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Table of Contents

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1 Introduction

Before the start of the AtLAST design study, two working groups already started to investigate the site selection of a large submm telescope. The ESO submm single dish scientific strategy working group looked mostly at science cases, but already started looking into sites at different elevations (3000, 5000 and 5600m). As part of the workshop discussing these results, a working group on site selection and operations laid the foundations for the AtLAST work package 3. Overall, this working group recommended to look preferentially at sites in the wide area of the Atacama Astronomical Park (AAP). The AtLAST WP3 therefore only considers these locations.

2 Site selection criteria

2.1 Scientific criteria

The AtLAST science cases are being defined by WP6, but they all assume that the telescope is located at a site suitable for submm astronomy.

Otarola et al. 2019 published a detailed study of the meteorological conditions on the Chajnantor area, based on decades of site monitoring observations. The current document does not intend to reproduce this analysis. However, the overall conclusion is within a given area, the atmospheric transparency is driven by the amount Precipitable Water Vapour (PWV), translated mostly into altitude of the site above mean sea level (AMSL). A site of at least 5000m AMSL is required to obtain a sufficiently large fraction of time to observe up to 500 GHz. To improve the transparency in the submm bands up to 1 THz, moving beyond the Chajnantor plateau to the 5600m AMSL Chajnantor peak could increase this observability window by a factor of 2 to 3, assuming one would require PWV<0.3mm for such THz observations.

However, low PWV is not the only relevant scientific criterion. For a telescope with a 50m diameter dish, anomalous refraction (AR) is a concern. AR is created by cells of air with different refractive index due to their different PWV content passing through the telescope aperture. The net result of AR is that it creates varying pointing offsets during a scientific integration. The influence of AR on (sub)mm astronomy has been discussed in a number of ALMA Memos 186, 188 and 223, but also by Altenhoff et al. 1987, Downes & Altenhoff 1990 and Olmi 2001. An important point is that in mountain sites, the effect of AR may be enhanced when the inversion layer rises above the altitude of the telescope, which at Chajnantor occurs on a daily cycle (see Otarola et al. 2019). ALMA has solved the different AR values over the array with the installation of water vapour radiometers in all the antennas (see ALMA memos 224), but as a single dish, AtLAST won't be able to use this solution. Satoki 2018 discusses the effect of AR on a 50m AtLAST telescope, based on experience from the ALMA long baseline campaigns. From the analysis of phase fluctuations, the phase spatial structure function has been determined. For the ALMA site, the larger fraction of phase (or pathlength) fluctuations can be explained by fluctuations in PWV (see ALMA memos 496 and 541). Similarly, for the AtLAST telescope fluctuations of PWV across the aperture of the telescope will induce anomalous refractions. Extrapolating the information learned at the spatial scales of ALMA down to the aperture diameter of the AtlAST (50m) [Satoki 2018] and for median PWV conditions at the Chajnantor plateau, it can be inferred that the ratio of anomalous refraction to the beamsize of AtLAST ranges from 5% at 350 GHz up to 15% at 1THz. For the best 10% conditions (i.e. PWV at about 0.3 mm) this effect gets smaller by about a factor of 2 at the highest frequency bands. Consequently, important for minimizing the effect of anomalous refraction, is to locate AtLAST at a site where the atmospheric flow is less turbulent (i.e. more laminar). This implies avoid sites that may be affected by vortex shedding by upwind natural or artificial structures, or to steep slopes that may be affected by turbulence vortices created by wind shear, e.g.

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the area between Cerro Chajnantor and Cerro Chascón, between Llano de Chajnantor and Pampa La Bola. To better characterize the susceptibility to AR effects, it is important to have a good knowledge of the wind turbulence and the evolution of the vertical wind profile during the day, in particular at times when the inversion layer passes through the site.
A separate science driver would be the possibility to combine AtLAST with other submm telescopes as part of a global VLBI array, such as the EHT. To achieve this, AtLAST could be sited (like APEX) either very near ALMA to provide calibrations, or it could be sited several hundred km away to provide a new and unique baseline. The latter would have the disadvantage that AtLAST could not share any infrastructure with existing observatories. For the former, uv-plane coverage simulations of potential sites when combining AtLAST with ALMA would be required.

2.2 Telescope requirements

An important consideration for AtLAST is that the 50m telescope will be free-standing without the protection of a dome. The telescope should therefore withstand the elements such as wind, snow, and lightning. The exposure can vary significantly over the Chajnantor area depending on the geographical terrain and the exposure to the prevailing winds. We look at each of these three separately, as well as at the soil shape and composition.

2.2.1 Wind

The statistics of the wind speed and direction on Chajnantor are quite well known and have been presented by Otarola et al. 2019, where the longest observations have been obtained with APEX. Sustained winds are generally below 25 m/s, with gusts measured up to 38 m/s. However, there are also significant variations of the wind speed over the plateau, with mountain ridges and peaks exposed to the prevailing westerly winds generally suffering higher wind speeds due to the orographic forcing. AtLAST should therefore avoid a site which is too much exposed to the West and North-West. We can even reduce the average wind speed by selecting a site leeway of the prevailing winds. While looking for a protected site is beneficia from the pointing of view of mechanical pointing stability, and overall infrastructure safety, we should keep in mind that peaks upwind from the telescope give rise to turbulent vortices that may increase the spatial variability of absolute humidity (PWV), inducing anomalous refraction.
For a large moving structure like the AtLAST telescope, we should also have the wind power spectrum determined with high accuracy. The telescope design WP 2 has requested to know the power spectrum up to 10 Hz, which requires to measure the wind speed at rates of 20 Hz to have it Nyquist sampled.
Finally, the vertical wind profile on Chajnantor is already know from radiosonde launches (Otarola et al. 2019). However, the daily and seasonal variation of this vertical wind profile would also need to be measured to determine if strong gradients are expected on the telescope structure.

2.2.2 Snow

Experience from existing observatories on Chajnantor have shown that snow comes mostly in the form of small drift ice particles rather than classical snowflakes. The disadvantage of these small snow particles is that they can easily enter in small openings such as air intakes, doors, etc. This can lead to significant snow accumulations inside the telescope structures, where the snow can melt and lead to damage to sensitive electronics. From the outside, it can also block entrances. Hence a minimization of the expected snow at a given site would be beneficial to AtLAST.
To determine the snow coverage, WP3 members have used the technique developed by Juliette Ortet (Masters thesis ENSG, 2019), based on images of the SENTINEL satellite from 2015 to 2021. This provides an image every 5 days with a spatial resolution of 10m on the ground. Using a

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combination of bands, we can calculate the probability of snow coverage per pixel. While relatively uncertain per pixel, using this technique over a long period of time and a wide area provides a good statistical average of the probability of snow coverage. Using these maps, we have selected areas with low snow coverage. Figure 1 shows the resulting map with the two selected sites marked with red crosses. The darker the map, the less chance of snow accumulation.

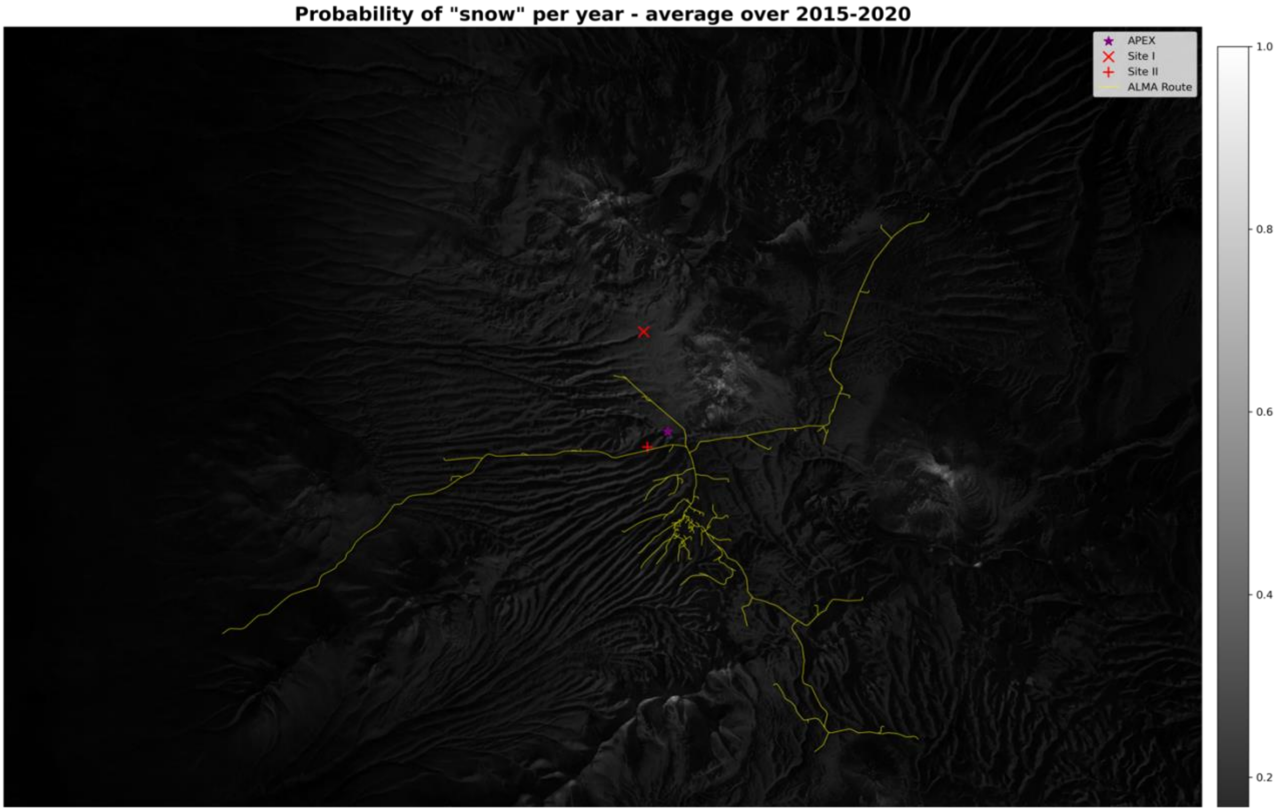

Figure 1: probability of snow as determined over the period 2016 to 2021. The greyscale bar on the right shows to probability of snow with increasing whiteness. One can notice the peaks of Cerros Chajnantor, Toco and Chascon, as well as the wavy terrain over the Llano de Chajnantor where snow remains longer on the slopes shielded from direct sunlight. The ALMA road network is overlaid in yellow, and the AtLAST sites I and II as red crosses.

2.2.3 Lightning

High mountain sites are also more susceptible to lightning strikes. A reliable grounding of the telescope is complicated due to the high resistivity of the soil, which is mostly composed of volcanic rocks and permafrost (see also ALMA memo 326, 346 and 413). It is therefore important to avoid areas with high lightning activity. Local experience shows that such areas often coincide with those mostly exposed to the prevailing westerly winds, such as the observatories on Cerro Toco and Cerro Chico where APEX has a telecommunications hub. A local lightning monitoring system would be required to verify the electrical activity at a proposed site.

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2.2.4 Terrain and soil composition

The current design of the footprint of the AtLAST telescope includes a circular Azimuth rail track with a diameter of roughly 35m [CHECK]. The telescope structure will be surrounded by additional nearby structures. This requires a relatively extended terrain of at least 100m x 100m, ideally relatively flat. Certain areas with unstable soil, steep slopes or ravines should be avoided.

Soil studies have investigated the depth of the bedrock on Chajnantor (see e.g. ALMA memo 413). During the lightning protection excavation works for the weather tower on site I, the depth to the bedrock was determined to be 125cm. As the AtLAST telescope will require a massive excavation for the azimuth track, a difference in depth of a few metres will not have a significant impact on the required civil works. It may be more important for the smaller supporting buildings, but this would also go along with the above point of the slope and ravines.

Experience from current observatories have shown that exposed metallic surfaces often experience corrosion. The exact cause of this is still under investigation, but it may be due to a combination of Sulphur and Chloride in the atmosphere. The Sulphur can be traced back to the abandoned open-air sulphur mine on Cerro Toco, while the Chloride may originate much further away, possibly related to mining activities. A recent sample collection campaign has investigated the geographical distribution of the soil contaminants and is currently under analysis. If it turns out that the proximity of Sulphur is detrimental to the surfaces, it would be best to avoid those areas. Moreover, a long-term exposure of Sulphur may be detrimental to the health of the AtLAST construction and maintenance staff.

2.2.5 Sky visibility

The design of the AtLAST telescope (see WP2) implies it will observe down to elevations of 20° but not lower. Any selected site should not be located too close to any high mountains which would block parts of the sky at elevations higher than 20°. This is a higher limit than most existing telescopes and allows to move closer to high mountains. There may even be an interest to get close to this limit if one would like to install a holography tower on one of the nearby mountains.

2.3 Accessibility and sharing of infrastructure

This class of requirements is set by the operations WP4.3 and will be described in further detail there. The main requirement is that the telescope should be easily accessible from one of the major roads such as the roads used by the ALMA transporter or the road of the Atacama Astronomical Park. This is required not only during the construction phase, where several very large parts will need to be transported, but also during the maintenance phase, e.g. when segments of the telescope may need to be brought down to San Pedro for photogrammetry. Also instrument installation and major maintenance may require transport using a sufficiently wide road.

For more regular maintenance activities, it is important that the access road be kept free of snow/ice. After significant snowfall, the first road to be cleared is usually the main ALMA access road. The AAP road is currently not yet being regularly cleared of snow, and would have to be done by the respective observatories using it.

As WP5 is looking into sharing renewable energy resources between AtLAST and the other observatories, connecting power lines should be envisaged. A site near existing power and network lines would be preferable to share existing resources.

2.4 Society and legal requirements

The legal requirements to install AtLAST will be covered by the WP3.3 and are part of deliverable D3.3 [CHECK]. WP3 is currently considering sites in two different concessions: Site I is part of the ALMA concession, while Site II is outside of the ALMA concession, but still within the AAP. The boundaries of the AAP have been defined to minimize the visual and environmental

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impact of the observatories, which should not be visible from the town of San Pedro de Atacama nor from the main Chilean roads (RCH-23 and RCH-27). As a 50m telescope, AtLAST would be the largest telescope up on Chajnantor, and should therefore be one of the first ones to be seen from a distance.

Both within the AAP and ALMA concessions, the environmental site selection studies have already been covered by a blanket approval. However, there are also several Chilean labour laws to consider for the site selection. Sites between 2500 and 5499m are considered "high altitude", but sites of 5500m or higher are considered "extreme altitude", where even stricter laws apply. The latter would severely complicate the operation of a complex observatory with innovative instrumentation, like the one foreseen for AtLAST. Hence, sites below 5500m should be strongly preferred.

In addition to the legal requirements, AtLAST should not interfere with any other observatories on Chajnantor. The most likely impact would be with ALMA, which has 238 antenna pads spread over the Chajnantor plateau. To avoid shadowing of ALMA antennas by AtLAST, or stray electromagnetic emission, AtLAST should be located at least 200 metres from any ALMA antenna pad or any other telescope.

3 Summary of selection criteria

Based on the above, we consolidate the selection criteria:

- Geographical altitude: between 5000m and 5500m
- Stable PWV, to minimize anomalous refraction effects
- Potential to combine AtLAST with other submm telescopes in VLBI
- Avoid exposure on a mountain top facing the prevailing W/NW winds
- Minimize exposure to lightning activity (mostly West facing mountain tops/ridges)
- Have a determination of the wind power spectrum up to 10 Hz
- Have knowledge of the vertical wind profile daily and seasonal variability
- Have minimized snow accumulation
- Have a stable soil, ideally with bedrock not deeper than a few metres
- Have a terrain that is relatively flat over 100m x 100m, avoid nearby ravines
- Minimize exposure to elements (e.g. Sulphur) causing corrosion on metallic surfaces
- Have an unobstructed view of the sky above 20° elevation
- Have an access road at least 10m wide and is kept free of snow
- Be near existing power and fibres
- Be located >200m from any existing/planned telescopes or ALMA antenna pads

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4 Preliminary results

Based on the above criteria, WP3 has selected two possible sites for further investigations. The figure below shows the two sites relative to the other telescopes and infrastructure on Chajnantor. The area of the AAP is shown in shaded blue:

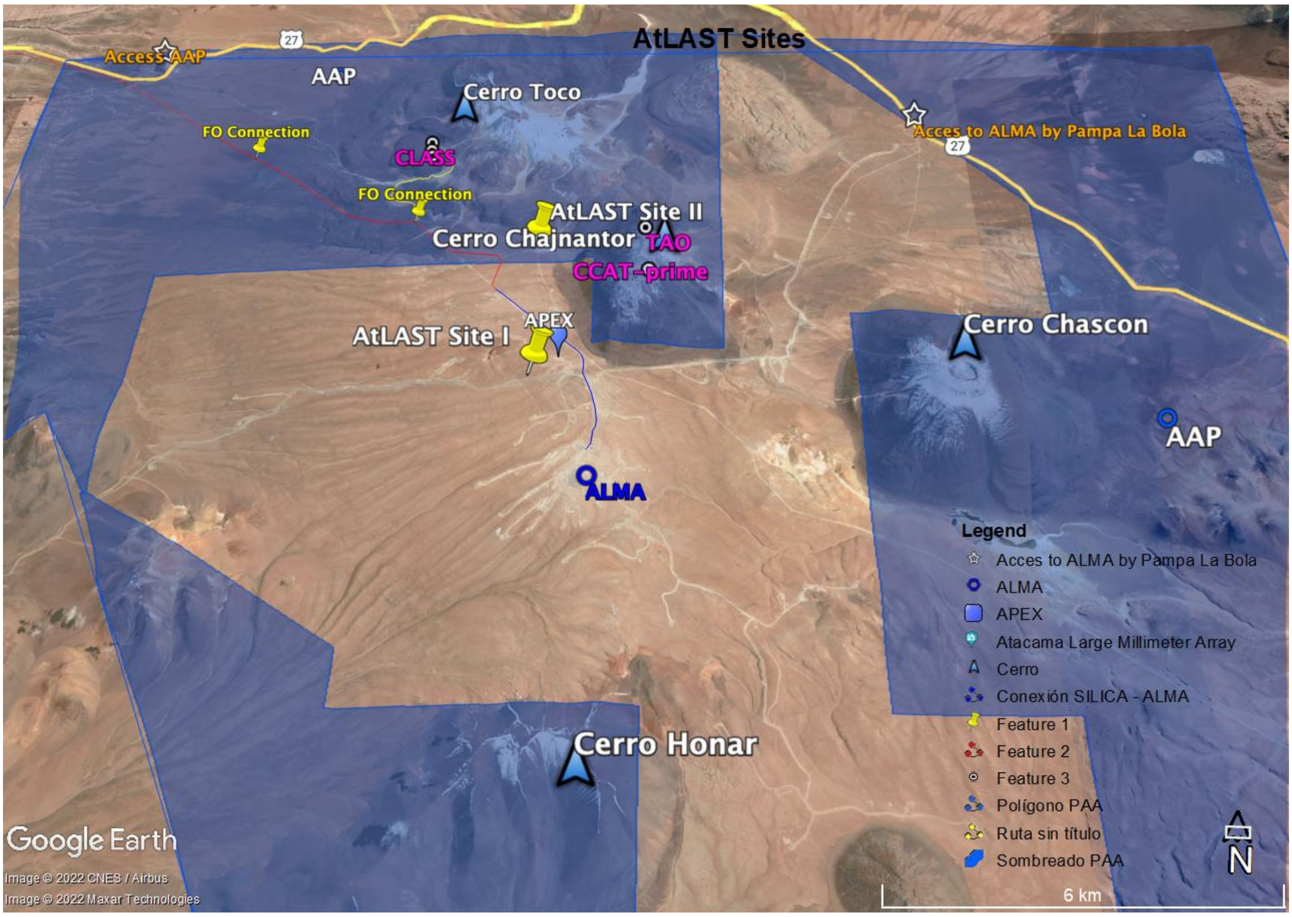

Figure 2: overview of the areas considered with the major geographical features marked. The AtLAST Sites I and II are indicated with yellow pins.

4.1 Site I

Latitude = South 23 00 34.2; Longitude = West 67 45 51.9; 5050m AMSL
This site is located in the ALMA concession, 10m North to the ALMA road between km 41.5 and 42, which makes it ideal in terms of accessibility and to share power/fibre infrastructure with ALMA. The nearest existing telescope is APEX, which is >400m away. It is a flat terrain of 200x400m with a gentle slope varying by ~5m. The soil is stable with the bedrock just 125cm below the surface. The snow coverage maps show it receives less snow accumulation, probably because it is shielded from the prevailing winds by Cerro Chico. This shielding may also reduce the exposure to lightning. One possible concern of Site I is that the vertical wind profile may show some turbulence being leeway of Cerro Chico. This needs to be determined with a wind measurement campaign, which is the main activity of WP3.2.

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4.2 Site II

Latitude = South 22 58 52.3; Longitude = West 67 45 56.4; 5000m AMSL
This site of ~300x500m is located outside of the ALMA concession, but inside the AAP on the north side of the AAP road, between Cerro Toco and Cerro Chajnantor. This makes it quite accessible, though snow clearing needs to be organized with the AAP. The site is near the start of a small canyon, but is sufficiently wide to locate the telescope far enough to avoid risk of flooding. A fibre connection is available 700m from the site. The selected area is quite flat, and unlike the nearby terrain South of the AAP road, there are no ravines. One concern could be the abandoned open-air sulphur mine on Cerro Toco. The proximity to Cerros Toco and Chajnantor would not be an issue with the telescope pointing >20° elevation. The prevailing winds may be partially shielded by Cerro Toco, which could also reduce the exposure to lightning. The wind speed has not yet been measured at this location and requires a dedicated campaign as part of the WP3.2 activities.

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