SUBMILLIMETER ARRAY TECHNICAL MEMORANDUM

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FROM : Philippe Raffin, Alan Kusunoki

Introduction

This report describes a search for potential sites for an interferometer array for submillimeter and millimeter astronomy in northern Chile. Twenty two sites were found during a survey of the region during the southern summer (end of January, beginning of February). One of these (Site #19/20) clearly surpasses the others for its location and access. It is also the highest in elevation of our list. Many other sites look very attractive but are comparatively much less accessible. It is manifest that any site needs to be tested thoroughly for water vapor content and atmospheric opacity, as this trip only involved reconnaissance of the region.

A long cooperation exists between Chile and the astronomical community, both American (Cerro Tololo Inter-American Observatory run by AURA, and Las Campanas Observatory run by the Carnegie Institution of Washington) and European with La Silla Observatory (European Southern Observatory). Before choosing Cerro Paranal as the site for the Very Large Telescope, ESO has been surveying and testing a fair number of sites for the past decade. Their work has been of great help for the present survey.

1. General features

The region described in this report is located in the Atacama Desert, one of the most arid deserts on Earth. Appendix 1.3 shows a comparison between precipitations according to latitude for the driest coastal deserts on Earth along American, African and Australian coastal regions. The main reason for the formation of the north Chilean coastal desert is the existence of the Humboldt Current. This is a cold offshore current which subjects the northern part of Chile to a thermal inversion, thus preventing the approach of the warm and humid air from the South Pacific. On the eastern side of the region, the Andes is a continuous high barrier. Only the northern and easternmost part of the region is affected by precipitations coming from the Amazon Basin during the summer months, between December and February, the so-called Bolivian Winter (see below). Furthermore, the region is located to the E of the South Pacific Anticyclone.

The extreme aridity of the coastal desert of Chile is also a consequence of human factors. Man has wrought a devastation on the natural vegetation which existed in the central *pampas*, especially concerning the *tamarugo* tree (Proposis tamarugo), cut in great number at the end of the last century for use as fuel in the processing of nitrate (see Reynaldo Böergel O., 1973).

Nowadays in the north Chilean desert, there is almost no vegetation. It only appears above an altitude of 2800 meters at the foot of the Andes. There, wild bunch-grasses can be seen as far as 4500 m. Above 4000 m, the *llareta* (Laretia compacta) slowly grows, in danger of extinction from overuse as a fuel. The llareta is a resinous plant looking like a very dense moss-cushion.

2. Sites

2.1. Glossary

Altiplano	the arid plateau of the Andes
azufrera	sulfur mine
cerro	mount, mountain
El Chaco	very humid plains in northern Argentina and Paraguay
cordillera	mountain system
estación	railway station
laguna	lake
pampa	dry plain
planta	processing plant
rio	stream
salar	salt flat
volcán	volcano cone

2.2. Maps

Two different groups of maps have been used to locate sites. Copies of IGMC maps showing the sites are shown in Appendix.

(1) Maps of the Instituto Geográfico Militar de Chile (IGMC), scale 1:50,000

(2) Tactical Pilotage Charts (TPC) from the US Defense Mapping Agency, scale 1:500,000

2.3. Roads

Most of the roads travelled were unpaved, only roads between Antofagasta and Calama and portions between Calama and San Pedro de Atacama were paved with bitumen.

distances :	Santiago to La Serena	474 km (Pan American highway)
	Santiago to Antofagasta	1361 km (Pan American highway)
	Antofagasta to Calama	187 km (two-lane highway)
	Calama to Ollagüe	198 km (unpaved road)
	Calama to Socaire	179 km (unpaved road)
	Calama to San Pedro de Atacama	92 km (unpaved road, partially paved)

2.4. Description of selected sites

The sites are separated into three main regions (from North to South) :

(1) the Ollagüe region, around Mount Aucanquilcha, latitude 21°S

(2) the Calama region, on the Altiplano NE of Calama in the Tatio region, Latitude 22°S to 22°15'S

(3) the Socaire region or E of the Salar de San Pedro de Atacama, latitude 23°30'S to 24°S

The site number designations were established by the chronological order in which we found them. For each site, general data on location are given in the table of Appendix 1.1. If the site is precisely located on the IGMC map, the elevation given is interpolated from the contours of the map within a precision of ±25 m. Otherwise the elevation given is the reading of our altimeter with an incertitude that may reach 200 m, especially after having climbed passes over about 5000 m (altimeter's limit).

2.4.1. Ollagüe area

Ollagüe, population 500, at an elevation of 3700 m, is located at the Bolivian border on a vast salt flat, surrounded by volcanoes sticking up above the horizon. It has the arid climate of the high Andes. It is a four to five hour drive from Calama to Ollagüe, with a stop at a police check-point about half way. The road crosses salt flats and almost not inhabited and superb areas. Ollagüe is on the railroad Antofagasta/Calama to Uyuni and La Paz, Bolivia. Basic supplies can be found here, as well as very basic lodging facilities at pensions. The population works mainly in the nearby sulfur mines. The Amincha mine has its own very well-frequented shop.

Airfields :
- Ollagüe (minor)
- Amincha (minor); probably private; 10 km from Ollagüe

The sites in this area are as follows :

#17 Map elevation = 3950 m; 27 km from Ollagüe on the road to Cosca, at the railway crossing (spur railroad of a meter gauge that goes to the Collahuasi mine); flat; soil = volcanic with *caliche* (impure sodium nitrate formed in dry regions by evaporation of rising aqueous solution); the road was totally washed out for about 500 m by recent rains (we had to make a detour off-road to get to the site); on IGMC map *Ollagüe*, see Appendix 2.8.

#18 Altimeter = 4480 m; 19 km from Ollagüe on the road to Azufrera Polán; not precisely located on the map as the contour intervals are too large (50 m); at the base of Mount Aucanquilcha (elevation 5867 m) to the W; the road to the site was very bad (washed out for about 3 km by recent rains); soil = small boulders ranging in size from 150 to 500 mm, which could be a problem if rain or wind erodes the smaller granular material surrounding the boulders (this is evidenced by adjacent areas which consist primarily of exposed boulders).

#19/20 Map elevation = 4650 m; 23 km from Ollagüe on the road to Azufrera Polán; site #19 is located just off the main road while site #20 is recessed about 1 km behind #19; both sites are environmentally sound as they are not visible from below (Ollagüe and the railroad to Bolivia); very flat; the only obstruction is Cerro Aucanquilcha to the NW (11°); minor airfield at Amincha, probably belongs to the nearby mining company, but it is closer to the site (by 10 km) than Ollagüe's airfield; the sky is amazingly blue; the road that we drove on was bad (as described in site #18 above) but it could probably be avoided as there were several other existing alternate routes; on IGMC map *Salar San Martín o Carcote,* see photos in Appendix 3.1 and location map in Appendices 2.9 and 2.10. The latter shows the area just S of the area shown on the map of App. 2.9 (Ollagüe and Co.Aucanquilcha). This is our best choice.

#21 Map elevation = 4075 m; in Pampa Polán, 61 km from Ollagüe. The road to the site consists of 13 km of very steep downhill, unpaved road, through the Aucanquilcha Pass. This part of the road is probably not used very often as the heavy traffic to the Aucanquilcha mine (located almost at the top of the mountain) ends at the pass; however it is possible to reach the site from the N via Cosca (from somewhere between Ollagüe and Ujina). This road is parallel to the same railroad passing by site #17. The location of this site on the map is approximate (±2 km). This is a very large area, gently sloping to the W; the Aucanquilcha range is to the S; on IGMC map *Volcán Miño,* see Appendix 2.11.

To summarize the Ollagüe area where we found the best potential site, the following common features apply :

- high elevation,
- flat and large areas,
- short drive from a town with basic supplies,
- all sites are close to a railway,
- this is the most northern area,

2.4.2. Calama area

Calama, population 81,000 is a desert oasis at an altitude of 2265 m. The town is modern and has developed commercial center. It is located at 16 km from Chuquicamata, the world's largest open-pit copper mine.
San Pedro de Atacama, population 1000, at an elevation of 2140 m, 87 km from Socaire, is a small town with one gas station, a few hotels, restaurants, post office, located on the edge of the Salar de Atacama, a depression of more than 3000 km2. San Pedro de Atacama was the center of the ancient Atacameña culture and has a most impressive archaeological museum.
The mean annual precipitation measured over a 24 year period is 5 mm at Calama and 25 mm at San Pedro de Atacama over a 28 year period (Vuille, 1991).

Airfields :
- Calama El Loa (major airport)
- San Pedro de Atacama (minor)
- El Tatio (minor, probably private)

The sites in this area are as follows :

#1 Map elevation = 3650 m, 9 km E of Estación San Pedro de Conchi (railway station), about 85 km from Calama, very large plateau to the S of the road and large, gently sloping plain to E of plateau, at the foot of Volcán San Pedro (to the NNE); S is completely unobstructed; Rio San Pedro parallels the road to the N; water pipe line along the road; overhead line (supported on poles), probably telephone, follows the road; good unpaved road; soil = volcanic (cinders); vegetation = *ichu* bunch-grass, sparse; see photos in Appendix 3.3; on IGMC map Volcanes San Pedro y San Pablo, see Appendix 2.4.
The mean annual precipitation measured over a 20 year period is 45 mm at San Pedro de Conchi (see Vuille, 1991).

Note : Sites #2 through #4b are along the road from Estación San Pedro de Conchi to El Tatio.

#2 Altimeter = 4330 m; 90 km from Conchi, 165 km from Calama via Chiu-Chiu, 15 km from intersection of Inacalari and Cabana roads, 57 km from site #1, big flat area, some obstruction; windy; located on the TPC map, IGMC maps (*Inacaliri and Linzor*) are missing from our set; soil = volcanic (cinders); vegetation = bunch-grass, sparse.

#3 Altimeter = 4330 m; after a sort of pass at 14500 ft; 100 km from Conchi (155 from Calama), 11 km from site #2; very flat, large area; Bolivian border quite close to the E; located on the TPC map, IGMC maps (*Inacaliri and Linzor*) are missing from our set; soil = volcanic (cinders); vegetation = bunch-grass, sparse.

#4 Altimeter = 4540 m; 124 km from Conchi, 130 from Calama, 22 km from Tatio; located on the TPC map, IGMC maps *(Inacaliri and Linzor)* are missing from our set; soil = volcanic (cinders); vegetation = bunch-grass, very sparse.

#4b Altimeter = 4570 m; big flat area bounded by the road on N,E,S; no obstruction S,W,N; windy (thermal); possible accumulation of snow at the center, evidenced by sedimentary deposits, possibly coming from the mountains to the E; located on the TPC map; IGMC maps *(Inacaliri and Linzor)* are missing from our set; vegetation at the center is sparse, no vegetation on the S side.

Note : the road between sites #4, #4b and the geysers of El Tatio is atrocious; roads were cut along steep embankments, leaving many unstable boulders above the roadway, which made us very nervous driving through the area; an easier access exists from the S, through Chiu-Chiu and El Tatio.

#5 Altimeter = 4480 m; 139 km from Conchi, 115 from Calama, between El Tatio (6 km) and Paso Las Vizcachas (pass); is in an area marked as "future national park" on the Chilean tourist map so this site, together with the other in the same area, are unlikely to be given up for astronomy; on the IGMC map *Toconce*, but our copy has no contours !

#6 Elevation at sign = 4380 m; at 7 km S of Paso Las Vizcachas; in area marked as "future national park"; on the IGMC map *Toconce*, without contours !

Note : the next two sites are on the way to a main tourist attraction of the area : the geysers of El Tatio; located N of San Pedro de Atacama; the sky is beautiful but so is the area; these sites appear to be out of sequence because we discovered them 4 days later along a different route.

#15 Altimeter = 4390 m; 51 km from San Pedro de Atacama; in "future national park"; long site on the Altiplano at the foot of Volcán Putana.

#16 59 km from San Pedro de Atacama; in "future national park".

Apart from site #1 which is almost in the absolute desert, all the sites in this area are located on the Altiplano and are fairly remote. The access can be either long or somehow difficult. Part of this area might be transformed into a national park for its natural features and landscapes.

2.4.3. Socaire area

Socaire is just about a small village with some farming but it is near the center of this area. San Pedro de Atacama is the closest town and Toconao (Population 450, 50 km from Socaire) is another small town where basic supplies can be found. Toconao is the only oasis of the area where many varieties of fruit are grown.

2.4.3.1. E of Salar de San Pedro de Atacama

Airfields (both are at about the same latitude as Antofagasta)
- Peine (minor, probably private); 284 km from Antofagasta, 196 km from Calama
- El Salar (minor, probably private); 261 km from Antofagasta, 198 km from Calama

The sites in this area are as follows :

#7 Map elevation = 4300 m; 95 km from San Pedro de Atacama on the road to Paso de Guaitiquina, 34 km from sign Ruta 23 / 3450 m, 57 km from Toconao; N and S are slightly obstructed by mountains; not very windy and not chilly, unlike the previous areas along the road; soil = volcanic (cinder); the IGMC map showing the site is missing (Volcán Lascar), but the coordinates of the site can easily be interpolated; just S of the Tropic of Capricorn.

#8 Map elevation = 4500 m; 105 km from San Pedro de Atacama on Route 23; between Laguna Lejia and Salar de Aguas Calientes, near Paso del Cerro Overo (pass); no major obstruction, volcanoes all around (<8°) over the horizon, very clear; windy; the location on the map is approximate (±1 km); soil = volcanic (smooth basalt stones ranging from 50 to 200 mm in diameter with underlying lighter colored cinder); see photo in Appendix 3.2; on IGMC map *Cerro Miscanti,* see Appendix 2.5.

#9 Map elevation = 4425 m; 127 km from San Pedro de Atacama, 6 km from the intersection of the road to Paso Sico and the road to Paso de Guaitiquina, still on Route 23; S of Pampa Esquina Amarilla and Salar de Aguas Calientes; absolutely flat; no obstruction all around but S horizon is especially clear; 6 hours drive since we left San Pedro de Atacama (including stops); high cloud formation (late afternoon so the effect of the Bolivian Winter,

see discussion below is probably more pronounced since we drove considerably E into the Andes range); the location on the IGMC map *Cerro Miscanti* is approximate (at ±1 km), see attached map in Appendix 2.6, and photos in Appendix 3.3.

2.4.3.2. S of Socaire, W of El Laco

El Laco is a unique iron mine at an altitude of 5000 m, where the quaternary iron is extracted from erupted volcanic material, the concentration of which is very high. Here we met two Chilean geologists who told us about the area; they informed us that the winters are severe and there is much snow. No significant data about snowfall are available yet as the weather stations implemented in the area by the Swiss are too recent (two years only).
On the flat areas in this region (where sites #11 to #14^b are located), the soil is composed of rhyolite, a volcanic lava of granitic composition, the same type as at Mont Pelé in Martinique.

The sites in this area are as follows :

#10 Map elevation = 4000 m; 12 km from El Laco mining camp, on the road from Socaire to Paso Sico; perfectly flat; no wind; only minor obstruction to the S; probably as inaccessible as El Laco in winter because of snow; no IGMC map of the area *(Tuyajto)* but located on the TPC P-26C chart, thus location is approximate.

#11 Altimeter = 4200 m 48 km from El Laco; cloudy (see discussion of Bolivian Winter below); many sandy patches on the road; very windy; no obstruction, large flat area W of Cerro Miñiques; difficult to locate on the map since the road we drove on is not shown; same for sites #12 and #14.

#12 Map elevation = 3975 m; 61 km from El Laco; W of Cerro Miñiques, 40 km from Socaire (per road sign), overlooking Salar de San Pedro de Atacama; very large area to the W of the road; site could be set in several places along the road (4 km); very good soil; no obstructions; on IGMC map *Cerro Miñiques*.

#13 Map elevation = 3775 m; 73 km from El Laco, exactly W of Cerro Miñiques; not very large but is recessed about 1/2 km E of the road; not windy at that time (3:20 pm); no obstruction N nor S; circular area covered by small yellow bushes (ichu); approximate location only (±2 km); the map does not show the road we drove on; see photos in Appendix 3.2; on IGMC map *Cerro Miñiques*.

#14 Altimeter = 3990 m; NW of Cerro Miñiques; large and flat, slightly lower than the road level; difficult to locate on the map.

#14b Map elevation = 3975 m; at the very foot of Cerro Miñiques, S of Laguna Miñiques, W of Pampa Varela; pea gravel type of soil; large and very flat; between 50 and 100 m below the road, in a very large depression; no obstruction, except NE (13°); shown on IGMC map *Cerro Miñiques* see Appendix 2.7, and photo in Appendix 3.2.

The area E of the Salar de San Pedro de Atacama contains the largest number of potential sites to implement an array. The area is in the main range of the Andes, the elevation is high and all the sites selected are very flat with good soil characteristics. It is the southernmost prospected area, and the easternmost too. The access to this region is fairly easy by road, but no railway facility could be smartly used.

2.5. Sites tested by ESO

(1) Cerro Paranal — elevation 2650 m, longitude 70°25'W, latitude 24°40'S, 15 km from the coast, site of the Very Large Telescope (VLT) four 8-meter telescopes and auxiliary 2-meter telescopes

(2) Armazoni — 3100 m, 70°10'W, 24°35'S, 37 km from the coast - a two hour drive E of Cerro Paranal

(3) mountain chain to the W of Salar de Punta Negras, 3500 to 5000 m, 69°15'W, 24°40'S

(4) Aucanquilcha

(5) mountains above 4500 m, between San Pedro de Atacama and El Tatio, 68°W, 40'S

Volcán Apagado : 5600 m, 68°W, 22°30'S, 200 km from the coast.

Why did ESO prefer Paranal, located in the coastal range, to an inland site in the main Cordillera of the Andes, for the VLT ?

> The higher inland sites tested have an integrated water vapor content which is very low. High winds occur in the inland sites but not with very great frequency; but at the same time, photometric sky quality tends to be less favorable than for the coastal sites. Finally the overall accessibility of coastal sites is considerably better than for the inland sites (see Sarazin, 1990). Aucanquilcha and Volcán Apagado were among the inland sites investigated by ESO for the VLT.

3. Meteorology in Northern Chile

A lot of climatological data can be found and sometimes for long periods of time for the northern stations along the coast, such as Antofagasta, Iquique, Arica. To some extent, data also exist for places like Calama or San Pedro de Atacama, but very few exist for the areas east of the extreme arid part of the Atacama desert. The Universidad del Norte in Antofagasta and the Geographisches Institut in Bern, Switzerland are involved in research programs for the area we are concerned about. They have started a systematic recording of meteorological data for different places of the Altiplano.

3.1 Precipitation

Between latitude 21°S and 27°S even the high western range of the Andes and much of the adjacent Altiplano are very dry with few places receiving as much as 100 mm per year. The few rivers in this zone are nothing more than ravines, occasionally carrying some water, except Rio Loa which has a fairly constant flow of water throughout the year (Schwerdtfeger, 1986).

Ollagüe and the nearby sites (Sites #18 to 21) are in a semi-arid zone with occasional summer (January/February) showers. At Ollagüe, during the years 1964-65, precipitations were representative of the arid high Andes region, with an annual rainfall of 90 mm of which 70 mm occurred in February (see Caviedes, 1973).
To the east of the region and very close by is a sub-humid to semi-arid zone with summer rain and occasional winter rain or snow (Altiplano). Appendix 1.6 shows the precipitation pattern of the region of interest, while Appendix 1.5 integrates this region in all of South America. Above an altitude of 3000 m, there is a significant amount of rainfall in the northern regions. Approximately

N of 25°S the rainfalls in the warm season is a result of diurnal convective circulation on the Andean slopes (Fuenzalida, 1983).

All the other sites are located in this same semi-arid zone, except Site #1. The latter is at the limit of the arid zone with very rare winter rain and is the closest to Calama and the extremely arid zone, but the elevation in this zone culminates at around 3600 m.

We must note that even if there is some precipitation in the arid Andean piedmont and the arid high Andes, these regions receive less precipitation than the evaporation potential (Caviedes, 1973).

During 8 days in December 1984 and 11 days in February 1985, ESO gathered data from a mobile automatic meteorological station at Volcán Apagado at an elevation of 5600 m, close to the sites #4 and #15, on the Altiplano north of San Pedro de Atacama. The sampling period is very short and right into the Bolivian Winter. This probably explains the rather high values of humidity shown on the plot of Appendix 1.8. The plot shows average relative humidity at 2.5 m height in percent, on a daily scale.

So far, no reliable data exist for the Socaire region, but the weather stations of El Laco should provide interesting information about this area, especially regarding snowfall.

3.2 Temperature

Although the annual temperature range over the high cordillera is relatively small, the diurnal range can be very high in areas protected from the winds. For example, at Ollagüe the annual range of the monthly mean is only 8°C but the diurnal range averages more than 20°C in January and is sometimes as much as 35°C in August. In the clear air of the Altiplano, the net fluxes of both incoming and outgoing radiation are very great (Schwerdtfeger, 1986).
According to Caviedes, at Ollagüe the extreme values of temperature for the years 1964-65 are : a maximum of 23.5°C in January and a minimum of -32.3°C in June. Average temperatures at stations in the northern Chilean desert are shown in Appendix 1.7. Collahuasi is a mine at 4800 m, higher than Ollagüe, and the other stations are located either in the coastal or interior desert or in the Andean piedmont.

ESO recorded also temperatures at Volcán Apagado. Again, the sampling period is very short but gives some information about the conditions in summer. It shows an average air temperature at 5600 m of about -4°C in December and -3°C in February with daily variations of less than 13°C in December and less than 8°C in February (see App.1.9). Appendix 1.10 shows the diurnal air temperature variation and the diurnal ground temperature variation under a few cm typical soil cover, on a cumulative plot of average values for the whole period on a 24 hour basis.

3.3 The Bolivian Winter

This is a climatic event affecting the Andes that occurs from December to March between Arica (latitude 18°30'S) and Copiapó (latitude 27°20'S) with major effects in January and February. Violent precipitations occur, with snow at high elevations. During these months, the sun is closer to the Tropic of Capricorn and high evaporation from the Argentinean and Paraguayan Chaco creates rain which is pushed westward by the Atlantic high pressure system. Appendix 1.4-1 shows a map of the pressure distribution above South America for the summer months. The map is self-explaining, it shows the high pressure cell over the eastern South Pacific and the center of the

continental heat low located between 20°S and 30°S. The intensity of this phenomenon varies according to the area, but when it occurs it can bring rain that normally begins in the afternoon and ends in the evening. Rainy days occur in episodes from a few days to a week and are separated by clear periods of variable duration (see Fuenzalida, 1991).
Appendix 1.4-2 shows a map of the pressure distribution above South America for the winter months. It shows the two high pressure cells of about equal strength and equal latitudinal extension of the eastern South Pacific and western South Atlantic.

During our two week survey of the region from January 22 to February 5, at latitudes between 20 and 24°S, we experienced, in the afternoon, some cloud formation above us which would clear in the evening, but the Argentinean or Bolivian skies would remain completely covered by clouds for a much longer time with frequent thunderstorms, clearly visible in the distance (at or about 100 to 150 km to the E). The Ollagüe region had experienced a short period of heavy rainfall a few days before our arrival. Some portions of the roads through the rocky terrain had been washed out, making driving very difficult.

3.4 Cloudiness

In summer, in the northeast slopes of the Andes, daytime convective activity gives rise to cumulus almost daily (at 18°S). Such activities appear where the terrain elevation exceeds 3000 m and decreases southward, becoming almost nonexistent south of 25°S (Fuenzalida, 1983). The region surveyed (between 21°S and 24°S) is in the middle of this latitude range, thus one can expect this effect to be more pronounced in the Ollagüe area than in the Socaire area.
Caviedes notes that the cloudiness in the Ollagüe region is rare apart from the increase in summer, but no comparative measurements exist inside this region.

4. Construction methods and cost

During our visit to the ESO site at Paranal, we were fortunate to be able to see an actual construction project in progress. Much of the current work comprised heavy excavation work, with the use of very large excavators and trucks. We did, however, interview the ESO construction manager about the ensuing work in order to learn about local costs and methods.

4.1 Construction methods

One method of construction of particular interest was a road compaction technique called *salt stabilization*. This rather inexpensive and time-tested procedure involves the introduction of common salt into the soil mixture used for the construction of the road. This stabilizes the material and aids in the compaction of the material. The result is an unpaved roadway which possesses greater soil strength and therefore a harder surface, without loose gravel and fewer "soft spots". ESO's construction team were particularly interested in the method because experience indicated that dust is markedly reduced.

ESO tested this procedure by having about 100 meters of the old Pan American highway treated with salt (see photos in Appendix 3.4). We were impressed with the section that we saw and would suggest that this method be studied more if a site in Chile will be further investigated.

4.2. Construction costs

Since our primary task was to find potential sites, we obtained very little cost information during our site investigation. However, we did interview the ESO staff at Paranal and obtained the following from a quotation recently received by ESO from Interbeton, a very large Dutch construction firm who are currently doing the major excavation work at Paranal:

4.2.1 Contractors bid most projects with a 15% to 25% mark-up for overhead (OH) and profit (P).

4.2.2 Road construction costs: unpaved road, specified as (a) repair the subbase (b) 50 cm of classified subbase (c) 25 cm of classified subgravel from within 20 km radius of site.

4.2.2.1 Excavation into medium hard to hard rock, including blasting and spreading (no transport to remote dump site) = $\$7.00/m^3$.

4.2.2.2 Asphaltic cold mix-bituminous-with classified, sieved material. rolled and compacted-no seal-6 cm thick = $\$5.50/m^2$.

4.2.2.3 Road shoulders - 4 cm thick - 1.0 m wide = $\$1.70/m^2$.

4.2.2.4 Overall cost = $\$7.30/m^3$ for a total of 35,500 m^3 volume on a 75 km length of road. Note: very inexpensive by US standards.

5. Infrastructure

5.1 Transportation facilities

Chile is connected throughout its length by sea and air, and by road if one excepts its southernmost section between 47°S and 55°S (S of Cochrane). Its road network is extensive, although roads are unpaved outside of major arteries between urban areas. Railroads belong to the state railway system. Empressa de Ferrocarriles del Estado, and is organized into three main lines totalling 7860 km. Shipping, organized by the Empressa Marítima del Estado, is very important in Chile, primarily because of the country's lengthy coastline. Commercial air transport began in 1932 with the creation of LAN Chile (Línea Aerea Nacional Chile); another major carrier is LADECO (Línea Aerea del Cobre or Copper Airline).

The national highways connected to the Pan American Highway have a total length of nearly 80,000 km of which 56,000 correspond to "permanent" roads and 22,000 to "seasonal" roads. Only 10,000 km are first class. The region around the capital and the Central Valley are the best served. The Chilean highway network runs continuously from Arica to S of Puerto Montt. As described above, most of the roads to the study sites are unpaved, some good and some bad. Depending on the sites chosen, significant road improvements may be needed. Existing astronomical sites at La Silla, Cerro Tololo, and Las Campanas have privately built lengthy segments of roads to their sites.
Chile has an extensive bus network. Buses are many and frequent. Luxury buses connect Antofagasta to the capital in 20 hours (1360 km).

The northern railway line, with 38% of the total railway length, runs from Iquique to Calera. It specializes in cargo, especially iron ore transport. The southern railway line, with 62% of the total railway length, runs between La Calera and Puerto Montt. The third line is the Arica-La Paz line, with a length of 252 km inside Chile; it carries passengers and cargo and covers the internal commerce of Arica and foreign trade with Bolivia.

6. Conclusion/Recommendations

The site off Polán sulfur mine road, at the foot of Mount Aucanquilcha in the Ollagüe region (site #19-20) is our best choice for the following reasons :

(1) The altitude is high (4650 m) but appropriate work can be envisaged at the site.

(2) The sky was the brightest of all the places we went to during this survey.

(3) Apart from an obstruction of 11° by Mount Aucanquilcha to the NW, the outlook is very good, especially to the S.

(4) The area is large (2 km x 5 km) and flat.

(5) The soil is easy to trench as made of small volcanic cinders, with sparse vegetation.

(6) An array would not be visible from anywhere except from the summit of Mount Aucanquilcha.

(7) The access to the site is easy and short by 4x4 vehicle, a 23 km drive from Ollagüe, the closest town, population 500. Ollagüe has an airstrip and is 198 km from Calama by road.

(8) The site is not located on a traveled road, but just one to two kilometers off the road to the sulfur mine.

(9) The area was not windy at the time we were there.

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APPENDICES

List of Figures, Tables, Maps and Photos