

## SITE CHARACTERIZATION AND MONITORING

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View south from Cerro Chajnantor of ALMA site.  
Photo: S. Radford, 1994 November.

**Revision History:**

- 2001 July 25: Reorganized, merged NRAO and European efforts.
- 2000 September 6: Updated, removed WBS numbers.
- 1999 February 4: Updated URLs.
- 1998 October 16: Reorganized to match WBS, added section numbers.
- 1998 July 15: Original version.

**14 SITE CHARACTERIZATION AND MONITORING**

**14.1 Goals**

The ALMA will be located on the high (5000 m) plateau southwest of Cerro Chajnantor, [Chile](#), about 40 km east of the village of [San Pedro de Atacama](#). Measurements since 1995 have demonstrated the existence of exceptional atmospheric conditions, i. e., transparency and stability, at this site for observations at millimeter and submillimeter wavelengths. The goals of continued site characterization and monitoring are:

- to identify and quantify site conditions and their influence on the instrument design or operations concepts,
- to provide a historical record of site conditions to guide priorities for instrument development and operation,
- to maintain a continuous presence on the site through development and construction to the start of operations, and
- to maintain contact and coordinate efforts with other groups working on or near the site.

## 14.2 History

The ALMA site characterization program at the the Llano de Chajnantor grew from the efforts of the individual partners for their constituent, predecessor projects.

For the Millimeter Array (MMA) project, the National Radio Astronomy Observatory (NRAO) conducted extensive measurements to characterize several candidate sites in the southwest U. S. and on Hawaii from 1986 to 1995. In 1994, the NRAO chose to study a high (5000 m) plateau southwest of Cerro Chajnantor, Chile, and installed atmospheric monitoring equipment in 1995. These studies led to the recommendation ([NRAO 1998](#)) of the Llano de Chajnantor as the site for the MMA.

For the Large Southern Array (LSA) project, the European partners decided to study a lower (3700 m) site near the Salar de Pajonales. In 1997, the European Southern Observatory (ESO) and the Onsala Space Observatory (OSO) installed monitoring equipment in this area.

When the LSA and MMA projects were merged to form the ALMA project, Chajnantor was selected as the site. In 1998 June, the European equipment was moved to Chajnantor and installed adjacent to the NRAO equipment.

The ALMA site characterization program is carried out by the NRAO on the US side and, on the European side, by ESO with contributions from the OSO and the Mullard Radio Astronomy Observatory (MRAO). ESO provides field support with assistance from the other partners.

## 14.3 Atmospheric and site studies

At millimeter and submillimeter wavelengths, pressure broadened molecular spectral lines make the atmosphere a natural limitation to the sensitivity and resolution of astronomical observations. Tropospheric water vapor is the principal culprit. The translucent atmosphere both decreases the signal, by attenuating incoming radiation, and increases the noise, by radiating thermally. Furthermore, inhomogeneities in the water vapor distribution cause variations in the electrical path length through the atmosphere. These variations result in phase errors that degrade the sensitivity and resolution of images made with both interferometers and filled aperture telescopes. The site characterization effort addresses these areas:

- Radiometric properties of the atmosphere
  - stability
  - transparency
- Physical structure of the atmosphere
  - meteorology
  - stratification
  - turbulence
- Physical characteristics of the site
  - topology
  - geology

#### **14.4 Geography, Climatology, and Geology**

Located in the Chilean Andes about 40 km ESE of the village of [San Pedro de Atacama](#), the ALMA site on the Llano de Chajnantor is a high (5000 m) plateau of about 25 km<sup>2</sup>. It is open the west and north-west, but bounded by several 5600 m peaks in other directions. The geographic coordinates are 23° 01' S and 67° 45' W (Radford [1999](#) & [2000](#)). The entire area, which includes the Chajnantor plateau as well as Pampa la Bola, has been declared a "scientific preserve" by decree of the Chilean government. The preserve has been assigned as a 5 year concession to the official Chilean science agency, CONICYT.

Climatological conditions in the high Andes of northern Chile were studied by Schmidt (1997) and are briefly described by [Otárola, et al. \(1998\)](#). Long term and seasonal climate variations have been investigated by [Bustos et al. \(2000\)](#) and [Bustos \(2001\)](#). Assessments of seismic and volcanic hazards at the site were made by [Barrientos \(1996\)](#) and [Gardeweg \(1996\)](#). In 2000, a geotechnical study of six locations in the science preserve area was carried out by NRO, NRAO, and ESO to identify soil characteristics ([Geo Ambiental 2000](#)).

##### **14.4.1 Maps, digital elevation model, and coordinates**

In 1996, 1999, and 2001, contour maps and a digital elevation model of the science preserve and the adjacent land to the west were prepared from aerial photographs ([Maps of the Chajnantor Zone](#)). These maps, which together cover about 24 × 52 km at 10 m resolution, are used for planning the array configurations and civil works and for hydrodynamic studies of airflow over the site. For compatibility with the published Chilean topographic maps these maps use the Provisional South American 1956 datum. These maps were used to identify sites for the compact configurations ([Butler et al. 2000](#)) and were the basis for an antenna location mask for configuration designs ([Butler 2001](#)). Coordinates of installations, roads, and other landmarks have been recorded with a GPS receiver ([Sakamoto 2001a](#)).

## **14.5 Infrastructure**

For site characterization and monitoring, the ALMA operations base on Chajnantor is a group of four 6 m (20 foot) long ocean shipping containers. These provide shelter for personnel and physical support for the instruments. The first container was installed by the NRAO in 1995 April. In 1998 June, when the MMA and LSA projects were combined to form the ALMA project, ESO installed a second container about 15 m north of the NRAO equipment. In 1998 October, a third container was installed 1 km west of the other containers as a launch base for radiosondes. Most recently, in 2000 December, ESO installed a fourth container adjacent to the east end of its earlier container to expand the solar electric power system and provide additional space for equipment.

### **14.5.1 Safety program**

While working at Chajnantor, all ALMA staff are governed by the ALMA [safety rules](#). These rules include provisions for physical examinations prior to work at high altitude and for emergency training for ALMA staff who frequently work at Chajnantor. The containers contain emergency supplies (first aid kits, breathing oxygen, food, water, sleeping bags, etc.) and are equipped with both cellular and satellite phones that provide permanent communications.

### **14.5.2 Transportation**

Four wheel drive vehicles are required to access to Chajnantor, especially during inclement weather.

### **14.5.3 Solar electric power systems**

All four containers have arrays of solar panels and battery banks to supply electrical power. The system on the NRAO container supplies 24 VDC and 110 VAC at 60 Hz. Its continuous capacity is about 500 W, with sufficient reserve capacity to weather a storm of a few days. With current instrumentation, this system operates near capacity. The systems in the two ESO containers supply 24 VDC and 220 VAC at 50 Hz. Combined, they have a somewhat larger capacity than the NRAO system. The radiosonde container has a small system (12 VDC and 110 VAC 60 Hz) adequate to run the radiosonde tracking equipment. System maintenance includes periodic checks and refills of battery water. Although system performance is slowly degrading with age, etc., these systems should remain adequate until the permanent ALMA infrastructure is installed.

### **14.5.4 Computers and network**

All the ALMA site characterization instruments are controlled by PCs interlinked with an ethernet extending between the containers. The PC clocks are synchronized to a GPS receiver that provides an absolute time reference good to about 1 s. The GPS receiver was also used to determine the position of the NRAO container (Radford [1999](#) & [2000](#)).

### **14.5.5 Communications**

Voice and low-speed ( $\leq 4800$  baud) data are transmitted over cellular telephones. In 2001 April, an Inmarsat M4 satellite terminal was deployed to provide voice and high-speed (64 kbaud ISDN) data communications. This provides a connection to the NRAO intranet and the

internet for authorized users. Handheld radios are occasionally used for communications around the site.

### **14.5.6 Gases and cryogenic liquids**

Liquid helium, liquid nitrogen, and industrial gases can be delivered to the site by AGA, which has a depot in Calama, about 160 km by road north east of Chajnantor. Liquid helium and liquid nitrogen were required to operate the SAO FTS.

## **14.6 Instrumentation**

### **14.6.1 Atmospheric Transparency and Water Vapor Content**

Pressure broadened molecular spectral lines, principally of tropospheric water vapor, make the atmosphere semi-opaque at millimeter and submillimeter wavelengths. The translucent atmosphere radiates thermally, which increases the system noise, and attenuates incoming radiation, which decreases the signal.

#### **14.6.1.1 [183 GHz radiometers](#)**

Two radiometers measure the sky brightness temperature in several frequency bands close to the 183 GHz water vapor line ([Delgado et al. 1999](#)). These instruments were built in a collaborative effort between OSO and MRAO and were installed at Chajnantor in 1998 and 1999. One radiometer is deployed at each end of the 300 m baseline of the 11.2 GHz site test interferometers.

The [radiometers](#) are three channel DSB heterodyne receivers with room temperature mixers. The shape and intensity of the 183 GHz line are determined from the calibrated antenna temperatures for the three channels. The measured line parameters are iteratively compared with the predictions of an atmospheric model to determine the atmospheric water vapor density, which then is integrated to obtain the precipitable water vapor (PWV) and the associated electrical pathlength. Since the atmosphere is non-dispersive at millimeter frequencies, electrical pathlength variations translate directly to phase variations at any given frequency.

Data are recorded every 2 seconds and retrieved about once a month. After analysis, the PWV time series is posted on the ESO ALMA [site page](#) together with the raw data. The data are also used to study the dynamics of the turbulent layer and, in conjunction with the 11.2 GHz interferometer data, atmospheric phase correction schemes.

#### **14.6.1.2 [225 GHz tipper](#)**

The NRAO 225 GHz tipping radiometer ([Liu 1987](#) & [McKinnon 1987](#)) is the benchmark instrument for site characterization. It measures the atmospheric transparency every 10 minutes and the stability of atmospheric emission every fifth hour. The data are retrieved weekly over the ISDN link and [daily](#) and [monthly](#) data summaries are posted on the NRAO web page along with the reduced data in machine readable form. Operation is automatic, so current activity includes maintenance, including sporadic repair as required, data retrieval, and data analysis.

### 14.6.1.3 [Submm tipper](#)

A tipping photometer was developed by NRAO in collaboration with Carnegie Mellon University to directly measure the atmospheric transparency at 350  $\mu\text{m}$  wavelength. This instrument is based on an ambient temperature, pyroelectric detector. The spectral response is defined by a resonant metal mesh. A compound parabolic (Winston) cone and offset parabolic scanning mirror together define the 6° beam on the sky. The detector is internally calibrated with two temperature controlled loads and views the sky through a woven Gore-tex window. Identical instruments have been deployed on Chajnantor (1997 October), at the CSO on Mauna Kea (1997 December), and at the South Pole (1998 January). An incomplete fourth unit was supplied to the University of New South Wales in 1999 July for modification prior to remote Antarctic deployment. In 2000 June, a fifth instrument equipped with a filter wheel and 200, 260, 350, and 1300  $\mu\text{m}$  filters was deployed at Chajnantor. To investigate the dependence of transparency with altitude, one unit will be redeployed in late 2001 to 5700 m on Cerro Sairecabur, about 40 km north of Chajnantor.

The instruments operate autonomously. Status reports are received daily and data are retrieved about once a month. The data from these instruments are being analyzed with the aim of making an unbiased comparison of the three sites. Current activity includes operation and maintenance, including sporadic repair as required, data retrieval, and data analysis. Further work includes cross calibration between the submm tipper and other instruments, namely the 225 GHz tipper, SCUBA, CSO, and AST/RO.

### 14.6.1.4 [Fourier Transform Spectrometer](#)

To measure the atmospheric emission spectrum at Chajnantor, the [Smithsonian Astrophysical Observatory Submillimeter Receiver Lab](#) deployed a Fourier transform (polarizing Martin-Pupplet) spectrometer. This cryogenic instrument covers 350 - 3000 GHz with 3 GHz resolution and a 3° beam ([Paine et al. 2000](#)). The NRAO container provided a base for field operations where the FTS recorded data from 1997 October to 2000 August. Subsequently, the instrument was redeployed to 5700 m on Cerro Sairecabur.

## 14.6.2 Atmospheric stability

Inhomogeneities in the distribution of water vapor cause variations in the electrical path length through the atmosphere. The resulting phase errors degrade the sensitivity and resolution of observations with both interferometers and filled aperture telescopes.

### 14.6.2.1 [11.2 GHz interferometer](#)

The site test interferometers directly measure the tropospheric phase stability. They observe unmodulated 11.2 GHz beacons broadcast from geostationary satellites and measure the phase difference between the signals received by two 1.8 m diameter antennas 300 m apart ([Radford, Reiland, & Shillue \(1996\)](#)). Because the atmosphere is largely non-dispersive away from line centers, the results can be scaled to millimeter and submillimeter wavelengths. Four instruments have been constructed by NRAO's Tucson office. The first was operated near the VLBA antenna (3720 m) on Mauna Kea, Hawaii, from 1994 September to 1996 June, then installed at the VLA in 1997 May. The second has been operating on Chajnantor (5000 m) near San Pedro de Atacama, Chile, since 1995 May. A third was built for the LSA project. ESO installed it at Pajonales in 1997 April and moved it to Chajnantor

in 1998 June. A fourth instrument, with a 100 m baseline, was installed at Green Bank in 2000 March.

From the phase time series, we obtain the r. m. s. path fluctuations on a 300 m baseline, the power law exponent of the phase structure function, and the velocity at which the turbulent water vapor moves over the array. [Holdaway et al. \(1995\)](#) describe the site test interferometer data reduction in detail, and [Holdaway \(1995\)](#) illustrates the agreement between two different methods of deriving the mean velocity of the turbulent water vapor flow in the atmosphere. In 1998 June, the ESO interferometer was set up alongside the NRAO interferometer. They share essentially the same baseline, but observe different satellites about 5° apart on the sky. Lag correlation of the data from the two interferometers will indicate the height of the turbulent layer ([Holdaway & Radford 1998](#) & [Robson et al. 2001](#)).

The interferometers operate autonomously. The data are retrieved about once a month and analyzed in Tucson. Monthly [summaries](#) are posted on the NRAO web page. Current activity includes operation and maintenance, including sporadic repair as required, data retrieval, and data analysis.

#### **14.6.2.2 GPS**

A geodetic GPS receiver was installed in 1999 by the OSO to measure the variations in the total radio propagation path delay as well as the stability of the site coordinates ([Gradinarsky et al. 2001](#)).

### **14.6.3 Physical structure of atmosphere**

The vertical profiles of atmospheric water vapor and turbulence may affect the success of radiometric phase calibration schemes.

#### **14.6.3.1 [Radiosonde campaign](#)**

Radiosondes carried by weather balloons provide in situ measurements of pressure, temperature, humidity, and wind speed and direction over the launch site. From these data we learn about the stratification of the water vapor over Chajnantor and about shear layers that may generate turbulence. Two surplus radiotheodolites was acquired by NRAO, upgraded by the manufacturer, tested in Tucson, and deployed at Chajnantor. In 2001, the radiotheodolites were again upgraded to accomodate switching to a different type of radiosonde package. Beginning in 1998 October, balloon flights have been made whenever appropriate personnel are at the site. This campaign is a collaboration between NRAO, Cornell, ESO, SAO, and NAOJ. The balloons are launched from a container placed 1 km west of the main site.

#### **14.6.3.2 Sodar**

Acoustic sounding, or sodar, senses thermal turbulence in the lower atmosphere. Engineering tests of an ESO sodar unit were made in 1999 November. We are evaluating our interest in pursuing further measurements.

#### **14.6.3.3 Hydrodynamic models**

Calculations of airflow over Chajnantor, with an emphasis on the turbulence generated by local topography, are being pursued in collaboration with NOAO.

## **14.6.4 Meteorology**

### **14.6.4.1 Weather stations**

ESO and NRAO operate four weather stations near the main containers and one station near the radiosonde launch container. Additional stations may be deployed to measure the variation of meteorological parameters across the site.

### **14.6.4.2 Fast anemometers**

To study the wind power spectrum, a fast vortex anemometer was deployed in 1999. This reads the wind speed and wind direction at a rate of 1 Hz. The results, however, were unexpected, as the power in fast fluctuations seemed too small. In early 2001, therefore, a cup anemometer reading at 10 Hz was deployed.

### **14.6.4.3 Hygrometer**

A high precision, chilled mirror hygrometer will be deployed in late 2001. This includes a precision barometer and thermometer.

## **14.6.5 Auxiliary instruments**

### **14.6.5.1 [Surveillance cameras](#)**

Two surveillance [cameras](#), installed on top of the containers, take [pictures](#) of the horizon every two hours. Data are retrieved about once a month and the [images](#) posted on the web sites.

### **14.6.5.2 Seismometer**

A seismometer was installed in 1995 in collaboration with a group at the University of Chile (K. Bataille). The firmware was updated in 2000 July to accommodate GPS date rollover.

### **14.6.5.3 Subsurface temperature probe**

A subsurface temperature probe was operated 1997 June - October and 1998 March - May. [Snyder et al. \(2000\)](#) analyzed the data.

### **14.6.5.4 Lightning detector**

In late 1999, a lightning detector was installed at the NRAO container to quantify the frequency of lightning strike in the area (Sakamoto et al. in preparation).

## **14.6.6 Instruments installed by other groups**

Several other groups are carrying out site characterization studies or astronomical experiments nearby. The ALMA project encourages these groups and takes interest in their results. As needed, ALMA and the other groups coordinate activities.

### **14.6.6.1 [NAOJ/NRO](#)**

At Pampa la Bola, about 8 km northeast of the ALMA equipment and 250 m lower, the NAOJ/NRO has installed:

- [Weather stations](#) (Sakamoto et al. 2000),
- Two [220 GHz tipping radiometers](#) (Kohno et al. 1994),
- Two [11.2 GHz interferometers](#) (Ishiguro et al. 1990),
- A [492 GHz radiometer](#) (short term deployment; Hirota et al. 1998),
- A [Fourier Transform Spectrometer](#) (short term deployments; Matsuo 1998 & Matsushita et al. 1999 & 2000),
- A [Lightning Detector](#) (Sakamoto & Radford 2001 in preparation), and
- Several auxillary instruments.

#### **14.6.6.2 Cornell and partners**

Cornell, together with the University of Texas and the University of Virginia, is making optical seeing (DIMM) measurements in the area. Campaigns started in 1998 and have been done about every three to six months (Giovanelli et al. 2001a & 2001b).

#### **14.6.6.3 CTIO**

In collaboration with Cornell, CTIO deployed a weather station and a robotic seeing monitor during 2000 at Cordon Honar, about 400 m above the Chajnantor plateau.

#### **14.6.6.4 Cosmic Background Imager**

Since late 1999, a Caltech group has been observing fluctuations in the Cosmic Background Radiation ([Padin et al. 2001](#))

#### **14.6.6.5 MAT**

In 1997 and 1998, a group from Princeton and the University of Pennsylvania observed fluctuations in the Cosmic Background Radiation from Cerro Toco, about 5 km north of the ALMA site ([Torbet et al. 1999](#), [Miller et al. 1999](#)).

#### **14.6.6.6 SAO Submillimeter Receiver Lab**

In 2000, the [Smithsonian Astrophysical Observatory Submillimeter Receiver Lab](#) redeployed their [Fourier transform spectrometer](#) to 5700 m on Cerro Sairecabur, about 40 km north of Chajnantor.

#### **14.6.6.7 Princeton**

In 2001, a Princeton group will deploy [MINT](#), an interferometer to study the Cosmic Background Radiation, on Cerro Toco.

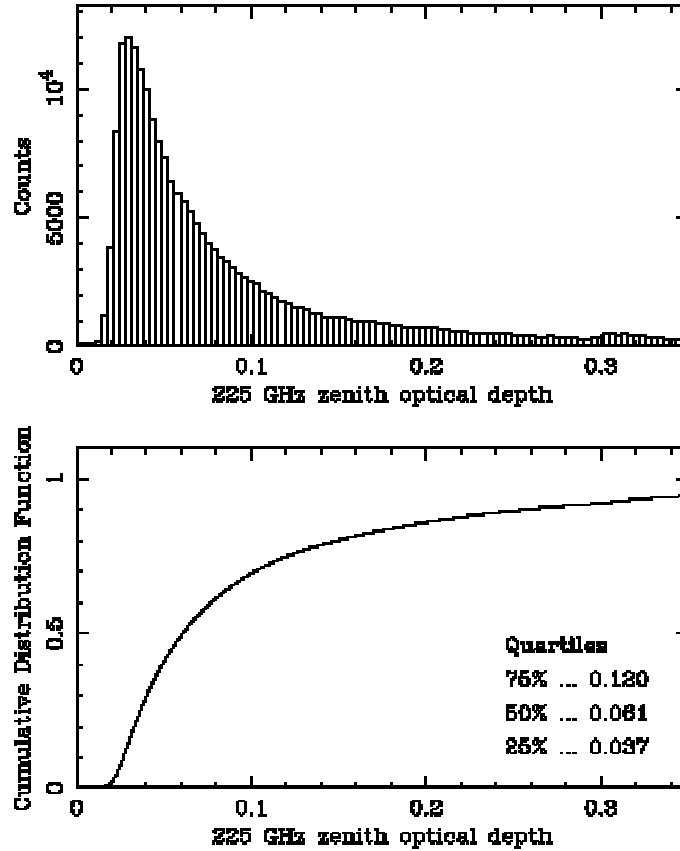
### **14.7 Results**

A number of ALMA Memos and other reports discuss the results of the site characterization in detail. Some highlights:

### 14.7.1 Atmospheric Transparency

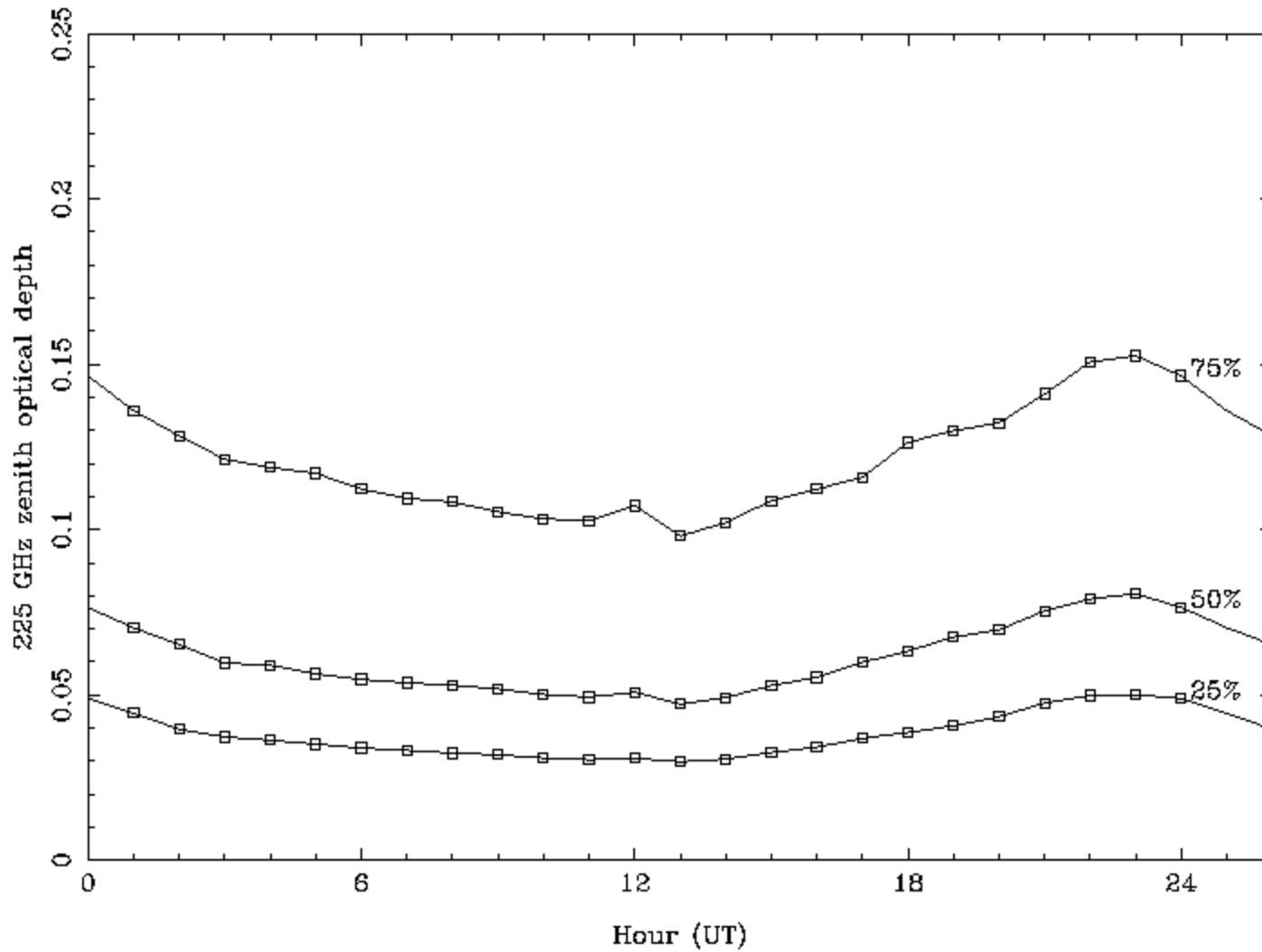
The 225 GHz atmospheric transparency at Chajnantor has been measured continuously since 1995 April. Overall, the median zenith optical depth is 0.06. The diurnal variation is less than a factor of two, with higher optical depths in the afternoons. The lowest transparency occurs from January through March, when the median optical depth is about twice as high as it is during the rest of the year. Year to year, there is considerable variation in the the severity of the summer season.

Chajnantor: 1995 April to 2002 February



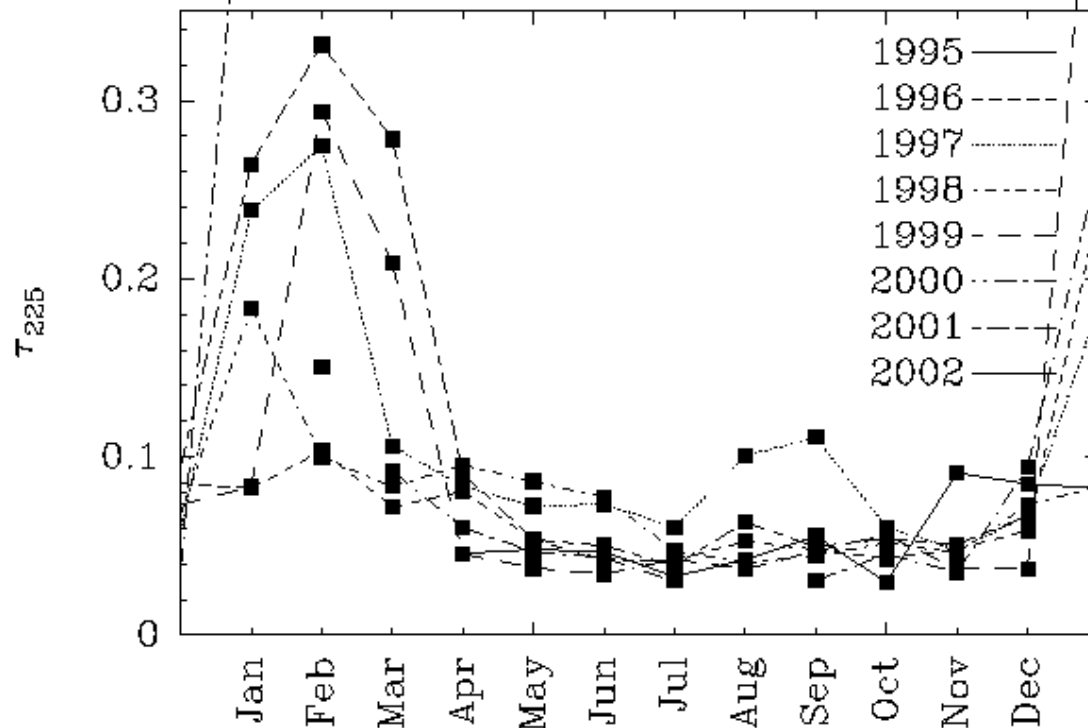
Distribution of 225 GHz optical depths

Chajnantor: 1995 April to 2002 February



Diurnal variation of 225 GHz transparency.

Chajnantor: Median 225 GHz Zenith Optical Depth ( $\tau_{225}$ )

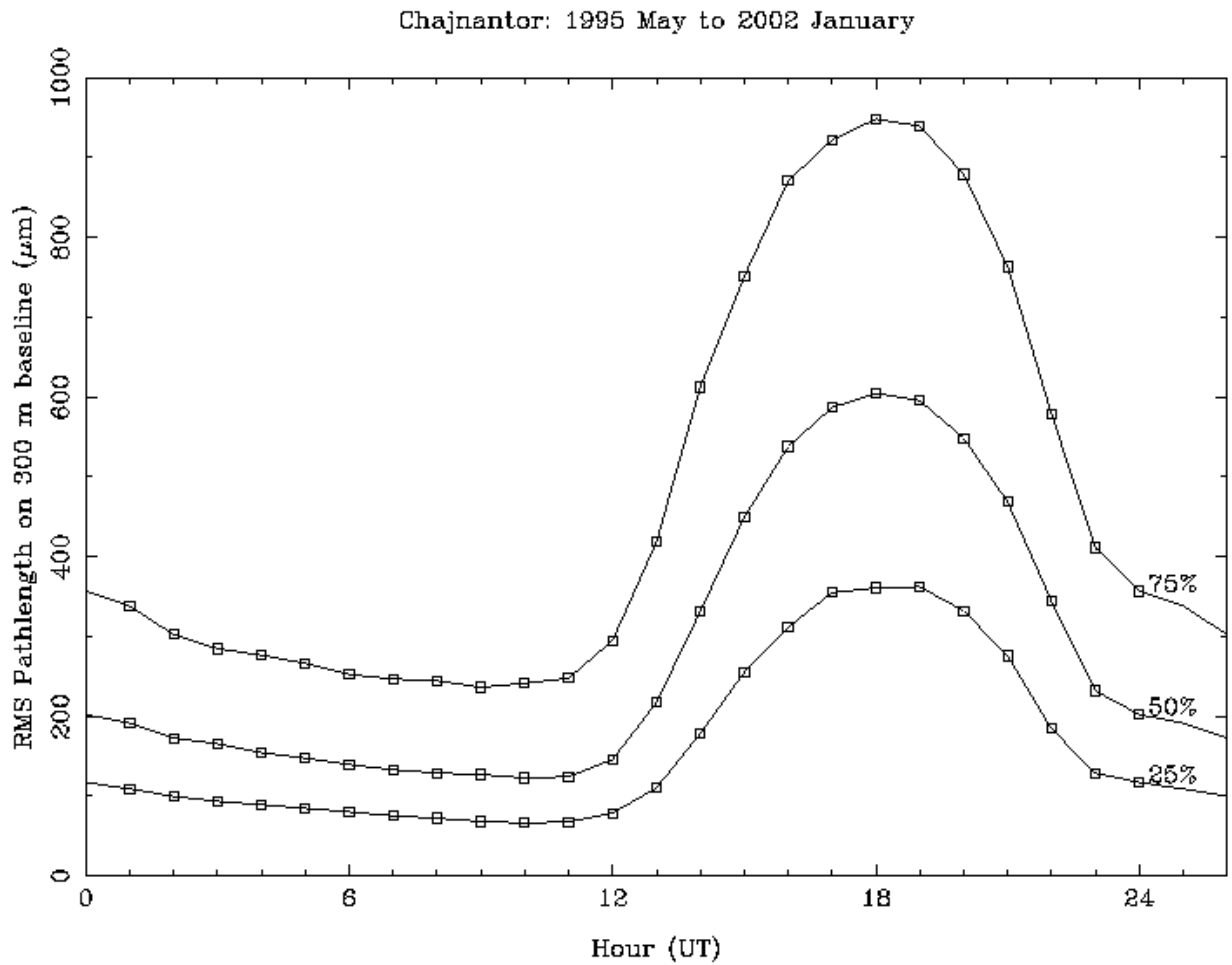


Seasonal variation of 225 GHz transparency.

The atmospheric transparency is largely determined by the water vapor content. The precipitable water vapor (PWV) is measured by the 183 GHz radiometers. For all of 2000, the median PWV was about 1.8 mm, but during the winter (May to August) the median was 0.6 mm. Under normal conditions, the PWV is 2-4 times higher during the day than at night.

### 14.7.2 Atmospheric Stability

At Chajnantor, the measured phase stability shows a diurnal variation. At local noon, the median phase variations are about seven times larger than at midnight. This is also when the surface wind speed is highest. Day time observations will be limited, then, unless phase correction methods can be employed.

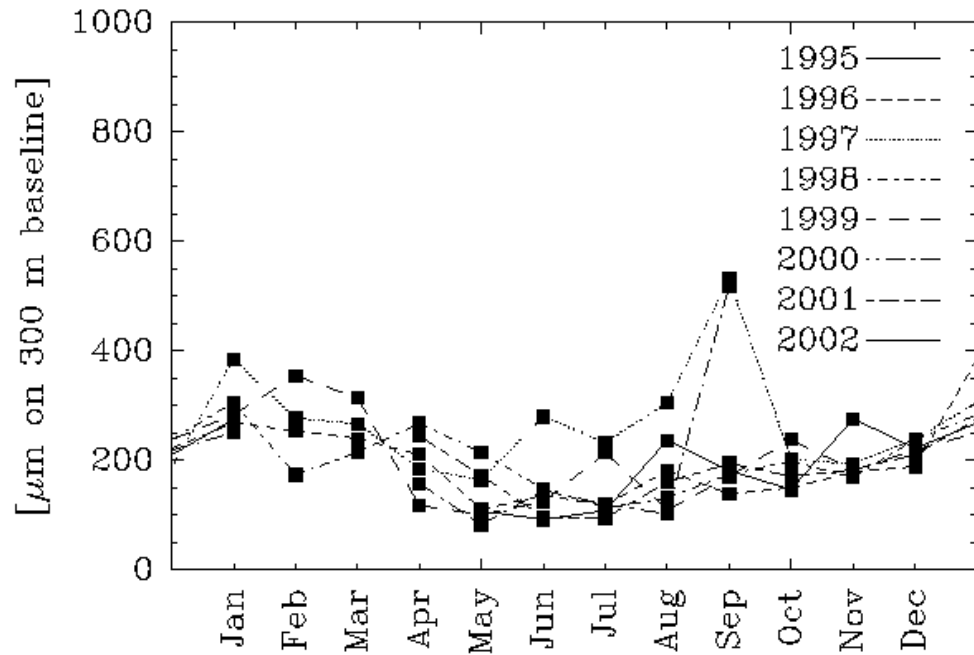


Diurnal variation of phase fluctuations.

Seasonal variations in the phase stability are much less pronounced than diurnal variations.

The best conditions occur during winter, when the diurnal variations in phase stability are also less pronounced than in the summer. There appears to be a seasonal anticorrelation between wind speed phase stability. Even though the wind speed is higher in the winter than in the summer, the phase stability is better in the summer. It should be possible, therefore, to do high-resolution observations throughout the day for a large fraction of the winter.

### Chajnantor: Median RMS Phase Fluctuations at Zenith

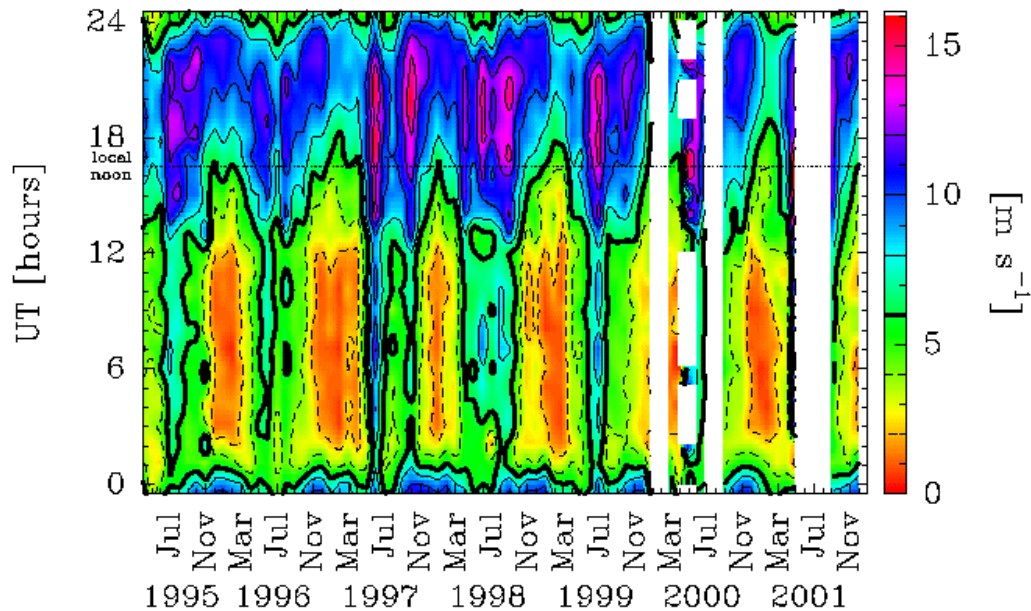


Seasonal variation of phase fluctuations.

#### 14.7.3 Meteorological Conditions

The measured air temperature at Chajnantor shows the expected diurnal and seasonal variations about an overall median somewhat below freezing,  $-2.5^{\circ}\text{C}$ .

### Chajnantor: Median Wind Speed



Variation of hourly and monthly median windspeed.

The diurnal variation of the wind speed is quite pronounced in all seasons with stronger winds in the afternoons. Winters are windier than summers. Westerly winds prevail almost exclusively during the winter, while easterly winds prevail 30-50% of the time during summer.

Except during the summer, the relative humidity remains fairly constant throughout the year, with an average of about 30%. In summer, altiplanic storms bring humidity from the Amazon basin into the area.

The daily and yearly maxima, averages, and ranges of the insolation are among the highest recorded in the world. The average daily maximum reaches almost  $1300 \text{ W m}^{-2}$  during summer.

#### 14.7.4 Physical Structure of the Atmosphere

Each radiosonde flight provides a profile of pressure, temperature, relative humidity, range (horizontal distance from launch site), and wind speed and direction as the balloon rises through the troposphere. From these data, inferred parameters including the partial pressure, density, and total precipitable column of water vapor are computed after each flight.

Since 1998 there have been about 185 [radiosonde launches](#) from Chajnantor. Some show the lower troposphere can be quite complex with the presence of many inversion layers while others there are no inversion layers present. The time scale for a significant change can be of the order of a few hours.

### **14.7.5 Climate Trends**

A 52 year climatological study was conducted in order to investigate possible long-period cycles. The data used were prepared by the National Center for Environmental Prediction (NCEP) and the National Center for Atmospheric Research (NCAR) from historical weather observations and state of the art climatological models. The results ([Bustos et al. 2000](#)) conclude there are no climatological trends in Chajnantor, but a few cycles with periods of the order of several years are seen. Seasonal cycles are clear and very strong, with a correlation between the ENSO phenomena and the winter dryness ([Bustos 2001](#)).

### **14.7.6 Phase Correction Experiment**

Atmospheric phase fluctuations during millimetre and submillimetre interferometric observations lead to a loss in resolution and a decrease in the signal strength. A proposed method to correct the phase fluctuations is to estimate the amount of PWV in the observed column of atmosphere from measurements close to the strong 183 GHz water vapor line, and to use this value to determine the excess path delay. By measuring the variations of the PWV at each interferometer element, the relative phase differences can be determined and used to compensate for phase fluctuation.

At Chajnantor the differential phase derived from the PWV measured with the 183 GHz radiometers along the same line of sight as the 11.2 GHz interferometer has been used to correct the phase variations measured by the interferometer.

The improvement in phase variations after this correction is applied varies during the day, ranging from very good, with better than 75% correction, to little or no correction at all. The degree of success appears correlated with the height of the turbulence layer. (Delgado et al. [2000](#) & [2001](#) & Delgado 2001).

### **14.7.7 Height of the turbulence layer**

The height of the turbulence layer is an important parameter because it defines the geometry of the intersecting beams during the phase correction. For the ALMA antennas, the astronomical beam will be offset from the 183 GHz water vapor monitor beam, so the separation of the beams at the height of the turbulence layer will vary, affecting the success of the phase correction.

The ESO and NRAO interferometers on Chajnantor share essentially the same baseline, but observe different satellites about 5° apart. Lag correlation of the data from the two interferometers indicates the height of the turbulent layer ([Holdaway & Radford 1998](#)). The results show most of the time the turbulence layer is less than 500 m above the plateau & [Robson et al. 2001](#)).

### **14.7.8 Comparison between Chajnantor and Pampa La Bola**

Within the science preserve, measurements of atmospheric conditions have been carried out at two particular locations. The NRAO and the European partners have studied the Llano de Chajnantor while the Japanese have investigated Pampa la Bola, about 8 km northeast of Chajnantor and 250 m lower. Sakamoto ([2001b](#)) gives an overall comparison of the two sites. A comparison of meteorological data since 1996 from the two adjacent sites of Pampa La Bola and Chajnantor shows generally similar conditions, with some differences in seasonal and diurnal variations ([Sakamoto et al. 2000](#)).

Measurements with the 220 and 225 GHz tipping radiometers indicate the atmosphere is more transparent at Chajnantor than at Pampa la Bola. The optical depth at Pampa la Bola is typically 10% to 50% higher than at Chajnantor. Side-by-side measurements with both instruments at Chajnantor in 2001 April–May confirm this is not an instrumental artifact. Especially for observations at submillimeter wavelengths, these differences imply Chajnantor enjoys a significant advantage in observing time or sensitivity (Radford et al. 2001 in preparation).

The overall distribution of the phase fluctuations is similar for the two sites, but the median stability is 12% better at Chajnantor ([Butler et al. 2001](#)). At any given time, however, the phase fluctuations on a 300 m baseline may be quite different at the two sites, sometimes by a large factor. Presumably this is the effect of local topography on turbulence. The wide range of phase stability seen at the two sites at the same time implies the phase stability may vary significantly across the array when observing with the larger (> 3 km) configurations ([Holdaway et al. 1997](#)).

#### **14.7.9 225 GHz Atmospheric Transparency at Chajnantor, Hawaii, and the South Pole**

Measurements of the 225 GHz atmospheric transparency with functionally identical tipping radiometers at Mauna Kea, the South Pole, and Chajnantor indicate periods of excellent observing conditions at all three sites. Conditions at Chajnantor and the South Pole are better than at Mauna Kea. The first quartile zenith transparency at Chajnantor and the South Pole are roughly equal. During the best conditions at Chajnantor, however, the zenith transparency is better than during the best conditions at the South Pole ([Radford & Chamberlin 2000](#)).

#### **14.7.10 Subsurface Temperatures**

By monitoring the subsurface temperature at Chajnantor, the thermal diffusivity of the soil and the damping of diurnal temperature fluctuations with depth have been measured. The thermal diffusivity is of roughly the range expected for sandy soil, and varies daily. For the maximum observed diffusivity the diurnal temperature swing 1 m deep is only 0.02% of the surface amplitude. Shorter period variations are damped more strongly. This damping is sufficiently strong that the overall phase stability of the ALMA optical fibers may be determined not by the 25 km long buried sections, but by the shorter lengths above ground ([Snyder et al. 2000](#)).

#### **14.8 Instrumentation needed for ALMA operations**

ALMA will be operated in a service mode and with flexible scheduling. It will be necessary, therefore, to constantly monitor the atmospheric conditions to decide what frequency band should be observed. It may also be useful to employ a weather prediction scheme based on satellite data as is presently done at Paranal. In addition, current meteorological data will be needed for antenna safety, for the array control system, and for various calibration schemes. The instrument suite for a the monitoring station is yet to be defined, but it might include some or all of these:

- centrally located, high precision meteorology sensors for wind, temperature, pressure, and humidity;
- distributed, moderate precision meteorology sensors;

- millimeter and submillimeter wavelength tippers;
- an 11 GHz interferometer;
- radiosonde launches;
- a 183 GHz radiometer to monitor the isoplanatic angle;
- a Fourier transform spectrometer, perhaps multibeam;
- a 60 GHz temperature profiler;
- a radar wind profiler;
- a 10  $\mu\text{m}$  cloud monitor; and
- a 20  $\mu\text{m}$  water vapor monitor.

#### **14.9 Site Characterization Reviews**

Periodic reviews are held to assess the site characterization activities and the data obtained by all groups. A mailing list ([alma-site@nrao.edu](mailto:alma-site@nrao.edu)) has been set up for communication among the [ALMA site characterization group](#). Previous meetings include:

- 1998 March, Tucson  
Joint meeting on Site Characterization.
- 1999 January, USNC/URSI National Radio Science meeting, Boulder  
At a session on [Atmospheric Transmission at Millimeter and Submillimeter Wavelengths](#), results from the ALMA site characterization program were presented.
- 2000 March 22  
[teleconference](#)
- 2000 November, [Astronomical Site Evaluation in the Visible and Radio Range](#), Marrakech  
Results from the ALMA site monitoring program made up much of the program at this IAU Technical Workshop. A working meeting also occurred.
- 2001 January, USNC/URSI National Radio Science meeting, Boulder  
A session on Millimeter and Sub-millimeter Wavelength Atmospheric Radiometry included several ALMA results.

## 14.10 References

### 14.10.1 Web pages

Several web pages present data and results from the site characterization program.

ALMA Site Studies at NRAO: <http://www.tuc.nrao.edu/alma/site>

ALMA Site Studies at ESO: <http://alma.sc.eso.org>

NAOJ/NRO Site Studies: <http://www.nro.nao.ac.jp/~lmsa/siteWG/siteWG.html>

Cornell: <http://astrosun.tn.cornell.edu/atacama>

CTIO: <http://www.ctio.noao.edu/sitetests>

CBI: <http://astro.caltech.edu/~tjp/CBI>

### 14.10.2 Reports

Safety rules for ALMA Personnel on the ALMA 5000 m Site:

NRAO version: <http://www.aoc.nrao.edu/~pnapier/mmasafety.htm>, 2000 May

ESO version: Volume 4, Appendix C of the Proposal for Phase 2 construction of the ALMA, 2000 December

NRAO 1998 May, Recommended Site for the Millimeter Array [also ps]

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