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Comparison of the Pampa La Bola and Llano de Chajnantor Sites in Northern Chile

Seiichi Sakamoto
National Astronomical Observatory of Japan
Mitaka, Tokyo 181-8588, Japan

Abstract.
Conditions of Llano de Chajnantor and Pampa La Bola locations in northern Chile are reviewed. If we simply focus on the seeing and transparency in millimeter and submillimeter ranges, Llano de Chajnantor is better than Pampa La Bola by about 20% in opacity and about 10% in seeing. These differences are, however, much smaller compared to those between this area and Mauna Kea. On the other hand, there are trade-offs chiefly related to the easiness (or cost) of construction, flexibility and easiness of operations, and available lengths of baselines, most of which are hardly evaluated quantitatively.

1. Introduction

1.1. What Is a "Good" Site?

In general, a site for an astronomical project should be good — at least not critically bad — in terms of atmospheric and geographical conditions, as well as other non-technical conditions. The atmospheric conditions include atmospheric transparency, seeing, meteorological conditions (e.g., surface wind, snowfall, near-surface temperature, lightning safety), and sky brightness/interference. Geographical and geological conditions include local topography (i.e., slope, roughness), seismicity, mechanical/electric/thermal properties of rocks/soils, and source availability (i.e., latitude and skyline). Non-technical issues such as existing infrastructure, accessibility, status of the host country (e.g., political status, environmental issues, satisfactory agreement, labor level), construction cost, and easiness of getting fund sometimes play major roles in determination of the site. The scores and relative weighting of these conditions depend on the scientific objectives, specifications, and cost of the instrument, as well as who is to promote and who is to fund. Even more complicated, they are often time variable and need to be modified within the boundaries of given budget, schedule, and manpower of the project.

1.2. Pinpointing Candidate Site for ALMA

We have surveyed several tens of sites in the world that meet the above criteria for the Atacama Large Millimeter/Submillimeter Array (ALMA) as a joint effort among Nobeyama Radio Observatory (NRO), National Radio Astronomy Observatory (NRAO), and European Southern Observatory (ESO), and finally selected an $\sim$ 20 km $\times$ 20 km area near Cerro Chascón in northern Chile as the candidate site. In this area, there are at least two candidate locations suitable for construction of the ALMA instruments and facilities — Llano de Chajnantor (5050 m) and Pampa La Bola (4800 m) — located less than 10 km apart. Although both of the locations will be used to realize the largest 10 km configuration, smaller configurations and infrastructure will be located at either of these locations.

The largest difference of these two candidate locations include altitude, upwind/downwind, and local topography. Llano de Chajnantor is a ridge located 250 m higher than Pampa La Bola and upwind of nearby peaks. It is natural to expect better seeing and stronger wind at upwind sites (e.g., Llano de Chajnantor) whereas upslope winds mean fog, rain, and snow. Pampa La Bola is a $\sim$ 4 km $\times$ 4 km flat area adjacent to the international highway, and has obvious topographical and operational advantages. We should determine which site is better for installation of the ALMA instruments. We have been measuring atmospheric and geological conditions to quantitatively discuss this issue. Here we report current status of the comparison.

2. Atmospheric Conditions

2.1. Opacity

Since 1995 April, NRAO has operated at Llano de Chajnantor a 225 GHz tipping radiometer that is a DSB heterodyne receiver operating at 225 GHz with a 1.0–1.5 GHz IF bandpass (McKinnon 1987; Liu 1987). NRO installed at Pampa La Bola a similar tipping radiometer that is also a DSB heterodyne receiver but operating at 218.5 GHz with a 1.0–1.4 GHz bandpass (Kohno et al. 1995). Synchronization of these instruments were done to a few minutes.

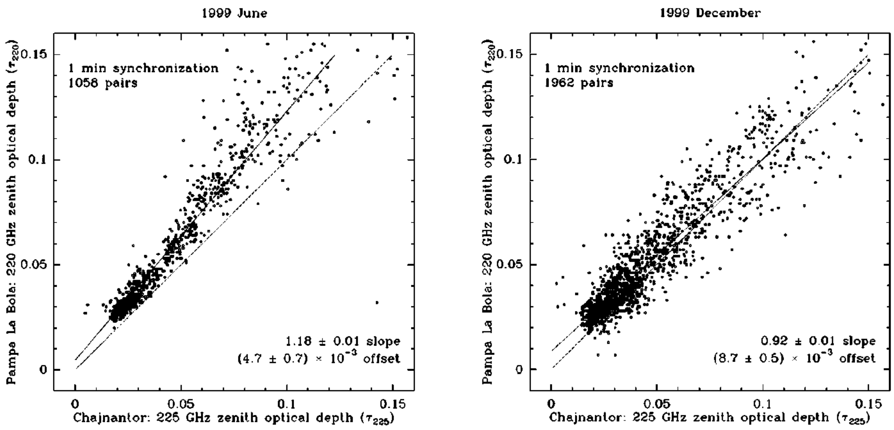

Figure 1. Comparison of 220 GHz opacity at Pampa La Bola and 225 GHz opacity at Llano de Chajnantor during 1999 June (winter) and December (summer). Adopted from Radford et al. (2001).

For the period from 1999 June to December, when the median 225 GHz opacity was 0.040 at Llano de Chajnantor, the 220 GHz optical depth at Pampa

La Bola was 15–30% higher (Radford et al. 2001). These data taken with radiometers operating with different frequencies and bandpasses may be directly comparable since results of the side-by-side calibration of these instruments carried out at Paranal on 1994 November 5–6 indicate that the difference is small ($|\tau_{225} - \tau_{220}| < 0.01$) at least with the median zenith opacity of 0.13 (Radford et al. 2001). Closer calibration will be needed to quantitatively discuss the difference under better conditions.

2.2. Radio Seeing

A preliminary comparison of seven weeks of phase stability site testing data from the Pampa La Bola and Llano de Chajnantor sites were carried out by Holdaway et al. (1997). The comparison indicates that the overall distribution of rms phase errors is similar for the two sites (the median rms phase error is about 17% higher at Pampa La Bola). However, at any given time the rms phase on the site testing interferometers' 300 m baselines may be very different at the two sites, sometimes by as much as a factor of 10.

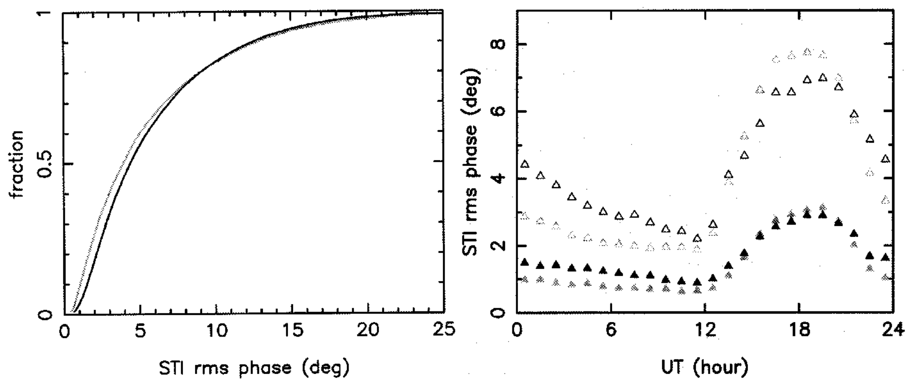

Figure 2. Left: Cumulative distributions of the rms phase measured with site testing interferometers located at Pampa La Bola (*black line*) and Llano de Chajnantor (*gray line*). Adopted from Butler et al. (2001b).
Right: Tenth (*filled triangles*) and fiftieth (*open triangles*) percentiles of the rms phase at Pampa La Bola (*black*) and Llano de Chajnantor (*gray*) plotted versus hour. Adopted from Butler et al. (2001b).

Statistical comparison of the radio seeing at these two sites were carried out by Butler et al. (2001b) using the data concurrently taken at both sites. Analyzed in their study included 25221 of 10-minutes periods in from July 1996 through March 1999. The median phase fluctuations at Llano de Chajnantor were $\sim$ 11% better than at Pampa La Bola (and $\sim$ 25% better than at Mauna Kea; NRAO 1998), confirming the trend reported earlier by Holdaway et al. (1997). Interestingly, the phase stability at Pampa La Bola is better than at Llano de Chajnantor during the windy daytime. Generally accepted hypothesis that the phase stability may be worse at Pampa La Bola because of wind coming up over the local peaks and becoming turbulent need to be revisited.

2.3. Surface Weather

NRO has been monitoring meteorological conditions at these two sites since 1996 with identical automated weather stations. Measurable differences exist in the meteorological conditions at these two sites (Sakamoto et al. 2000b). The wind was significantly weaker at Pampa La Bola than at Llano de Chajnantor during the nighttime (UT−4h = 22h–9h) of the summer (January–April) and marginally weaker during the daytime of the winter, while it was marginally stronger during the daytime of the summer and the nighttime of the winter. On the other hand, the wind flow appeared to be slightly less organized (as determined from the variation of wind direction) at Pampa La Bola than at Llano de Chajnantor, possibly because of the mountains located to the west of Pampa La Bola. The site at Pampa La Bola had a marginally larger fraction of clear days than did the site at Llano de Chajnantor. The near-surface temperature was lower at Llano de Chajnantor by 1.8 K on average, probably reflecting the 250 m height difference between the two sites. During many summer mornings, however, Pampa La Bola was colder than Llano de Chajnantor, likely due to a temperature inversion in the lower atmosphere at the altitude of the sites. The 250 m height difference also results in 3.3% difference in barometric pressure. The surface water vapor pressure was generally lower at Pampa La Bola than at Llano de Chajnantor, probably reflecting local surface effects.

2.4. Precipitation and Snow Cover

Precipitation, snow cover in particular, have significant weight in terms of efficient operations and site safety. Although there is no instrument directly measuring precipitation and snow in this area, the CBI team operating at Llano de Chajnantor claims that their site has more snow cover than Pampa La Bola (A. Readhead 2000, private communication). LANDSAT Thematic Mapper image of this area suggests that there is more snow left in the western part of the ridge including Llano de Chajnantor. The road that directly links Llano de Chajnantor to the Jama pass road through the western (upwind) slope is often covered with snow and nobody now uses that road for safety reasons. All of these are naturally understood by the natural trend that upwind slopes of mountains tend to have more precipitations than downwind. Lower temperature and more undulating topography at Llano de Chajnantor may also be contributing to keep the surface covered with snow for longer (but still short enough) period.

3. Geographical and Geological Conditions

3.1. Topography

Local topography has relatively high priority for interferometers like ALMA. Butler et al. (2000) presented considerations involved in finding the best location for the compact (maximum antenna separation $<$ 200 m) ALMA configuration on the science preserve. Several candidate locations for the compact configuration are then suggested.

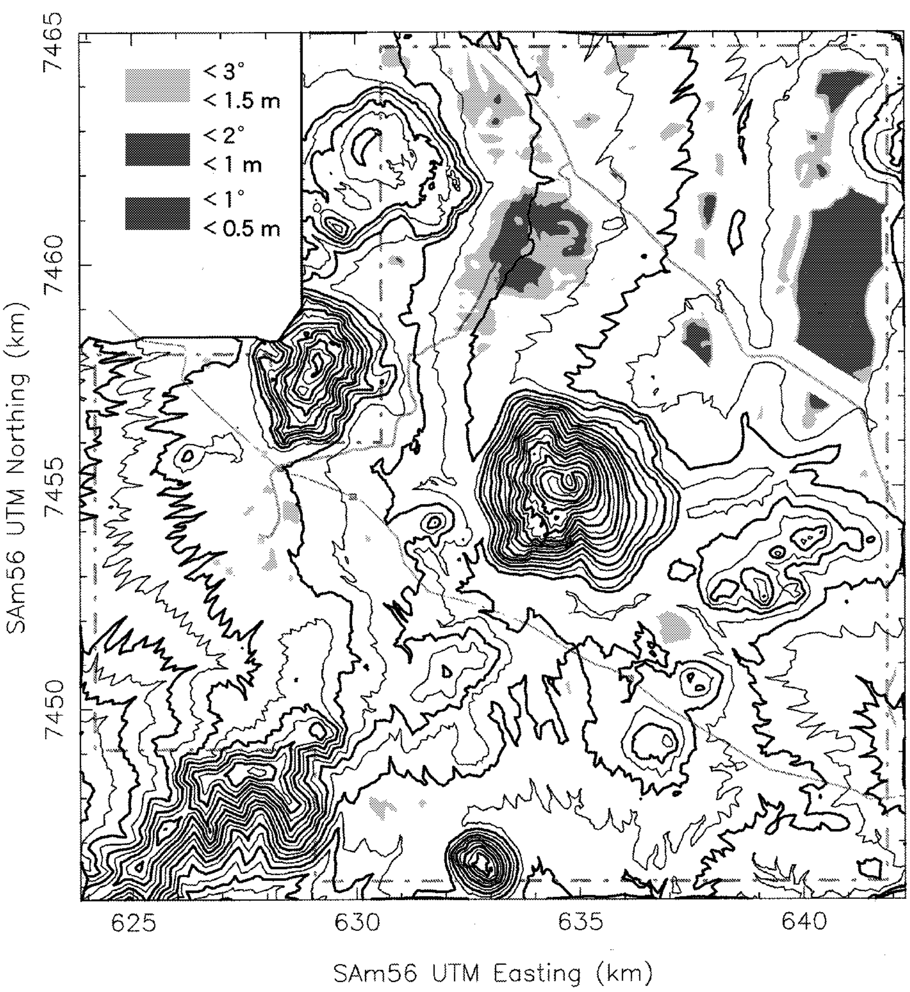

Figure 3. Topography of the Cerro Chascón science preserve area. Thick contours are at 100 m intervals, thin contours are at 50 m intervals. The central peak is Cerro Chascón, and the peak northwest to Cerro Chascón is Cerro Chajnantor. Llano de Chajnantor, Pampa La Bola, and Pampa El Vallecito are flat areas to the west, to the north, and to the northeast of Cerro Chascón, respectively. Centers of areas of 500 m diameter that are smooth and flat in the study area are shown: Areas with tilt angle $< 1°$ and roughness < 0.5 m are in dark gray, $< 2°$ and roughness < 1.0 m in medium gray, and $< 3°$ and roughness < 1.5 m in light gray. Note that study areas do not include those with $> 15°$ shadowing or those too close (< 400 m) to gas pipelines. Adopted from Butler et al. (2000).

As for the larger configurations, Pampa La Bola has obvious advantages both in terms of configuration design and operations. We may manage 3 km array to fit in Llano de Chajnantor though not optimal. We can optimize the array configurations at Pampa La Bola up to 4–5 km configuration with a 5° slope criterion. This will avoid a huge gap to the largest 10 km configuration.

3.2. Soil Conditions

Mechanical Stability Geotechnical characteristics of the subsurface at six positions spreading over the Cerro Chascón science preserve area were examined with boreholes of 15 m depth each (NRO–NRAO 1999). The results show that the upper horizon of broken to very broken changes in depth with location, while the depth to massive rock is not high, varying from 1.6 m to 7.0 for five of the six sites investigated. Thickness of very broken layer that can be excavated with a small backhoe is typically 30 cm at Llano de Chajnantor and 70 cm at Pampa La Bola, probably reflecting history of weathering processes depending on local topography and drainage.

Resistivity Near-surface soil resistivity is a basic parameter to the design of effective grounding and lightning prevention/protection system. Located at very flat site without any trees or man-made structures other than the ALMA instruments and facilities themselves, we might expect some of the element antennas being hit by lightning if the site was covered with storm clouds. In fact, the ESO camp at Llano de Chajnantor was hit by lightning at 9:41 UT on January 27, 2000, with their power inverter failed. Three computers inside the adjacent NRAO container were also damaged due to surge currents. One hazard in our five years' activities in the Cerro Chascón science preserve suggests that we should not be too optimistic about the threat of lightning in this region. Even worse, lightning is expected in summer when the array is most likely in the compact configuration, and significant fraction of the array elements might be damaged due to surge currents by even single lightning event. Because no significant difference in the occurrence of the storm clouds was found over this area (Sakamoto & Radford 2001), only grounding resistance may concern about this issue.

Results of resistivity sounding of eight locations in the Cerro Chascón science preserve area were reported by Sakamoto et al. (2000a). The depths of the upper layer of broken rock found at these sites are of order a few meters, and are consistent with depths found from borehole cores obtained near each location. The soil resistivity near the surface measured with the Wenner method was $\sim$ 1000 Ω m at the five locations in the Pampa La Bola area. The values at the three locations in the Llano de Chajnantor area were much higher, exceeding 3500 Ω m. This difference probably reflects differences in water content in the upper soil layer due to local topography and drainage. Sakamoto & Sekiguchi (2001) further examined near-surface soil resistivities of twenty-one sites in the Cerro Chascón science preserve area in the Wenner method with a fixed electrode spacing of 2 m. There were systematic differences in soil resistivities near the surface: The values in the Llano de Chajnantor area were much higher than those in Pampa La Bola and exceeded 4400 Ω m, resulting in > 20 times larger area to realize the same grounding resistivity in the Llano de Chajnantor area.

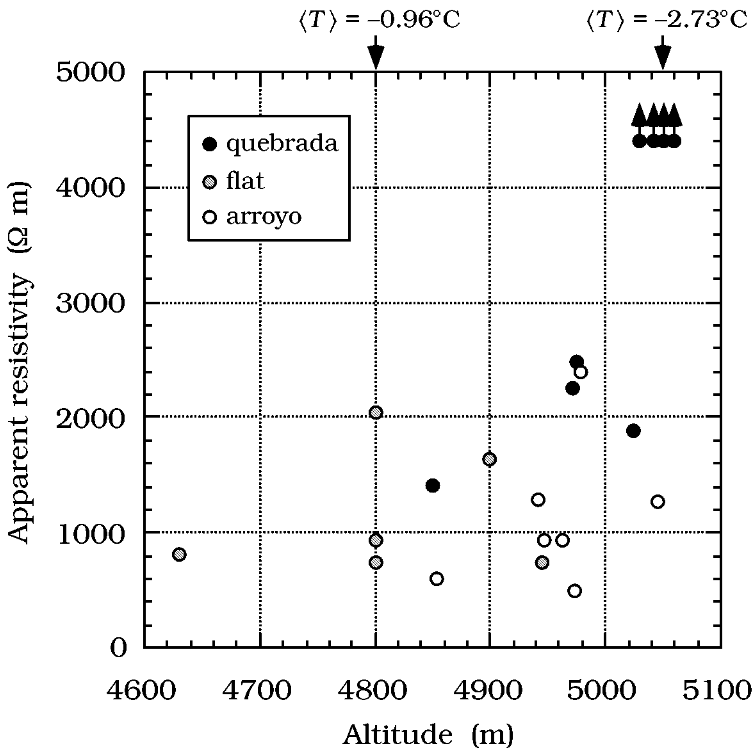

Figure 4. Apparent resistivity at the twenty-one locations measured with a fixed Wenner electrode spacing (2 m) as a function of the altitude. Filled circles, shaded circles, and open circles indicate that the topography of the corresponding location is quebrada, flat, or arroyo, respectively. Mean atmospheric temperature measured at Pampa La Bola (4800 m) and Llano de Chajnantor (5050 m), which will be reflected in the subsurface temperature, is also indicated on the top. Adapted from Sakamoto & Sekiguchi (2001).

Thermal Conductivity Thermal conductivity of soil has impact on needed depth of trenches to thermally insulate fiber optic cables. Thermal conductivity of the upper layer at Llano de Chajnantor was measured by NRAO down to 30 cm, and was found to be very low with the median value of only 2.4×10^{-7} m^2 s^{-1} (Snyder, Radford, & Holdaway 2000). NRO has been monitoring subsurface temperature profile at Pampa La Bola down to 1 m since the end of 2000 January, and found significantly higher thermal conductivity (Sakamoto 2001). This may reflect probable difference of water content due to local topography and drainage. Because of the difference of very broken layer at these locations, thermal insulation at the depth that can be easily trenched with a small backhoe is comparable at these two locations.

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