ALMA Memo 314
Underground Temperature Fluctuations and Water Drainage at Chajnantor

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Abstract

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, $a = (1\text{–}5) \times 10^{-7}\,\mathrm{m^2\,s^{-1}}$, 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 the overall phase stability of the ALMA optical fibers may be determined not by the 25 km long buried sections, but by shorter, above ground lengths.

Large diffusivity values are correlated with precipitation and soil moisture. At 30 cm depth, soil moisture persisted for about 15 days after a snowfall that melted from the surface in 7 days. Subsurface freezing and melting episodes suggest the soil salinity is sufficiently high to enable drainage and prevent permafrost.

1 Introduction

Because some parts of the ALMA will be built underground, it is important to understand the thermal properties of the soil at Chajnantor. For example, the median air temperature is $-2.4\,^\circ\mathrm{C}$ and locations with poor drainage may have permafrost, which might complicate the engineering of foundations for precision antennas. Diurnal temperature fluctuations will result in thermal expansion and contraction of the underground fiber optic cables, introducing phase errors.

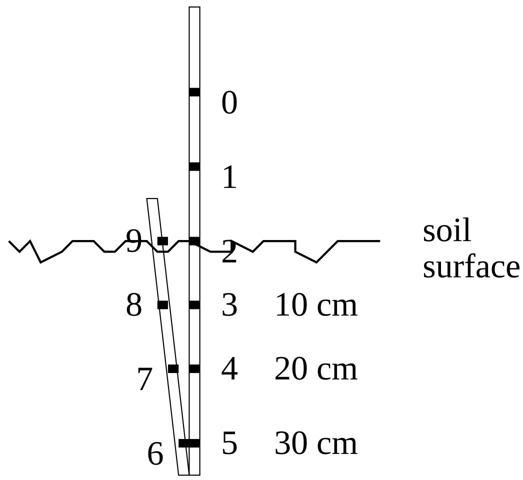

Figure 1: Thermometer positions above and below the surface. The thermometers, spaced by $100 \pm 3\,\mathrm{mm}$, are rigidly attached to a stick. The stick was broken and folded between sensors 5 and 6, so the relative depths of the sensor pairs are only accurate to $\pm 1\,\mathrm{cm}$, which is about the absolute accuracy of the sensor depths.

2 Heat Flow Theory

Time dependent heat flow is well studied (e. g., Carslaw & Jaeger 1959). As the depth, h, increases, surface temperature fluctuations are both delayed and exponentially damped. For a sinusoidal surface variation with angular frequency ω and with amplitude ΔT about an average temperature T_0, the temperature

$$T(h,t) = T_0 + \Delta T \exp\left[-h\left(\omega/2a\right)^{1/2}\right] \sin\left[\omega t - h\left(\omega/2a\right)^{1/2}\right], \qquad (1)$$

where t is the time and a is the thermal diffusivity, which equals the thermal conductivity divided by the heat capacity of the material. For dry sandy soil, $a \approx 2 \times 10^{-7}\,\mathrm{m}^2\,\mathrm{s}^{-1}$. Unless it gets wet, high porosity sand is a fairly good insulator (for rock, a is 5–10 times higher). Rather than rely on a guess at the soil properties and on the diffusivity values in four decade old heat transfer books, however, we measured the subsoil temperature variations directly.

3 Apparatus

Digital thermometers (Dallas DS 1820) were placed above the soil surface, level with the soil surface, and in pairs 10, 20, and 30 cm below the soil surface (Figure 1). The sensors were mounted on a 19 mm square pine wood stick and connected in parallel with a twisted pair of solid 0.128 mm^2 (26 AWG), teflon insulated copper wires. Both the wood stick and the wires have lower thermal conductivites than the surrounding soil. We had originally planned to bury the thermometers up to 1 m below the soil surface, but the hole diggers weren't up to the task. Every 10 min, a PC in the equipment container recorded temperatures sequentially, one sensor every 10 s. The sensors have a readout accuracy of 0.015 K and two probes placed on ice in the laboratory read a flat 273 K for about an hour. Every two hours, when the PC recorded a surveillance image, the temperatures were recorded somewhat less frequently. The temperature probe operated from 1997 June 15 through October 28 (135 days) and also 1998 March through May.

4 Data

Overall, the data are clean, with only minor glitches. For example, some, but not all, sensors would get temporarily stuck at a certain temperature until the temperature changed by three or four readout quanta. Also the two thermometers at the same (nominal) depth did not always read the same temperature, likely because of differences ($\approx$ 1 cm) in the actual depths. The biggest discrepancies were observed with the 10 cm deep sensors, which agreed very well during the hottest part of the diurnal cycle, but could differ by about half a degree during the cooler part of the cycle.

The data (Figures 2–6) are dominated by the diurnal cycle, which is modulated by longer term trends and singular events (storms). As expected, the temperature variations are much smaller below ground than at the surface. For 1997 June–October, the median surface temperature measured with the subsoil probe was $-5.3\,^\circ$C. This agrees well with the median air temperature, $-5.0\,^\circ$C, measured for the same period with the thermometer attached to the 225 GHz tipping radiometer. The median temperature below ground was about 1 K warmer than at the surface, with only about 0.1 K difference between 10 cm and 30 cm depths.

At the surface, a seasonal trend is apparent as the median temperature increases 8 K from June to September (Figure 7). The monthly median air temperatures measured with the thermometer attached to the 225 GHz tipping radiometer historically show a similar seasonal trend (Figure 8), although the actual air temperature in 1997 did not track the surface temperature trend very well. There is no systematic seasonal trend in the median subsurface temperatures and month-to-month variations are less than 1.5 K at any depth.

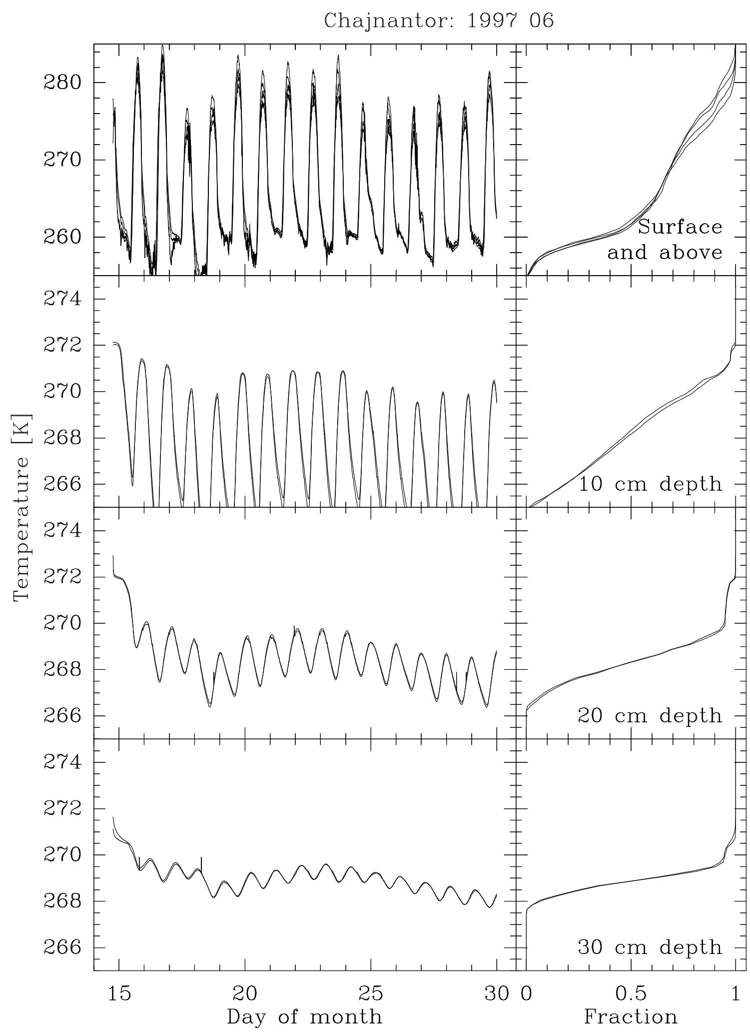

Figure 2: Temperature at the surface and 10, 20, and 30 cm below ground level at Chajnantor during 1997 June. Note change of scale between surface and subsurface data.

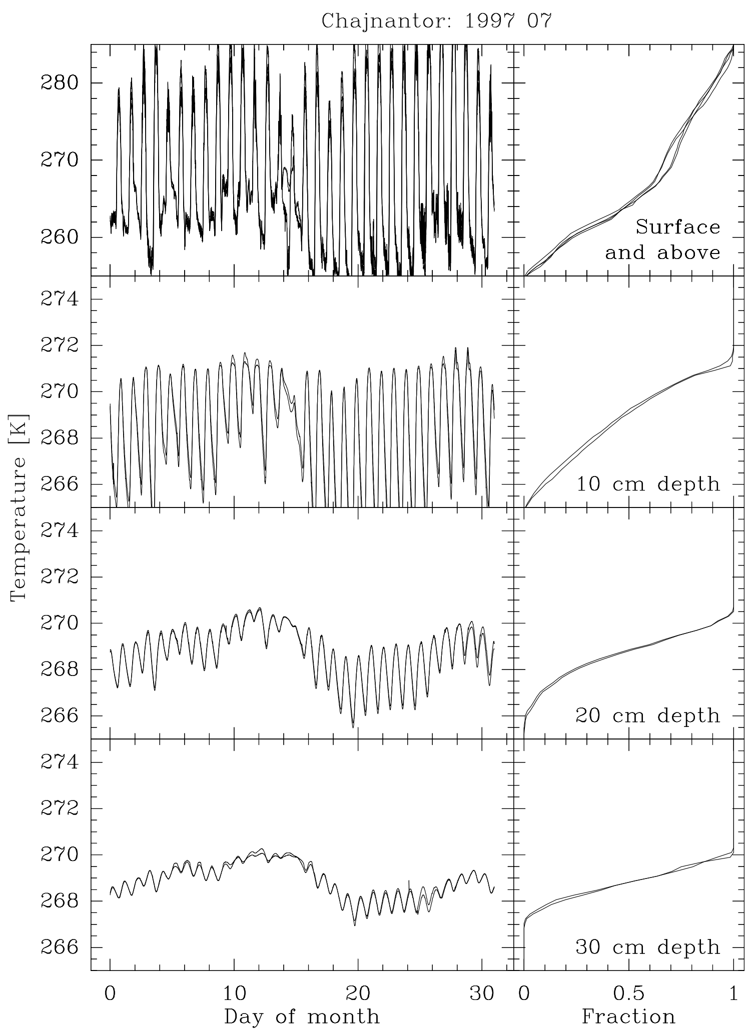

Figure 3: Temperature at the surface and 10, 20, and 30 cm below ground level at Chajnantor during 1997 July. Note change of scale between surface and subsurface data.

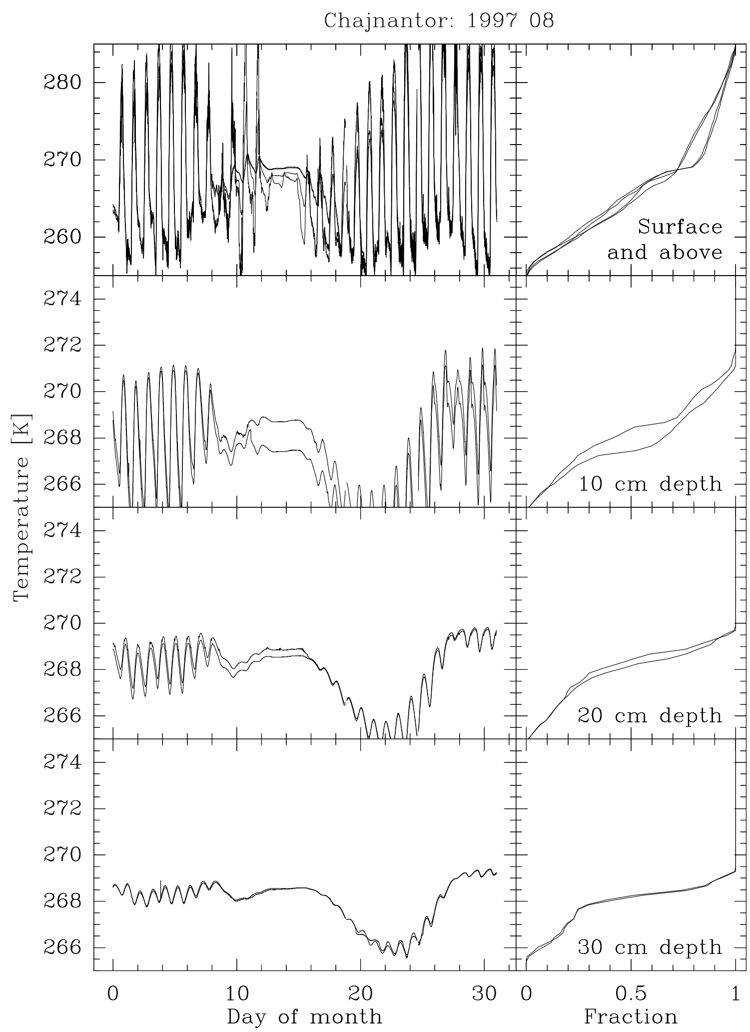

Figure 4: Temperature at the surface and 10, 20, and 30 cm below ground level at Chajnantor during 1997 August. Note change of scale between surface and subsurface data.

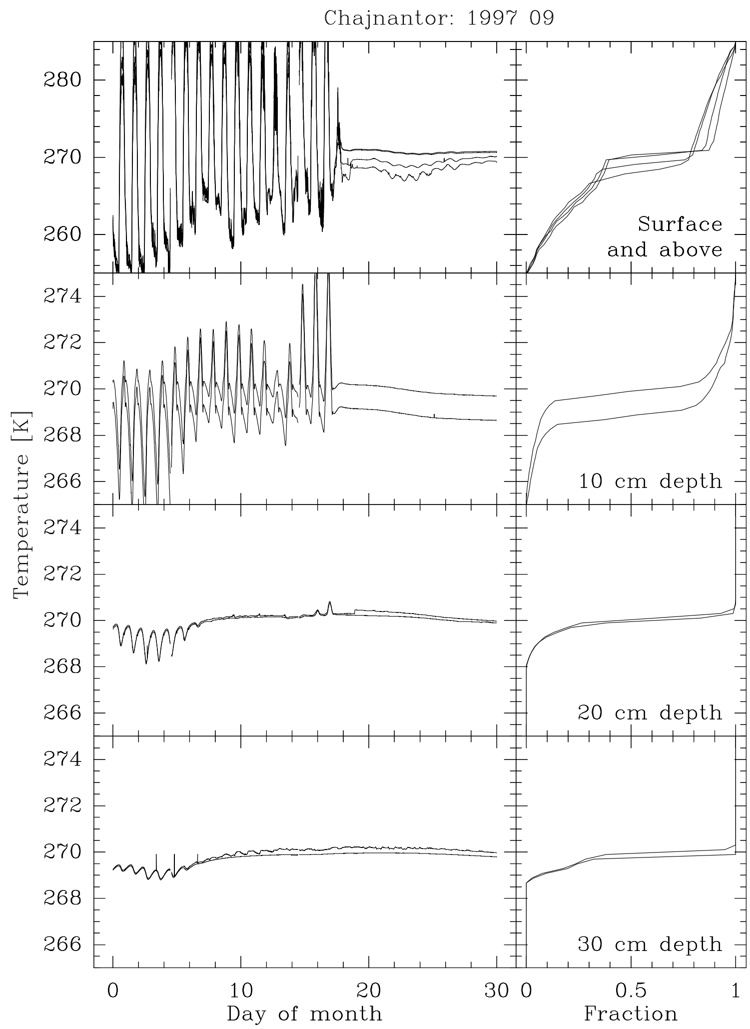

Figure 5: Temperature at the surface and 10, 20, and 30 cm below ground level at Chajnantor during 1997 September. Note change of scale between surface and subsurface data.

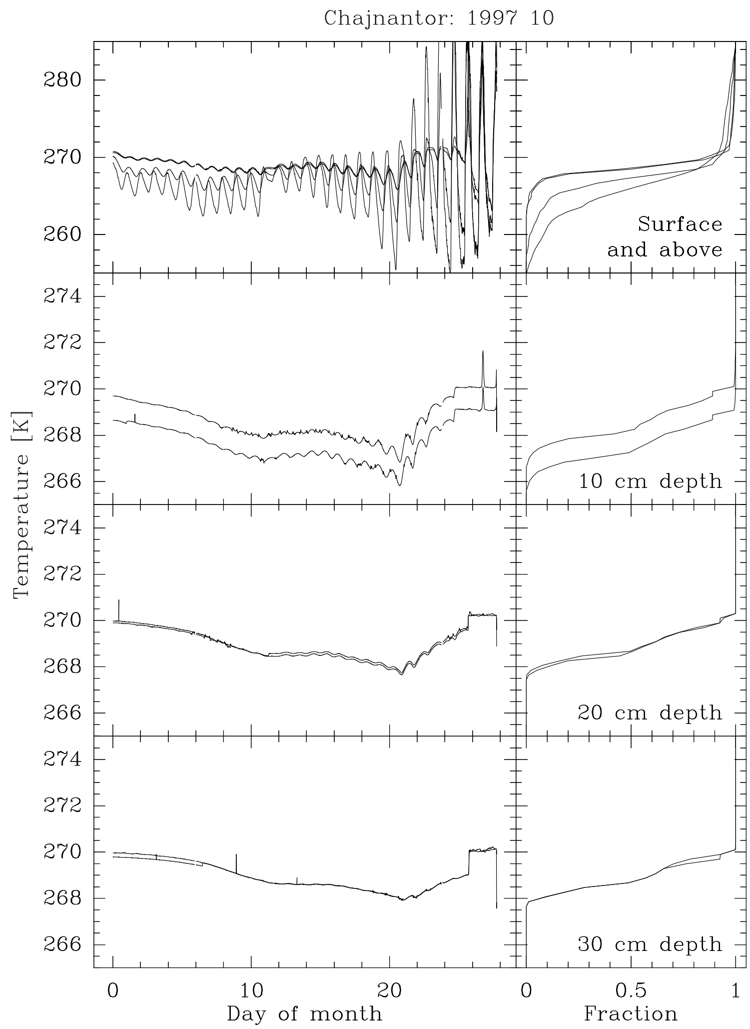

Figure 6: Temperature at the surface and 10, 20, and 30 cm below ground level at Chajnantor during 1997 October. Note change of scale between surface and subsurface data.

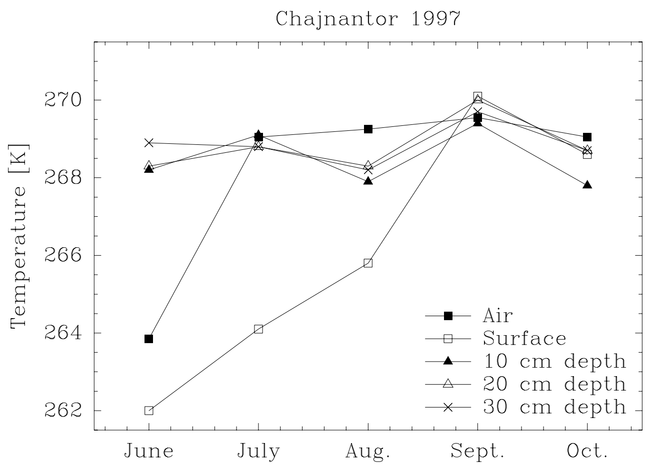

Figure 7: Monthly median temperatures at Chajnantor during 1997 June-October in the air, at the surface, and 10, 20, and 30 cm below ground level. The air temperature was measured with the thermometer attached to the 225 GHz tipping radiometer.

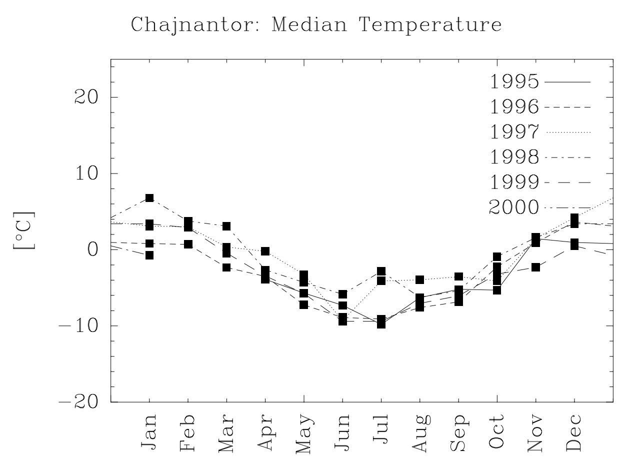

Figure 8: Historical seasonal variation of monthly median air temperature at Chajnantor measured with the thermometer attached to the 225 GHz tipping radiometer.

Storms, with associated snowfall, dramatically disrupt the diurnal cycle several times, notably mid-August and mid-September through October. On these occasions, the surface sensors were buried by snow, so the diurnal cycle was largely masked. The snow has a clear insulating effect on the subsurface temperatures. Under these conditions, reliable data analysis was not always possible.

The diurnal temperature variations do not, of course, follow a pure sinusoid (Figures 9 and 10). Higher frequency components clearly distort the time series at the surface and at 10 cm depth, especially during the cold part of the cycle. As the depth increases, however, the high frequency components are damped more strongly. This effect roughly balances the errors for the sensors at different depths. Although the readout error is a larger fraction of the diurnal variation at 30 cm depth, high frequency distortions are greater at 10 cm depth.

5 Thermal Diffusivity

The diffusivity, a, can be determined both from the amplitude decrease with depth and from the delay increase with depth. To estimate the amplitude and delay of the temperature variations at different depths, we fit the daily maxima and minima with 0.3 day wide parabolae. For the deeper sensors, we made sure to fit the corresponding maxima and minima, which occur about 0.5 day later than the surface extrema. Fitting the logarithm of the daily fluctuation amplitude (maximum − minimum) as a function of depth then yields $(\omega/2a)^{1/2}$. This determination of a is insensitive to any systematic offset in the sensor readouts. Also, the parabolic fits smooth out the temperature variations so the sticky sensors do not matter very much. Because the cooler part of the diurnal cycle is markedly less sinusoidal than the warmer part, we measured the delay using only the daily maxima. Then fitting the delays as a function of depth gives another estimate of a. Diffusivity determinations were possible for 61 days from June through September.

Although the daily diffusivity values (Figure 11) determined from the delays are systematically $(0.5–1.0) \times 10^{-7}\,\mathrm{m^2\,s^{-1}}$ higher than those calculated from the damping, they track each other remarkably well. Hence the day-to-day variation in a might actually be real. Both methods indicate the diffusivity is in the range $(1–5) \times 10^{-7}\,\mathrm{m^2\,s^{-1}}$ with an overall median $a = 2.4 \times 10^{-7}\,\mathrm{m^2\,s^{-1}}$.

6 Implications for Buried Optical Fibers

For the maximum observed diffusivity, $a = 5 \times 10^{-7}\,\mathrm{m^2\,s^{-1}}$, the diurnal (24 h) variation at a depth of 1 m is attenuated to only 0.02% of the surface amplitude and is delayed by 33 h. At Chajnantor, the diurnal temperature swing is almost always less than 30 K

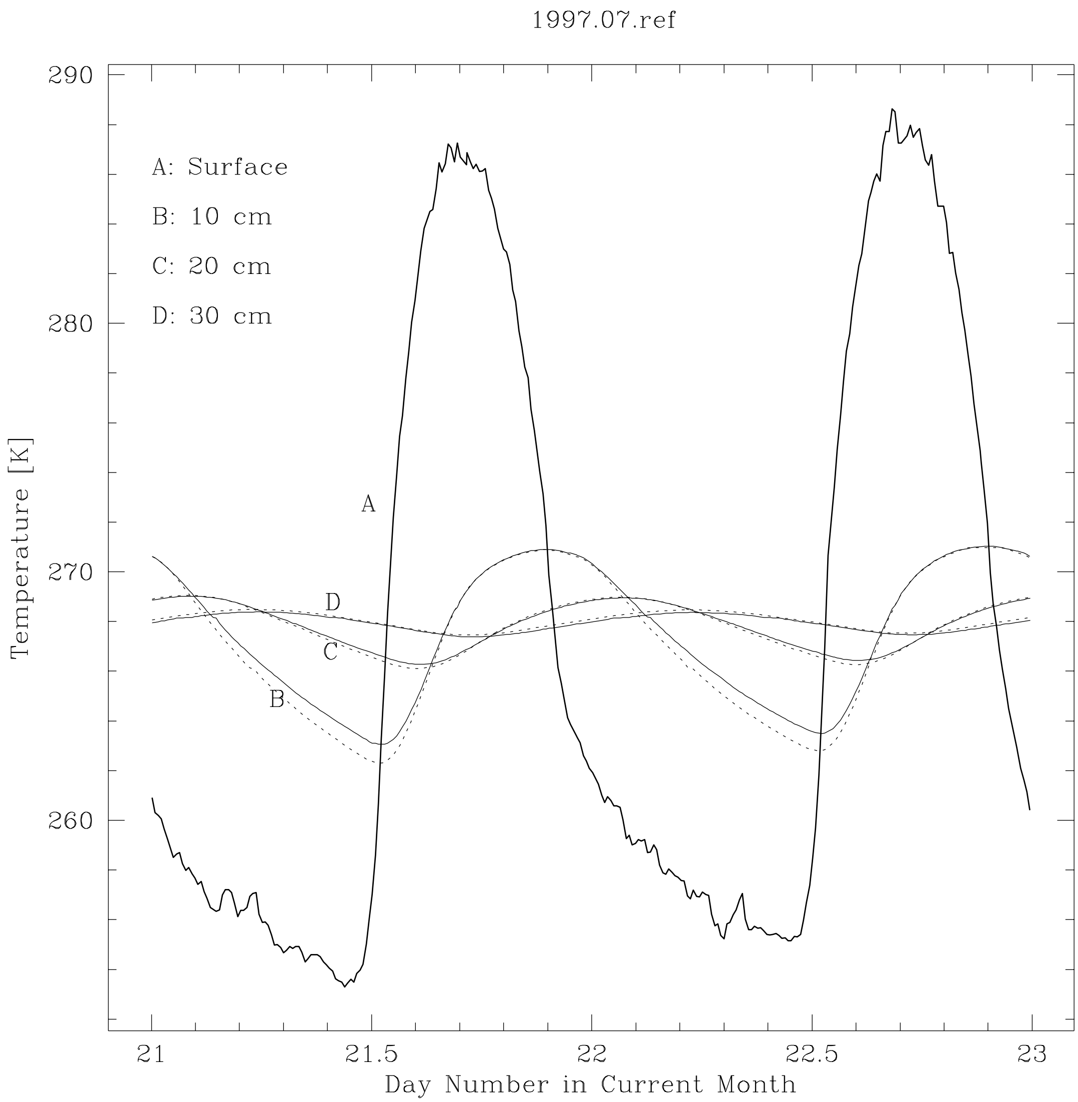

Figure 9: Temperature at the surface and 10, 20, and 30 cm below ground level at Chajnantor during 1997 July 22-23. Day numbers start at 0, so day 21.5 is 12 UT July 22.

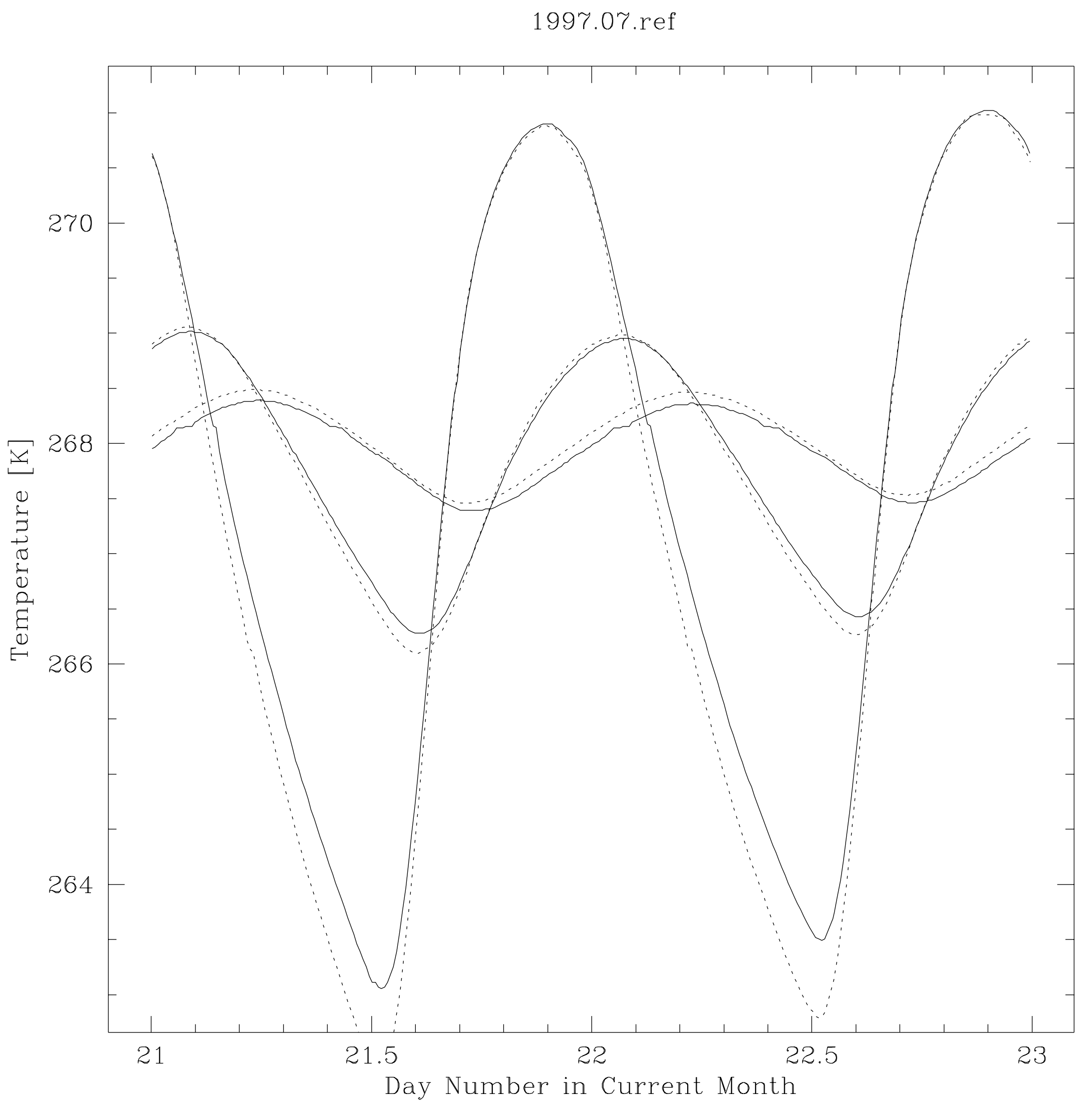

Figure 10: Temperature 10, 20, and 30 cm below ground level at Chajnantor during 1997 July 22-23. These are the same data as Figures 9, but without the surface temperature to emphasize the deep fluctuations.

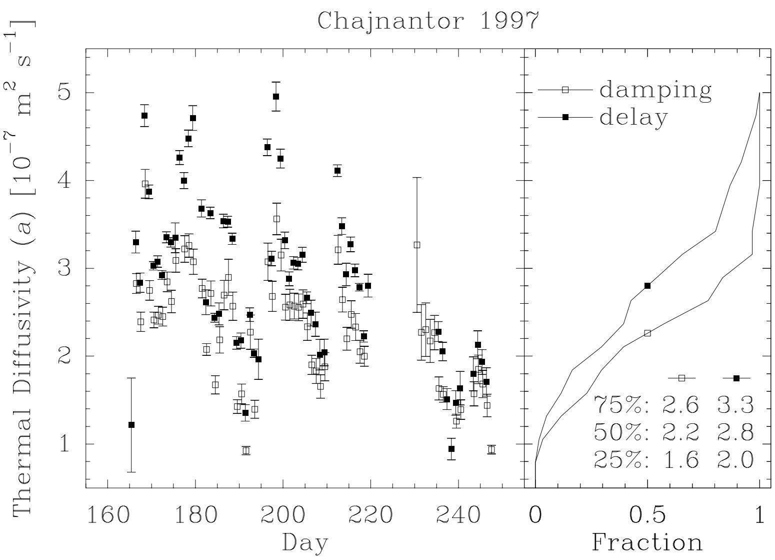

Figure 11: Thermal diffusivity, a [$\mathrm{m^2\,s^{-1}}$], of the soil at Chajnantor during 1997 June-September, calculated from both the delay *(solid squares)* and the amplitude damping *(open squares)* with with uncertainties derived from the fit residuals. Day numbers start at 0, so day 212.5 is 12 UT August 1. Snow blanketed the site on July 15 (day 195), wetting the soil and increasing a. It took about 15 days for the diffusivity to return to its previous value.

at the surface, so 1 m deep the swing will be less than 6 mK and the maximum rate of change will be $1.6\,\mathrm{mK\,hr^{-1}}$. Silverberg (1998) reported similar variations in the 1 m deep SMA conduits on Mauna Kea. Because thermal diffusion is a very efficient low pass filter, faster variations are damped much more strongly (and delayed less).

Ordinary bare single mode fiber has an expansion coefficient of about $10^{-5}\,\mathrm{K^{-1}}$ and jacketed fibers have expansion coefficients in the range $(1–5) \times 10^{-5}\,\mathrm{K^{-1}}$. The fiber chosen for ALMA will have an expansion coefficient below $1.5 \times 10^{-5}\,\mathrm{K^{-1}}$. Then a 25 km fiber buried 1 m deep would experience a diurnal change in length of 2.25 mm with a maximum rate of change of $0.6\,\mathrm{mK\,hr^{-1}}$. Any path length compensator must accomodate this range over the time between astronomical calibrations (≈ 20 min). In practice, these underground temperature fluctuations are small enough that changes in the overall fiber length may be dominated by thermal changes in much shorter lengths of fiber between the buried conduits and the receiver cabin or by mechanical strains at cable wraps.

7 Subterranean Freezing and Permafrost

On the morning of 1997 July 15, surveillance images showed the site blanketed in snow. Non-sinusoidal temperature fluctuations precluded a good determinations of the diffusivity on that day, but on subsequent days, it rose to a peak near $5 \times 10^{-7}\,\mathrm{m^2\,s^{-1}}$. By July 21, the last of the snow had melted from the surface and by the end of the month, the diffusivity returned to a near-minimum value. Presumably, melt water from the snow seeped into the ground and probably froze in the pores. Water and ice in the soil pores would have substantially increase the thermal conductivity but only moderately increased the heat capacity, thereby increasing the thermal diffusivity until the soil dried out. Although the daytime surface temperature rose well above freezing, the temperature 10–30 cm below ground never exceeded freezing during the entire month. But if the soil temperature was always below freezing, how did the water drain? Perhaps soil salts depress the freezing point of water enough to permit drainage. During the warming trend 5–15 days after that snow storm, the temperature at 30 cm depth was as high as $-3.5\,^{\circ}\mathrm{C}$ (as compared to $-6\,^{\circ}\mathrm{C}$ shortly after the snow fall), warm enough for salty water to remain liquid.

From 1997 September 18 through October 12, heavy snow covered the site and patchy snow persisted until October 21. During this period, the subsoil temperatures clearly show repeated melting and freezing episodes, which appear as inflection points in the temperature slope (Figure 12). When the temperature decreases, flattens out to zero slope, and then continues to fall, the flat zone marks the freezing point. Likewise, when the temperature increases, the flat zone indicates melting. Freezing and melting

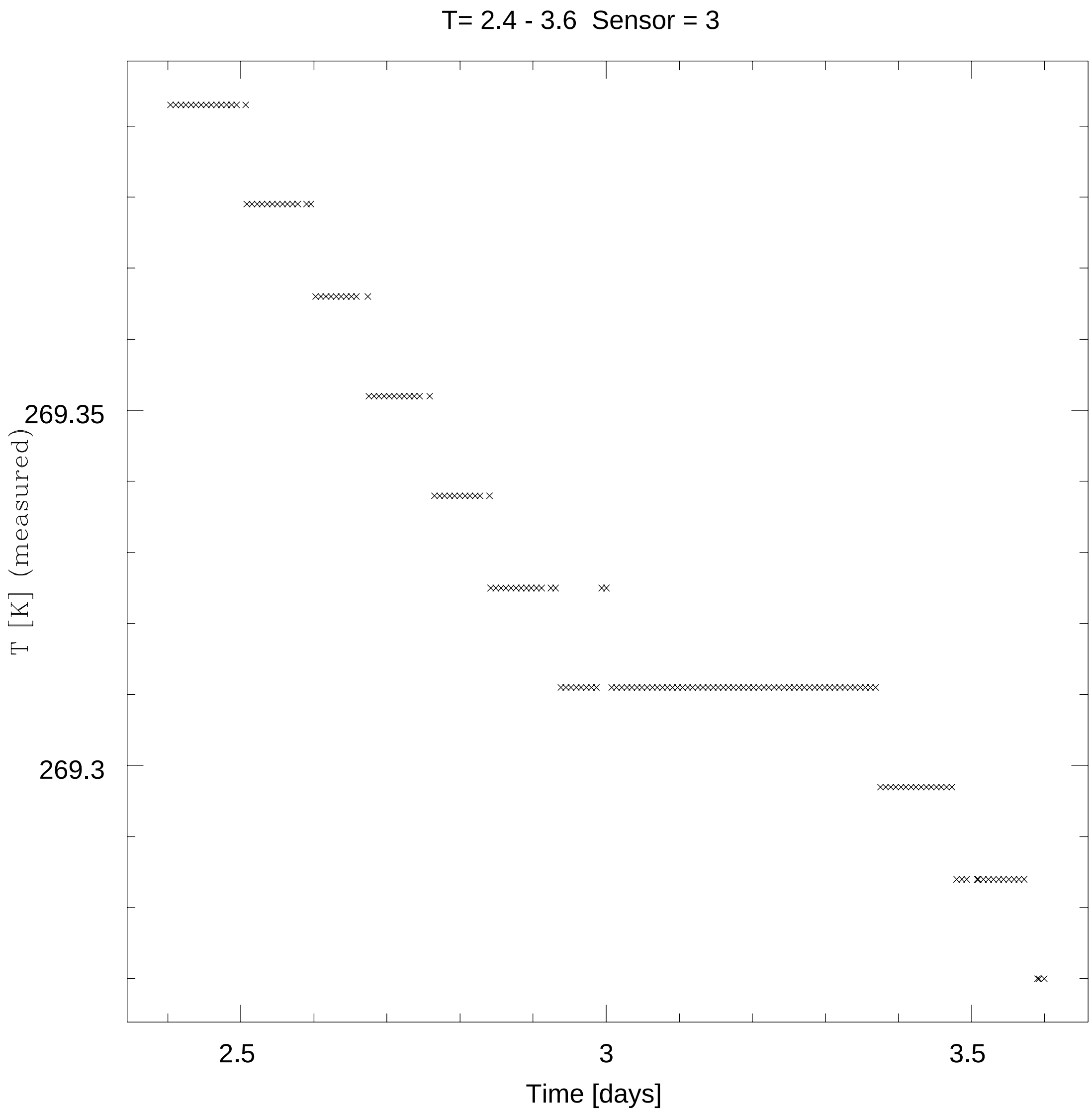

Figure 12: Freezing epsiode 10 cm below ground level at Chajnantor on 1997 October 3-4. Day numbers start at 0, so day 2.5 is 12 UT October 3.

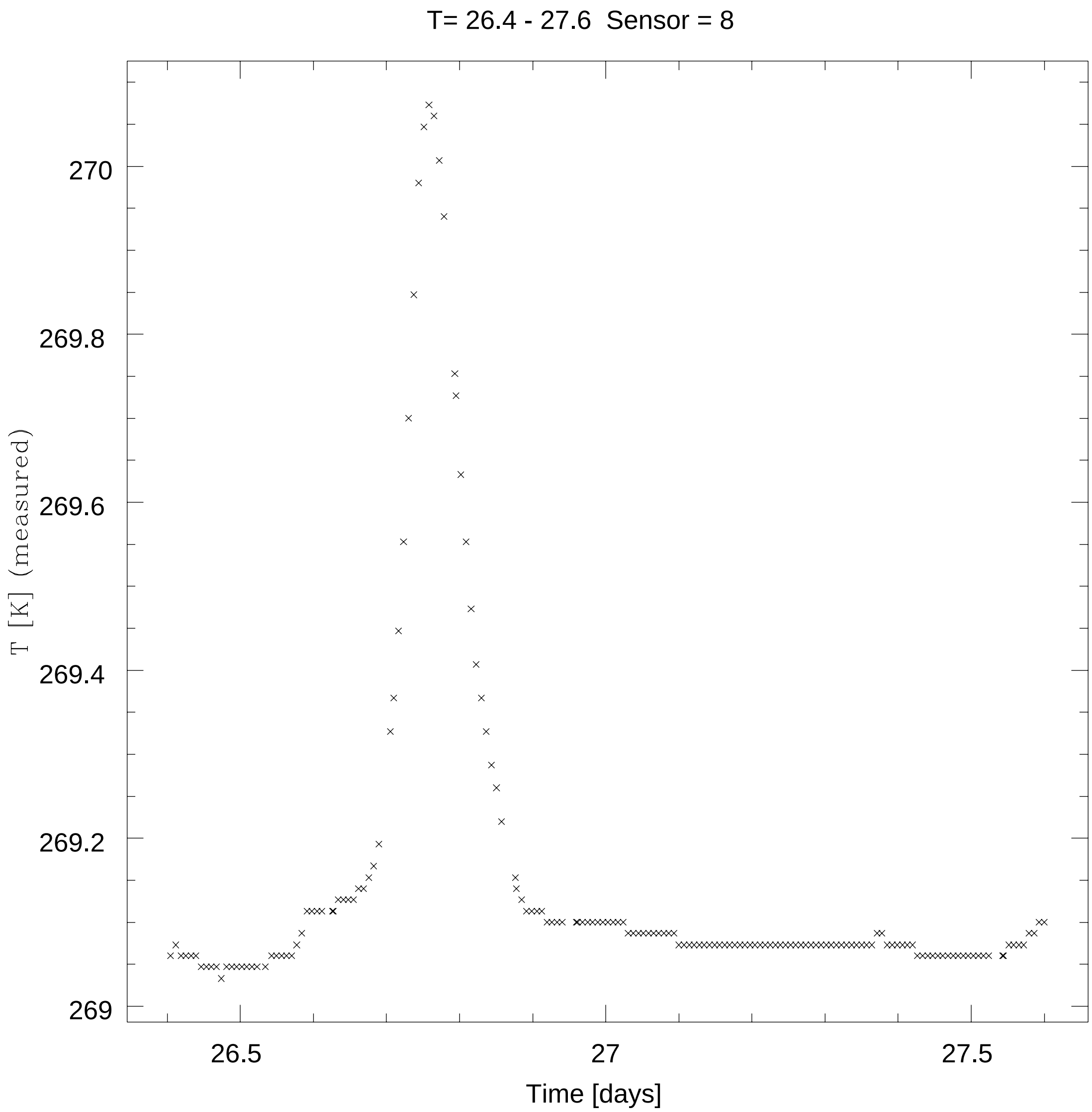

Figure 13: Partial freezing epsiode 10 cm below ground level at Chajnantor on 1997 October 27-28. Day numbers start at 0, so day 26.5 is 12 UT October 27.

Table 1: Freezing and Melting Episodes

Depth [cm]	Sensor	Complete Freezing [K]	Complete Melting [K]	Partial Freezing [K]	Partial Melting [K]
10	3	269.01	——	270.06	——
	8	268.26	——	269.07	269.12
20	4	269.16	270.27	——	——
	7	269.28	269.13	——	——
30	5	268.54	268.14	270.07	——
	6	268.89	——	——	——

occurred primarily during the first half of October, when the snow cover was heaviest.

Episodes of partial freezing (melting) also occurred (Figure 13), when the temperature decreased (increased), flattened out, and then increased (decreased). On these occasions, the ground was not cold (warm) enough to completely freeze (melt) the water. Partial freezing and melting were observed mostly in the sensors 10 cm underground, where surface effects are still strong.

Brief positive temperature excursions (spikes) also appear in the data. These are perhaps associated with water drainage, although 38 of the 41 spikes observed did not occur on days when a melting or freezing episodes happended.

The observed freezing points (Table 7) range from $-5\,^\circ$C to $-2.9\,^\circ$C, suggesting the soil salinity is equivalent to a 5–8% NaCl solution (Weast 1970). For comparison, seawater (3.5% salinity), freezes at $-1.9\,^\circ$C. For 1997 June–October, the median subsurface temperature was $-4.3\,^\circ$C, in the middle of the observed range of freezing points, and the median air temperature was $-5.0\,^\circ$C. Because the freezing points are all below the overall median air temperature, $-2.4\,^\circ$C, it seems no permafrost should exist below ground. The observed melting episodes confirm this.

In 2000 February, soil borings were made at several locations around Chajnantor and Pampa la Bola by the LMSA project. Although some cores were ice-free, others from low lying areas did have ice. Is this ice permafrost? Our measurements suggest the soil salinity is sufficiently high to preclude general permafrost, although local icy areas ice may exit. Measurements of soil resistivity would shed further light on soil salinity and the existence of permafrost at the ALMA site.

We thank Frank Gacon for assembling the temperature probe, Tony ("Me Tony, dig hole") Beasley and Jeff Kingsley for digging by hand the hole where the probe was buried, Angel Otárola for invaluable site support, and Bill Shillue for information about fiber properties. In 1998 Laura Snyder was an REU summer student from Iowa State University.

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