Remote sensing of precipitable water vapour and cloud cover for site selection of the European Extremely Large Telescope (E-ELT) using MERIS

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ABSTRACT

Remotely sensed data can be of great interest for the site selection of astronomical observatories. In particular, candidate sites of the future European Extremely Large Telescope (E-ELT) of 30-60 m diameter from ESO need to be assessed and analytically compared in their observing characteristics. Parameters such as cloud cover and precipitable water vapor which are important for optical and infrared astronomical observations have been assessed with the MEdium Resolution Imaging Spectrometer (MERIS) instrument on the Envisat satellite with a resolution of 1km pixel. A validation of the data was made by comparing MERIS data and in situ measurement available from ESO observatories in Chile, La Silla and Paranal, combined with lower resolution values from the GOES weather satellite. A detailed analysis of daytime cloud cover from 2002 to 2006 at four sites under study both in the northern and in the southern hemisphere for the E-ELT is presented.

Keywords: Cloud cover, Water vapour, Site survey, telescope, MERIS

1. INTRODUCTION

The **European Extremely Large Telescope** (**E-ELT**) is a project for the next-generation optical telescopes by the European Southern Observatory with a mirror diameter of 42 meters. Current fabrication technology limits single mirrors to being roughly 8 meters in a single piece. The next-largest telescopes currently in use are the Gran Telescopio Canarias and Southern African Large Telescope, which each use hexagonal mirrors fitted together to make a mirror more than 10 meters across. The E-ELT would need to use a similar design. In addition, E-ELT would also need to use techniques to work around atmospheric distortion of incoming light, known as adaptive optics. Project E-ELT has the aim of observing the Universe in greater detail than even the Hubble Space Telescope. A mirror of approximately 42 meters would allow the study of the atmospheres of extrasolar planets. The 5-mirror anastigmat design is estimated to cost €800 million and could be completed by 2017.

The location of the biggest telescope ever built has yet to be defined and plays a crucial role for the performance of the instrument. ESO conducts a systematic approach on site comparison and among others; we investigate the usefulness of medium resolution polar satellites to estimate parameters such as cloud cover and precipitable water vapour at selected candidate sites. In order to avoid atmospheric turbulences, observatories are often located on high sites in mountainous regions. A resolution of about 1km is therefore an interesting asset in these regions where climatological conditions change rapidly with the local orography. The MEdium Resolution Imaging Spectrometer (MERIS) instrument on the Envisat satellite from ESA was considered as a potential source of data for this purpose. First, a verification between MERIS data and the data used by ESO in the past years was made. This ESO data stems from a combination of in-situ measurements and GOES satellite images with a lower resolution than MERIS. The period of the comparison is from 2002 to 2006 which corresponds to the availability of MERIS data and the location where the verification took place are the two observatories La Silla and Paranal where ESO collects data every 3 hours for years now. Second, an analysis on an application on site testing was conducted where the 14.30 UTC MERIS data was compared to GOES night data, this lead to an evaluation of the error done between night and day measurement for both cloud cover and PWV. Third the impact of window size was analyzed on a coarse terrain and finally four candidate sites - Aklim in Morocco, Roque de los muchachos on the Canary Islands in Spain, Macon in the Argentinean Andes and Paranal in Chile where ESO's very large telescope is already operational - were compared with the MERIS data set at a resolution of 1km.

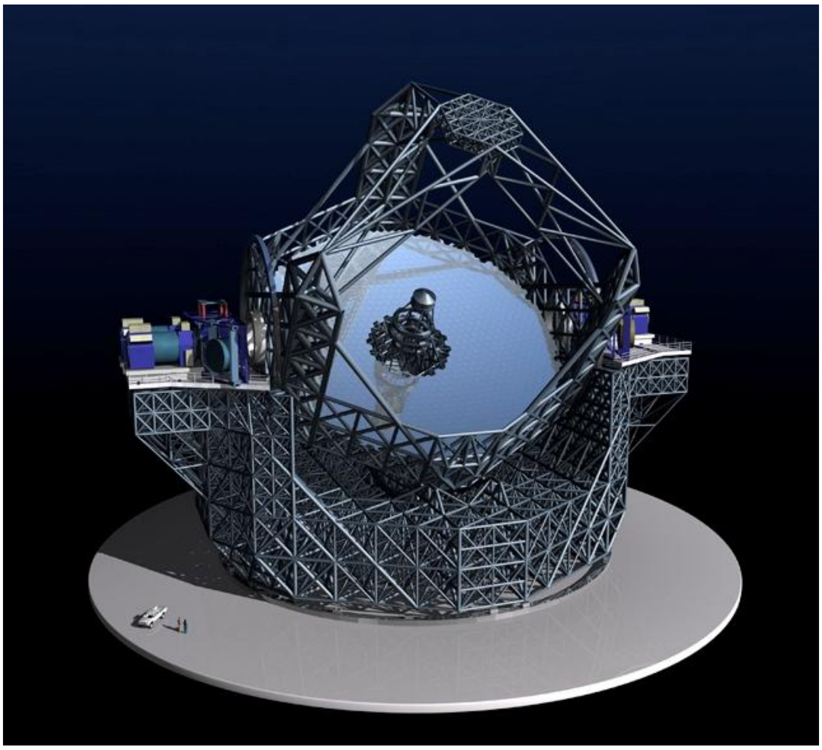

Fig. 1. 42m Diameter E-ELT design (http://www.eso.org/projects/e-elt/)

2. VERIFICATION OF MERIS DATA

2.1 MERIS data

MERIS is a passive imaging spectrometer that looks in the nadir direction. It performs simultaneously spatial and spectral imaging of the Earth, it is one of the main instruments on-board the European Space Agency (ESA)'s Envisat platform.The spatial resolution of the detectors provides for samples every 300 m this is known as the 'Full Resolution (FR)' product. In this study the Reduced Resolution was used 1,2 km by 1,2 km. The total field of view of MERIS is 68.5 degrees around nadir (yielding a swath width of 1150 km), which is enough to collect data for the entire earth every 3 days (in equatorial regions). Polar regions are visited more frequently due to the convergence of orbits. The observation is performed simultaneously in 15 programmable spectral bands, ranging from the visible to the near infrared (390 nm to 1040 nm). Each of these 15 bands is programmable in position and in width. The water vapor retrieval algorithms for MERIS are based on the work of Bartsch, (1996) and Bartsch et al. (1997). The general algorithm approach is to relate the PWV content to the ratio of MERIS channels 14 and 15, located at 890 nm and 900 nm, respectively (Fisher, 1997).

The cloud albedo and cloud optical thickness are estimated from measurements of the MERIS channel centered at 753.75nm. An algorithm is established to transform the radiance measurements into hemispherical quantities by integration over viewing angles, since clouds do not reflect the sunlight isotropically.

2.2 GOES data

In order to make a verification of the MERIS data, measurements of cloud cover and PWV are derived from a combination of satellite observations made by passive remote sensing at ±10.7μm and ±6.5μm from the satellite GOES and in situ measurements of temperature and humidity at the observatories La Silla and Paranal. Satellite observations at about 6.5µm are sensitive to emissions from WV resident in the layer between about 600mb (±4400m) and 300mb (±9000m). If high altitude (cirrus) clouds exist above this layer their presence and thickness can be determined. The other channel is used to detect clouds at middle level. Low levels clouds, with a cloud top temperature comparable to the ground conditions, are difficult to detect with this method. The analysis can be performed for a specific site or an area of interest. Above a particular location, a more realistic picture of "the observable sky" is obtained using a 9 (3×3)-pixel area of 12x12 km. For the area analysis the 9-pixel template is passed over the area of interest, counts compiled and contours drawn. For a detailed description of the methodology employed in the above mentioned studies please consult Erasmus & Sarazin (2000), Erasmus & Sarazin (2002).

2.3 Time resolution

In order to be able to use MERIS data, a verification process was established where the results of the GOES analysis described previously were compared to the MERIS output. The MERIS overfly time of the region in Chile were both observatories La Silla and Paranal are located is varying between 13.50 and 14.50 UTC every two or three days. The GOES measurement have a much higher time resolution of every 3 hours. The MERIS data was compared to the GOES measurement of the corresponding day at 15.00 UTC. Unfortunately for optical and IR astronomy this measurement time is only during the day and therefore one has to be careful with the interpretation of MERIS data for site selection since it does not contain any data during the night.

2.4 Cloud cover

The cloud cover GOES measurements are done on a window size of 12km square while MERIS resolution is 1 km. Therefore MERIS data were combined out of a 12 x 12 pixel square and compared with the GOES data in order to have an identical window size. The 12 km window on top of the observatories corresponds to a viewing angle of 67 degrees for clouds at 3km above ground. Fractional cloud cover over la Silla and Paranal observatories obtained with the two methods between April 2002 and August 2006 were compared. The following tables show the percentage of the measurement where both methods agree or not. The results are classified in three categories hit, neutral and miss defined as follows,

Hit: x< 25%

Neutral; 25%<x<50%

Miss: 50%<x

Where x is the difference between both measurements.

Table 1 Percentage of the agreement of GOES data and MERIS data for cloud cover analysis. Window size 12km x 12km. Hit, neutral and miss are defined as Hit: x< 25%, Neutral; 25%<x<50% Miss: 50%<x where x is the difference between both measurements.

Paranal clear fraction: MERIS 93%, GOES 96%		
Hit	453	98%
Neutral	5	1%
Miss	5	1%
Sum	463	100%

La Silla clear fraction: MERIS 85%, GOES 80%		
Hit	430	93%
Neutral	16	3%
Miss	17	4%
Sum	463	100%

Table 1 shows that for cloud cover measurements both methods have similar results within +/-5% . The scatter increases with cloudiness.

2.5 Precipitable water vapor

For the water vapor, instead of using 12 km window size as for the cloud cover, a more sensible comparison of both data sets is to use a window size of 2 km which corresponds to the area just above the observatory. If we would use an equivalent 12 km window size with MERIS we would end up with water vapour values of regions below the observatory. The GOES measurements combined with the pressure and temperature are described in detail in Erasmus & Sarazin (2002).

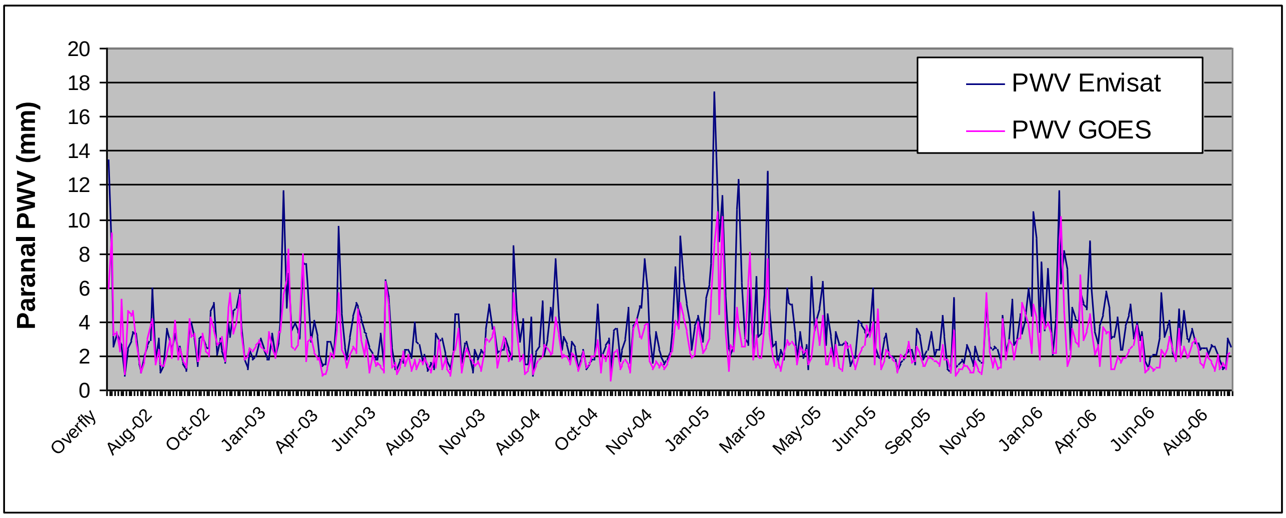

Fig. 2. Comparison of GOES and MERIS measurements of PWV on Paranal between 2002 and 2006. MERIS Window size is 2km x 2km. The GOES and MERIS measurements are qualitatively very similar. However MERIS is often measuring slightly higher values during humid events. For color graph, please refer to electronic format.

Paranal PWV (mm)	10%	50%	90%
GOES 15 h	0.52	2.88	5.26
MERIS	0.9	3.46	6.07

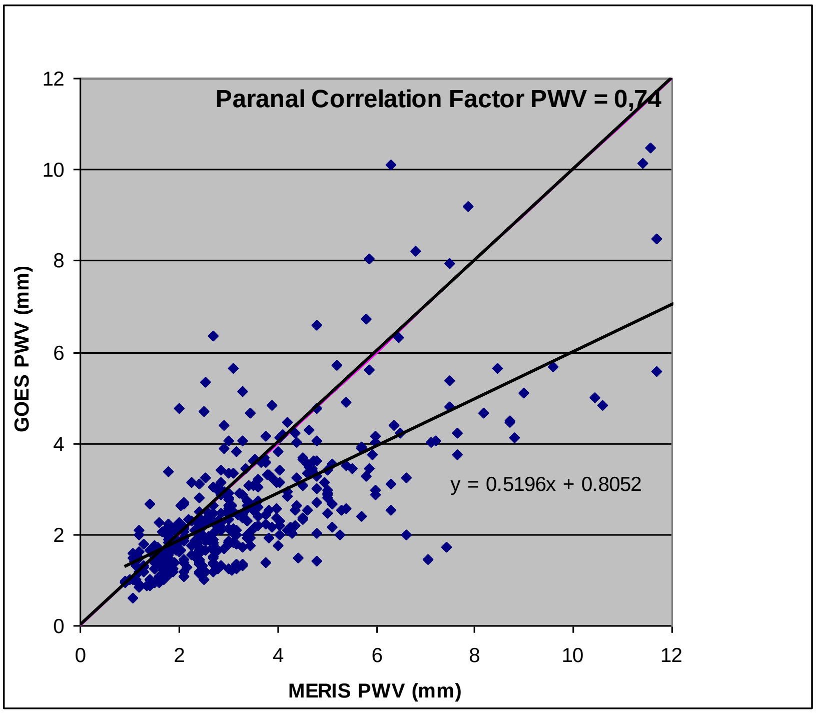

Fig. 3. Correlation between GOES and MERIS measurements of PWV on Paranal between 2002 and 2006. MERIS Window size is 2km x 2km.

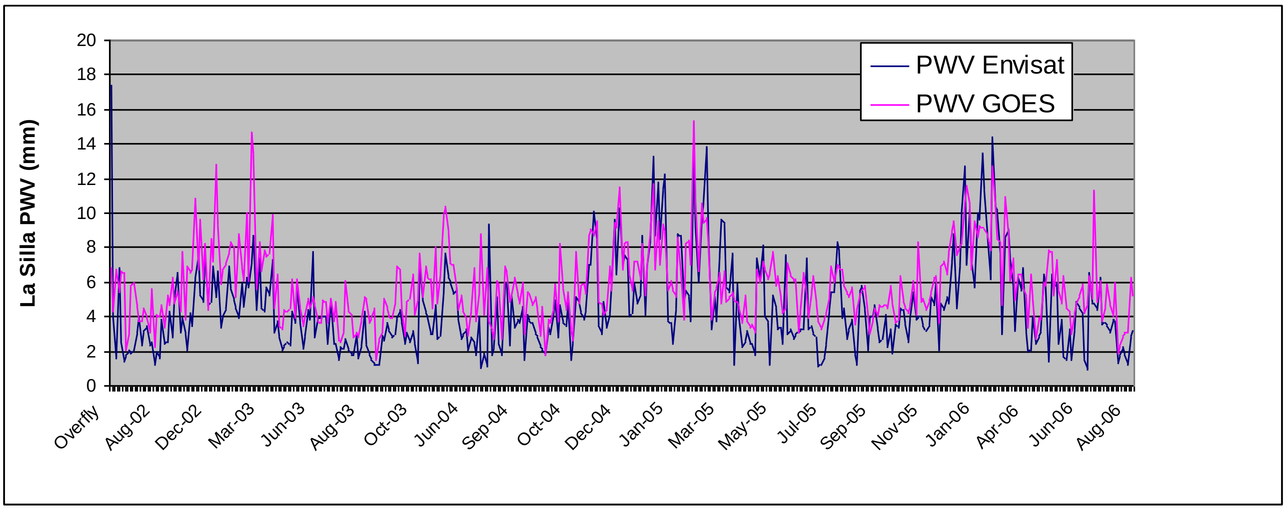

Fig. 4. Comparison of GOES and MERIS measurements of PWV on La Silla between 2002 and 2006. MERIS Window size is 2km x 2km. The GOES measurements seem to fit pretty well the MERIS measurement. As opposed to the Paranal situation GOES measurement are higher than the MERIS ones. For color graph, please refer to electronic format.

La Silla PWV (mm)	10%	50%	90%
GOES 15h	2.91	6.02	9.15
MERIS	1.2	4.52	8.17

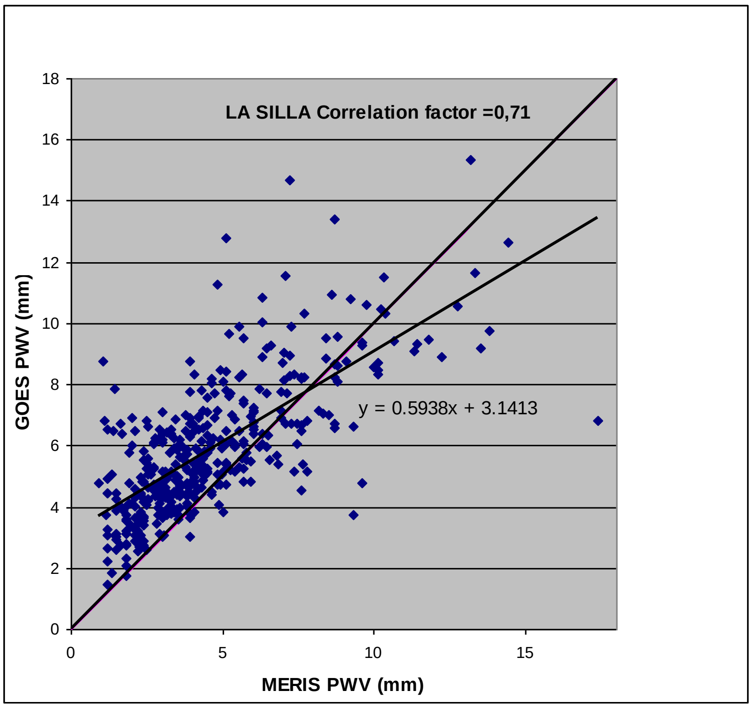

Fig. 5. Correlation between GOES and MERIS measurements of PWV on LA SILLA between 2002 and 2006. MERIS Window size is 2km x 2km. A significative offset of 1.5 mm can be noticed for the GOES measurement especially in the lower PWV values.

3. APPLICATION ON SITE TESTING

3.1 Usefulness of MERIS daytime measurement for the assessment of nighttime quality

What counts for an optical telescope is the amount of clear night where scientists are able to observe, the verification of the MERIS data has been done with data taken from both satellites at the same time. Now in order to estimate the misinterpretation we could do by using MERIS we compare the 3-hourly GOES night data with the MERIS day data taken around 14 UT. First, a cloud cover analysis is being done with a window size of 12 km x 12 km and second, PWV is statistically analysed with a window size of 2 km.

Table 2. Comparison between GOES and MERIS amounts of clear nights that would be interpreted with both satellites. Clear nights are defined as 100% free of cloud. MERIS Window size is 12km x 12km. GOES measurements are taken during the night as opposed to MERIS that always measures around 14 UTC. Time period is between 2002 and 2006.

Number of clear nights	Paranal	La Silla
GOES Fraction of clear nights	93%	75%
GOES Fraction of clear sky measurements at 15 UT	93%	80%
MERIS Fraction of clear sky around 14 UC	96%	85%

On both Chilean sites MERIS satellite is more optimistic than GOES, with up to 10% error at La Silla. The difference between night or day seem to be different from site to site. Interpretation of clear night should be taken with care using MERIS data.

Paranal PWV (mm)	10%	50%	90%
GOES night	0.86	2.88	4.91
GOES 15 h	0.52	2.88	5.26
MERIS	0.9	3.46	6.07

La Silla PWV (mm)	10%	50%	90%
GOES night	3.54	6.77	10.02
GOES 15h	2.91	6.02	9.15
MERIS	1.2	4.52	8.17

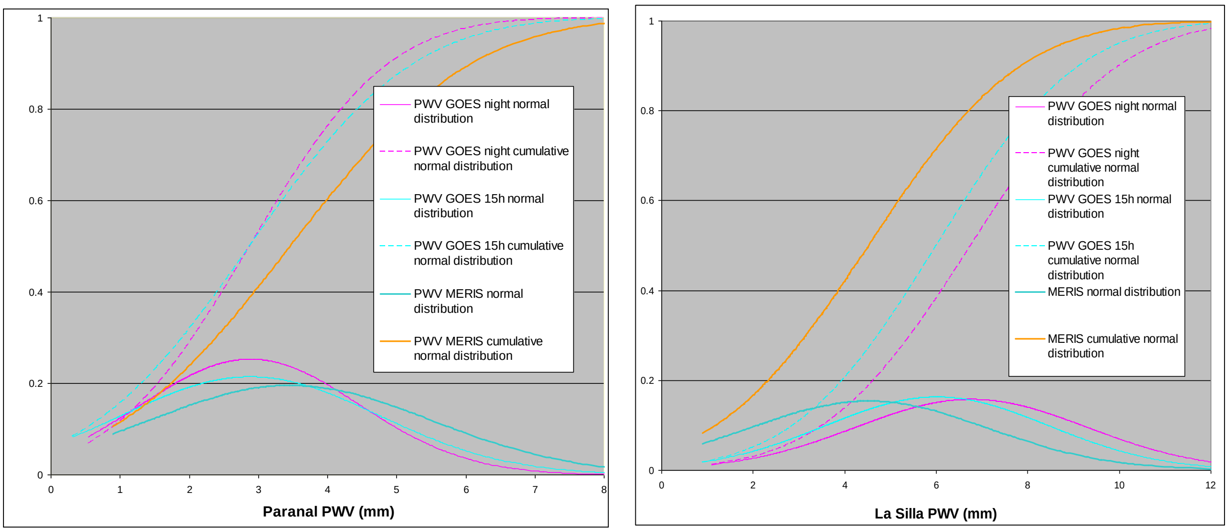

Fig. 6. Comparison of the normal distribution of both GOES during day, during the night and MERIS measurements of PWV in Paranal and La Silla. Window size is 2km x 2km. For the water vapour the difference between night and day of the two GOES measurements is below 0.8. Time period is between 2002 and 2006. For color graph, please refer to electronic format.

3.2 Influence of window size over sites with variable orography

The main reason to use MERIS instead of GOES is the possibility to analyze cloud cover and PWV with a better resolution. Since observatories are often located on high sites, the coarse mountainous terrain presents rapidly changing climate around the sites. It is therefore of great interest to analyze how cloud cover and PWV values are altered by changing the window size. For this analysis we chose the site Roque de Los Muchachos on La Palma, Canary island (Spain) which presents these coarse geographical features. Figure 8 shows the Output of the Earth Observation Grid Processing-on-Demand from ESA/ESRIN tool to extract MERIS data. The white pixel shows clouds and the green ones correspond to clear sky. This image is characteristic of the island where the clouds are often located under the summit where the observation site would be located. In this case the measurement would be classified as clear night for a small window size such as 1 km and as non-clear night if the window size is 12 km .Table 5 indicates the huge difference in fraction of clear days by changing the window size. Although there is another effect that has to be taken into account, by increasing the window size we also increase the probability to have a cloud in the field of view.

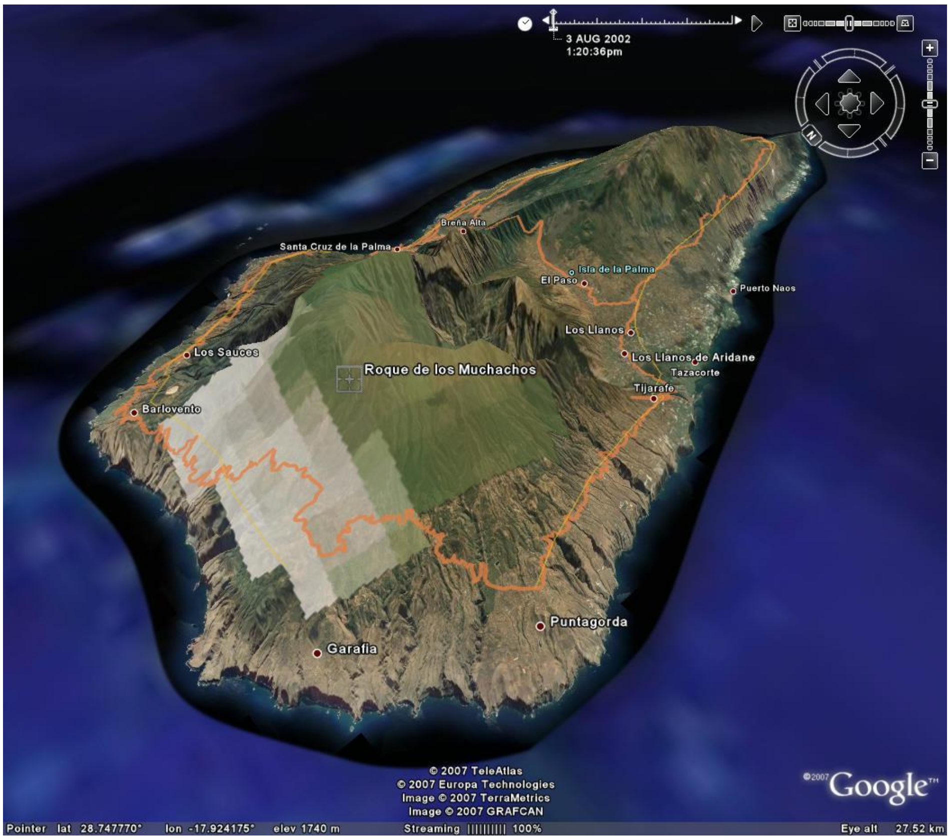

Fig. 7. Output of the Earth Observation Grid Processing-on-Demand from ESA/ESRIN tool to extract MERIS data. The figure shows La Palma Island with Roque de los Muchachos on top of the Volcano. The white pixels correspond to clouds and the green ones to clear sky. This situation is common on La Palma because the temperature inversion resides below the summit. Window Size is 12 x 12 km and the Pixel size is 1 km. For color graph, please refer to electronic format. Time period is between 2002 and 2006.

Table 3. Comparison of the fraction of clear days that would be interpreted with a window size respectively of 1 km and 12 km with MERIS data. The difference is substantial.

Window Size Influence		
Window size	1km	12km
Fraction of clear days	65%	27%

4. COMPARATIVE SITE ANALYSIS

Figure 8 shows the location of four of the candidate sites for the E-ELT. In this paragraph we compare cloud cover and PWV at all four sites with the MERIS data set.

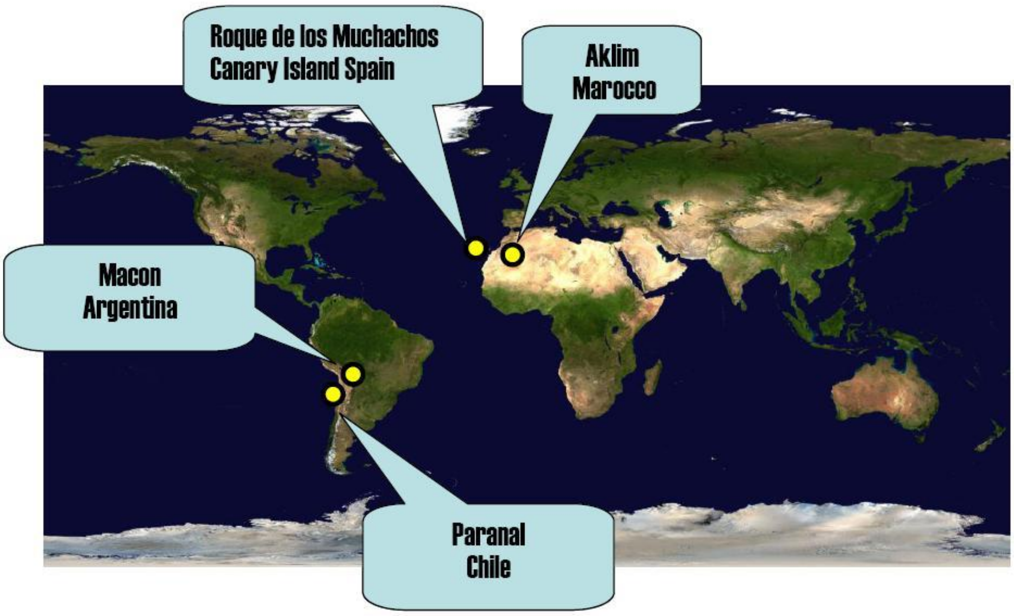

Fig. 8. Location of four candidate sites for the E-ELT.

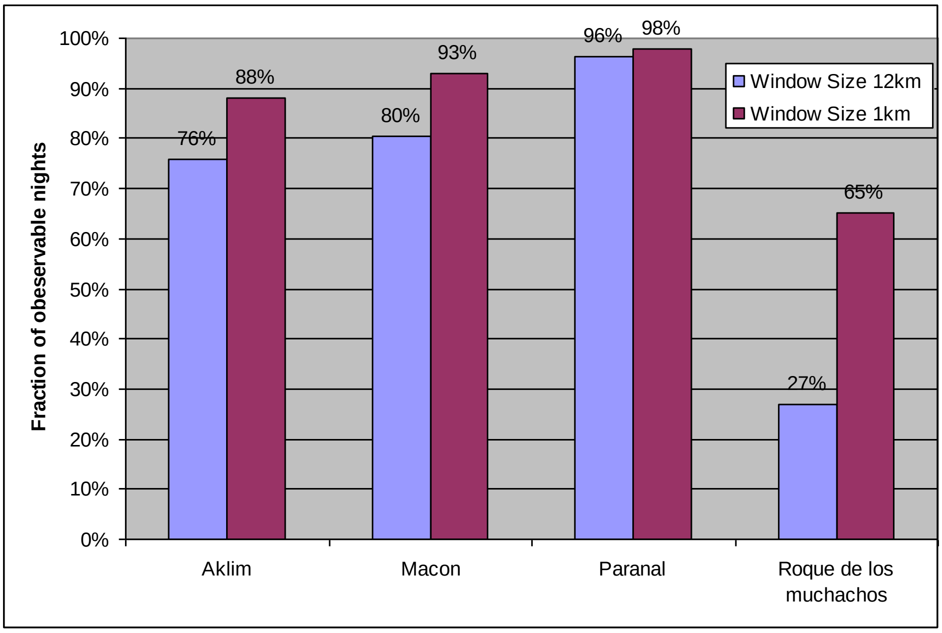

Fig. 9. Comparison of clear nights for four E-ELT candidate sites. The interpreted fraction of clear nights has to be taken carefully since MERIS measurements just occur during day time and not at night. Especially Roque de los Muchachos presents a big difference in cloud cover between night and day. MERIS window size is 12 x 12 km and 1x 1 km. Time period is between 2002 and 2006. For color graph, please refer to electronic format.

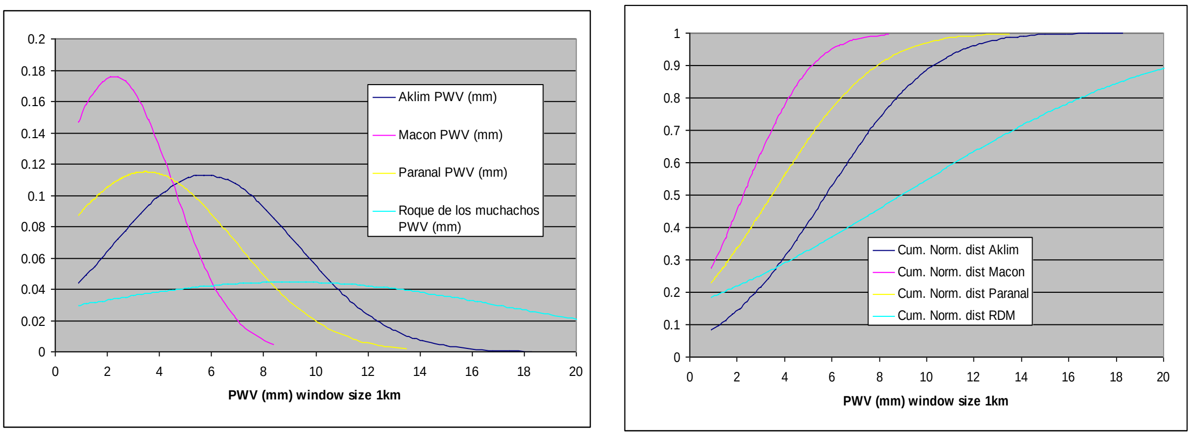

Fig. 10. Comparison of the PWV at four E-ELT candidate sites. The graphs show the normal distribution and the cumulative normal distribution of all four sites. The MERIS Measurements are done with a window size of 1km. Time period is between 2002 and 2006. For color graph, please refer to electronic format.

5. CONCLUSION

Analysis of PWV and cloud cover has shown that MERIS is a powerful tool that can be useful for the site selection process of the E-ELT. The MERIS resolution of 1 km is necessary for some sites where the coarse terrain leads to large changes in climate over small distances. Nevertheless the lack of night data leads to some serious disadvantages for cloud cover estimations over the geostationary satellites such as GOES which has a time resolution of every three hour including night time. All cloud cover results have to be taken carefully since the night climate conditions could be totally different or not. MERIS seems to work well for PWV values which do not present a high difference during the night or during the day. An accurate and systematic analysis of the candidate site should comprise different methods including in situ measurements, geostationary satellites and polar satellites for the better resolution.

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