Optical Seeing and Infrared Atmospheric Transparency in the Upper Atacama Desert

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Abstract. With plans to build a large optical/IR telescope in the Atacama Desert, a site survey campaign has been under way since 1998 to characterize the optical seeing and the IR transparency in the Chajnantor Plateau region in Chile. Results of that campaign are herein presented.

1. Introduction

The Atacama Desert in northern Chile is one of the driest regions on Earth. It lies between the Coastal Cordillera to the west and the Andes to the east. The region of the Altiplano to the east of the Salar de Atacama known as Llano de Chajnantor, a plateau of altitude near 5000 m, was selected by the U.S. National Radio Astronomy Observatory (NRAO) as the future site for its Millimeter Array Project, while a neighboring plateau, Pampa La Bola, was selected by the Nobeyama Radio Observatory (NRO) of Japan for its Large Millimeter and Submillimeter Array (LMSA) Project. These sites are within a few km from each other (see Fig. 1), at elevations between 4800 and 5050 m above mean sea level. Successively, the Millimeter Array Project has evolved into a U.S.–Europe consortium to build the Atacama Large Millimeter Array (ALMA), which may also be joined by Japan. Other radio and optical Astronomy consortia are under development for operation in this region, which has the potential for expanding into a major world astronomical center. Cerro Paranal, the site of the European Southern Observatory’s (ESO) Very Large Telescope Project, is about 300 km to the southwest, on a peak on the Pacific Coastal Cordillera.

The climatic qualities that make the Atacama region especially attractive to astronomers extend over a latitudinal band a few hundred kilometers wide, about the Tropic of Capricorn. The access to good quality services and good communications further focuses attention on the regions in the vicinity of the cities of Antofagasta, Calama and the village of San Pedro de Atacama. The presence of the VLT and the likely establishment of major national and international research centers, such as ALMA, adds promise of scientific and operational synergism to the region. The government of Chile has legislated the protection of an area which includes the Llano de Chajnantor, the Pampa La Bola and the surrounding peaks, as a National Science Preserve.

Cornell University, jointly with U. of Texas and U. of Virginia, has initiated a project to build a 15–m class optical/IR telescope in the region. Since mid–1998, a survey campaign has been under way to characterize the optical and IR astronomical properties of the sites in the Chajnantor Plateau region. Here
Figure 1. Satellite view of the Chajnantor Plateau region. The image subtends approximately 40 km to the side. North is up and left is West. The labeled features, as referred in the text are (elevations in parenthesis): 1. Cerro Chico (5150 m); 2. ALMA test site (5050 m); 3. Sonde launch (5030 m); 4. Cerro Honar (5400 m); 5. Cerro Chajnantor (5650 m); 6. Cerro Chascón (5750 m); 7. Cerro Toco (5650 m); 8. Cerro Negro (5150 m); 9. Pampa La Bola, NRO test site (4800 m); 10. Cerro Licancabur, Bolivian border (5950 m).
we report on preliminary results, particularly regarding seeing and water vapor measurements.

2. Weather at Chajnantor

Weather conditions have been monitored for several years at the NRAO, ESO and NRO testing stations in the Chajnantor region. In spite of the altitude, those conditions are not extreme. The median temperature at 5000 m is $-2.6\,^\circ\mathrm{C}$; the amplitude of the diurnal cycle is about $13\,^\circ\mathrm{C}$ and that of the annual cycle is about $11\,^\circ\mathrm{C}$. Wind speeds are high during the day, but at the plateau level they drop drastically soon after sunset. Details can be seen in the NRAO and ESO websites. At peaks in the plateau region, however, circumstances are less benign, as shown in Figure 2, which displays median profiles of wind speed and temperature, as a function of elevation above the plateau, obtained from radiosonde data as mentioned below. Temperature changes little in a few hundred m height, but while at night the wind speed at 5000 m drops typically below $4\,\mathrm{m/s}$, at elevations of only a few hundred m above the plateau, median speeds near $10\,\mathrm{m/s}$ are encountered. These speeds are safely within the operational limits at modern observatories; however testing in situ of gusting conditions will be necessary.

As discussed by Erasmus (2000) in these proceedings, the Chajnantor region enjoys a high fraction of clear nights. He reports a fraction higher than 90% of nights with limited or no cloud cover above 7500 m elevation in 1995. Our visual records of 84 nights between May 1998 and October 2000 yields a fraction of
63% photometric nights, and an additional 18% deemed astronomically useful but not photometric.

3. Optical Seeing

We aim to establish the statistical properties of seeing at the best sites in the National Science Preserve region and vicinity, in Atacama. A seeing campaign strategy was developed that would follow three phases:

I. We would first establish a reference frame for seeing statistics in the region at an easily accessible site, possibly above the local boundary layer. We would determine reliably the site’s average seeing properties and seasonal variations, by carrying out a series of seeing runs spread over the seasonal cycle. This phase requires the deployment of a single seeing monitor.

II. Next, we would compare characteristics of potentially attractive sites by means of relatively brief runs of seeing measurements at those sites, simultaneous with measurements at the reference site. This phase requires the deployment of two seeing monitors.

III. Finally, once the site with the best comparative characteristics is identified, a long-term campaign of continuous monitoring with a robotic seeing monitor would be carried out.

Given its accessibility, partial emergence above the atmospheric boundary layer and central location in the Science Preserve Area, we chose Cerro Chico as the site at which a seeing reference standard for the region would be established. So far, we have carried out seven runs of 8–10 days duration each, spaced by approximately 2–3 months.

We used a Differential Image Motion Monitor (DIMM) obtained on loan from ESO. It operates at a wavelength of 0.5 μ and as described by Sarazin & Roddier (1990). It consists of an 11” Celestron telescope with two 8 cm apertures separated by 19.2 cm. Data taking with the device alternates images of 10 ms and 20 ms exposure; pairs of 10 ms and 20 ms images are used to extrapolate to an ideal “zero exposure seeing” figure, which would “freeze” the flow of atmospheric turbulence past the telescope apertures. During operation, the DIMM apertures stand some 2.5 m above the ground. As a result, some fraction of ground boundary layer turbulence contributes to the seeing values thus obtained. This contribution may not be larger than 0.2” (Martin et al. 2000). For simultaneous operation at two different sites, we have built a second device, identical to the ESO DIMM, which we started deploying in April 2000. A robotic DIMM is under construction.

Our first seeing run, of May 1998, was carried out near the NRAO testing site (“ALMA Container”, position labeled ‘2’ in Fig. 1), at an elevation of 5050 m. This decision was made in order to ascertain our and the equipment’s ability to effectively function at high altitude; caution advised that such verification be made near a shelter. Successively, all runs discussed here were carried out at the summit of Cerro Chico, some 2 km NW and about 100 m higher than the ALMA Container.

Figure 3 displays the median “zero exposure seeing” data for each day of the December 1998 run (other runs were in July, October 1998, March 1999, April, July and October 2000). The median FWHM seeing for the December 1998 run
Figure 3. Time series of “zero exposure FWHM seeing” measurements for the December 1998 run. Filled circles are 8-min seeing averages at Cerro Chico; thin solid lines represent simultaneous seeing at Cerro Paranal. Dashed lines are nightly Cerro Chico medians. Analogous plots for other runs can be seen at http://www.astro.cornell.edu/atacama/. Midnight is at 4:31 hrs UT.
was 0.66\". The median for the 38 nights of Cerro Chico measurements, July 1998 to October 2000, was 0.71\". By comparison, the median for the May 1998 run at the ALMA Container was 1.09\". The median seeing at Cerro Paranal, for the same nights for which we have data from Cerro Chico, was 0.80\" (measured with a similarly calibrated DIMM). The 10ms and 20 ms median seeing (i.e. values not extrapolated to zero exposure) for Cerro Chico were respectively 0.61\" and 0.52\".

Note that the seeing at Cerro Paranal during the Cerro Chico survey was markedly worse than the Paranal historical median (0.66\", or 21% lower than the value of 0.80\" of the “Chico nights”). This was noted by Sarazin & Navarrete (1999), who ascribed it to an exceptional El Niño/La Niña anomaly, which would have affected the Cerro Chico seeing as much as it it did Paranal’s.

In summary, we have obtained a reliable reference frame for measurements of seeing in the Chajnantor region. Provided by observations at Cerro Chico over 38 nights spread over the year, such reference frame is currently being used to compare different neighboring sites. While Cerro Chico does not qualify as a site expected to deliver the best observing conditions in comparison to other astronomically attractive sites in the region, it has easy access, it produces results of repeatable statistics and is thus a good choice for benchmarking quality comparisons through simultaneous measurements at different sites. Perhaps surprisingly — for the summit of Cerro Chico at 5150 m may still be significantly affected by boundary layer turbulence and katabatic winds from Cerro Chajnantor — it also turns out to deliver high quality seeing, comparable with that of the best observatories on Earth. This fact allows for good expectations for the quality of other sites in the region. The next phase of our campaign involves a series of simultaneous seeing runs at Chico and other summits, in the course of which we will learn the differential qualities of the various sites, and wil be able to tie those to the increasingly robust data sample for Cerro Chico itself.

4. Precipitable Water Vapor and Infrared Transparency

Since October 1998, a radiosonde launch facility has been operated at the Chajnantor Plateau jointly by Cornell, NRAO, ESO, SAO and NRO. In these proceedings, Butler (2000) reports on results from the sonde launch campaign. We have used data from 108 sondes to obtain vertical profiles of atmospheric variables, which can help us estimate the conditions at high elevation sites which, in the absence of roads, cannot currently be easily reached. Most interestingly, we verify the occurrence of patterns in the vertical distribution of precipitable water vapor (PWV), which make sites even a few hundred m higher than the plateau quite attractive because of their infrared transparency.

The PWV at the plateau level, as indicated by radiosonde, tipping radiometry at 225 and 183 GHz and FT spectroscopy, varies around a median level of about 1.2 mm. There are clear diurnal and annual variations: driest conditions are found between late March and early December, and between local midnight and 11 a.m. Median PWV during winter nights is significantly lower than 1 mm at the Chajnantor Plateau.

The water vapor density profile above the plateau is quite variable. While the median scale height exceeds 1000 m, temperature inversions form often below
Figure 4. Radiosonde data showing a case of temperature inversion below 5400 m. Panels display: at upper left, temperature (thick) and dewpoint temperature; at upper right, wind speed (thick) and direction; at lower left, relative humidity (thick) and water vapor pressure; at lower right, water vapor density (thick) and PWV. The horizontal dotted lines are at the elevations of Cerro Honar (5400 m) and Cerro Chascón (5750 m). Note the T inversion at 5.3 km (the ground is at 5.0 km), above which the water vapor density drops steeply. This launch took place on November 24, 1998, at 5 UT.
the elevation of local summits (say, below 5600 m), and a large fraction of the PWV is trapped below them. This is illustrated in the example shown in Figure 4. Often, PWV above some of the peaks surrounding the Chajnantor Plateau, which may be above the temperature inversion, can be very low. We estimate the winter night median PWV in the free atmosphere above 5400 m (e.g. the elevation of Cerro Honar) to be \( \sim 0.50 \) mm, with a first quartile of \( \sim 0.30 \) mm. Above 5700 m (e.g. the elevation of Cero Chascón), the winter night median may fall near 0.35 mm. While local topography will have an impact, the PWV at summit locations is expected to approximate that of the free atmosphere at the same elevation.

While the results presented here are preliminary, they nonetheless suggest that exceptional possibilities for IR and submm astronomical observations from the ground exist in the Chajnantor Plateau region. The combination of low water vapor and excellent seeing allow for low atmospheric background in the near and mid–IR. At a telescope sited on a summit in the vicinity of the Chajnantor plateau, numerous atmospheric windows would appear in the mid IR, up to about 50 \( \mu m \). In the far IR and submillimeter regime, the 350 \( \mu m \), 450 \( \mu m \), 600 \( \mu m \), 750 \( \mu m \) and 870 \( \mu m \) windows reach exceptional transparency, while two useful windows appear near 200 \( \mu m \).

5. Conclusions

Preliminary results indicate that the Chajnantor region offers excellent astronomical observing conditions in the optical and IR. The region is isolated yet easy to reach, and high quality services are available nearby. We can expect to find: median optical FWHM seeing approaching values of 0.5”–0.6”, a percentage of photometric nights of 65% or better, of astronomically useful nights in excess of 80% and median PWV well below 1 mm (with best quartile below 0.5 mm). We will have to contend with the important limitations — physiological, operational, etc. — imposed by the high altitude environment.

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