Solar Activity-driven Variability of Instrumental Data Quality

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The unexplained variability of the data quality from Very Large Telescope instruments and the frequency of power cuts have been investigated. Origins for the variability in ambient temperature variations, software, data reduction pipelines and internal to hardware could be discarded. The most probable cause appears to be correlated with the evolution of the cosmic ray rate, and also with solar and terrestrial geomagnetic activity. We report on the consequences of such variability and describe how the observatory infrastructure, instruments and data are affected.

Context

With the improvement over time of detector stability and the increase in frequency and level of instrument health monitoring, any deviations in quality control parameters due to larger than normal changes in ambient conditions (for example, temperature and air pressure) are now easier to detect. Sometimes, unusual glitches are registered. Once hardware and software problems have been discarded as the probable cause, a few events still remain unexplained. Such problems can have real consequences for data quality.

The primary cause for such variability lies in the Sun–Earth relationship. The solar maximum occurred around 2012–2014, although this cycle (24) is characterised by a low level of activity. Solar activity and geomagnetic changes induced by the Sun lead to a number of consequences on Earth as listed in Table 1.

There are five classes of geomagnetic storm, from G1 (minor, ~ 1500 per solar cycle of 11 years) to G5 (extreme, 0 to 4 per solar cycle), as classified by the US National Oceanic and Atmospheric Service (NOAA[1]). The consequences of geomagnetic storms can range from the appearance of aurorae and disturbances to migration patterns, to complete blackout of the electrical systems on Earth and failure of satellite electronics. The largest recorded geomagnetic superstorm (combination of consecutive severe to extreme storms) that hit the Earth occurred in 1859 (the Carrington event[2]) with aurorae down to sub-equatorial regions, although they are usually limited to the polar circles. The terrestrial apparent magnetic field inverted and some induced currents caused the telegraph to fail and to deliver electric shocks to operators. More recently, in 1989, a power blackout occurred in Canada and northern USA due to strong induced currents generated by another storm, but three times weaker than the 1859 one.

Northern Chile lies in the South Atlantic Geomagnetic Anomaly, where the magnetic field is much lower than everywhere else on Earth[3]. As a consequence, the geomagnetosphere is less effective in protecting this region from the effects of cosmic rays and particles coming from the Sun. Most satellites crossing this region are set in safe mode to protect them from the higher cosmic ray and particle flux. In addition, it is known that at a defined latitude, higher altitude regions receive more cosmic rays. The increase is also larger for latitudes ranging from the equator to ± 30°, including all ESO observatories; the NOAA World Magnetic Model gives details[4]. Therefore, it is pertinent to ask whether some or all of the types of activity listed in Table 1 have an impact on the measured instrument variability and data quality, as well as in the dependability of the observatory infrastructure.

There are very few cosmic ray/neutron monitoring stations in the southern hemisphere. They represent less than 20 % of the worldwide network covered by the Neutron Monitor DataBase[5]. In addition, there are no neutron monitoring stations in South America and Africa and others are located in regions with a stronger magnetic field. As a consequence we have compared the measurements from the monitoring stations in the Kerguelen Islands (southern Indian Ocean, latitude −49°) and Terre Adélie (continental Antarctica) with our data.

Cosmic ray monitoring during the minor geomagnetic storm 4–5 September 2015

The monitoring of the health of the instruments at Paranal Observatory is carried out daily during morning calibrations. Various parameters[6] are obtained concerning the detectors, such as the bias and dark levels, readout noise, etc. However, X-shooter (Vernet et al., 2011) is the only instrument to specifically monitor the number of transient events, from the detector dark exposures with the near-infrared arm. The level of the dark current is partially caused by radioactive decay within the instrument itself. However, the main cause of variability for the darks is caused by the impact of particles originating outside the observatory, such as "real" cosmic rays. Unfortunately, as for other instruments, the monitoring is only carried out once a day, leading to a low temporal sampling.

However, during the night 4–5 September 2015, regular sequences of three 5-minute darks were specifically executed to determine whether the dark cosmic ray rate and readout noise (RON) levels were affected together. Figure 1 shows

Table 1. Solar and geomagnetic activity and their consequences.

Type of solar/geomagnetic activity	Consequences on Earth	Consequences on data and instrument
Solar flare — radiation/proton storm (RS)	Aurora, airglow	Increase/decrease in flux of cosmic rays
Coronal mass ejection (CME)	Radio burst and blackout	Instrumental parameter level variability
Fast dense coronal solar wind (SW)	Geomagnetic storms	Electronics failure
Magnetic fluctuations (MF)	Variation of Earth's apparent magnetic field including its axis	Power loss
Co-rotating interaction region (CIRC)	Induced Foucault currents, Forbush effect	

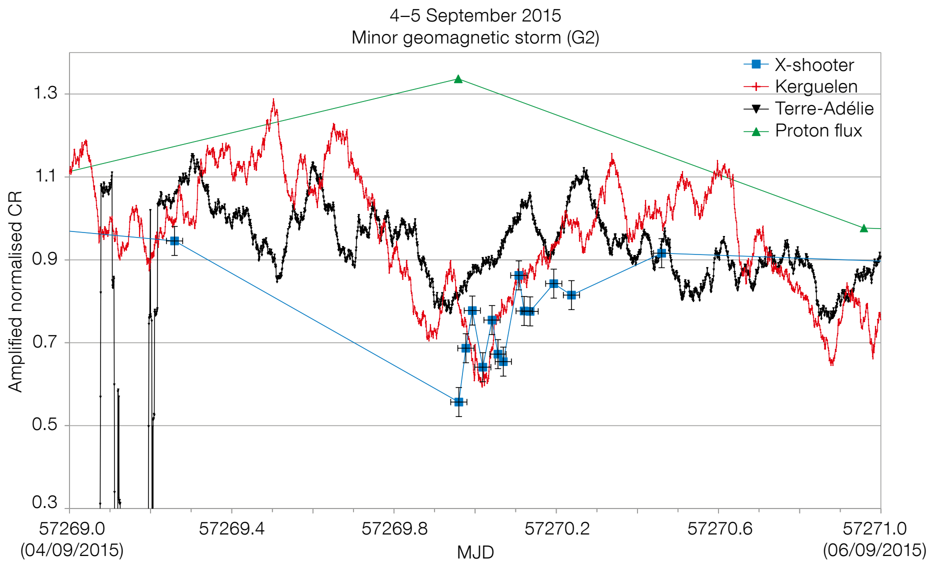

Figure 1. Relative evolution of the cosmic ray rate during the minor geomagnetic storm of 4–5 September 2015. The *x*-axis gives the Modified Julian Day (time) and the *y*-axis corresponds to the relative CR rates. The X-shooter (blue squares), Kerguelen Islands (red), Terre-Adélie (black) CR rates all show first a decrease then a return to the normal level once the solar wind intensity is back to normal (Forbush effect). The density of protons carried out by the fast dense solar wind, which causes the storm, is shown in green.

the comparison of the time evolution of the relative cosmic ray rate measured by X-shooter (blue squares) *vs.* the CR rates from the Kerguelen Islands and Terre-Adélie stations (red and black curves respectively, hereafter KERG and TERA). At the beginning of this minor geomagnetic storm (G1 level), all the curves show a dip. This paradoxical behaviour is called the Forbush effect (Forbush, 1937; 1938). The solar magnetic loops, often extended by the solar matter beyond the Earth, act like a shield, deviating the cosmic rays. As these are mostly of extra-Solar System origin, this effect causes a decrease in the CR rate. However, in this event, a fast, dense solar wind brought protons (green curve in Figure 1) that reached the Earth, generating the geomagnetic storm.

A linear regression between the X-shooter CR rate and those of KERG and TERA indicates a strong correlation, with a Pearson coefficient larger than 4–5σ.

The follow-up of this event with X-shooter illustrated its capability to serve as a CR rate-monitoring instrument. This monitoring can be carried out at almost no cost during the day and at night, when the instrument is not being used for calibrations or scientific observations, without disturbing operations.

Impact of solar and geomagnetic activity on X-shooter dark exposures

One can also ask whether the instruments and their subsystems can be affected by other geomagnetic and/or solar events besides cosmic rays. Before investigating this question a few considerations are necessary. Firstly, it should be noted that the dark current rate of the X-shooter near-infrared arm shows a reproducible and slow increase over several months following each thermal cycle that is not understood. The same behaviour is also noticeable in other near-infrared instruments like the High Acuity Wide field *K*-band Imager (HAWK-I). Therefore, in order to better assess the impact of the local variations related to astronomical events in the X-shooter dark

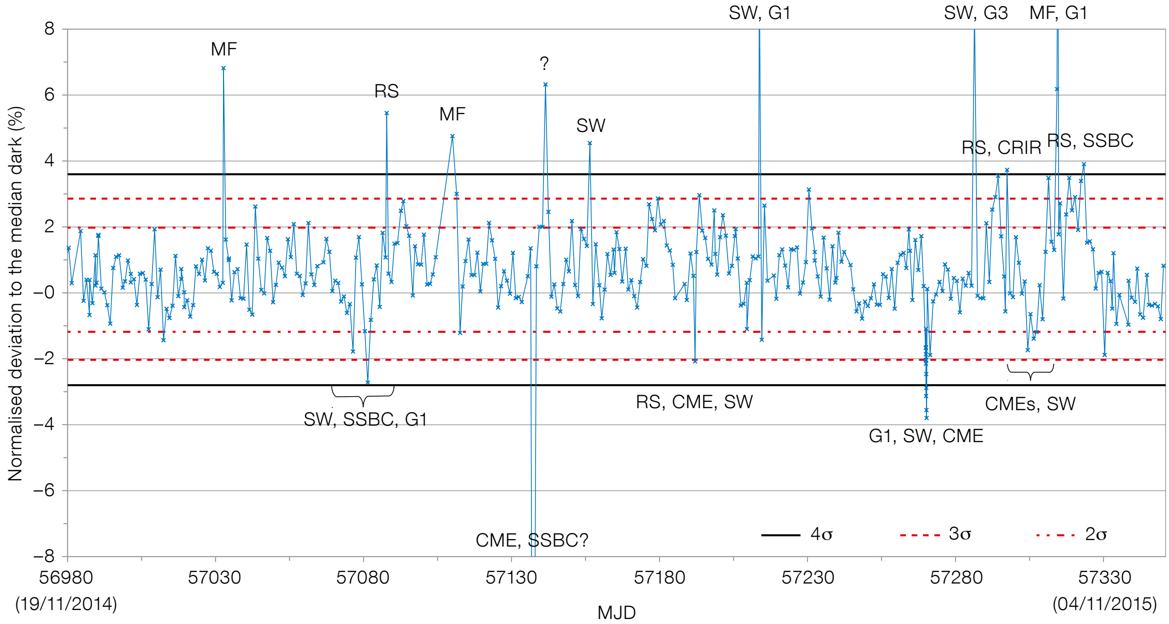

Figure 2. X-shooter normalised near-infrared detector dark level after removal of the long-term trend (blue points and line). The 2, 3 and 4σ standard deviations are shown with horizontal lines. The events at more than 3σ are annotated with a possible explanation: CME: coronal mass ejection; CRIR: co-rotating interaction region; Gx: geomagnetic storm of class x (1 to 5); MF: magnetic fluctuation; RS: radiation and proton storm; SSBC: solar sector boundary crossing; SW: fast dense solar coronal wind.

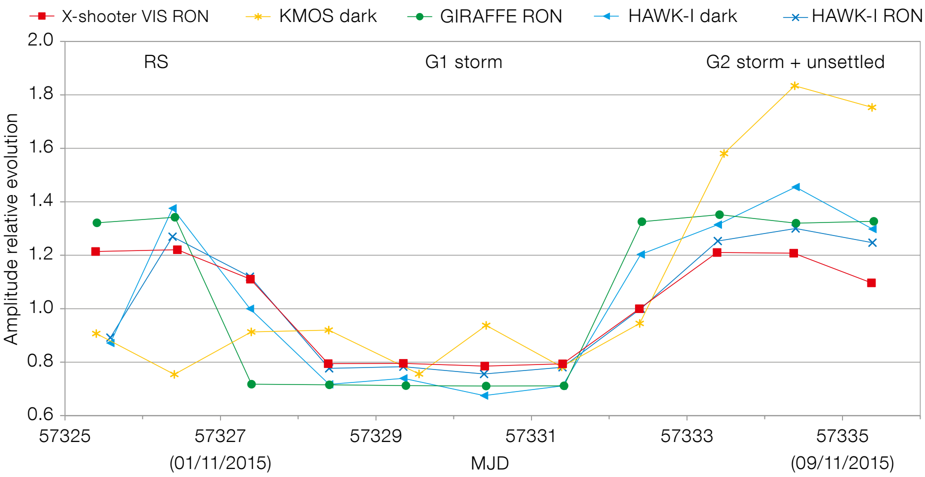

Figure 3. Temporal evolution of a few instrumental parameters (X-shooter VIS readout noise, KMOS median dark, GIRAFFE readout noise, HAWK-I median dark and readout noise) which correlate, over the period 30 October to 12 November 2015.

level, this slow long-term trend was removed. Secondly, the median and standard deviation (σ) of the dark rate are computed and frames showing absolute deviations larger than 3σ are visually examined. The dark level and its glitches over the period 19 November 2014 to 29 November 2015 are shown in Figure 2. At the epochs of the noted events indicated on Figure 2, all instrumental and pipeline problems, as well as variations in ambient temperature, can be discarded as the probable cause. Manual inspection of the individual frames showed confirmatory evidence of frames deviating from the normal.

We found that 94 % of the deviating X-shooter dark levels can be matched to specific geomagnetic or solar activity, as recorded[7]. Only one event in this one-year period remains unexplained. The probability of a random temporal coincidence between dark glitches and solar events would be 1 % (for example, non-random correlation of more than 3σ). Sometimes, aurorae and geomagnetic storms can happen even without obvious registered phenomena. Often, events like a CME apparently decrease the dark level (even if it is difficult to explain). Others, such as the magnetic fluctuation of the geomagnetosphere (crack), or recoupling with the solar magnetosphere, usually lead to an increase in the dark level. In some cases, it is difficult to conclude whether there is a positive or negative effect of the solar event on the data quality, as the dark level can increase or decrease. This is especially true if there is a combination of events including CME, SW, etc.

However, as already mentioned, the temporal sampling of X-shooter near-infrared darks is usually too low, meaning that the calibrations must be taken at the time of the event in order to record it. The duration of the events range from a few minutes to several days. In most cases, because no calibrations were taken during the event, the sampled dark curve remains unaffected, while it would have probably shown a glitch at the time of the event occurrence. Despite this limitation, one can recognise an event representing the Forbush effect, as shown in Figure 1, visible in Figure 2 at MJD ~ 57 270. During this event, there is a moderate to strong (2.5–3σ) correlation of the near-infrared dark level, and also of the X-shooter ultra-violet–blue (UVB) and visible (VIS) detector bias levels and the UVB and VIS readout noise, with the Kerguelen/Terre Adélie and X-shooter near-infrared CR rates.

Impact of solar and geomagnetic activity on the Paranal instruments and data quality

Since X-shooter darks show a response to solar and geomagnetic activity, it is justifiable to ask whether other Paranal instruments might react as well. Two strong limitations are apparent: the first is the infrequent temporal sampling, the second the lack of simultaneity of the calibration for a particular instrument with the reference data of X-shooter dark/CR and the Kerguelen/Terre Adélie CR record. Despite these difficulties, we chose the time interval from 30 October to 12 November 2015. During this period, several CMEs and geomagnetic storms G1 to G2 occurred, but there was also a quiet time.

Over this period, a search for a correlation between various detector parameters and the X-shooter or Kerguelen/Terre Adélie CR rates was carried out. On average, three parameters (among them bad pixel number, pattern noise, bias or dark level, readout noise) per instrument were examined. The instruments that were tested are: FORS2, KMOS, GIRAFFE, X-shooter (UVB/VIS arms), VISIR, SINFONI, HAWK-I, VIRCAM and OMEGACAM. They were chosen because at least one is located at each of the VLT Unit Telescopes and the VLT survey telescopes. As an example, a comparison of the temporal relative evolution of a few parameters from four instruments showing a similar trend is displayed in Figure 3.

Linear regressions between the chosen instrumental parameters and the CR values were carried out. The regression and Pearson coefficients were computed. To define whether the instrumental quantity correlates with the CR, values of the Pearson coefficient of more than 2σ and

Table 2. Correlation of instrument parameter values with evolution of the X-shooter or KERG/TERA CR rates.

Type of CR monitoring	Fraction of instrument parameters with correlation > 2σ (%)	Fraction of instruments with correlation at:	
		≥ 2σ	≥ 3σ
X-shooter	54	6/9	2/9
KERG/TERA	60	6/9	3/9

3σ were considered. During the events, instrumental parameter variations of less than 1 % (no change) to 155 % were found. The main results are given in Table 2.

Slightly more than half of the tested parameters per instrument apparently vary with the CR evolution as indicated by the percentages in Table 2 column 2. Not only is the number of bad pixels affected, but also the dark/bias level and/or the readout noise. In Table 2 columns 3 and 4, the correlation of the parameter variation with the CR evolution is given. It is better than 2σ in two thirds of the instruments and better than 3σ in the remaining one third of the cases. These results indicate that all the tested instruments seem to be impacted in some way by geomagnetic and solar activity. It is also worth mentioning that some simultaneous disturbance in several instruments located on different telescopes occurred, pointing to a common origin. Other more sophisticated statistical methods seem to confirm the correlations.

The temporal coverage and the samples used are still quite small. Ideally, obtaining better sampling would improve the significance, but this is difficult to reconcile with normal Paranal operations. However, geomagnetic activity cannot be blamed for all variations or glitches that occur. In all cases, severely affected calibrations are stored in the archive (but are not generally available) and the calibration data are retaken. Such events can occur during both daytime and nighttime but monitoring activity is generally confined to the daytime, so occurrences at night may be missed. However, one might take advantage of the Forbush effect (decrease in cosmic rays) to observe faint objects and avoid the magnetic fluctuation events (increase in readout noise) as often as possible.

Other impacts on the observatory infrastructure

Beyond the effect on the data quality and health of Paranal instruments, solar and geomagnetic activity can also disturb operations in another way. Severe/extreme storms are known to generate possible widespread voltage control problems and some protective systems will mistakenly trip out key assets from the grid, inducing pipeline currents, etc., according to NOAA[1]. In particular, the solstice G4+G4 superstorm (22–23 June 2015) and the Halloween G5+G5 superstorm (29–30 October 2003) generated power cuts in Sweden, possibly also in Argentina, induced currents in various countries, aurorae in tropical areas, magnetic declination fluctuations reaching 20 degrees, etc.

At Paranal, power cuts occurred in some areas at the times of these storms, damaging hardware, including on the telescope platform and systems under stabilised current control. No other specific reason could be found for these power cuts. Generally, the main electrical systems destroyed during these powerful geomagnetic storms are the transformers, breakers, etc. This is exactly what happened at Paranal. A correlation between power cuts and superstorms corresponds to a random probability of ~ 0.0005 %, which is highly unlikely. In addition to monitoring solar and geomagnetic activity, preventive and corrective actions to be taken when a new superstorm occurs have been defined.

Prospects

Paranal instruments, being highly sensitive, are affected by external disturbances, such as solar and geomagnetic events. In some cases, the data quality benefits from them, but not always and it could be strongly and negatively impacted. When several solar events occur simultaneously, their consequences on the day-to-day functioning of the observatory, the instrument health and data quality are difficult to predict. X-shooter appears to be able to follow, with adequate temporal sampling, the evolution of the cosmic ray rate and some of the solar and geomagnetic events. Such monitoring could be harnessed to provide added value to the community.

The Sun should now evolve towards the quiet phase of its unusual cycle number 24 and that will help in improving the stability of the instruments and their data. Fortunately, because the South Atlantic Magnetic Anomaly is drifting eastwards with time, in almost a century Chile should be free from its effects.

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Links

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