Analysis of the fraction of clear sky at the La Palma and Mt Graham sites

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ABSTRACT

The amount of available telescope time is one of the most important requirements when selecting astronomical sites, as it affects the performance of ground-based telescopes. We present a quantitative survey of cloud coverage at La Palma and Mt Graham using both ground- and satellite-based data. The aim of this work is to derive clear nights for the satellite infrared channels and to verify the results using ground-based observations. At La Palma, we found a mean percentage of clear nights of 62.6 per cent from ground-based data and 71.9 per cent from satellite-based data. Taking into account the fraction of common nights, we found a concordance of 80.7 per cent of clear nights for ground- and satellite-based data. At Mt Graham, we found a 97 per cent agreement between the Columbine heliograph and the night-time observing log. From the Columbine heliograph and the Total Ozone Mapping Spectrometer–Ozone Monitoring Instrument (TOMS–OMI) satellite, we found that about 45 per cent of nights were clear, while satellite data (GOES, TOMS) are much more dispersed than those of La Palma. Setting a statistical threshold, we retried a comparable seasonal trend between the heliograph and satellite.

Key words: atmospheric effects – methods: statistical – site testing.

1 INTRODUCTION

The identification of a site for the future European Large Telescope (E-ELT) is a key issue. Moreover, a quantitative survey of cloud cover for the areas selected as candidate sites for the telescope is and will continue to be an essential part of the process of site selection for future large telescopes in the same class as the E-ELT.

In fact, the performance of large telescopes at optical and infrared wavelengths is critically dependent on the atmospheric cloud cover. Cloud cover is a key parameter at the time of site selection and also affects scientific output during the life of the telescope. For instance, a night-time seasonal trend of fewer clear skies can reduce regular access to the sky.

Typically, it is possible to quantify the presence of clouds at telescope sites using ground-based observations that provide real-time knowledge of the atmospheric conditions. The fraction of clear sky can be determined using either instruments (i.e. all-sky cameras) or observer estimates. Long-term records from many ground-based telescopes, which list the number of nights available for observing, are now accessible, and it is possible to begin a reliable statistical study. However, this technique alone is not suitable for identifying future candidate sites where there are no telescopes.

An easy evolution of this analysis is the use of meteorological satellites, which provide measurements of cloud cover and other critical parameters for site testing, covering large areas with different spatial and temporal resolutions. Taking into account that most meteorological satellites are equipped with similar instrumentation, it is not difficult to compare distinct sites observed by two or more different satellites. Additionally, as satellite data archives now cover long time periods, it is possible to have, for each site, the trend of these parameters in both long and short time-scales. Erasmus & Sarazin (2002) were among the first to demonstrate the successful application of satellite data to monitoring, comparison and forecasting evaluations. Erasmus & van Rooyen (2006) quantified cloud cover at La Palma using the Meteosat satellite and validated the data using ground-based measurements from the Carlsberg Meridian Telescope (CMT).

In this paper, we present the results of a study of cloud cover using satellite- and ground-based data obtained from two important astronomical sites: the Observatorio del Roque de Los Muchachos (ORM) located in La Palma (Canary Islands), which hosts several international telescopes, among them the Telescopio Nazionale Galileo (TNG), and Mount Graham (Arizona, USA), hosting the Large Binocular Telescope (LBT). The results are compared with those of Erasmus & van Rooyen (2006) and Erasmus & Sarazin (2002). The paper is organized as follows. In Section 2, we describe both the ground and satellite data bases adopted. In Section 3, we...
describe the satellite data acquisition procedure, and in Section 4 we show the data reduction procedure. Section 5 gives a discussion of the results.

2 DATA

The primary aim of this work is to derive the number of clear nights. To quantify the amount of clear sky over the ORM and Mt Graham sites, we used different set of data collected at both ground and satellite facilities, which are available partially via the World Wide Web and partially thanks to the courtesy of the observatory staff. The validation of satellite data is also performed using correlations between ground-based and satellite-based data. In particular, we have used meteorological satellites that have geostationary orbits because these ensure large coverage of the globe and suitable resolution. Fig. 1 shows the time coverage of the data bases used.

2.1 Ground-based data

The first detailed analysis of more than 10 yr of meteorological data, obtained using the TNG meteorological station at the ORM, can be found in the following two papers: Lombardi et al. (2006, hereafter Paper I) and Lombardi et al. (2007, hereafter Paper II). Paper I shows a complete analysis of the vertical temperature gradients and their correlation with the astronomical seeing. In contrast, Paper II shows an analysis of the correlation between wind and astronomical parameters as well as the overall long-term weather conditions at the ORM. Differences in the microclimate at the ORM have been demonstrated in a detailed comparison between synoptic parameters taken at three different locations at the observatory on a spatial scale of about 1 km. Moreover, the ORM is shown to be almost dominated by high pressure and characterized by an average relative humidity lower than 50 per cent. The first detailed reports on night-time cloudiness at La Palma were given by Murdin (1985), who reported that 78 per cent of nights at La Palma were usable during the period 1975 February–September (see table 2 of Murdin 1985).

Table 1. Annual mean downtime as a result of the weather at the TNG.

| Year | Annual mean downtime (per cent) |
|------|---------------------------------|
| 2000 | 26.7                            |
| 2001 | 26.6                            |
| 2002 | 26.1                            |
| 2003 | 28.2                            |
| 2004 | 37.3                            |
| 2005 | 39.4                            |
| 2006 | 30.2                            |
| 2007 | 26.4                            |
| 2008 | 29.6                            |

Thanks to the kindness of the staff at the TNG and LBT, the updated end-of-night reports have been made available, allowing us to extend the time baseline to the range 1975–2008 for the TNG telescope. The LBT logbook, available from the National Institute for Astrophysics (INAF) and the Max Planck Institute time, is only available since 2008 and this gives a time baseline of only two years.

Fig. 2 shows the distribution of the mean monthly values for nights lost as a result of bad weather (i.e. cloudy nights, nights with strong wind or nights affected by the calima) for 2007 (long-dashed line) and 2008 (short-dashed line), derived from the first analysis of the TNG logbook. The continuum line of Fig. 2 shows the monthly mean value computed from 2000 to 2008. It is evident that June is the month that has the minimum number of bad nights. The maximum number of nights lost as a result of the weather does not reach 50 per cent of the total allocated nights. Table 1 reports the annual mean values of the downtime computed from 2000 to 2008. We can see that the mean value is almost stable over the last nine years, giving a value of 30 per cent for lost nights.
Table 2. Mean monthly percentage of useful nights at the TNG. The selection is derived using the number of observed hours extracted from the TNG log.

| Month  | 2007 100 per cent used | 2007 Used > 5 h | 2008 100 per cent used | 2008 Used > 5 h |
|--------|------------------------|-----------------|------------------------|-----------------|
| January| 25.8                   | 29.0            | 35.5                   | 29.0            |
| February| 46.4                  | 24.1            | 20.7                   | 24.1            |
| March  | 38.7                   | 12.9            | 32.2                   | 22.6            |
| April  | 46.6                   | 26.7            | 40.0                   | 23.3            |
| May    | 70.9                   | 9.7             | 54.8                   | 29.0            |
| June   | 73.3                   | 10.0            | 86.7                   | 13.3            |
| July   | 90.3                   | 6.4             | 87.1                   | 9.7             |
| August | 90.3                   | 3.2             | 67.7                   | 22.6            |
| September | 73.3             | 16.7            | 33.3                   | 20.0            |
| October| 38.7                   | 32.2            | 35.5                   | 22.7            |
| November | 20.0               | 16.7            | 48.3                   | 20.7            |
| December| 51.6                  | 16.1            | 32.2                   | 19.3            |
| Mean   | 55.5                   | 17.0            | 47.8                   | 21.3            |

We have also analysed, for the years 2007 and 2008, all the astronomically useful nights at the TNG using two different criteria. In the first criterion, we extracted the information from the lost time weather string reported in the end-of-night report. If the night was fully used, no lost time should be found in this string. Using this information, we separated the nights used into fully useful nights (i.e. the dome is open the whole night) and partially useful nights (i.e. less than 5 h are lost because of the weather). The results are given in Table 2. As discussed in the following, the adopted criterion is more stringent than that of Ardeberg (1984).

From Table 2, it can be seen that the TNG is opened for the whole night and without interruption for more than 50 per cent of all of the nights considered. If we compute the mean percentage of the two years, considering both totally and partially useful nights, we find that the telescope operated for 70.8 per cent of the total nights. We can conclude that this value is in agreement with the values expected for good astronomical sites. Erasmus & van Rooyen (2006) gave a percentage of 74.7 per cent for usable nights at Cerro Tololo Inter-American Observatory for the period 1997 June to 1999 April, derived from ground-based observations. Moreover, at the ORM, Ardeberg (1984) measured 47 per cent of nights to be photometric in 1982, and 67 per cent in 1983. In his analysis, Arderberg defined as ‘photometric’ every night having at least 6 h of uninterrupted clear sky. The mean value of 57 per cent of photometric nights, computed in 1982 and 1983 by Ardeberg (1984), is in agreement with our mean value of 51.7 per cent, obtained using the more restricted criterion of 100 per cent fully used nights. This means that in the case of six consecutive hours of clear sky, a full night is very likely to be photometric according to Arderberg’s definition.

In the second criterion, we classified the nights using the sky condition comments. We classified the nights as clear (i.e. cloud-free) and mixed (i.e. partially used because of the presence of clouds during the night). We also took into account the calima. In this type of selection, if the night presents strong wind or humidity, it appears mixed in our classification, while it may appear not usable using the previous criterion because the dome may be closed for safety. Table 3 shows the mean monthly percentage obtained. A comparison between Tables 2 and 3 shows that the percentage of fully used nights is similar to the percentage of 100 per cent clear nights. This means that when a night is fully used it is very likely to be completely clear. However, Table 3 gives a higher number of total usable nights. This is probably because, as we have just said, the mixed sky conditions may include also strong wind or humidity.

Table 3. Mean monthly percentage of useful nights at the TNG. The selection is derived using the sky quality comments extracted from the TNG logbook. The fraction is relative to the total number of available nights per month.

| Name Month | Clear (per cent) | Mixed (per cent) | Calima (per cent) | Clear (per cent) | Mixed (per cent) | Calima (per cent) |
|------------|------------------|------------------|-------------------|------------------|------------------|-------------------|
| January    | 25.8             | 25.8             | 3.2               | 19.3             | 35.5             | 6.4               |
| February   | 53.6             | 17.9             | 3.6               | 17.2             | 41.4             | 10.3              |
| March      | 26.7             | 20.0             | 10.0              | 35.5             | 29.0             | 16.1              |
| April      | 56.7             | 13.3             | 3.3               | 46.7             | 30.0             | 6.7               |
| May        | 58.1             | 6.4              | 9.7               | 48.4             | 29.0             | 0                 |
| June       | 83.3             | 13.3             | 0                 | 83.3             | 6.7              | 10.0              |
| July       | 61.3             | 0                | 35.5              | 67.7             | 0                | 25.8              |
| August     | 93.5             | 3.2              | 3.2               | 45.2             | 9.7              | 35.5              |
| September  | 76.7             | 6.7              | 0                 | 33.3             | 33.3             | 0                 |
| October    | 51.6             | 35.5             | 0                 | 38.7             | 54.8             | 0                 |
| November   | 16.7             | 43.3             | 0                 | 48.3             | 17.2             | 0                 |
| December   | 58.1             | 25.8             | 0                 | 33.3             | 32.3             | 0                 |
| Mean       | 55.2             | 17.6             | 5.7               | 43.1             | 26.6             | 9.2               |
Table 4. Monthly sky conditions at Mt Graham in 2008 using the sky quality comments of the LBT logbook. The monsoon months are excluded.

|          | Clear (per cent) | 2008 Cloudy (per cent) | Mixed (per cent) |
|----------|------------------|-------------------------|------------------|
| Mean     | 60.0             | 10.0                    | 30.0             |

conditions. We notice that 14.5 per cent of nights in 2008 were lost as a result of high humidity or strong wind.

The same classification has been made for the LBT. Table 4 shows the distribution obtained for the quality of nights. The LBT logbook is limited to a sample of only 50 nights (July and August do not have data because the telescope is closed because of the monsoon), but for the completeness of the discussion we decided to include them in Table 4. A comparison between Tables 3 and 4 shows a comparable percentage of clear days, while at Mt Graham the percentage of mixed nights is higher. Unlike the La Palma site, no calima event has been found at Mt Graham.

The criterion to discriminate between photometric and spectroscopic data is not unique. It is difficult, for example, to judge at the beginning of the night before starting the observations whether the sky is completely clear, in the sense of cloud-free, or whether the airborne dust will significantly affect the observing conditions. For this specific point, we used the CMT extinction files to set the clear-sky quality at the La Palma site.

Regarding Mt Graham, an interesting criterion was used, based instead on the morning sky conditions (Steward Observatory 1987), but this is not used in this analysis. Thanks to the weather station of the United States Forest Service (USFS), located 2.1 km from the LBT (Columbine Peak), we correlated the log of night observations with data from the heliograph, an instrument that records the Sun’s radiation in wavelengths from ultraviolet to infrared. This data base covers the whole period since 2001 September.

We also used the rainfall data base of the weather station of the Safford Agriculture Center because of its long-time baseline, since 1940. The cross check gives complementary results to those of Columbine Peak.

2.2 Satellite-based data

Data were derived using Geostationary Operational Environmental Satellite (GOES) 12 for the ORM and GOES 8 and GOES 12 for Mt Graham, which are meteorological satellites monitoring cloud cover and water vapour. Both satellites are the new generation of the GOES family, an American geosynchronous weather facility of the National Oceanic and Atmospheric Administration (NOAA). GOES 12 is able to observe the full Earth disc in both visible and infrared regions of the electromagnetic spectrum and can observe and measure cloud cover, in addition to other important meteorological parameters. Two GOES satellites are typically used to provide coverage of the entire hemisphere. When the two satellites are in operation, one satellite covers the GOES east position, located over the equator at 75° E, and the other is located at the GOES west position over the equator at 135° W. These two satellites provide imagery of the North and South American continents as well as the Pacific and Atlantic Oceans, with an overlapping area of coverage. GOES 8 was launched in 1994 April and operated from 1994 November to 2003 April. GOES 12 was launched in 2001 July and replaced GOES 8 in 2003 April. The two spacecrafts carry an imager, a ‘sounding’ and an X-ray imager. The imager is a Cassegrain telescope covering five wavelength channels, one in the visible band (0.55–0.75 μm) and four in the infrared bands (3.80–4.00, 6.50–7.00, 10.20–11.20 and 11.50–12.50 μm). It can provide images covering 3000 × 3000 km² every 41 s, by scanning the area in 16 km² sections. Full Earth disc scans are scheduled every 3 h. It should be noticed that GOES 12 covers the La Palma area near the edge of the field of view. Taking into account the curvature of the Earth, we obtain a projection of about 57° in latitude and 28° in longitude, corresponding to a factor of 1.1 in latitude and 1.8 in longitude.

Thanks to this set up, it is possible to have the same instrumental configuration for the ORM and Mt Graham, and to compare them in a suitable way.

We have also included data from the polar satellite of the Total Ozone Mapping Spectrometer (TOMS) family to extend the statistics of clear days at Mt Graham. These satellites were planned to study atmospheric ozone, but their data can also be used to study cloud cover. Four TOMS satellites have been launched from 1978 to the present. Because of the failure of the second satellite, Meteor-3, we have only used data from the remaining three: Nimbus-7 (1978–1993), Earth Probe (1996–2005) and the Ozone Monitoring Instrument (OMI; from 2004). We used the overpass data² covering 110 km² centred on Tucson, Arizona (USA). Table 5 summarizes the main parameters of the satellites used.

3 SATELLITE DATA ACQUISITION

For this work, we used GOES 12 equipped with the imager. Among the five available channels, we selected the water vapour channel (channel 3, hereafter called the b3 band) centred at 6.7 μm, and the cloud coverage channel (channel 4, hereafter called the b4 band) centred at 10.7 μm. The b3 band is sensitive between 6.5 and 7.0 μm, and is able to detect high-altitude cirrus clouds. The b4 band is sensitive between 10.2 and 11.2 μm, and is able to detect middle-level clouds. The output of the detector is proportional to the energy reaching the detector areas per unit time (radiance). It is also possible, given the intensity and the wavelength of the radiance, to derive the equivalent brightness temperature using an appropriate Planck function. This was the procedure adopted by Erasmus & van Rooyen (2006).

We selected the infrared channel because water vapour absorbs electromagnetic radiation and then re-emits it in various wavelength bands, in particular in the infrared region at 6–7 μm. If clouds are not present, the emissions at 10.7 μm reaching the satellite are largely not absorbed by the atmosphere, so that the radiance values measured are a result of emission from the surface. However, when clouds are present, they behave as absorbing and emitting ‘surfaces’, so that, under these conditions, radiation reaching the satellite is from the cloud top, which has a lower emissivity as a result of a lower temperature.

The GOES data have the highest spatial resolution (4 × 4 km²) for channel b4 and 8 × 8 km² for channel b3) compared with the old generation satellites. Data are prepared by the Comprehensive Large Array-data Stewardship System (CLASS), an electronic library of NOAA environmental data,³ and are stored as rectified full

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1 See http://www.wrcc.dri.edu/cgi-bin/cliMAIN.pl?azsaff
2 See ftp://Toms.gsfc.nasa.gov/pub/omi/data/overpass/
3 See http://www.class.ngdc.noaa.gov/
The mean parameters of the satellites used.

| Name     | Longitude | Latitude | Range (μm) | Spatial res. (km) | Temporal res. (h) | Years used     |
|----------|-----------|----------|------------|------------------|------------------|----------------|
| GOES 12  | −75°      | 0°       | 6.5–7.0 (B3) | 8                | 3                | 2007–2008      |
|          |           |          | 10.2–11.2 (B4) | 4                | 3                | 2007–2008      |
| GOES 8   | −122°     | −5°      | 6.5–7.0 (B3) | 8                | 3                | 2007–2008      |
|          |           |          | 10.2–11.2 (B4) | 4                | 3                | 2007–2008      |
| Nimbus-7 | Polar     |          | 0.32–0.40   | 111              | 24               | 1978–1993      |
| Earth Probe | Polar   |          | 0.32–0.40   | 111              | 24               | 1996–2005      |
| OMI      | Polar     |          | 0.35–0.50   | 3                | 24               | 2004–present   |

Earth disc images in a format called area files. We have processed these using MCIDAS-V Version 1.0beta1, a free visualization and data analysis software package. The first step to collecting data was to extract the right sector centred close to the TNG and LBT.

Regarding the TNG, we know that it has latitude 28°45′28.3″N and longitude 17°53′37.9″W. We identified and extracted from the sector a subimage of 1° × 1° having a central pixel centred on (or near to) the TNG coordinates. We obtained subimages having a central pixel of 28°46′32.16″N latitude and 17°52′08.4″W longitude. Both the TNG and subimage coordinates reside in the same pixel, which is also the instrumental resolution. For each night, we took into account available observations at four different hours to cover the entire observing night, at 20:45, 23:45, 02:45 and 05:45 UTC. The mean of these four values has been used in our analysis.

Regarding Mt Graham, data from 1995 January to 2008 December have been analysed; until 2003 April, the data come from GOES 8, and then GOES 12 has been used. For each night, we selected data at two different hours: at 17:45 and 02:45 UTC (10:45 and 19:45 local time, respectively). When no data were available at those times, we used images taken at different times, up to 1.5 h after or before. Our aim was to select two hourly sets of data, one during daytime and one during night-time. However, it was not possible to built homogeneous series at 05:45 or 08:45 UTC (22:45 and 01:45 local time, respectively) because during spring and autumn the GOES change acquisition timetables and do not often cover these times.

The analogous data base has been extracted for the LBT, located at 32°42′33.2″N latitude and 109°54′7.6″W longitude. We selected subimages with the pixel centred at this position. After a detailed analysis of the GOES daily signal coincident with the log data, we found the best correlation with the signal at 10:45 and 19:45 local time (see also Fig. 7).

4 DATA ANALYSIS

Fig. 3 shows the distribution of the mean infrared emission at the ORM for the b3 and b4 bands in the upper and lower panels, respectively, for 2008. It is evident that the b3 band (6.7 μm water vapour) shows higher values of emissivity in the summer time period, corresponding to a higher temperature and a low percentage of clouds (180–200 d), than those in the autumn. The lower panel of Fig. 3 for the 10.7-μm band shows a flatter distribution of emissivity.

Fig. 4 shows the daily distribution of the emissivity for the b3 and b4 bands at Mt Graham. The seasonal effects of this site are evident in both bands, distinguishing the monsoon period. This seasonal trend requires normalization of the flux in order to allow a selection of the night quality from a predetermined fixed threshold (see later for discussion). The monsoon period is seen in July and August. A
spline interpolation was adopted because of the discontinuity of the monsoon period.

Fig. 5 shows the distribution of the emissivity in the b4 band (top) and the distribution of normalized emissivity (bottom) centred at Mt Graham. The normalization function is used to extract the other values of emissivity under the assumption that the behaviour is the same all year.

A comparison of Figs 3 and 4 shows that the satellite reaches higher values of emissivity in both bands at Mt Graham compared to La Palma. A deeper analysis has to be carried out to check the existence of correlations with other parameters in order to understand this different value of emissivity between the two sites. In this paper, we have checked possible seasonal effects, and Fig. 6 shows the distribution of the emissivity at the ORM for the b3 (filled squares) and b4 (open triangles) bands in two different periods of the year. The upper panel of Fig. 6 shows the distribution of three consecutive days (clear, mixed and cloudy) in winter time. The clear day reaches a value of about 14 000 units in the b4 band and a mean value of about 9700 units on the cloudy day. The presence of cold cirrus produces the oscillation of the counts on the cloudy day. A similar behaviour can be seen in the b3 band with a lower value of counts. The bottom panel of Fig. 6 shows the distribution of two consecutive days in summer time (only clear and cloudy, because we found no mixed consecutive day). We see that the clear day reaches a value of about 16 000 units in the b4 band, a greater value with respect the winter value, probably because of the different mean air temperature. A more evident effect of the arriving perturbation can be seen in the b3 band with a drop of the counts.

To make an easy comparison of the seasonal behaviour of the two sites, we include here the analogous distribution for Mt Graham. Fig. 7 shows the distribution of the b3 (triangles) and b4 (squares) bands of GOES 12 during some winter (upper panel) and summer (lower panel) days in 2008, compared with the temperature of the air measured by the Columbine weather station (diamonds, right axis). We confirm that the signal from La Palma is systematically lower than that at Mt Graham, in spite of the lower altitude. A tentative explanation could be a higher extinction of the satellite signal because of the longer optical path.

Fig. 7 clearly shows the difficulty in finding the right threshold of GOES fluxes. When the day (and night) is clear, air temperature and b4 band values follow a day/night cycle. When perturbation arrives, the daily peak usually disappears. However, the winter graph shows a peak of the b4 band flux during the night, even if the air temperature remains stable. The satellite probably measured the temperature of the clouds, which in that case had a greater temperature than the ground. Using the threshold method to distinguish clear days from cloudy days, this day would be identified as clear. In our sample, there is only marginal evidence (if any) of lower minimum temperatures during covered nights compared to clear nights. The most evident difference, instead, is a lower emissivity in the late
afternoon just before a cloudy night. The local ground temperature may have an important role in GOES measurements. Furthermore, the higher signal during the summer does not seem to lead to better discrimination between clear and cloudy nights. Noise in the data and resolution effects have also been tested, comparing the single-pixel data to nine-pixel averages during nights recorded from the ground; however, the plots are almost identical. More tests are needed to check the reliability of night-time GOES at Mt Graham.

4.1 La Palma: the threshold method

Considering the sky quality comments as derived from the end-of-night reports at the TNG, we correlate the values of the b3 and b4 bands of GOES with the corresponding night quality. Fig. 8 shows the distribution of the emissivity obtained from the b3 (x-axis) and b4 (y-axis) bands as a function of the different type of nights for 2007 (filled triangles) and 2008 (open squares). Each type of night is plotted separately to better identify the distribution along the panels. Fig. 8 shows good correlation between the TNG classification and emissivity. In fact, it is evident that at higher b3 and b4 band values it generally corresponds to a clear night, and at lower b3 and b4 band values it corresponds to a cloudy night. In contrast, mixed nights have a distribution among all possible values, probably as a result of the season.

In order to have a more objective analysis of clear conditions, we used and cross-correlated the same satellite data with the corresponding atmospheric extinction, as published on the website of the CAMC telescope. In this analysis, we presumed that the sky conditions (with the two telescopes having close locations) were the same, and the extinction parameter is able to identify not only useful nights but also photometric nights. The nightly values of extinction were derived from CCD frames in the Sloan Digital Sky Survey (SDSS) r′ band.

Each frame contains an average of 30–40 photometric standard stars. In our analysis, we assumed that if no extinction value existed or if it was equal to zero, it was probable that no observation took place because of the bad sky conditions. Nights with technical problems have not been included (233 nights). Fig. 9 shows the distribution of the extinction as a function of the GOES b3 (upper panel) and b4 (lower panel) band emissivity.

See http://www.ast.cam.ac.uk/~dwe/SRF/camc_extinction.html
Analysis of the fraction of clear sky

Figure 8. Distribution of GOES 12 emissivity at the ORM separated according to the different sky quality (extracted from the TNG log). The years 2007 (filled triangles) and 2008 (open squares) are plotted.

points represent all the nights with an extinction value not equal to zero and are classified by extracting information from the TNG logbook for 2007 and 2008. They show a large spread of extinction values in both infrared bands, some of which have been classified as cloudy at the TNG. Clear nights are located in a well-defined locus of the b4 band. It is interesting to note that 72.1 per cent of all the nights reporting the calima in the TNG report in 2007 and 2008 have extinction values greater than 0.13. Moreover, those nights having reported no calima but some clouds have extinction values greater than or equal to 0.13, but lower b3 and b4 values than the nights with calima. Most of our selected clear nights (88 per cent) present an astronomical extinction of less than 0.13 mag. The extinction value of 0.2 mag airmass\(^{-1}\) on clear nights was found to be discriminant for calima events by Lombardi et al. (2008).

Fig. 10 shows the distribution of the GOES 12 emissivity as a function of the TNG night report only for those nights not plotted in Fig. 9 because no extinction value was reported (about 123 nights with ‘zero extinction’ classification). We can see that the majority of the plotted points are located in the panels marked mixed and cloudy. In fact, considering the TNG logbook for 2007 and 2008, we found that 63.4 per cent of these nights with no extinction at the CMT are classified as cloudy or mixed nights, while only 36.4 per cent are classified as clear nights or with the calima.

To conclude, we decided to use Fig. 9 to define the threshold values for both b3 and b4 bands to distinguish satellite clear nights from cloudy nights. In particular, we decided to obtain the satellite sample of clear nights, setting the GOES threshold to 6500 for the b3 band and to 13 200 for the b4 band. The ground sample is obtained using all nights with CMT extinction values. The result is shown in Fig. 11 where dashed lines indicate the threshold that we have chosen to separate clear nights. All GOES nights present in the b3 band with values greater than 6500 and in the b4 band with values greater than 13 200 are clear, all nights with b3 band values less than 6500 and b4 band values less than 13 200 are cloudy, and the other cases are mixed. This choice has been adopted by optimizing the discrimination of the different nights and minimizing the contamination. It should be noted that this empirical criterion is different from the method used by Erasmus, based instead on the derived temperatures. With these adopted limits, we obtained the following statistics: GOES identified 73.6 per cent of clear nights for 2008 and 70.2 per cent for 2007, while from ground observations we know that 61.6 per cent of all nights were clear for 2008 and 63.6 per cent for 2007. Thus, it seems that, using our GOES processing method, clear nights are overestimated by about 10 per cent.

4.2 Mt Graham: a new approach

Fig. 12 shows the results of the same adopted procedure that correlates night quality based on the LBT report and GOES emissivity.
Figure 10. Emissivity distribution of the GOES 12 b3 and b4 band emissivity at the ORM in 2007 and 2008 for all nights with ‘zero extinction’ classification in the CMT log (no observations). Sky quality classification has been carried out using the TNG log.

Figure 11. Distribution of the GOES 12 b3 and b4 band emissivity at La Palma in 2007 and 2008 for all nights reporting an extinction value different from zero in the CMT extinction file. Sky quality classification has been carried out using the TNG log. The dashed lines indicate the thresholds chosen to separate clear nights from mixed and cloudy nights.

The separation between clear, mixed and covered nights on the basis of the b3 and b4 GOES bands is not as evident as for the La Palma data. This could in part be the result of an intrinsic GOES data interpretation at Mt Graham, and in part a result of poor statistics. In order to improve the latter, after a number of tests, we decided to follow a new, different approach using the heliograph data from Columbine Peak. The archive is maintained by the Western Regional Climate Center\(^5\) and the data can be freely downloaded. For the purpose of this paper, we downloaded the daily table from 2001 March (from when the heliograph data are available). This data base is not complete; for some days no data were recorded or were only partially recorded; for the first case the event is highlighted, but not for the second. So, we verified the reliability of the data by checking the data base day by day and classifying days for completeness: ‘perfect’, if the data covered the entire day; ‘good’, if only 1 h of data were missing; ‘bad’, if more than 1 h of data were not recorded. We found that perfect days make up 64.2 per cent of the total, good days 8.7 per cent, and bad days 27.1 per cent. We only used perfect and good days in this analysis, which cover 72.9 per cent of the considered period. Fig. 13 shows the distribution of Sun emissivity, as integrated daily fluxes, for 2008, where bad days appear as flux drops.

The monsoon period (day 180 to about day 240) is evident. Because of the strong seasonal effect, the heliograph data have been normalized like the GOES data using a spline fit. Finally, the normalized daily fluxes have been compared with the end-of-night reports from the LBT. The correlation is presented in Fig. 14, where the correspondence of the heliograph flux with the night-time data is very tight, with a concordance of 97 per cent of clear nights when the threshold of the normalized flux is set at 0.9. It is evident that the day/night difference at Mt Graham is almost negligible if we consider only clear days, but not when considering mixed/cloudy days, 30 per cent of the samples fall in the other category.

A similar procedure was used to compare the TOMS–OMI reflectivity with the logbook of the LBT. In this case, the best threshold was found to be 0.08. The results can be seen in Fig. 15. It is evident that the heliograph and TOMS–OMI data distinguish clear nights better than the GOES. The upper-right panels of Figs. 14 and 15 show, respectively, the flux and the reflectivity distribution of GOES 12 b3 and b4 band emissivity at La Palma in 2007 and 2008 for all nights reporting an extinction value different from zero in the CMT extinction file. Sky quality classification has been carried out using the TNG log.

\(^5\) See http://www.wrcc.dri.edu/cgi-bin/rawMAIN.pl?arACOL

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Figure 13. Yearly distribution of Sun emissivity, from integrated daily fluxes, for 2008. The bad days appear as flux drops.

Figure 14. Daily heliograph flux distribution at Mt Graham separated according to the different sky quality (extracted from the LBT report). Dashed lines indicate the thresholds chosen to separate the clear nights from the mixed and cloudy nights.

Figure 15. Daily TOMS–OMI reflectivity distribution at Mt Graham, separated according to the different sky quality (extracted from the LBT report).

We found two different thresholds, where the percentage of clear nights found by the GOES was comparable with that obtained with TOMS–OMI and the heliograph in the overlapping period. The two values are 0.66 and 0.8 for the b3 and b4 normalized fluxes, respectively, for the heliograph and for the TOMS.

5 DISCUSSION

5.1 La Palma site

In our analysis at La Palma site, we used 731 nights, obtaining the sky comments from the TNG end-of-night reports. After the cross-correlation of the TNG nights with the CMT extinction, the total number of nights used for the final statistics was 375; these we can define as photometric or, at least, spectroscopic on the basis of Table 2. We obtained 700 nights from the GOES data base, covering the period 2007–2008. Fig. 11 shows the thresholds adopted to select night quality. All those having emissivity greater than 6500 counts in the b3 band and values greater than 13 200 counts in the b4 band are defined as clear nights. In contrast, we defined as cloudy all nights with b3 band values less than 6500 and b4 band values less than 13 200; all other cases are classified as mixed. For ground observations, we defined clear nights as all those with no clouds, humidity, strong wind or the calima.

With these adopted limits, we found a mean statistical percentage of clear nights of 62.6 per cent from ground data and 71.9 per cent from satellite data. It seems that there is a good correlation between ground and satellite data, but the satellite overestimates the clear nights by about 10 per cent, as already found by Erasmus & van Rooyen (2006).

The next step was to quantify the nights classified as clear using both ground and satellite data. We found that 79.7 per cent of the common nights (365, i.e. half of the total sample) are clear for both ground and satellite data. We found 7.9 per cent of the common nights (365, i.e. half of the total sample) clear for both ground and satellite data for 2007, and 81.6 per cent for 2008, with a mean percentage of 80.7 per cent. Table 6 shows the distribution...
of the monthly percentage of common clear nights at La Palma in 2007 and 2008. Moreover, we note that most clear nights have an extinction less than 0.13. Months with ‘−’ indicate that no data are available from the GOES data base or from the CMT extinction file. There is a large spread of agreement during the months and also in the two considered years.

Using the Meteoros in geostationary orbit at 0°, at the ORM Erasmus & van Rooyen (2006) found 68.7 per cent of clear nights (i.e. cloud-free) from ground-based data, on the basis of 629 nights in the period 1999–2002, compared with our percentage of 62.6 per cent. In contrast, they found a percentage of 65.0 per cent from satellite data, compared with our mean of 71.9 per cent. Moreover, they found 52.5 per cent of photometric nights from both satellite and ground data, a much lower value than our mean value of 80.7 per cent. We note that Erasmus & van Rooyen (2006) report 83.7 and 85.3 per cent of photometric hours for satellite and ground data, respectively, including the time when only part of the sky was photometric. A summary of the number of photometric nights can be found at http://www.otri.iac.es/sitesting/UserFiles/File/photometric-time.pdf.

Instead, the estimated percentage of spectroscopic nights is different. If we assume that the partially used nights are spectroscopic, we find from the logbook a mean value of about 16.8 per cent. Erasmus & van Rooyen (2006) found a mean value of 20.7 per cent. Moreover, we find from the logbook a mean value of about 16.8 per cent.

Table 6. Mean monthly percentage of clear nights selected from both ground and satellite data for 2007 and 2008. The selection is computed using the logbook for the ground data and the established threshold values for satellite data. The monthly fractions are computed only for nights with extinction values.

| Month   | CMT (per cent) | GOES (per cent) | CMT (per cent) | GOES (per cent) |
|---------|----------------|-----------------|----------------|-----------------|
| January | 43.8           | 43.8            | –              | –               |
| February| 65.2           | 60.9            | 59.1           | 68.2            |
| March   | 30.0           | 60.0            | 66.7           | 100.0           |
| April   | –              | –               | 53.8           | 73.1            |
| May     | 100.0          | 100.0           | 89.5           | 100.0           |
| June    | 58.3           | 100.0           | 75.0           | 96.4            |
| July    | 91.3           | 100.0           | 50.0           | 92.3            |
| August  | 81.5           | 63.0            | 62.5           | 87.5            |
| September| 57.7         | 57.7            | 55.0           | 85.0            |
| October | 75.0           | 50.0            | 66.7           | 33.3            |
| November| –              | –               | 38.1           | 0.0             |
| December| 63.6           | 70.2            | 61.6           | 73.6            |

The mean percentage is 71.0 per cent, showing very good agreement between satellite data and ground-based observations. We can conclude that the satellite does not distinguish the calima event. Fig. 16 shows this result, where the monthly distribution of the fraction of clear nights is plotted using the TNG and CMT logbooks (dashed line) and GOES 12 (solid line). The agreement between the two plots is excellent, except for December.

The final step was to understand how many nights were clear for both ground and satellite data in this data base including nights affected by the calima. We found that 81.9 per cent of all clear nights are effectively clear for both GOES and ground data for 2007, and 80.3 per cent for 2008. We found a mean percentage of 81.1 per cent, compared with the previous mean of 80.7 per cent of clear nights not including the calima. It is evident that the percentages are similar and this is probably because of the low number of nights affected by the calima. We emphasize that the satellite selects clear nights without making assumptions about the transparency of the sky.

5.2 Mt Graham site

At Mt Graham, the total numbers of clear days analysed in the period 2002–2008 are 912 from the heliograph and 964 from GOES. The common number of clear days is 661, with a relative fraction of 72.0 per cent of common days versus the total number of clear days from the heliograph. Fig. 17 shows the monthly composite distribution of the monthly average fraction of clear nights computed from the heliograph data base, the TOMS–OMI satellite, GOES data taken at 17:45 and 02:45 UTC (10:45 and 19:45 local time, respectively), data from the Mt Graham site testing (Steward Observatory 1987) and the rain distribution derived from the Safford (Agriculture Center) data base. With the obvious exception of the Mt Graham site testing, all the data are from the period 2007–2008. There is general qualitative agreement among the different methods (the rainfall is clearly anticorrelated with the fraction of clear nights) with the heliograph data. A high peak in May is evident, as well as a sharp cut-off between May and June, and a secondary peak in summer. This trend is in very good agreement with the Kitt Peak logbooks of the photometric time fraction analysed by D. L. Crawford (Steward Observatory 1987; see also the data of usable time.
The GOES data are higher than the average of the other data in September and October and lower in May. While the fraction of usable time (44.5 per cent) is in agreement with the other methods, the distribution is clearly more noisy. The 1982–1983 site testing data are in very good agreement with the heliograph data, except during October–December where these data are much lower. On average, the site testing data are lowest. We recall that winter time in Arizona presents high variability, connected with the episodic invasions of storms coming from the north-west. The resulting yearly usable fraction is between 43.0 and 46.0 per cent. It should be noticed that the GOES data analysis from Erasmus & Sarazin (2002) at Mt Graham gives a usable fraction much higher than all our indicators (61.0 per cent clear and 60.0 per cent usable), in particular during the monsoon season. This suggests that the GOES data interpretation at Mt Graham presents some unresolved multiparametric problems and the results are very sensitive to data treatment. The difficulty in the quantitative interpretation of the GOES data is extensively discussed in the literature (Stowe et al. 1988; Jung et al. 2004; Khaiyer et al. 2004).

Fig. 18 shows the long-term yearly composite distribution of the fraction of clear nights computed using the heliograph data base, the TOMS (OMI, Earth Probe and Nimbus-7) satellite data, the GOES 8 and 12 data taken at 19:45 and 10:45 local time and the rain distribution derived from the Safford data base. It can be seen that the rain distribution is very well anticorrelated with the distribution of the clear time, in particular with the record of clear time in the data base of Nimbus-7. A major drop in the fraction of clear time occurred between 1982 and 1983, corresponding to a sharp rainfall peak. This was also the period of the Mt Graham site testing. According to the suggestion discussed in the site testing report, we confirm that the lower fraction reported (and discussed above) was a result of a climate fluctuation. A general trend with decreasing rainfall and increase of the fraction of clear time between 1980 and 2008 can also be seen. The year 2008 (in particular, the spring) was recorded in Arizona as one of the driest of the last fifty years.

6 CONCLUSION

We have presented a quantitative survey of cloud coverage at La Palma and Mt Graham using both ground and satellite data. In order to quantify the amount of clear nights, we used different data bases, in particular the end-of-night reports obtained at the TNG and LBT, the CMT extinction file for La Palma and the heliograph and rainfall data bases at Mt Graham. Satellite data are derived from GOES 12 at La Palma and GOES 8 and 12 at Mt Graham. A further check has been carried out for Mt Graham only using the TOMS family of satellites.

The analysis mainly addresses the years 2007 and 2008 but a long-term analysis is also reported for Mt Graham. The sample at La Palma is composed of 731 consecutive nights. After the cross-correlation with the extinction file, this is reduced to 365 nights. The analysis at Mt Graham is based on 912 days. The sample from the satellite is composed of 700 nights at La Palma and 964 at Mt Graham. A fixed threshold in the GOES infrared emissivity selects clear nights using satellite data. At La Palma, we have found that 62.6 per cent of the 365 sampled nights are selected as clear from ground data, and 71.9 per cent of the 365 nights are selected as clear from satellite data. Taking into account the common nights between ground and satellite data, we have found that 81.1 per cent of nights are selected as clear for both. This shows good agreement but indicates that about 19 per cent of clear nights from ground data are lost from satellite data. At Mt Graham, we have found good agreement between the Columbine heliograph data and the night-time observing log. In this case, the satellite found only 72.0 per cent of the total of clear days found by the heliograph.

Two relevant additional conclusions can be derived from the Mt Graham analysis, as follows.

(i) The rainfall trend at Safford can be used as a tracer of the night-time conditions at Mt Graham and possibly also in the whole Arizona area.

(ii) The limited day/night weather evolution at Mt Graham makes the results of a very simple device, such as the heliograph,
useful to monitor, with high accuracy, the local status of the nighttime clear sky.

In addition, at La Palma we can derive the following conclusions.

(i) It is possible to define a threshold in satellite emissivity to select clear nights with an uncertainty of 20 per cent.

(ii) A good correlation exists between the GOES 12 satellite and ground-based data.

(iii) Using the common selected nights, we found that 80.7 per cent are classified clear by both the GOES 12 satellite and the ground logbook.

(iv) The marginal increase to 81.1 per cent of the concordance obtained including calima events confirms that the satellite is able to distinguish only the presence of clouds.

A further analysis of the satellite data (e.g. a wider field, the simultaneous use of different of different channels, etc.) is suggested to improve the prediction of clear nights. Furthermore, we are studying the fraction of clear nights lost because of high humidity or strong wind.

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