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The best sites for the compact ALMA configuration

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Introduction

We present considerations involved in finding the best location for the compact (maximum antenna separation $\lesssim 200$ m) ALMA configuration on the science preserve. Several candidate locations for the compact configuration are then suggested. Note that we distinguish here between the compact ALMA configuration and the so-called "Atacama Compact Array" (or ACA) which is a separate collection of smaller antennas. We do not consider the placement of the ACA in this memo.

Description of the study area

In this memo we consider the entire area for which we have high resolution digital maps, which encompasses the entire extent of the current science preserve. This study area is roughly bounded by UTM coordinates 624000 – 642000 E and 7446000 – 7465000 N (SAm56 datum; Radford 1999). Figure 1 shows the study area, along with the topography (taken from the work of Holdaway *et al.* [1996] and recent extensions of that work), and some landmarks. Included in this area is the so-called "Chajnantor" area - south of Cerro Chajnantor and west of Cerro Chascon, and the so-called "Pampa La Bola" area - east of Cerro Toco and north of Cerro Chascon. The Chajnantor area has been extensively studied by both NRAO and ESO for several years now (Radford & Holdaway 1998; Otárola *et al.* 1998). The Pampa La Bola area has been studied by the NRO for several years (Ishiguro 1998). Also included in this area is the so-called "Pampa El Vallecito" area - north and northeast of Cerro Chascon. We have little qualitative and no quantitative information on this area.

Placement considerations

In choosing the location of the compact configuration, many things must be considered, including accessibility, thickness of surface weathering layer, proximity to the gas pipeline, shadowing by nearby volcanic peaks, local terrain (including slope and roughness), and astronomical quality of the site (e.g., weather, opacity, and phase stability). Most of the

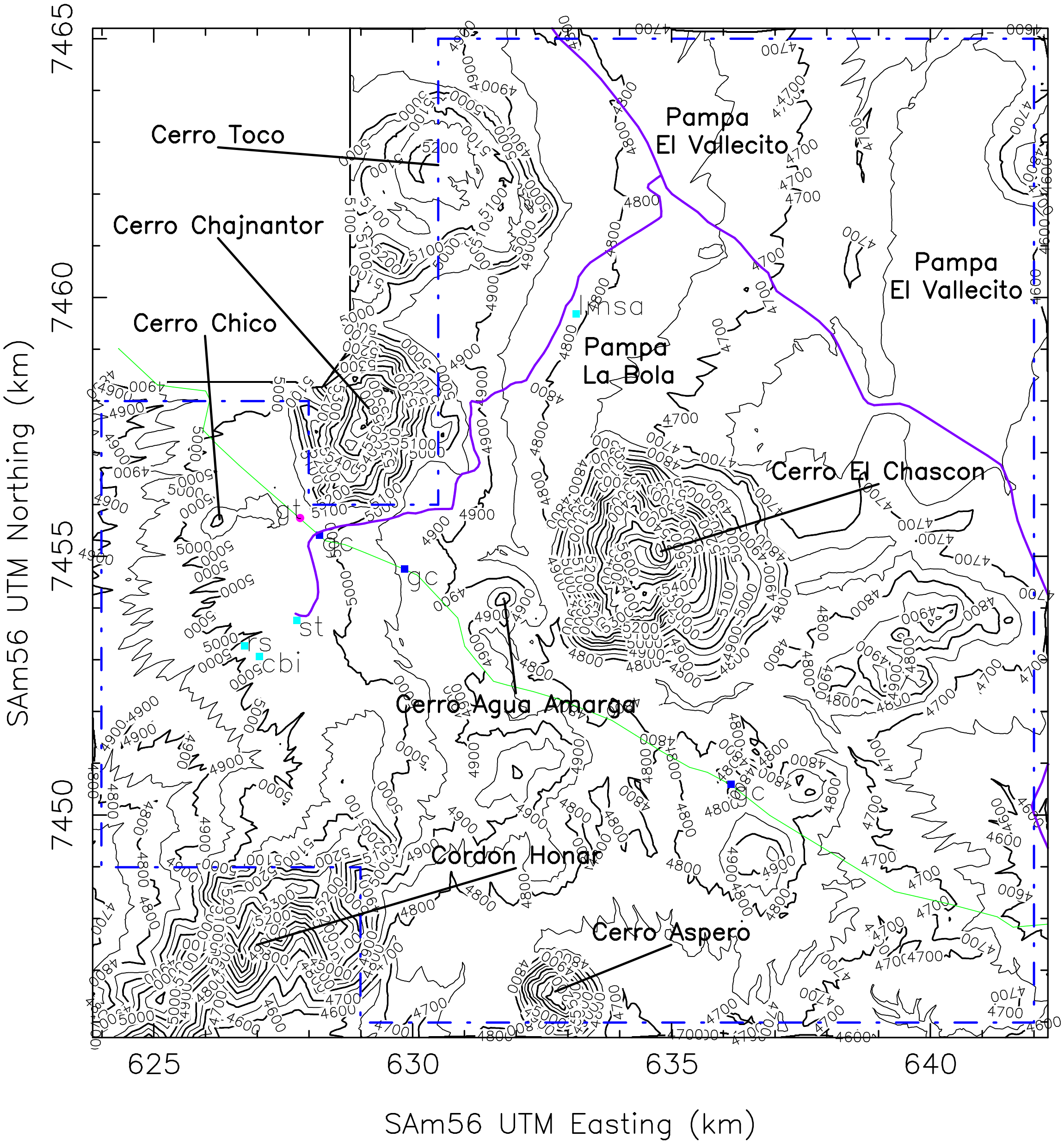

Figure 1: Topography of the study region. Thick contours are at 100 m intervals, thin contours are at 50 m intervals. Gas pipeline is shown as green line, gas crossings as blue squares (labelled 'gc'), and gas tap as pink circle (labelled 'gt') [all data from A. Otárola, L. Araya, and C. Arqueros]. Approximate locations of the Jama highway and the east access road to the site are shown in purple [data from S. Sakamoto]. CONICYT science preserve boundary is shown as a dot-dashed blue line. Cyan squares are as follows: 'st' → NRAO and ESO test containers; 'rs' → radiosonde container; 'lmsa' → NRO test container; 'cbi' → Cosmic Background Imager telescope and facilities.

locations in the study area are equally easily accessible, so we do not consider that as a limiting constraint. We only currently have limited information on the how the weathering layer thickness varies with location within the study region (see the NRO-NRAO Geotechnical Report in LMSA memo 2000-04), so we do not treat that consideration further here. We note, however, that the thickness of the weathering layer may have a large impact on construction cost, and so a more complete study of both the variation of the thickness of the weathering layer across the entire science preserve, and its impact on construction cost is needed. We exclude from consideration areas which are too close to the boundary of the science preserve. We take 100 m as an acceptable distance from the boundary, but no closer. We now treat each of the other considerations separately.

Proximity to gas pipeline

The Gas Atacama (GA) pipeline cuts through our study area from the southeast to the northwest. The current agreement with GA is to not build within 400 m of the pipeline. Therefore, locations in the study area closer to the pipeline than this were excluded from consideration for the compact configuration. There is another gas pipeline (built by Norandino) which runs approximately parallel to the Jama highway. There is no formal agreement with respect to building next to this pipeline (or the Jama highway for that matter), but we consider that there should be a similar distance from that pipeline to any antennas. We have no good coordinates for that pipeline, so we use rough coordinates for the Jama highway as a proxy for the pipeline coordinates (provided by S. Sakamoto).

Shadowing by volcanic peaks

The study area is surrounded by tall volcanic peaks, which will provide obstacles to observing astronomical objects at low elevations (and particular azimuths). We have calculated the shadowing at every location in the study area due to all other locations in the area. Not allowing areas which are shadowed by 15° or more (which we consider a sensible limit) excludes a significant portion of the study area from consideration for the location of the compact configuration. Figure 2 shows the 15° shadow regions from these peaks as colored areas on the topographic map, as well as the areas excluded because of proximity to the gas pipeline. Also included in Figure 2 are areas which are outside the science preserve, and those within 100 m of its boundary. One could argue that the shadowing constraint should be azimuthally dependent - because shadowing to the north is more critical than in other directions. This is probably valid when addressing questions of where to place individual antennas for the more extended configurations, but we feel that the stricter constraint is more appropriate when considering the position of the entire compact configuration.

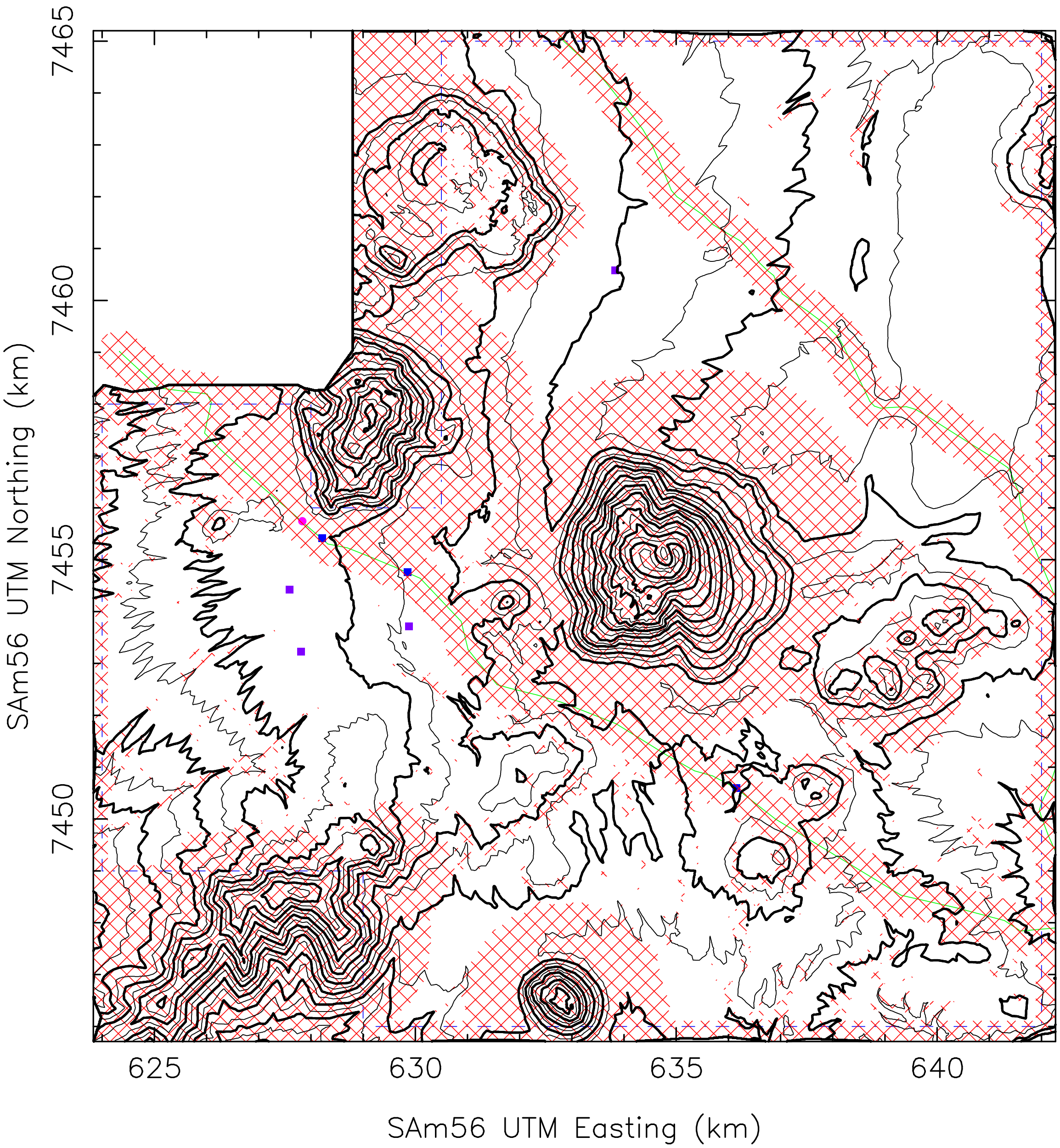

Figure 2: Areas shadowed by more than 15° by surrounding volcanic peaks, closer than 400 m to the gas pipelines, and outside or near the boundary (< 100 m) of the science preserve (all cross-hatched red). The topography contours and other markers are as in Figure 1.

Local slope and roughness

We should place the compact configuration in a place that is "smooth" and "flat", if possible. These terms are somewhat vague, but in practice this can be achieved by minimizing slope and roughness in the region where the compact configuration will be located. Places that are too steep or too rough will make construction more difficult and hence more costly.

We use here the surface tilt angle as a measure of slope. We define the surface tilt angle as the deviation from vertical of the normal of the best-fit plane to the points within a given radius of the location under consideration. We define the roughness as the rms deviation of the surface heights after the removal of that best-fit plane. The size of the regions we are considering here is 200 m (diameter), which is most likely somewhat larger than the compact configuration (the compact configuration is about 150 m in diameter for 64 12 m diameter antennas with 40% filling factor), but allows some room for outlying structures, roads, turnouts, etc... (if needed). Note that over 200 m, a 1° tilt angle results in about 3.5 m of relief. So, we would like the tilt angle to be $\lesssim$ a few degrees. We would probably like the rms roughness to be less than a meter or so, if possible. These two limits are somewhat arbitrary, but are based on the possibility of having to excavate into solid bedrock if the tilt angles or rms roughness are too large. Depths to solid bedrock as shallow as 1.6 m were encountered when drilling a number of boreholes - see Table 2 of the NRO-NRAO Geotechnical Report in LMSA memo 2000-04. Note, however, that if the cost of excavating into solid bedrock (and earth-moving in general) are very small, then we could allow for regions with larger tilts and roughnesses. We currently have no real estimates for these costs, so we have taken a conservative approach in this respect. Figure 3 shows a plot of the derived tilt angles over the entire study area, in 200 m diameter areas. In this figure, the regions with tilt angles less than 2° are colored red, orange, and yellow, and are the regions of interest. Figure 4 shows a plot of the derived rms roughness over the entire study area, in 200 m areas. In this figure, the regions with rms roughness less than 1 m are colored red, orange, and yellow, and are again the regions of interest.

We consider three combinations of maximum surface tilt angle and rms roughness: 0.5° tilt angle and 0.25 m roughness; 1° tilt angle and 0.5 m roughness; and 2° tilt angle and 0.5 m roughness. Figure 5 shows the centers of the areas that satisfy these constraints and also are not in the areas which are prohibited by proximity to the science preserve boundary, gas pipeline, or volcanic peaks.

Are there even larger regions which are relatively smooth and flat? This is of interest because it would be nice to be able to put the larger configurations in the same place (the next configuration size is of order 450 m). We went through the same exercise for 500 m regions and found the regions which are the smoothest and flattest in the study area on this scale. The only regions which satisfy the same criteria as for the 200 m regions which are plotted in Figure 5 are in the Pampa El Vallecito area. If we loosen the criteria somewhat, then regions in Pampa La Bola and finally in Chajnantor begin to satisfy these slightly relaxed criteria. Figure 6 shows these areas which satisfy constraints of 1° tilt angle and 0.5 m roughness, 2° tilt angle and 1 m roughness, and 3° tilt angle and 1.5 m roughness.

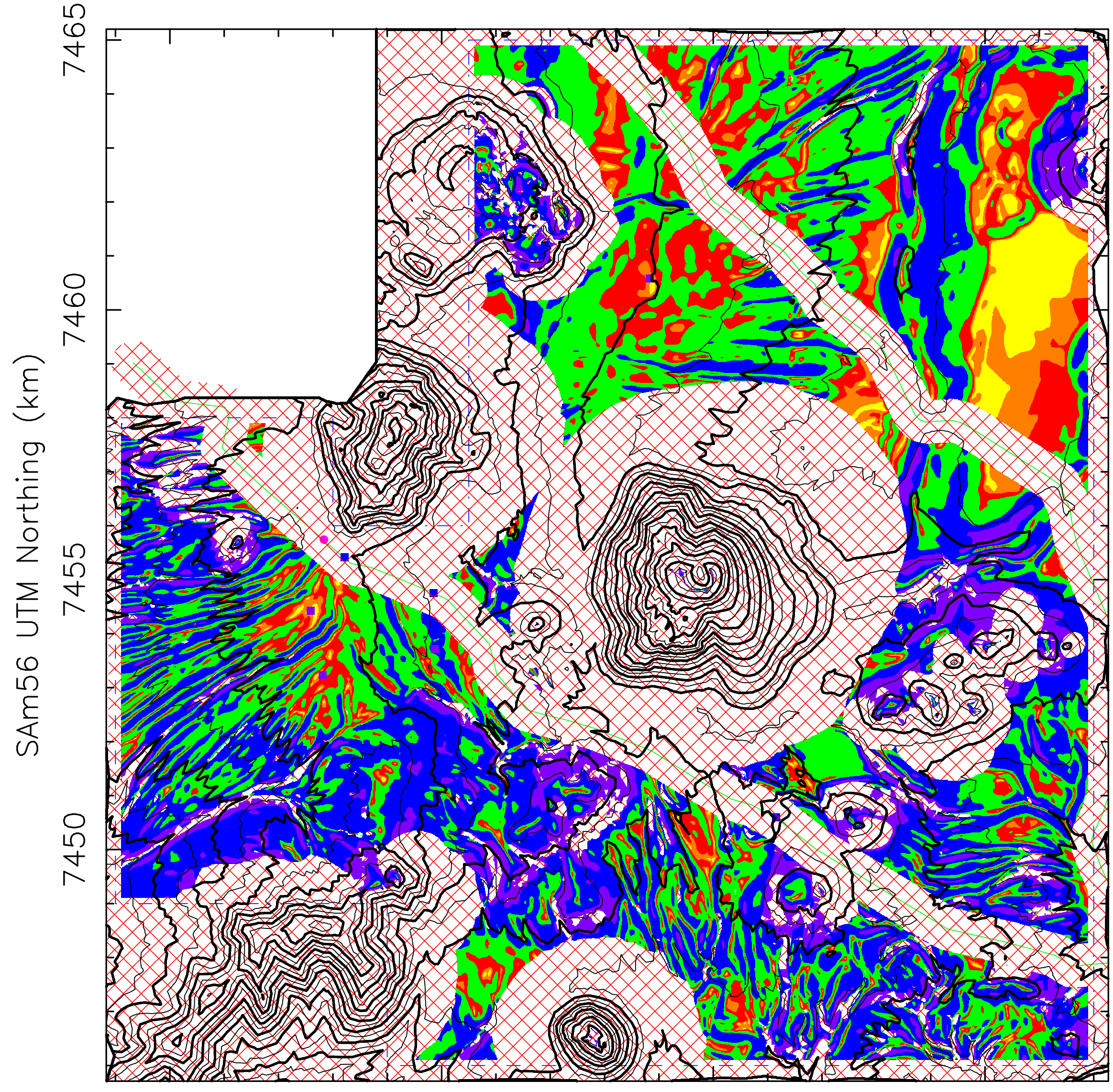

Figure 3: Surface tilt angles across the study area. This is tilt angle in a 200 m diameter region surrounding each point. Tilt angles are color coded: yellow = tilt angle < 0.5°; orange = 0.5° < tilt angle < 1°; red = 1° < tilt angle < 2°; green = 2° < tilt angle < 4°; blue = 4° < tilt angle < 8°; purple = 8° < tilt angle < 16°; black = tilt angle > 16°. Disallowed areas are hatched in red. The topography contours and other markers are as in Figure 1.

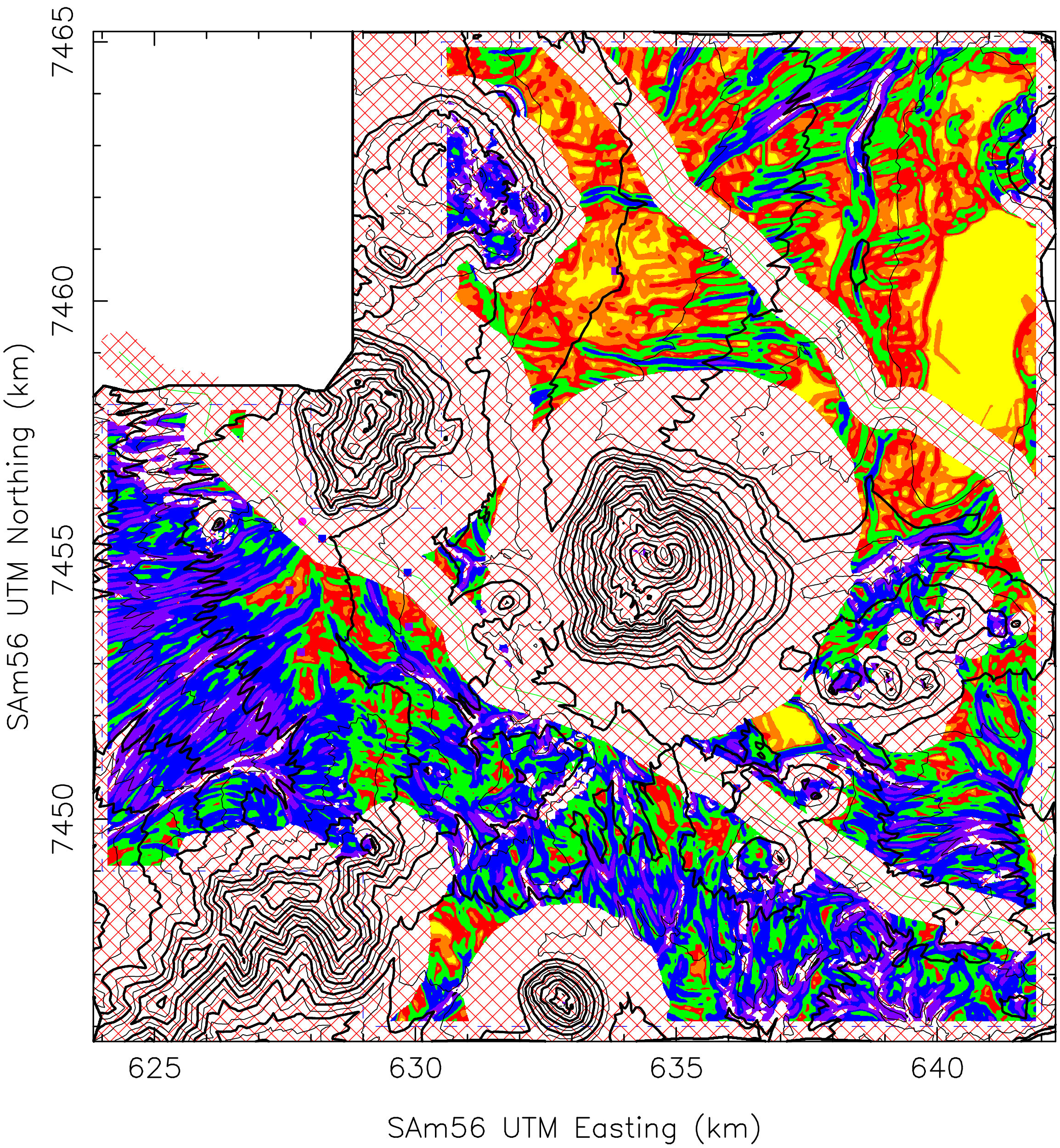

Figure 4: Roughness across the study area. This is rms roughness in 200 m diameter regions surrounding each point, after removing best-fit plane. Roughness is color coded: yellow = roughness < 0.25 m; orange = 0.25 m $<$ roughness < 0.5 m; red = 0.5 m $<$ roughness < 1 m; green = 1 m $<$ roughness < 2 m; blue = 2 m $<$ roughness < 4 m; purple = 4 m $<$ roughness < 8 m; black = roughness > 8 m. Disallowed areas are hatched in red. The topography contours and other markers are as in Figure 1.

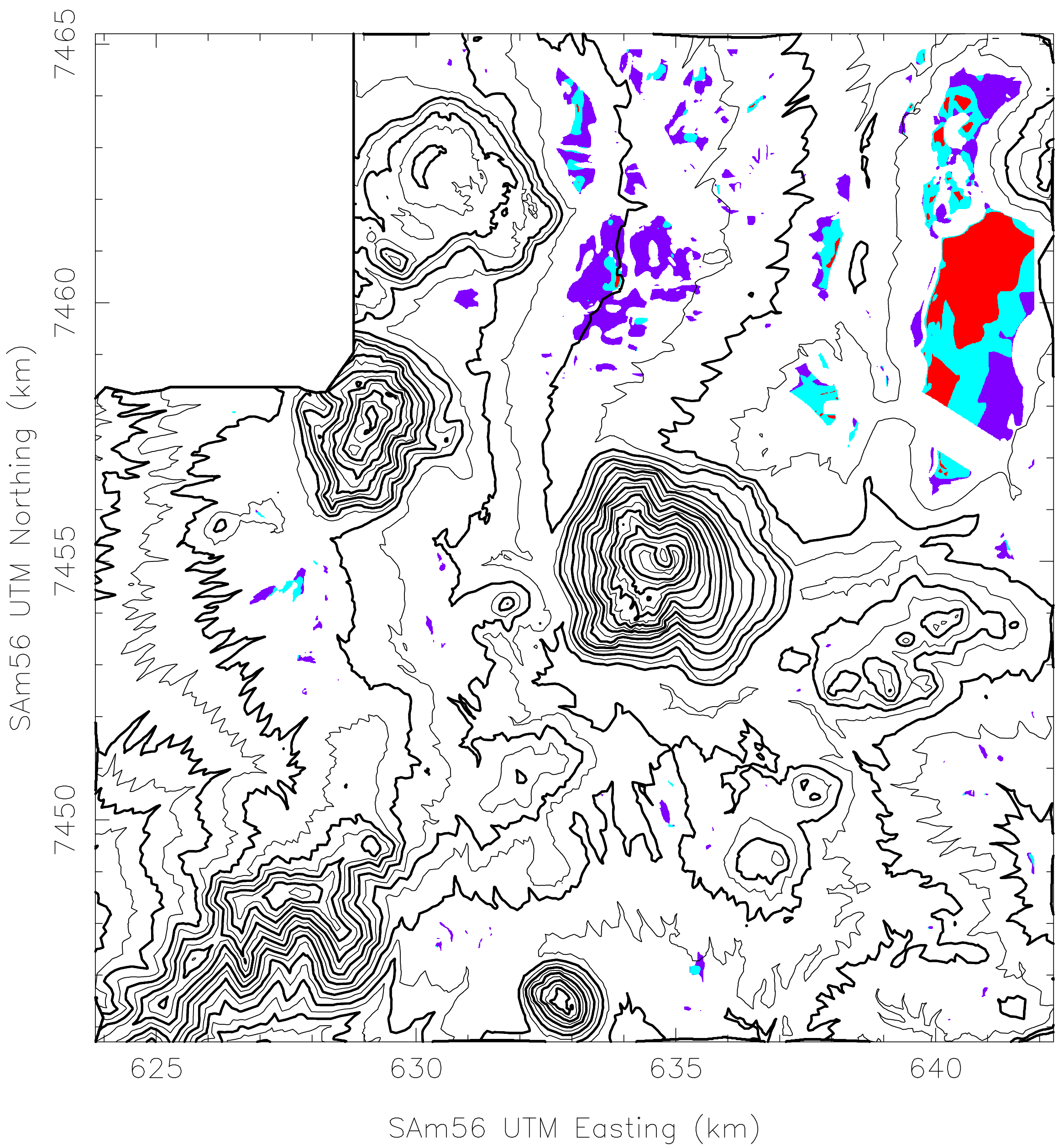

Figure 5: Centers of areas of 200 m diameter that are smooth and flat in the study area. Areas with tilt angle $< 0.5^\circ$ and roughness < 0.25 m are shown in red. Areas with tilt angle $< 1^\circ$ and roughness < 0.5 m are shown in cyan. Areas with tilt angle $< 2^\circ$ and roughness < 0.5 m are shown in purple. The topography contours are as in Figure 1.

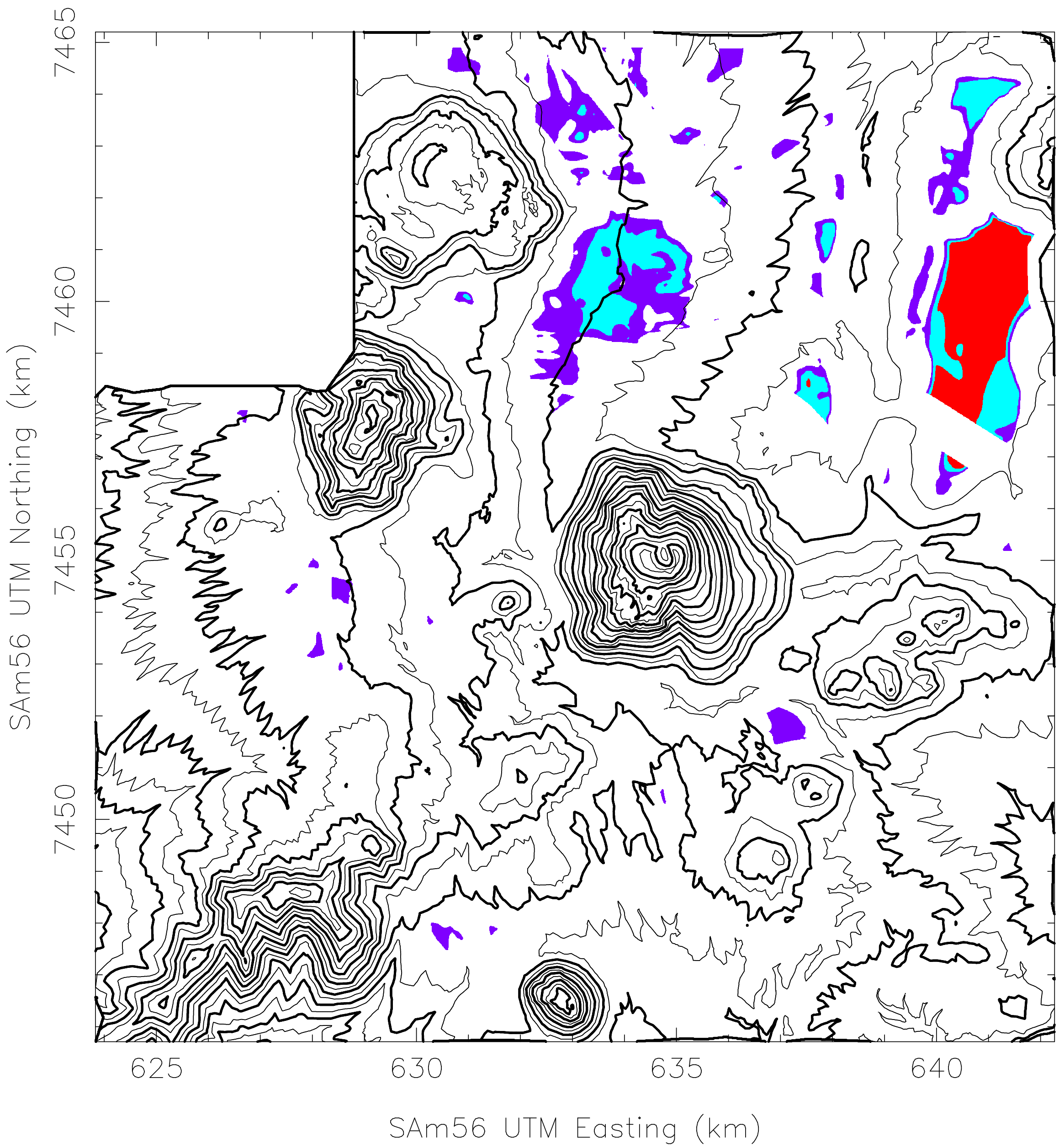

Figure 6: Centers of areas of 500 m diameter that are smooth and flat in the study area. Areas with tilt angle $< 1°$ and roughness < 0.5 m are shown in red, those with tilt angle $< 2°$ and roughness < 1 m are shown in cyan, and those with tilt angle $< 1°$ and roughness < 2 m are shown in purple. The topography contours are as in Figure 1.

Weather, opacity, and phase stability

We would like to know how the astronomical quality varies from place to place across the entire study area in detail. A rough indicator of this may be obtained from surface weather data. The analysis of several years of weather data (including wind, temperature, relative humidity, and solar flux) obtained at Chajnantor and Pampa La Bola indicates that while there are differences between the two sites, these differences are not significant enough to seriously influence a decision on which is the "better" astronomical site (Sakamoto *et al.* 2000). Much better indicators of the astronomical quality are the atmospheric opacity and phase stability. These two quantities have been measured at the locations of the site testing containers (at least sporadically) over several years now. A preliminary analysis of a small amount of phase stability data (from Jul-Sep 1996) from the NRAO and NRO container locations showed that the Pampa La Bola site was slightly worse in phase stability than the Chajnantor site (Holdaway *et al.* 1997). It has been postulated that this is due to local turbulence caused by the wind as it rises up over Cerros Chajnantor and Toco. This has yet to be shown conclusively, however, and a more complete comparison of both the phase stability and opacity data from the two locations is needed. We have no data for sites further to the east (e.g., Pampa El Vallecito) and thus no comparisons are possible. We can say crudely that we expect the opacity to be worse at lower elevations (and hence Chajnantor to be best, followed by Pampa La Bola, and finally Pampa El Vallecito), but without data, this is not quantifiable. Until a good comparison of site testing data is made, and one or the other site shown to be clearly better than the other, it seems somewhat hasty to exclude any site from consideration based on this criterion.

Discussion

There are locations in both the Chajnantor and Pampa La Bola areas which are good candidates for the location of the compact ALMA configuration. There is also a very large region in Pampa El Vallecito which might be a good candidate for that location. Without any data in hand to evaluate the Pampa El Vallecito area, however, it seems that it will be hard to justify selection of this area for the location of the compact ALMA configuration. Table 1 shows all of the locations, along with an indicator of their "quality", in terms of flatness, roughness, and extent. Note that there are so many good locations in Pampa La Bola that we have not attempted to make an extensive tabulation of them, but merely put the best one in the table. Also note that in the Chajnantor area, the preferred locations are mostly along the high ridge in the western portion of the area. Table 1 also shows the proposed centers of the compact configurations in the two current strawperson configurations (Yun & Kogan 2000; Conway 2000) for comparison.

We note that the selection of the location of the compact configuration may have serious implications for the configuration designs, as designs with self-similarity (the "zoom" configurations - e.g., Conway 2000), have the compact configuration near the center of the geometry (spirals, circles, or triangles) whereas the more traditional fixed designs (e.g., Yun & Kogan 2000) do not necessarily. The best locations for the compact configuration in the

Table 1: Candidate compact ALMA configuration locations

SAm56 UTM Easting	SAm56 UTM Northing	elevation (m)	location	quality
627650	7454450	5030	Chajnantor	best
627750	7453100	5030	Chajnantor	better
628050	7453650	5025	Chajnantor	better
630400	7453550	4912	Chajnantor	good
633800	7460600	4801	Pampa La Bola	best
640700	7459400	4609	Pampa El Vallecito	best
628370	7453250	5013	Donut	—
628590	7454000	5013	Zoom	—

Chajnantor area we suggest here may not allow for zoom configurations, as there may be no room for a 3-5 km configuration to be designed with those centers. This deserves more study. Figure 7 shows visually how the locations in the current configuration designs compare with the ones determined here for the Chajnantor area.

We emphasize lastly that the final selection of the location for the compact configuration will certainly be influenced by more factors than we have considered here, including the political viability of the various sites when considered as a whole. In addition, the comparison of the opacity and phase stability data from the Chajnantor and Pampa La Bola site testing locations is of vital importance in making a decision as to the best location for the compact configuration.

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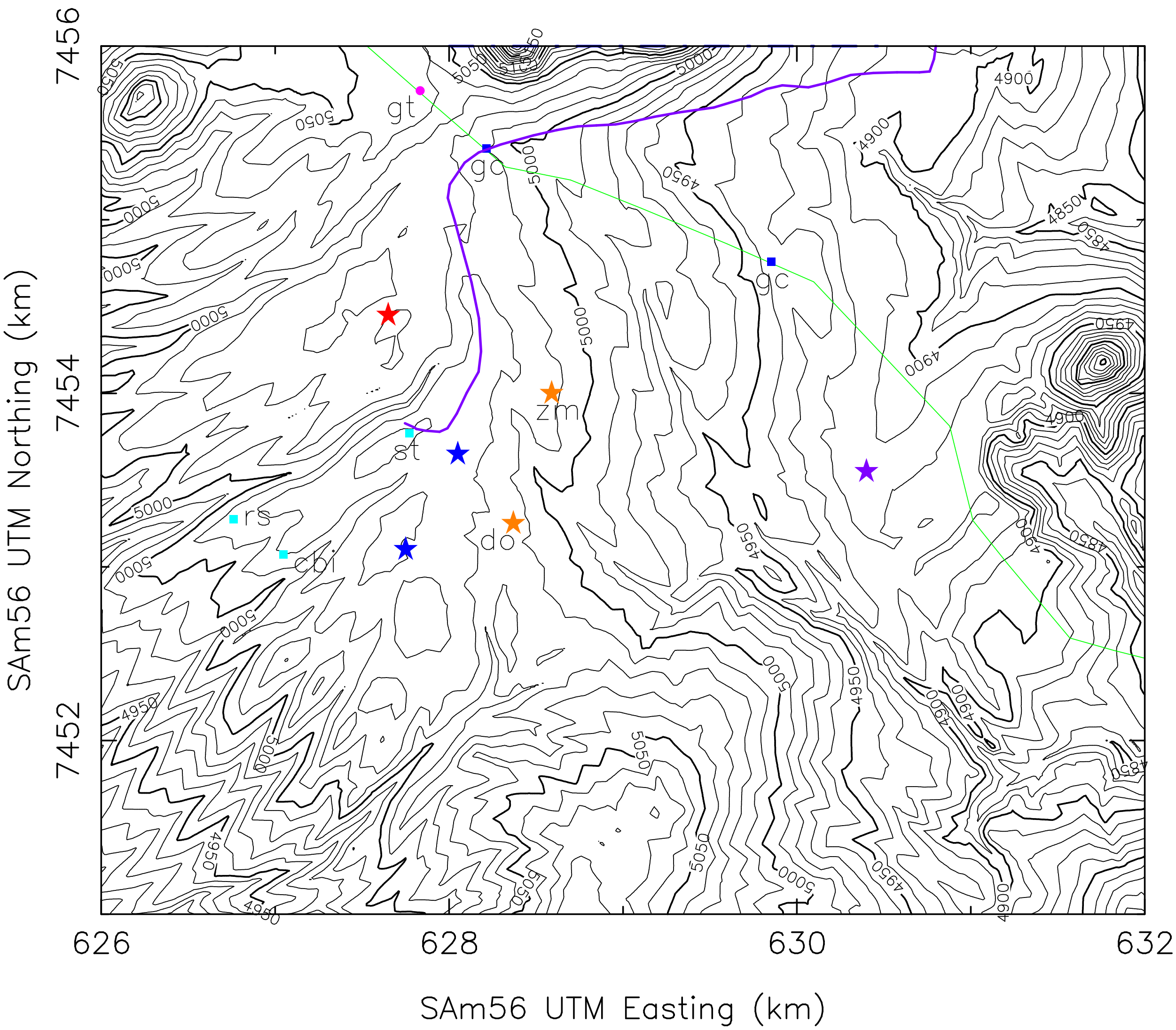

Figure 7: Best locations for the compact configuration as determined in this study for the Chajnantor region. The locations are noted by the colored stars, and are color coded as: red = “best”; blue = “better”; purple = “good”. The proposed centers of the two current configuration designs are shown as orange stars, with the center of the donut configuration (Yun & Kogan 2000) labeled ‘do’ and the center of the zoom configuration (Conway 2000) labeled ‘zm’. Thick (labelled) topography contours are at 50 m intervals, thin contours are at 10 m intervals. Other markers are as in Figure 1.