Chapter

ON THE USE OF REMOTELY SENSED DATA FOR ASTRONOMICAL SITE CHARACTERIZATION

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Abstract

This work concerns to the compilation of the key parameters retrieved from remote sensing techniques and climate diagnostic archives for astronomical site characterization and for selecting the best sites for hosting the future extremely large telescopes. Atmospheric extinction is the astronomical parameter that determines transparency of the sky. Extinction is associated with the absorption/scattering of incoming photons by the Earth's atmosphere. Sources of sky transparency degradation are clouds and aerosols (dust particles included). The precipitable water vapour (PWV) content is also an important source of opacity in the infrared spectral region, reducing the transmission in several atmospheric infrared windows and producing absorption bands in the spectra of astronomical sources observed from telescopes, therefore PWV is demanded to optimaze the scientific output of astronomical instruments working in the infrared spectral range. Recent works ([Varela et al.2008], [Bounhir2009]) have explored the useful of satellites platforms to retrieve parameters of astronomical interest such as the aerosol content, the cloud coverage, PWV and other related to the atmospheric turbulence (troposphere winds) and climatic trend . These data need to be critically considered and interpreted in accordance with the spatial resolution and spectroscopic channels used and complemented with those provided by in situ instruments.

Key Words: Site-testing-Optical-Infrared, atmospheric aerosol, clouds, troposphere winds, water vapour; remote sensing.

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1. Introduction

In this new era of design of a new generation of very large telescopes (larger than 25m), the site selection is a fundamental issue due to the very huge costs related to the construction and maintenance, but also ir order to optimize the useful observing time. In September 2003, during the 2nd Backskog Workshop on Extremely Large Telescopes (ELT), Sweden, the scientif community defined the key parameters for selecting the best site for hosting an ELT. A set of parameters is related with the optical atmospheric turbulence and wind profiles, other one is related to the climatology (cloudiness, water vapour content, sodium layer, dust, etc.), and the third set are parameters are related to the ground deformation, sesimicity, condensation trails, etc. ([Muñoz-Tuñón et al.2010] and [Schock2004]).

This paper presents new approaches to the study of the properties of astronomical sites. In particular, satellite data and climate diagnostics archives have recently been proposed as useful tools for astronomical site evaluation. Nevertheless, data need to be critically considered and interpreted in accordance with the spatial resolution and spectroscopic channels used. The main problem to use these values is their interpretation and their quantitative calibration. Data analysis need to be complemented with those provided by in situ instruments (telescopes, photometers, airborne particles counters, ground meteorological stations, etc.).

The Roque de los Muchachos Observatory (ORM) at La Palma island (Spain) is one of the best characterized astronomical sites of the world. In situ measurements at ORM has been used in this paper for comparing remote sensing and *in situ* techniques.

In Section 2 we discuss the usefulness of aerosol data retrieved from satellites for astronomical characterization. As a result, we find that aerosol data provided by satellites up to now are not reliable enough for aerosol site characterization, and *in situ* data are required.

In addition, from satellites it is possible to go back at the cloud cover, water vapour content, the climatic trend and troposphere winds.

In Section 3 we discuss the usefulness of satellite data for determining the cloud cover and related parameters (useful time) at the astronomical sites.

The climate diagnostics archives combine world-wide long-term climatological variables, including meteorological data from radiosondes and satellites, with sophisticated models to derive the parameters used to study climate conditions and evolution at a particular site or globally. To illustrate the applicability of data from climate diagnostic archives to astronomical site evaluation, a detailed study of the wind vertical profile at five astronomical sites is performed in Section 4.

The water vapour content is a crucial parameter for infrared (IR) astronomical site characterization. A summary of PWV statistical results at different astronomical sites is presented in Section 5, recalling that these values are not directly comparable as a result of the different techniques used to recorded the data.

Conclusions are summarized in Section 6.

2. On the Use of Satellites for Aerosol Content

The presence of aerosols -in particular, the mineral dust- is directly related to the atmospheric extinction. In 2004 satellite data measuring aerosols have been proposed as a useful technique for site characterization and searching for new sites to host future very large telescopes. Nevertheless, these data need to be critically considered and interpreted in accordance with the spatial resolution and spectroscopic channels used. Recent works ([Varela et al.2008], [Bounhir2009], and references therein) have explored and retrieved measurements from satellites with high spatial and temporal resolutions and concentrated on channels of astronomical interest. Satellite data retrieved from satellites need to be complemented with those provided by in situ instruments (telescopes, photometers, airborne particles counters, ground meteorological stations, etc.). A comparison of remote sensing and *in situ* techniques is summarized in this section.

The selected NASA's satellite platforms datasets are Earth–Probe/TOMS, Aura/OMI, Terra/MODIS and Aqua/MODIS. Ground measurements includes nighttime photometry (atmospheric extinction coefficient, KV) provided by the Automatic Transit Circle (ATC) – formerly known as Carlsberg Automatic Meridian Circle (CAMC) – at the ORM – 2400m above sea level.

As a result, we find that aerosol data provided by satellites up to now are not reliable enough for aerosol site characterization, and *in situ* data are still required.

2.1. Sky transparency and atmospheric extinction coefficient

Atmospheric extinction is the astronomical parameter that determines transparency of the sky. Extinction is associated with the absorption/scattering of incoming photons by the Earth's atmosphere and is characterized by the extinction coefficient, K. Sources of sky transparency degradation are clouds (water vapour) and aerosols (dust particles included). This coefficient is wavelength-dependent and can be determined by making observations of a star at different airmasses. For details of the astronomical technique for deriving the extinction coefficient values we refer the reader to [King1985].

Long baseline extinction values for the ORM have been measured continously at the Automatic Transit Circle (ATC, http://www.ast.cam.ac.uk/$\tilde{d}$we/SRF/ATC_extinction.html), in the V band (550 nm) and from april 1999 in the Sloan r' band (625 nm). Recent statistical of database spanning more than 20 yr at the ORM has been performed by [García-Gil et al.2010]. To our knowledge, this is the largest available homogeneous database for an observing site. The threshold that identifies the presence of dust is at KV =0.153 mag/airmass ([García-Gil et al.2010]).

Nevertheless, a dedicated telescope as the ATC is not always available in other existing or potential astronomical sites of the world, and in these cases, other parameters such as the aerosol index (AI) and aerosol optical depth (AOD) (or thickness) from satellites are provided as a possible tool for aerosol content monitoring.

The advantages of the use of satellite data archives are mainly that the analysed sites can be reliably compared and permit a comparison over reasonably long time period (larger than five years). Another advantage is the temporal sampling, e.g. the use of geostationary satellites give high temporal resolution.

2.2. Comparison of AI provided by EP/TOMS and Aura/OMI with in situ measurements

In this section we shall summarize the results of comparing the atmospheric extinction coefficient with the aerosol index provided by TOMS (Total Ozone Mapping Spectrograph) on board NASA's Earth Probe satellite and by OMI (Ozone Monitoring Instrument) on board NASA's Aura satellite.

In situ measurements used for comparisons are KV provided by the ATC and AOD provided by AERONET instruments.

AERONET (AErosol RObotic NETwork) is an optical ground based aerosol monitoring network and data archive supported by NASA's Earth Observing System and expanded by federation with many non-NASA institutions (http://gcmd.nasa.gov/records/GCMD_AERONET_NASA.html).

2.2.1. AI from TOMS vs KV

TOMS Level 3 data are gridded in squares of $1^\circ \times 1.25^\circ$ (latitude and longitude respectively) and are available online at ftp://toms.gsfc.nasa.gov/pub/eptoms/data/aerosol/. The temporal resolution is daily.

In Figure 5 in [Varela et al.2008] we represent the atmospheric extinction in the V band (KV) provided by the ATC against the aerosol index provided by EP/TOMS from 1996 to 2004 at the ORM. The whole period extends till 2005, but the last months EP data are not included since the instrument experienced some calibrating problems (http://jwocky.gsfc.nasa.gov/eptoms/ep.html). Data from 2004 will be retrieved from OMI (see next subsection). The threshold that indicates the presence of dust in the atmosphere is KV > 0.15 ([García-Gil et al.2010]) and AI > 0.7 ([Siherbet al.2004]).

There exist a large number of TOMS data indicating the presence of absorbing aerosols coincident with ATC values that show low or no atmospheric extinction This result is due to the presence of a layer of dust below the Observatory level. This dust layer is high and/or thick enough to be detected by the TOMS. This condition appears in 17% of all cases.

The case of agreement between large extinction coefficient and large AI is associated with dust presence in the upper troposphere layer (TL). We have verified that this case occurs in only 11% of all measurements, with 58% of these corresponding to the summer months (June–September), when the warmest surface winds sweep dust from the African continent and rise towards the upper layers by convective processes.

The opposite case, *i.e.*, low extinction coefficient and low aerosol index happens in 59% of cases.

The possible explanations of the lack of correlation are:

- The TOMS Level 3 data considered in this paper have a resolution of $1^\circ \times 1.25^\circ$, i.e. 111km x 139km, so the AI is averaged over areas whose size covers the entire islands of La Palma and Tenerife. High resolution Level 2 data should be used for a better fit (Instantaneous Field of View -IFOV- of 35 km $\times$ 35 km).
- The TOMS is very sensitive to the presence of highly reflective clouds because it uses channels centred on the UV to measure AI. Moreover, AI incorporates absorbing particles in ranges that do not affect atmospheric transparency in the visible range.

- A large part of the TOMS pixel over La Palma island is dominated by low altitude terrain and by sea surface, mostly below the thermal inversion layer (1000m-1500m a.s.l.- which plays an important role on the retention of aerosols below the level of the Observatory (2400m a.s.l.).
- TOMS measurements are retrieved at local noon while ATC values are averaged over night hours.

This lack of correlation is consistent with that provided by [Romero & Cuevas2002] comparing the AI provided by TOMS and the daytime Aerosol Optical Depth (AOD) recorded by a multi–filter rotating shadow band and radiometer (MFRSR) installed at the Izaa Atmospheric Observatory (OAI) at Tenerife island, at 2400m a.s.l. and 80km distant to the ORM. Therefore it seems that the main cause of such non-correlation is focused on the lack of spatial resolution.

For this reason the EP/TOMS database is not useful for the characterization of the presence of dust above either the Canarian astronomical observatories (2400 m above mean sea level) or for other high mountain sites (Mauna Kea and San Pedro Mártir) ([Varela et al.2007]).

The accuracy of the AOD over land retrieved by TOMS comparing to ground-based AERONET values is widely discussed by [Torres et al.(2002)]. The difference is 30% and 20% for absorbing and non-absorbing aerosols espectively, pointing to the cloud contamination and to the coarse resolution of the TOMS product as the main sources of error.

In order to obtain the best possible spatial and vertical resolution assuring that the retrieved data fields in remote sensing from different satellites (as aerosol values or geolocation parameters) are precisely over the ORM site coordinates to compare with the atmospheric extinction by ATC. For this reason, the parameters which have conditioned our choice are:

1. Large spatial resolution
2. Good vertical resolution
3. Near Ultraviolet, Optical and Near Infrared channels
4. Long-term database

2.2.2. AI from OMI vs KV

We have explored the use of other detectors on board different satellites that operate in bands of astronomical interest (the visible and NIR) and with better spatial resolution than TOMS. The selected parameters were the aerosol index provided by Aura/OMI—with visible and ultraviolet channels and with a spatial resolution from 13 km $\times$ 24 km to 24 km $\times$ 48 km–. In order ot obtain the best spatial, spectral, radiometric and temporal resolutions, we have decided to work only with Level 2 data that have the same resolution as the IFOV satellite.

OMI on the EOS (Earth observing Systems) Aura platform continues the TOMS record. OMI data derive from better horizontal and vertical spatial resolution compared with its predecessor, TOMS in Earth Probe. Data retrieved range from 2004 to 2006.

In Figure 11 in [Varela et al.2008] we compare KV provided by the ATC against AI provided by Aura/OMI. We conclude that the OMI instrument detects aerosol presence with more precision than TOMS and does not detect non-absorbing particles with high atmospheric extinction values (larger than 0.15 mag/airmass). This fact coincides with expectations because non-absorbing aerosols such as sulphates or marine aerosols do not give high extinction values (threshold greater than 0.15 mag/airmass). We can see that most of points fall at lower extinction values below the threshold for dusty nights, suggesting presence of non-absorbing or weakly absorbing (e.g. carbonaceous) aerosols.

In order to obtain the limits for dusty episodes on the AOD scale, we have checked the *calima* days from the records of the Instituto Nacional de Meteorología de Canarias Occidental, following Navy Aerosol Analysis and Prediction System (NAAPS), Centre on Insular Dynamics/Dust Regional Atmospheric Model (ICoD/DREAM) or SKIRON (developed by the Atmospheric Modeling & Weather Forecasting Group og Athens University) models for dust forecasting, dust concentration near ground and deposition of African dust at North Atlantic, including Canary Islands, and we obtain a threshold near AOD$>$0.1 units and AI$>$0.6 for dusty episodes.

We study where the *calima* events and cloud presence fall in the plot of correlation between atmospheric extinction and AI. Dust episodes measured at ground level are mainly below the threshold for dusty nights on the atmospheric extinction scale (KV$<$0.15 mag/airmass), meaning that the presence of *calima* affects low altitudes, and that only in a few cases does it reach the Observatory.

This lack of correlation has been recently confirmed by [Bounhir2009] when comparing the *in situ* aerosol optical depth measured by AERONET at Izaña versus the aerosol index provided by Aura/OMI and EP/TOMS. This comparison yields a yearly correlation of 0.88 and 0.60 respectively, with strong seasonal behaviour (larger correlation in spring and summer as it is expected).

This comparison have been also performed at Dakhla, Marrakech and Santa Cruz of Tenerife, yielding a correlation coefficient that ranges from 0.53 and 0.85 ([Bounhir2009]).

2.3. Comparison of the AOD by Terra/MODIS, Aqua/MODIS and Terra/MISR

We explored the use of the aerosol optical depth (AOD) provided by Terra (from 2000 to 2006) and Aqua (from 2002 to 2006) in MODIS—with its 36 spectral bands, from 0.47 to 14.24 μm, including two new channels at 0.405 and 0.550 μm, with a spatial resolution of 10 km $\times$ 10 km. In order ot obtain the best spatial, spectral, radiometric and temporal resolutions, we decided to work only with Level 2 data that have the same resolution as the IFOV satellite.

In Figures 12 and 13 in [Varela et al.2008] we shown AOD measured by MODIS on board Terra and Aqua against KV.

In both plots we distinguised among the terrestrial aerosols -mixed, dust, smoke and sulphate-, marine aerols -salts- and we marked the episodes of African dust instrusions over Canry Islandas at ground level. The majority of points that fall under the threshold of KV smaller than 0.15 correspond to AOD values lower than 0.2, i.e. non-absorbing (< 0.1) or weakly absorbing aerosols (marine particles, clouds above ocean and mixed scenarios with salt, sulphate particles and clouds). Most of situations of AOD larger than 0.2 correspond to dust episodes below the level of the Observatory.

The Fig. 1 from [Bounhir2009] shows the mean atmospheric extinction coefficent

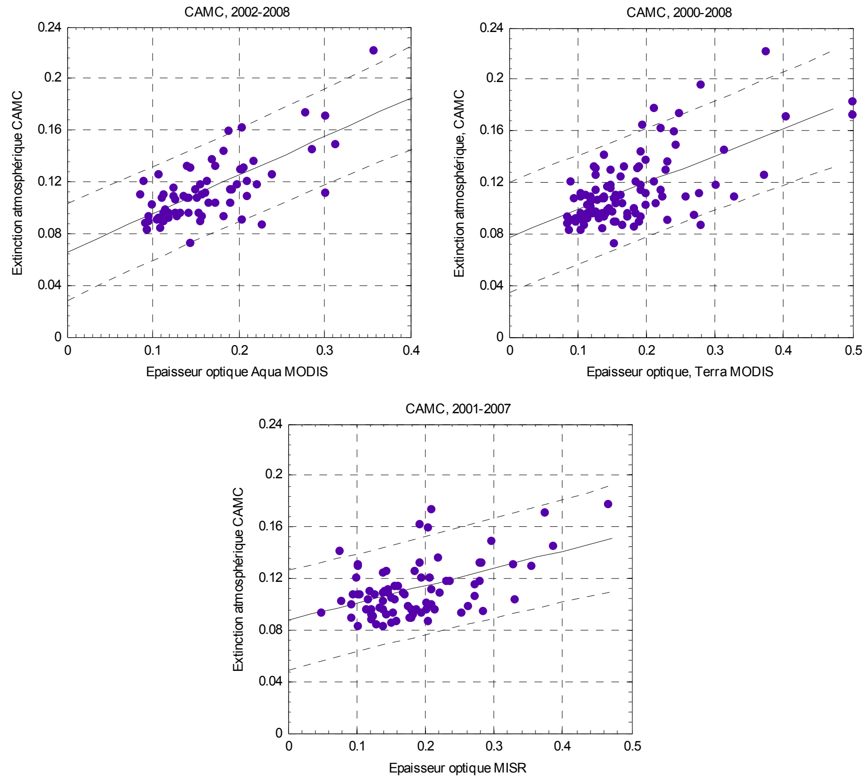

Figure 1. Correlation between monthly mean AOD provided by Aqua/MODIS, Terra/MODIS, Terra/MISR and the monthly mean KV measured by the ATC at the ORM ([Bounhir2009].

provided by the ATC versus the AOD retrived from Aqua/MODIS, Terra/MODIS and Terra/MISR. MISR (Multi-Angle Imaging Spectroradiometer) is an instrument on board Terra, that provides once a day AOD measurements at $\lambda = 557.5$nm. MODIS gives one data every two days at $\lambda = 550$nm.

The correlation between AOD and KV is 0.70, 0.65 and 0.45 for Aqua/MODIS, Terra/MODIS and Terra/MISR repectively, still poor to be used for site characterization. We expect better correlations with larger spatial and temporal satellite resolutions.

3. On the Use of Satellites for Clear Fraction of Sky

The determination of clouds cover and related parameters (useful time) has been the subject of study of A. Erasmus and collaborators for quite a large number of years. As result, they have carried out specific studies for determining the useful time for a large number of regions on the world, making use of satellites and defining very precisely the technique for the appropriate data interpretation. Erasmus reports have been promoted and purchased from different institutions. Below find a summary of results obtained at Paranal (Chile) and

ORM (La Palma, Spain).

3.1. Results at Paranal

From the satellite Survey of Cloud Cover and Water Vapor in Northern Chile by [Erasmus et al.2001] and conducted for CTIO and University of Tokyo, by using satellite data from the International Satellite Cloud Climatology Project (ISCCP) data set: Meteosat-3 (1993 - 1994) and GOES-8 (1995 -1999). The spatial resolution 9.1km x 8.0km and the temporal resolution 3 hours. The bands used were 6.7microns (water vapor) and 10.7microns (IR window).

They conclude that the photometric (or "clear") nights at Paranal is 84.6%, cross-calibrated at ground with LOSSAM (Line of Sight Sky Absorption Monitor) which provides "clear fraction" has been verified to be accurate within 1%.

A recent study using night time GOES12 satellite infrared images at Paranal in 2007-2008 provides a 88% of clear time (Cavazzani et al., private communication 2010). The difference with Erasmus & Maartens can be due to the time sampling and/or to the larger spatial resolution of GOES12 in the IR band which is 4km.

3.2. Results at the ORM

From Satellite Survey of Cloud Cover and Water Vapour in Morocco and Southern Spain and verification using La Palma ground-based Observatories, [Erasmus & van Rooyen2006], conducted by ESO, by using EUMETSAT (European Organization for the International Exploitation of Meteorological Satellites)-ISCCP data:
Over 7 years period (1996 to 2002).
Spatial resolution 5km x 5km and temporal resolution 3 hours.
Data channels: 6.4um (water vapour) and 11.5um (IR): cloud cover in the middle-upper troposphere and PWV.

They conclude that the photometric time at the ORM (also named "clear") is 83.7%. Cross-calibration at ground with the atmospheric extinction coefficient in V (KV) provided by the Automatic Transit Circle (ATC) has been verified to be accurate within 1.2%.

This result is in agreement with the global estimate of 20.7% of weather downtime by [García-Gil et al.2010] for the period 1999–2003, based on the log of the ATC. This value is also in a reasonable agreement with the reported average value for weather dowtime from 1984 to 2005 of 23.5%[1]

The good vertical resolution and the use of appropiate channels to determine different types of clouds make the satellite data a useful tool for clear/photometric time characterization for astronomical observations. The agreement between in situ and satellite data improves with large spatial resolution.

To show the effect on the correlation of the spatial resolution and of the scanning geolocation, we have compared, in collaboration with M. Sarazin and V. Zitelli, the percentage of clear nights at the ORM from *in situ* measurements provided by the logs of the Telecopio Nazionale Galileo (TNG) and from the number of photometric and non photometric nights

[1] Minutes of the CMT management Committee Meeting, 8 september 2005, Appendix D.

Figure 2. Image of 1km^2 scan centred at the Degollada del Hoyo Verde (DHV) at the ORM (La Palma) situated at the border of the Caldera. We mark on the figure the published coordinates of the ORM till 2009 at the web page of the Instituto de Astrofísica de Canarias, just inside the Caldera.

(non-photometric could be due to dust or clouds) provided by the ATC with the 3km^2 pixel size data provided by satellite.

The satellite scan has been centred on the preselected site at the ORM for hosting the ELT, called Degolladada del Hoyo Verde (DHV), located at the border of the Caldera. For comparison we have displaced the scan one pixel towards the south of the DHV (moving away from The Caldera). The Fig.2 shows 1km pixelsize centred at the DHV, southeast half of this area includes the Caldera.

The conclusions obtained over a sample of seven nights are:

- ATC and log of telescopes are 100% coincident
- Satellite centred at DHV and in situ measurements are 64%
- Satellite centred at 1 pixel below DHV (moving away from the Caldera) and in situ measurements are 86% coincident

Poorer correlation is found when satellite scan pixel is centred at the Degollada del Hoyo Verde, just located in the border of the Caldera, due to the sharpness of the terrain close to the summit compared to the 3km spatial resolution of the satellite. The pixel corresponding to DHV location is often contaminated by the inversion below the summit. By choosing the next pixel to the south the agreement is much better.

The influence of the window size over sites with abrupt orography have been also shown by [Kurlandczyk et al.2007] comparing cloud cover daytime measurements (14 Universal Time -UT-) provided by Medium Resolution Imaging Spectrometer (MERIS) instrument on the Envisat satellite with a resolution of 1km with lower spatial resolution GOES measurements (12 x 12 pixels). Results indicate a huge difference in fraction of clear daytime (larger than 58%) by changing the window size.

Astronomical observatories are often located on high mountains, and terrain can change very rapidly. Therefore, very large night-time spatial resolution satellite data would be recommend for cloud cover astronomical site characterization.

4. On the Use of Climate Diagnostics Archives for High-Altitude Winds Measurements

Astronomical observations from the Earth surface are strongly affected by atmospheric turbulence. Adaptive optics (AO hereafter) techniques try to compensate its effects on astronomical images and to reach the diffraction limit of telescopes. The larger the telescope diameter is more difficul is to reach a proper correction of the atmospheric turbulence. AO performance depends strongly on several atmospheric turbulence parameters, such as seeing, the isoplanatic angle and the coherence time. These quantities can be parametrized in terms of the average velocity of the turbulence, V_0 ([Roddier et al.1982]). However, a direct calculation of V_0 is possible only when vertical profiles of C_N^2(h) and wind velocity, V(h), are available simultaneously. High-altitude winds, in particular winds at 200 mbars pressure level, were proposed as a parameter for estimating the total turbulence at any particular site ([Vernin1986]) due to the lack of long-term information on turbulence structure at astronomical sites. This proposal was based on the hypothesis that the integrated C_N^2 profile is strongly related to the peak of the atmospheric wind vertical profile, which usually is at $\sim$200 mbar level. Later, winds at 200 mbars pressure level (V_{200} hereafter) were selected as a parameters to evaluate the quality of astronomical sites in terms of the suitability of a site for adaptive optics performances. The V_{200} as a site characterization parameter was supported by similar seasonal trend of the seeing and V_{200} at Mauna Kea and La Silla sites [Vernin1986], and the results found at Cerro Pachón and Paranal, where the average velocity of the turbulence (V_0) was found proportional to V_{200} in the form: $V_0 = 0.4V_{200}$. For details of the statistics baseline and discussion of the results see ([Sarazin & Tokovinin2002]). In addition, a good correlation–of the form $V_0 = 0.56V_{200}$ –was also found above San Pedro Mártir (Mexico) using an atmospheric model to simulate a large dataset of C_N^2 profiles ([Masciadri & Egner2006]). Such linear connection seems to be faint and only acceptable in those cases where the average altitude of the turbulence is larger than 3 km at the Teide Observatory (Izaña, Spain) ([García-Lorenzo et al.2009]). Changes in wind direction or wind regimes (in different seasons, for example) could have an important influence on the linear coefficient connecting V_0 or seeing with V_{200} ([García-Lorenzo et al.2009]).

Table 1. Statistical values for 200-mbar wind speed (m s^{-1}) for worldwide astronomical sites. Amplitude is the difference of maximum and minimum statistical winds.

Site	**Amplitude (m s^{-1})**	**Mean (m s^{-1})**	**Median (m s^{-1})**	**σ (m s^{-1})**
La Palma (Canary Islands, Spain) Lat.28^{0}46N Lon.17^{0}53W	13.69	22.13	20.79	11.67
La Silla (Chile) Lat.29^{0}15S Lon.70^{0}44W	12.46	33.35	32.77	12.94
Mauna Kea(Hawaii Islands, USA) Lat.19^{0}50N Lon.155^{0}28W	18.00	24.33	22.81	12.30
Paranal (Chile) Lat.24^{0}38S Lon.70^{0}24W	18.47	30.05	28.63	13.01
San Pedro Mártir (Mexico) Lat.31^{0}02N Lon.115^{0}27W	26.49	26.55	24.57	15.39
Izaña (Canary Islnads, Spain) Lat.28^{0}18N Lon.16^{0}30W	20.78	23.50	22.80	12.04
Oukaimeden (Morocco) Lat.31^{0}12N Lon.07^{0}52W	13.58	23.88	22.48	12.29

V_{200} statistics have been used as a parameter for ranking astronomical sites for their suitability for AO ([Ilyasov et al.2000]; [Sarazin2002]; [Carrasco & Sarazin 2003]; [Chueca et al.2004]; [Carrasco et al.2005]; [García-Lorenzo et al.2005]; [Bounhir et al.2008]). Despite poor empirical results connecting seeing and V_{200} ([Vernin1986]; [García-Lorenzo et al.2009]; [Bounhir et al.2009]), the idea of a relation between image quality and high-altitude wind speed is widespread among those of the astronomical community interested in AO. Unfortunately, the connections found between winds and AO parameters are relatively faint, and their relations induce large errors in most of the cases ([Masciadri & Egner2006], [García-Lorenzo et al.2009]).

A clear seasonal trend in the high-altitude wind behavior is found in all the studies performed (see e.g. Fig. 3): in general, the highest V_{200} occurs during spring and the lowest in summer in the North hemisphere sites, while La Silla and Paranal in the Southern hemisphere show high V_{200} values during the southern winter and spring. Table 1 presents the monthly average V_{200} at seven astronomical sites.

5. Precipitable Water Vapour

The total atmospheric water vapour in a vertical column of unit-cross-sectional area extending between ground level up to the stratopause is known as Precipitable Water Vapor (PWV). The atmospheric water vapour content is a relevant parameter affecting the infrared quality of astronomical sites. The PWV is an important source of opacity in the infrared spectral region (mainly in the mid and far infrared), reducing the transmission in several atmospheric infrared windows and producing absorption bands in the spectra of astronomical sources observed from telescopes. Therefore, the proper charaterization of PWV in

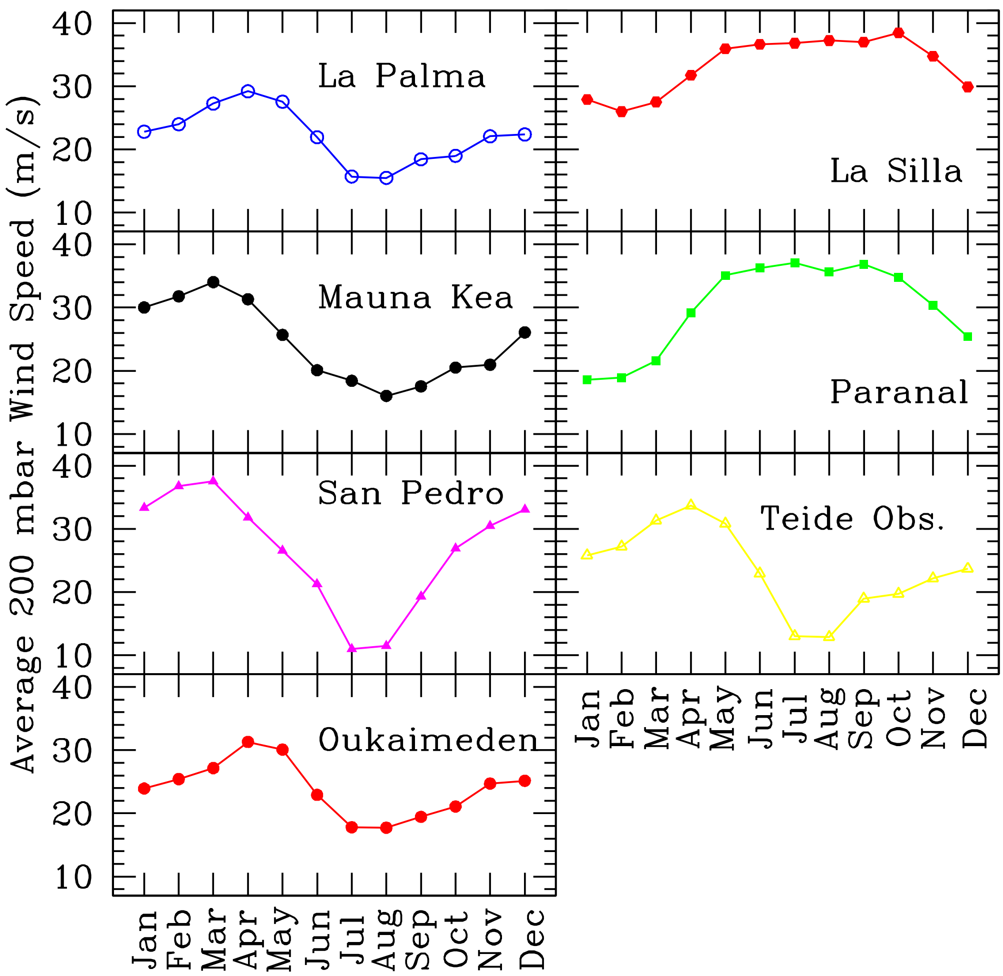

Figure 3. The monthly average wind velocity at the 200-mbar pressure level for the period 1980-2002 for La Palma, La Silla, Mauna Kea, Paranal, San Pedro Mártir (from [García-Lorenzo et al.2005]), Teide (from [Mendizabal et al.2005]), and Oukaimeden (from Bounhir et al. 2009 [Bounhir et al.2009]) observatories.

astronomical sites (temporal statistical behaviour and temporal stability) is demanded to optimaze the scientific output of astronomical instruments working in the infrared spectral range.

Measurements of PWV can be obtained from in situ measurements (radiosondes) to remote sensing techniques (photometers, radiometers, global positioning system...). However, different techniques provide different temporal coverages and samplings. The large variety of techniques and procedures used to have an estimation of the PWV at the different astronomical sites makes a comparison of statistical results of this parameter at different sites very complex. Some of the techniques used to evaluate the PWV are strongly affected by clouds or/and rain (e.g. radiosondes and microwave water vapour radiometers). Others techniques are only applicable near the zenith (e.g. photometers and radiometers). In spite of such differences, we summarize in table 2 statistical PWV values for different astronomical sites at a variety of altitudes above sea level. In some cases, we have PWV statistical results derived from two or more techniques, showing significant discrepancies between the values. Even using the same database but different temporal range, statistical values may differ significantly.

6. Conclusions

At present, the AI and AOD values provided by the NASA satellites are not useful for aerosol site characterization, and *in situ* data are required to study drainage behaviour, in particular at those astronomical sites with abrupt orography. Spatial resolution of the order of the observatory area will be required in these cases.

Very good spatial resolution satellite measurements have shown to be an useful tool for determining other astronomical site parameters, such as the photometric usable time (clouds).

The propagation of the wind flux in height and its correlation with ground level winds are crucial to understanding the influence of the trade winds on image quality. The high to low altitude wind correlation coefficients follow a similar behaviour at the sites studied except for Mauna Kea. This similar behaviour could suggest a similar relationship as that found at Paranal for La Palma, La Silla and San Pedro Mártir. Mauna Kea shows smaller Pearson correlation coefficients suggesting a weaker connection of high and low altitude winds. Winds at the lowest levels, 700mbar or 600mbar for Mauna Kea, could be affected by the topography of the sites, perhaps breaking the linear relationship.

High altitude winds can be a useful parameter for astronomical site evaluation when correlated with the surface layer winds.

Many remote sensing techniques provide PWV data for astronomical sites, although statistical results are only comparable when the same technique and methodology are used.

7. Appendix I

Products retrieved from satellites have four levels described below:

- Level 0 data are the raw data from the satellite.

Table 2. Precipitable water vapor median values for worldwide astronomical sites obtained through a large variety of techniques and procedures.

Site	Location: Lat, Lon	Height (m)	Median PWV (mm)	Technique	Temporal Range	Ref.
Las Campanas	29.01° S, 42.18° W	2200	2.8	225GHz-radiometer	2005/07-08	[Thomas-Osip et al.(2007)]
Cerro Tolar	21.96° S, 70.10° W	2290	4.02	GOES-8 satellite	1993/06-1996/02	[Otárola et al.2010]
			4.7	Surface PWV data	01/2004-12/2007	[Otárola et al.2010]
ORM	28.77° N, 17.88° W	2395	3.9	940nm-radiometer	1996-1998	[Kidger et al.(1998)]
			3.9	GPS	2001/06-2008/12	[García-Lorenzo et al.2010]
			2.6	IR Sky Radiance	2000-2002	[Pinilla2003]
La Silla	29.25° S, 70.73° W	2400	3.9	IR Sky Radiance	1983-1989	[Sarazin1990]
Paranal	24.63° S, 70.40° W	2635	2.3	IR Sky Radiance	1983-1989	[Sarazin1990]
San Pedro Mártir	31.04° N, 115.47° W	2830	2.63	GOES-8 satellite	1993/06-1996/02	[Otárola et al.2010]
			3.4	210GHz-radiometer	2006	[Otárola et al.2010]
Pico Veleta	37.07° N, 3.37° W	2850	2.9	940nm-radiometer	1984-1987	[Quesada1989]
Cerro Armazones	24.58° S, 70.18° W	3064	2.87	GOES-8 satellite	1993/06-1996/02	[Otárola et al.2010]
			3.2	Surface PWV data	01/2004-12/2007	[Otárola et al.2010]
Dome C	75.06° S, 123.23° E	3233	0.34	Satellite & Model	2008	[Saunders et al.2009]
			0.24	661GHz-radiometer	2008/01-2008/08	[Yang et al.2010]
Mauna Kea	19.83° N, 155.47° W	4205	1.7	225GHz-radiometer	2001/06-2008/12	[García-Lorenzo et al.2009]
			1.2	Radiosondes	1983	[Bely1987]
			1.86	GOES-8 satellite	1993/06-1996/02	[Otárola et al.2010]
			2.1	225GHz-radiometer	01/2004-12/2007	[Otárola et al.2010]
			2.3	GPS	2001/06-2008/12	[García-Lorenzo et al.2010]
			1.5	661GHz-radiometer	2008/01-2008/08	[Yang et al.2010]
Ridges A	81.5° S, 73.5° E	4053	0.21	Satellite & Model	2008	[Saunders et al.2009]
			0.12	661GHz-radiometer	2008/01-2008/08	[Yang et al.2010]
Dome A	80.73° S, 77.3° E	4083	0.23	Satellite & Model	2008	[Saunders et al.2009]
			0.14	661GHz-radiometer	2008/01-2008/08	[Yang et al.2010]
Cerro Toloncha r	23.93° S, 67.97° W	4480	1.7	GOES-8 satellite	1993/06-1996/02	[Otárola et al.2010]
			1.8	Surface PWV data	01/2004-12/2007	[Otárola et al.2010]
Chajnantor	23.02° S, 67.45° W	5080	1.0	Radiosondes	1998/10 & 2000/08	[Giovanelli et al.2001]
			1.2	225GHz-radiometer	1995/04-2000/04	[Thomas-Osip et al.(2007)]
			0.60	661GHz-radiometer	2008/01-2008/08	[Yang et al.2010]

- Level 1 data are calibrated and geolocated, keeping the original sampling pattern.
- The Level 2 data used in this paper are converted into geophysical parameters but still with the original sampling pattern. On examination, the Level 2 data have the same spatial resolution as the Instantaneous Field of View (IFOV) of the satellite.
- Finally the Level 3 data are resampled, averaged over space, and interpolated/averaged over time (from http://people.cs.uchicago.edu/∼yongzh/papers/-CM_In_Lg_Scale_Production.doc).

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References

[Bely1987] Bely, P.-Y. Weather and seeing on Mauna Kea. *PASP*, **99**, 560–570 (1987).

[Bounhir2009] Bounhir, A. Phd. on *Qualification des sites Astronomiques: Nouvelle approche par l'utilisation des mesures satellitaires et des données météorologiques*, Univ. Cadi Ayyad, Faculté des Sciences Semlalia, Marrakech (2009).

[Bounhir et al.2008] Bounhir, A., Benkhaldoun, Z., & Sarazin, M. Meteorological study of Aklim site in Morocco. *SPIE*, **7016**, 701621-701621-10 (2008).

[Bounhir et al.2009] Bounhir, A., Benkhaldoun, Z., Carrasco, E., & Sarazin, M. High-altitude wind velocity at Oukaimeden observatory. *MNRAS*, **398**, 862–872 (2009).

[Carrasco et al.2005] Carrasco, E., Ávila, R., & Carramiñana, A. High-Altitude Wind Velocity at Sierra Negra and San Pedro Mártir. *PASP*, **117**, 104–110 (2005).

[Carrasco & Sarazin 2003] Carrasco, E., & Sarazin, M. High altitude wind velocity at San Pedro Mártir and Mauna Kea. *Rev. Mex. AA*, **19**, 103–106 (2003).

[Chueca et al.2004] Chueca, S., García-Lorenzo, B., Muñoz-Tuñón, C., & Fuensalida, J.J. Statistics and analysis of high-altitude wind above the Canary Islands observatories *MNRAS*, **349**, 627–631 (2004).

[Erasmus et al.2001] Erasmus, D.A. & Maartens D. Maintenance, upgrade and verification of operational forecast of cloud cover and water vapour above Paranal and La Silla Observatories. *Final Report to ESO*, Purchase Order 58311/ODG/99/8362/GWI/LET (2001).

[Erasmus & van Rooyen2006] Erasmus, D.A. & van Rooyen, R. A satellite survey of cloud cover and water vapour in Morocco and Southern Spain and a verification using la Palma ground-based observations. *Final Report to ESO* **2006**, Purchase Order 73526/TSD/04/6179/GW/LET

[García-Lorenzo et al.2009] García-Lorenzo, B., Eff-Darwich, A., Fuensalida, J. J., & Castro-Almazán, J. Adaptive optics parameters connection to wind speed at the Teide Observatory. *MNRAS*, **397**, 1633–1646 (2009).

[García-Lorenzo et al.2005] García-Lorenzo, B., Fuensalida, J.J., Muñoz-Tuñón, C., & Mendizabal, E. Astronomical site ranking based on tropospheric wind statistics. *MNRAS*, **356**, 849–858 (2005).

[García-Lorenzo et al.2010] García-Lorenzo, B., Eff-Darwich, A., Castro-Almazán, J., Pinilla-Alonso, N., Muñoz-Tuñón, C., & Rodríguez-Espinosa, J. M. The Infrared Astronomical Characteristics of Roque de los Muchachos Observatory: precipitable water vapor statistics. *MNRAS*, **405**, 2683–2696 (2010).

[García-Gil et al.2010] García-Gil, A., Muñoz-Tuñón, C. & Varela A.M. Atmosphere Extinction at the ORM on La Palma: A 20 yr Statistical Database Gathered at the Carlsberg Meridian Telescope. *PASP*, **122**, 1109–1121 (2010).

[Giovanelli et al.2001] Giovanelli, R., et al. The Optical/Infrared Astronomical Quality of High Atacama Sites. II. Infrared Characteristics. *PASP*, **113**, 803 (2001).

[Ilyasov et al.2000] Ilyasov, S., Tillayev, Y., & Ehgamberdiev, S. High-altitude wind speed above Mount Maidanak. *SPIE*, **4341**, 181–184 (2000).

[Kidger et al.(1998)] Kidger, M. R., Rodríguez-Espinosa, J. M., del Rosario, J. C., & Trancho, G. Water vapour monitoring at the roque de los Muchachos Observatroy (1996–1998). *New Astronomy Review*, **42**, 537–542 (1998).

[King1985] King, D.L. Atmospheric Extinction at the Roque de los Muchachos Observatory, La Palma. *RGO/La Palma Technical note* no. 31 (1985).

[Kurlandczyk et al.2007] Kurlandczyk H. & Sarazin M. Remote sensing of precipitable water vapour and cloud cover for site selection of the E-ELT using MERIS. *SPIE*, *6745*, 674507-1 (2007).

[Masciadri & Egner2006] Masciadri, E., & Egner, S. First Seasonal Study of Optical Turbulence with an Atmospheric Model. *PASP*, **118**, 1604–1619 (2006).

[Mendizabal et al.2005] Mendizábal, E., García-Lorenzo, B., Fuensalida, J.J., Muñoz-Tuñón, C., & Varela, A.M. Estudio de la conexión entre el viento turbulento sobre el observatorio del Teide y la velocidad del viento a 200 mbars. *Proc. of XI Congreso Nacional de Teledetección* (2005).

[Muñoz-Tuñón et al.2010] Muñoz-Tuñón, C., Vernin, J., & Sarazin, M. Site selection for the European ELT Proceedings of SPIE 2nd B*ä*ckaskog Workshop on Extremely Large Telescopes, *Bäckaskog*, **5382**, 607–618 (2004)

[Pinilla2003] Pinilla, N. Research report to obtain the degree “Diploma de Estudios Avanzados”, Astrophysics department, Universidad de La Laguna (noe.pinillaalonsogmail.com) (2003).

[Quesada1989] Quesada, J.A. Precipitable water vapor content above Pico Veleta. *PASP*, **101**, 441–444 (1989).

[Roddier et al.1982] Roddier, F., Gilli, J.J., & Lund, G. On the origin of speckle boiling and its effects in stellar speckle interferometry. *Journal of Optics*, **13**, 263–271 (1982).

[Romero & Cuevas2002] Romero, P.M. & Cuevas, E. Comparación entre el espesor óptico de aerosoles medido en el Observatorio de Izaña y el índice de aerosoles determinado por el TOMS. *Proc. 3^a Asamblea Hispano Portuguesa de Geodesia y Geofísica, Valencia* (2002).

[Sarazin2002] Sarazin M. ESPAS Site Summary Series: Mauna Kea, Issue 1.1 (2002).

[Sarazin1990] Sarazin, M. VLT Report 62, VLT Site Selection Working Group Final Report, Nov. 14 (see also http://www.eso.org/gen-fac/pubs/astclim/) (1990).

[Sarazin & Tokovinin2002] Sarazin, M. & Tokovinin, A., in Vernet E., Ragazzoni R., Esposito S., Hubin N., eds, Proc. 58th ESO Conf. Workshop, Beyond Conventional Adaptive Optics. ESO Publications, *Garching*, 321 (2002).

[Saunders et al.2009] Saunders, W., Lawrence, J.S., Storey, J.W.V., Ashley, M.C.B.; Kato, S., Minnis, P., Winker, D. M.; Liu, G., Kulesa, C. Where Is the Best Site on Earth? Domes A, B, C, and F, and Ridges A and B. *PASP*, **121**, 976–992 (2009).

[Schock2004] Sch*ö*ck, M. Site selection and characterization for giant telescopes. *SPIE*, **5489**, 95–101 (2004)

[Siherbet al.2004] Siher, E.A., Ortolani, S., Sarazin, M.S. & Benkhaldoun, Z. , Correlation between TOMS aerosol index and the astronomical extinction. *SPIE*, **5489**, 138–145 (2004).

[Otárola et al.2010] Otárola, A., Travouillon, T., Schöck, M., Els, S., Riddle, R., Skidmore, W., Dahl, R., Naylor, D., & Querel, R. *PASP*, **122**, issue 890, 470–484 (2010).

[Thomas-Osip et al.(2007)] Thomas-Osip, J., McWilliam, A., Phillips, M. M., Morrell, N., Thompson, I., Folkers, T., Adams, F. C., & Lopez-Morales, M. Calibration of the Relationship between Precipitable Water Vapor and 225 GHz Atmospheric Opacity via Optical Echelle Spectroscopy at Las Campanas Observatory. *PASP*, **119**, 697–708 (2007).

[Torres et al.(2002)] Torres, O., Bhartia, P.K., Herman, J.R., Sinyuk, A., Ginoux, P. & Holben, B. A long-term record of Aerosol Optical Depth from TOMS observations and comparison to Aeronet Measurements. *Journal of the Atmospheric Sciences*, **59**, 398–413 (2002).

[Varela et al.2007] Varela, A.M., Bertolin, C., Muñoz-Tuñón, C., Fuensalida, J.J. & Ortolani, S. In situ calibration using satellite data results. *Rev. Mex. AA*, **31**, 104–110 (2007).

[Varela et al.2008] Varela, A.M., Bertolin, C., Muñoz-Tuñón, C., Fuensalida, J.J. & Ortolani, S. Astronomical site selection: On the use of satellite data for aerosol content monitoring. *MNRAS*, **391**, 507–520 (2008).

[Vernin1986] Vernin, J. Astronomical Site Selection–a New Meteorological Approach. *Proc. SPIE*, **628**, 142–147 (1986).

[Yang et al.2010] Yang, H., et al. Exceptional terhertz transparency and stability above DOME A, Antarctica. *PASP*, **122**, 490–494 (2010).