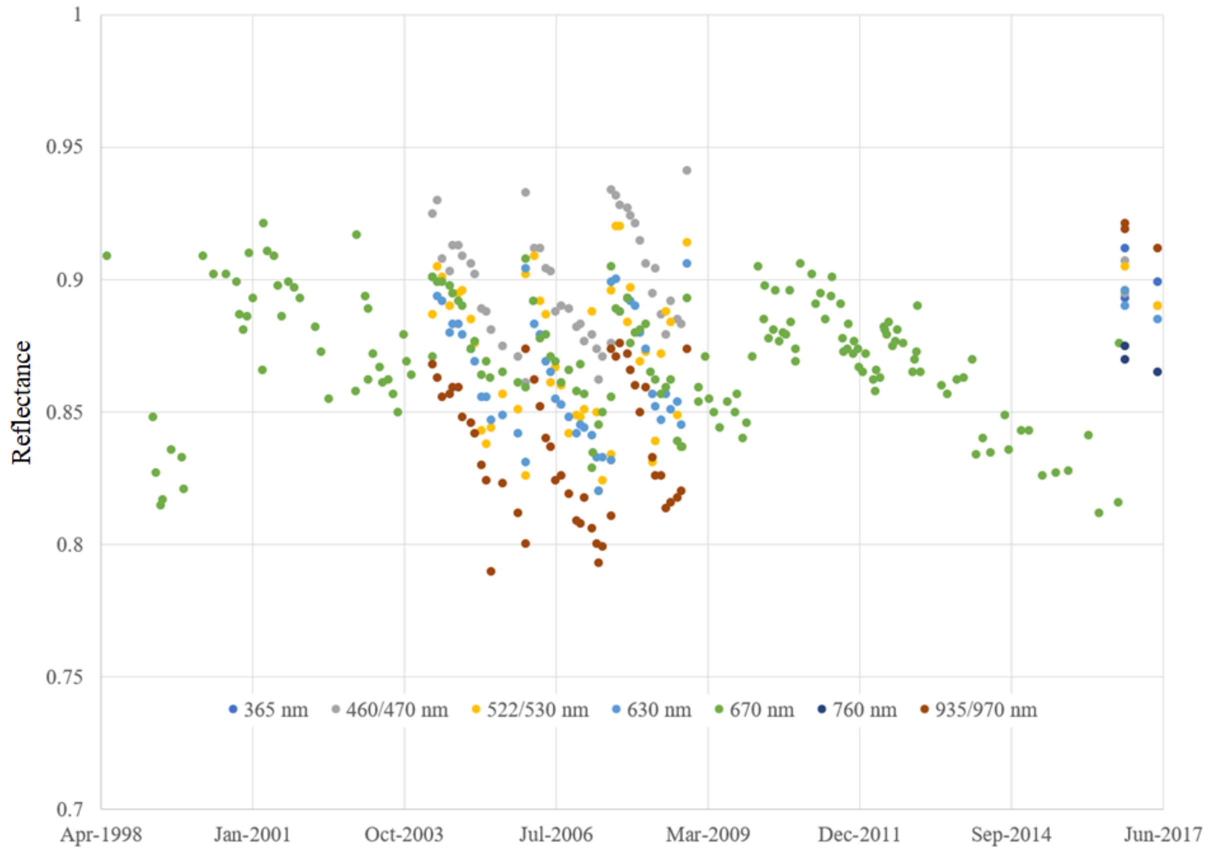

Figure 15: UT1 M1 reflectance measurements until June 2017

These measurements cannot be conclusive about the overall telescope throughput:

- Measurements are taken only on M1 and M3 after cleaning (about every six weeks) and re-coating (about every two years)
- The measurement is invasive due to the necessity of physical contact between the measurement device and the mirror surface, so its frequency its kept to the minimum necessary. Reflectance of the secondary mirror is not measured because the risk of damaging the mirror seems disproportionate with respect to the increase in performance knowledge, and the position of the mirror, facing down, makes it much less sensitive to particle deposition
- Measurements are taken only on a few spots and their purpose is to judge qualitatively the effectiveness of the performed maintenance operation
- The instrument currently used for measuring reflectance does it at a limited set of wavelengths. That means only instruments working in the visible and in the very near infrared can benefit for this qualitative information.

To measure overall throughput, test cameras adequate for photometry would be required. For the Nasmyth and Cassegrain *foci* of the telescope, the available technical cameras are not (see section 4.2.3).

The situation is slightly better for the Coudé focus and the VLTI. Throughput can be measured:

- In the visible spectrum and H/J bands with the adaptive optic modules used by the interferometric instruments
- In the J, H and K bands with an image stabilizer camera placed at the very end of the VLTI long reflections chain.

The above are already regularly used when troubleshooting vignetting, often with reference beacons, but one can conceive using calibrators for regular throughput measurements. However, these measurements include a much larger number of reflections from elements whose individual transmission is not known precisely, which again makes it impossible to make conclusive statements about the telescope throughput. Furthermore, making these measurements using celestial objects as sources (available beacons don't cover the required wavelength range and are not photometrically stable), implies subtracting time to science operations, and a trade-off needs to be made to assess whether uncertain throughput knowledge justifies the sacrifice.

Finally, the ultimate and more relevant throughput knowledge comes from the instrument 'zero-points', which obviously speak of a much more complex budget than the standalone telescope's, but are the one defining the quality of the science data as far as throughput is concerned.

4.7 Vibration Environment

In recent months, the UT vibration environment has been very much in the spotlight, with particular regards to interferometric science operations.

The term "vibration" shall be here intended in a wider-than-usual sense as any oscillatory phenomenon affecting piston, tip-tilt and higher order aberrations of wavefronts along the optical path. This certainly includes mechanical vibrations (e.g. caused by windshake or rotating/alternating machinery) and less obvious phenomena that might results from the interaction of external factors with the multiple control loops operating in the observatory.

The monitoring of mechanical vibrations is currently performed in a regular fashion only by a system called Manhattan 2[11], which is also integral part of the VLTI operations, providing the measurements used by the fine feed-forward control of the delay lines variable curvature mirror (VCM). It consists of a set of accelerometers, related conditioning/amplifying equipment and processing software. The accelerometers position and orientation are designed to record principally the piston component of the optical path length variations, but are often used as a general vibration monitoring facility at telescope level.

A metrology based on Michelson interferometry[12] will complement the accelerometers in monitoring the vibration level of the UTs. It will do that by accurately measuring difference in optical path length of light coming from different UTs, thus characterizing the interferometry baselines. However, due to the design of the system, it wont be possible to use it in normal operations because it occupies exclusively VLTI resources, therefore one can never be sure that the picture it gives is the same as during night observations.

Keeping the focus on the impact of vibrations of UT systems on VLTI instruments, currently the most sensitive to the tiniest oscillations of any kind, an activity took place recently to make a snapshot of the UTs vibration signature using all available devices, including the ones mentioned above and instruments able to detect tip/tilt and piston of the wavefront at pupil locations. Although the full processing of the data is still on going, the activity did allow early detection of unexpected vibration and triggered a troubleshooting leading to restoration of a more stable environment for science operations.

In any case, it is worth reporting that much work has gone into reducing the levels of oscillation detected in the optical path lengths differences, with the remarkable achievements shown by the comparison between Figures 16 and 17.

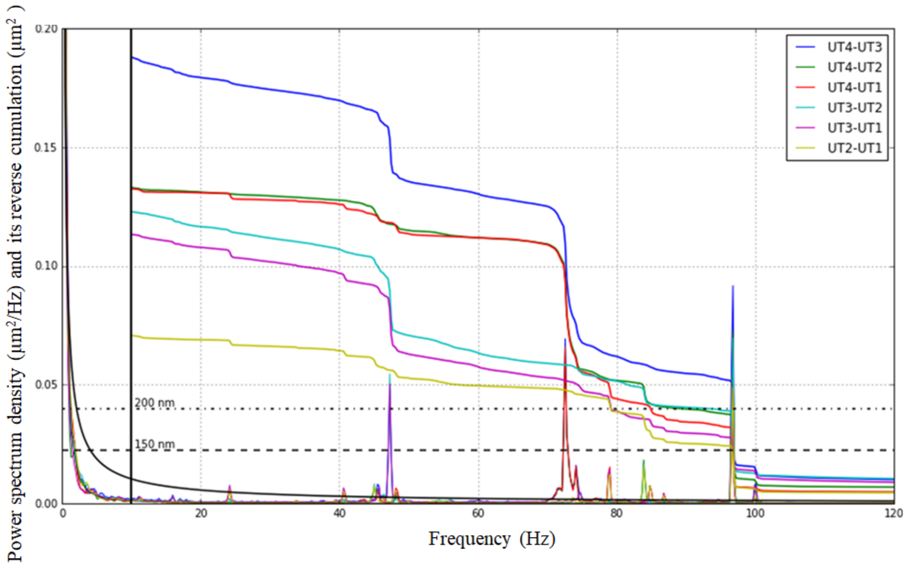

Figure 16: VLTI baseline optical path difference: cumulative power density spectra during May 2016

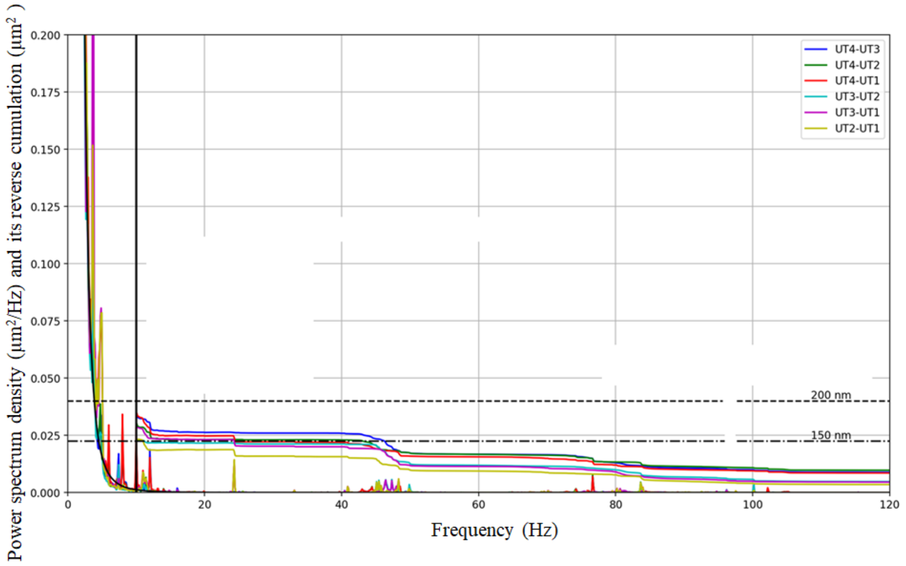

Figure 17: VLTI baseline optical path difference: cumulative power density spectra during August 2017

One key element of this kind of measurement is that if it cannot be implemented in a continuous fashion it needs to be accompanied by a strict configuration control process: the introduction of source of vibrations or changes in the characteristics of the existing ones might be very subtle to troubleshoot.

5. CONCLUSIONS

Monitoring thoroughly high-level performance of such a complex system as a UT at the VLT observatory in Paranal is not a straightforward task.

However, while in many cases the telescope is simply not equipped to do it, it does provide a wealth of data and information that, if appropriately processed, can say a lot about how well the telescope is working and the operations are run.

This paper has provided a non-exhaustive overview of the subject as it unfolded in the frame of the current, collaborative debate between scientists and engineers at Paranal, triggered by the developments brought to the observatory by more sophisticated and demanding instruments, and the consequent increased need of knowledge about performance.

Next steps in the standardization and modernization of UT performance monitoring will be:

- Dig further into the possibilities offered by browsing through and parsing the VLT logs
- Introduce new features when required and affordable
- Standardize, when appropriate and not subject equivocal interpretations, performance reports for sharing with the observatory community
- Explore in depth the sources of data alternative to the standard logs
- Investigate further data analysis and visualization techniques to provide the users with the most informative and synthetic view
- Investigate to what extent instruments can support the telescope performance monitoring and with what impact on operations
- Study the possibility to automate anomaly detection.

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