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Estimate of the ALMA Cryostat Hold Time

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Abstract

In this paper we attempt to calculate the operational hold time for the ALMA front-end cryostat, given the reported thermal loading, thermal capacity and leak rates.

Introduction

The ALMA front-end cryostat is a cylinder 1-m in diameter and 0.5-m high which holds up to 10 receivers operating in different frequency bands - for full details see [1]. Figure 1 shows the cryostat in a preliminary mounting frame which allows initial RF measurements to be made using the adjacent electronics and control racks. Figure 2 shows a close-up picture of the top of the cryostat with the windows for the 10 bands. Each receiver is inserted into the cryostat base plate and has an o-ring seal. The receiver base plate contains all the electrical and local oscillator (waveguide) feedthroughs. For more details see, for example, the Band 6 PDR presentation in [2].

Figure 1. Cryostat in test frame with electronics racks.

The RF signals enter through windows in the cryostat top plate [3], which are also sealed with o-rings. The windows for the highest frequency bands are made of quartz with matching layers, while the lower frequency bands are made of HDPE with matching layers machined on both sides. The cryostat itself has several o-rings for manufacturing and constructional reasons, and attachment points for vacuum pumps, gauges, and monitoring electronics.

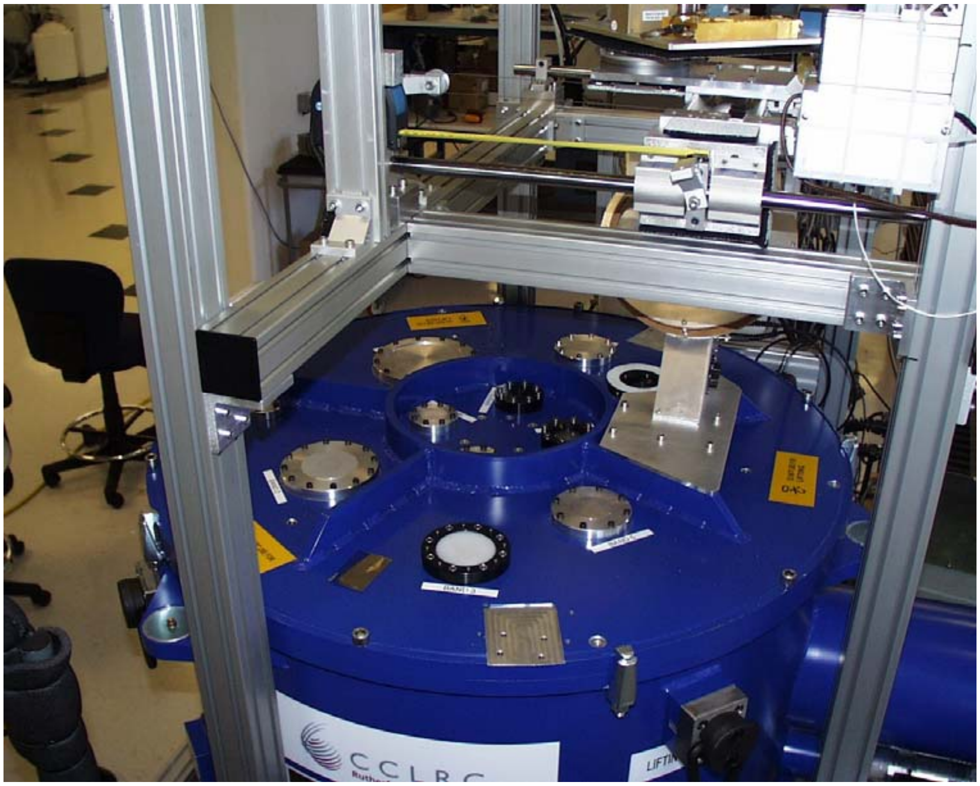

Figure 2. Close-up of the top of the cryostat.

Leak Rate

The helium leak rates of the various components have been measured [4] (see Band 6 comments [5]) and give an estimate of the total helium leak rate for the cryostat of probably 10^{-4} mbar*L/sec. There is difficulty in converting these helium-leak rates into rates for other atmospheric components (primarily oxygen (O_2), nitrogen (N_2) and water vapor (H_2O)) for the various materials (see discussion by Lazareff [6]). From [6], we will take as an estimate of the leak rate of dry air (nitrogen and oxygen) to be 10^{-2} of the helium rate, and the estimate of water vapor as equal to the helium leak rate. In order to convert leak rates, it is usual to take the square root of the ratio of atomic masses, but this does not match the few measured leak rates for various gases through the same material [7] and the ratio of molecular sizes of the leaking gases should probably also be taken into account ([8] and [9]).

These leak rates have to be measured over sufficiently long periods to ensure that steady state flow has been achieved; estimates of the required times are given in [10]. This indicates that for o-rings alone, time scales of order 10 minutes are required, but up to 20 times longer is required for the thicker HDPE windows for the low frequency bands.

Helium is not present at the site (except for leaks from the cryocooler – which would cause a failure to maintain the operating temperature) and will not be considered further.

Deposition Rates

For a rough order of magnitude calculation, we will assume the molecules which leak into the cryostat are evenly deposited on the cold surfaces inside the cryostat. This is probably not quite correct for several reasons, but with the very low vacuum (< 10^{-8} mbar) inside the cryostat during operation, the long mean free paths will tend to cause the molecules to be distributed rather evenly throughout the cryostat. Also, the molecules will steadily move to the coldest part due to finite (but small) evaporation rates on the intermediate temperature components.

Outgassing will not be considered here; it will add to the total amount of gas in the system, but if cool-down is slow that gas will be removed during pump-down. If the cool-down is rapid, most outgassed molecules will freeze in place and not affect the system hold time. The same is true for trapped gas volumes; if the cool-down is rapid, most of the trapped gas will be frozen in place. If the cool-down is slow, most of this gas will have diffused out of the trapped volume and will also have been removed during pump-down.

An estimate can be made of the gas molecule layer thickness on the cold surfaces. From Avogadro's number (6.02×10^{23} molecules/mole) and the Ideal Gas Law, one liter of gas at 10^{-4} mbar (for H_2O) contains 2.63×10^{15} molecules, and 2.63×10^{13} molecules at 10^{-6} mbar (for O_2 and N_2 combined). We will use this as the leak rate per second. Assuming the surface area of the cold components and shields to be 15 m^2 for the dry air components and 20 m^2 for H_2O (as the 90 K shield is too warm for the dry air components to condense), with the diameter of a molecule of 4.8×10^{-10} m (2×10^{-10} m for H_2O), the number of molecules needed to make a one molecule thick layer is 8.29×10^{19} for dry air and 7.86×10^{20} for H_2O. This leads to approximately 3.15×10^{6} seconds (875.6 hours) per layer for dry air and 2.98×10^{5} seconds (62.5 hours) for H_2O.

This indicates that if the cryostat is warmed up after one year, without pumping, it will achieve an end pressure of approximately 8.5 mbar.

As the number of molecules of the dry air components is 100 times less than those of water (even though fewer molecules are needed to make each layer), they are not considered here. These molecules would have an effect only if their solid phase absorption in the millimeter or in the infrared were 10 to 100 times higher than that of water ice.

Millimeter-Wave Losses

Measurements of the millimeter- and submillimeter-wave properties of ice at various temperatures are given in [11]-[12]. The loss factor rises linearly with frequency over the ALMA frequency range (33 GHz to 1 THz) and decreases with decreasing temperature of the ice.

Taking the imaginary part of the refractive index as 0.004 at 300 GHz and the real part of 1.79 [11] at 90 K, the loss is 0.815 dB/cm. The ice will form on both sides of the two infrared filters (90 and 12 K stages) and on the 4 K optics. If we assume uniform layer thickness on all the components, two mirrors on the 4 K stage (and loss doubling as the millimeter-wave signal travels through the layer twice on a mirror), we obtain a loss of 6.5 dB per cm of layer thickness. If we take the average temperature of the filters and optics as 20 K, the 300 GHz receiver noise temperature of 80 K will degrade to 100 K for a thickness of 120×10^{-6} m (over 615,000 layers). The filters will actually be at higher temperatures due to the IR loading through the vacuum window, and will tend to evaporate the condensed layer at a higher rate than the surrounding shield – tending to clean themselves.

Given the deposition rate above, it will take 1.8×10^{11} seconds (5,815 years) for this thickness (120×10^{-6} m) to be deposited. This is significantly longer than the time required to double the IR thermal load (see below) and will not affect the useful hold time of the cryostat. In the above section, we have ignored the losses due to reflections from the ice layer, which depend upon refractive index and layer thickness which will reduce the hold time.

It should be noted that the losses can be higher, as ice is well known to fracture at low temperatures, leading to scattering losses for the millimeter-wave signal which will also reduce the hold time.

The temperature of the mixers on the 4 K stage should not rise appreciably (see below) and will not affect receiver performance directly.

Even if these effects reduce the hold time to 1,000 years, we should not see any degradation of the receiver noise performance over the course of a year.

Infrared (IR) Load

The cryostat thermal loads on each of the stages, the thermal load due to radiation loading alone on the shield, and capacity at each stage are given in Table 1. As can be seen, the loading on the 90 K stage is so high that the shield temperature is actually 120 K. The 12 and 4 K stages can accept a very large increase in IR loading before their temperatures will be seriously affected. However, a doubling of the IR load on the 90 K stage will cause the stage temperature to rise significantly, possibly causing thermal runaway.

Table 1. Heat Loads and Capacity from [1].

Stage temperature (K)	Total heat load (W)	Radiation heat load (W)	Capacity at stage nominal temperature (W)
90	40	10.804	33
12	4.85	0.19	8
4	0.348	0.040	1

Extrapolating from [13] (for aluminum), the infrared absorbtivity of a water cryodeposit will be twice that of naked copper (0.02 [14]) for a thickness of approximately 0.005 mils (0.127 microns). Given the molecular diameter above, this means that 6.35×10^2 layers of ice need to accumulate. At 2.98×10^5 seconds per layer, the result is 1.89×10^8 seconds (6 years). This is most likely an over-estimate as the size of H_2O ice molecules is probably larger than in the gas phase (maybe by a factor of 2 due to the complicated structure of ice).

Conclusion

An order of magnitude calculation has been made of the hold time (> 3 years) of the ALMA cryostat, given the heat loads and leak rates reported for the initial cryostats. This is mainly due to the increase in IR heat load on the 90 K stage. The other stages will increase in temperature, but there is sufficient overhead that they will not cause thermal runaway of the cold head. Increases in the receiver noise temperature should be barely measurable over a time scale of one year. The main contaminant will be water ice condensation, the dry atmospheric gas leak rates being two orders of magnitude less.

In operations, the cryostat should be warmed up, and pumped out, regularly to purge the deposited water vapor. In this case, the pressure should not exceed 30 mbar as this would not permit the gate valve on the pumping system to be operated. Any unexpected warm-up of the cryostat would require manual intervention at the antenna. Given the leak rates assumed and a safety factor of 2, the cryostat should be warmed up and pumped every 1.75 years during operation. The present operational plan is to warm up and pump the cryostat out once per year.

These calculations were done for sea-level pressure (*i.e.*, at the front-end integration centers). Operation at higher altitudes will increase the hold-time in proportion to the reduction in water vapor pressure. The dry air components will also reduce, but they are not limiting factors.

References

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