ALMA Holography Overview

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1.0 Introduction

The use of "microwave holography" as the primary method of evaluating the ALMA antennas and setting their panels has been the project's baseline for several years. There is a long history of such measurements in radio astronomy (e.g., [3-5]). We are particularly drawing on experience at the NRAO in holographic measurements of the 12 M Telescope, 140 Ft Telescope, and VLA antennas; at IRAM on the 30 M and the Interferometer; at the CfA on the SMA antennas; and at the JCMT 10m telescope. Early design efforts for ALMA were summarized at a PDR in 1999-Apr. See Holography PDR documents and Holography PDR Summary and Recommendations. The current design is summarized in the Test Interferometer Project Book chapter , which will be updated as needed during the remainder of the development work. Readers are referred to these documents for additional background.

Since the PDR, many details of the design of the ground-based holography system have been worked out, and some of these differ from the earlier plan. The transmitter design is completely different, and will now make use of two phase-locked lasers driving a photomixer, rather than a millimeter-wavelength oscillator. Observing on two well-separated frequencies will be supported (both in the 75-110 GHz waveguide band), as will small changes in frequency about each nominal one. The receiver will be locked to the antenna LO system's fixed references, rather than to the transmitter. Cross-correlation will be done in a digital processor, rather than in a vector voltmeter.

The design is now being presented for CDR. Following a successful review, we will proceed to detailed design and then to implementation.

2.0 Requirements

The fundamental requirement is to measure the antenna surface profile sufficiently accurately to ensure that the specifications have been met by the manufacturer. The basic specification is that the final surface should be accurate to 20µm, computed as the RSS of various contributions; a sample error budget is shown in Table 1. The budget is required to allow for 10µm of RMS error in panel setting knowledge (called "holography" in Table 1) and 2µm of error in setting the panels to the desired places; otherwise, the budget allocations are at the manufacturer's discretion. Furthermore, the antenna as delivered may have the panels mis-adjusted such that the total error is as large as 100µm; it is our job to do the final adjustment. Neglecting the "holography" error and secondary mirror error in Table 1 (since we can do prime focus holography without the secondary), we see that the main reflector should be capable of a surface error as small as 15µm RSS. It is this error that we need to measure.

Table 1: Sample Surface Accuracy Budget

(from prototype antenna contract, attachment A, page A-18)

see antenna contract Table 3.4.2-1

Whereas we intend to use holography to obtain data for the final panel adjustments as well as to check the overall surface profile, errors in the holographic measurements come in twice. For this reason, as well as to allow some margin, our design goal is to achieve 5µm (1 σ) accuracy in the measurements, with a hard specification of 10µm. The transverse resolution needs to be small compared with the panel sizes, which are different for each of the two manufacturers and are not precisely known; however, we are confident that 0.1 m resolution will be adequate.

Radio holography has some inherent limitations. First, it is difficult to obtain separate profiles at widely different elevation angles, and thus to measure the gravitational component of surface profile variation. There are no artificial sources (satellites) at sufficiently high frequencies for these measurements, and natural sources are too weak. We therefore rely on a ground-based transmitter for the initial measurements, restricting us to low elevations. Second, temperature changes can affect the profile, so it is important to complete a set of measurements quickly or under equilibrium conditions. We set a goal of 30 minutes per measurement.

Later, when using a second 12 m antenna to obtain a reference signal ("interferometric holography") it should be possible to use natural sources to obtain profiles at many elevations.

Two new requirements have been added since the PDR, and both make it necessary to operate on more than one frequency. First, we want to have a secondary frequency that is sufficiently separated from the first to allow verification that frequency-dependent effects in the data processing have been accurately taken into account. Specifically, this includes corrections for diffraction from the subreflector support legs and other antenna structures; and corrections for the fact that the transmitter will be in the near field. Second, since the transmitter will be at a relatively low elevation angle, we would like to have a way to remove the effects of multipath propagation. This can be done if the frequency is varied a few percent from nominal (see section 4.3.2, below).

Table 2: Requirements for Single-Dish Holography

Parameter	Specification	Goal
Measurement error	<10 µm rms	<5 µm rms
Transverse resolution	0.1 m	0.1 m
Measurement time (per observing frequency)	60 min	30 min
Primary frequency, f	80-120 GHz	
Secondary freq, $f2$	$f2/f1$>1.2 or <0.8 (at least 20% separation)	
Tuning about $f1$ and $f2$		
Minimum step size	5 MHz	1 MHz
Range	130 MHz	200 MHz
Settling time	60 sec	1 sec

The above considerations result in the requirements for the ground-based holography system that are summarized in Table 2. Except for the additions described above, these are the same as were reviewed and approved at the PDR.

3.0 Observing Strategy

The basic observation consists of a raster of points around the boresight, where the complex cross power between signal and reference channels is measured at each. However, to maximize the observing efficiency, we intend to scan each row on-the-fly. Several factors affect the choice of scanning speed: it cannot exceed the antenna slewing limit; it cannot be so fast that synchronization of data recording with known antenna positions becomes difficult; and it should not be more $\lambda/2D$ in the integrating time needed to achieve the desired sensitivity. Depending on the design parameters, one of these will dominate. If we are sensitivity limited, it is also possible to scan as fast as other considerations permit and then to repeat the raster, averaging together several maps to achieve the necessary overall sensitivity.

At the speed specified for OTF interferometry, 0.5 deg/sec, the raster could be completed in just over 12 min, exceeding our 30 min goal. This would require an integrating time of about 10 msec and a correlator readout rate of about 100 measurements per sec.

If necessary for multipath mitigation, several nearby frequencies can be observed. We considered several strategies for this: frequency switching during a scan, with the scanning rate or the integrating time reduced by the number of frequencies; or scanning a complete raster, switching frequency, and then scanning again; or rapidly modulating the frequency, so that it covers the desired range in much less than one integrating time. We concluded that only the second option (switching between rasters) is practical. For the first option, it would be necessary to complete the transition between frequencies in 1-3 msec, for both transmitter and receiver; this is difficult with available hardware. For the third option, the receiver would have to be locked to the transmitter at large loop bandwidth; this would require a much larger transmitter power than would otherwise be necessary.

At some point, ground-based "interferometric" holography may be attempted, using the second ALMA antenna as the reference and using the astronomy receivers (rather than the holography receiver) on each. This will be possible when the antennas are on adjacent pads, so that the transmitter can illuminate both.

4.0 Summary Of Design

4.1. Signal source and path geometry

No suitable satellites have been identified for use as signal sources for these measurements. (A suitable satellite would have to be in near- geosynchronous orbit and transmit a stable, narrow-bandwidth signal at millimeter wavelengths, preferably above 75 GHz.) We must therefore rely on a ground-based transmitter. All mountains visible from the test site are at too low an elevation angle, so we are faced with erecting our own structure on which to mount the transmitter.

Considerations include: the tower should be as high as possible to increase the elevation angle, but cost goes up rapidly with height, as does the difficulty of servicing the equipment. Distance should be minimized to increase elevation angle, decrease cost of cabling, and make servicing convenient; but the largest possible distance is needed to minimize near-field corrections.

After careful consideration, the distance was fixed at 300 m and the height at 50 m. The tower cost increases rapidly above this height. The distance is .0039 of the nominal edge of the far-field region at 80 GHz, which was a concern. The JCMT and SMA have successfully accomplished similar near-field holography, but at somewhat greater fractions of the far field distance (around .01). Although we are convinced that the correction is still small enough to be handled accurately, this was part of the reason for requiring that the system work at a second frequency.

This results in the geometry shown in Fig 1. The nominal on-boresight elevation of the transmitter is 8.16 degrees, although this is slightly different depending on which pad the antenna occupies. The normal scanning angle in a holography raster is +-1.15 deg, so the minimum elevation is 7.01 deg. (However, larger scan angles might be used for special, high resolution maps.)

4.2 Frequencies

As was discussed at the PDR, operation in the general vicinity of 90 GHz is desired. This is a balance between the required SNR and dynamic range, on the one hand (favoring high frequencies), and the cost and performance of components on the other (favoring low frequencies). Additionally, at very high frequencies, cycle ambiguity can also cause confusion.
In choosing specific frequencies, we first considered legal issues. Some of this frequency range is allocated internationally to passive services only (no transmission), including radio astronomy. Nevertheless, at least in the U.S., we would be operating as a government station for experimental purposes, and as such we are permitted to make low-power, intermittent transmissions anywhere in this band without licensing or other authorization, on the condition of non-interference to any authorized users. In addition, even within the passive bands, transmission is allowed for some purposes, including antenna testing. We therefore concluded that we are under no legal obligation to avoid any particular frequencies. Nevertheless, we decided to avoid the passive bands if possible, so as to avoid setting any undersirable precedent. The passive bands are now 86-92 GHz and 115-116 GHz. Additional passive segments were approved at WARC-2000 and will be effective around 2003; these are 101-102 GHz, 109.5-111.8 GHz, and 114.24-115 GHz.

We also considered the potential for interference to the VLA and to the Pie Town VLBA station. At present the VLA has no receivers in this band; however VLBA-PT has a receiver for 80.0-90.0 GHz. We will avoid this band. However, the station is about 53 km from the holography transmitter so the EIRP required to reach the official harmful threshold for radio astronomy (-143 dBW/m^2 [2]) would be 0.2 mW due to free space attenuation alone; we will have about 100x less than this. In addition, the two locations are separated by a range of mountains.

Finally, in order to ensure reasonable availability of components at reasonable cost, and to allow the two frequencies of operation to share as many components as possible, we decided to keep both frequencies within the WR10 waveguide band (75-110 GHz).
In view of all these considerations, the nominal frequencies are now set at 78.9 GHz and 104.0 GHz.

4.3 Performance calculations

4.3.1 Transmitter power

Using the performance requirements of Table 2, and making reasonable assumptions about the performance of components, the minimum required EIRP at the transmitter is calculated to be about 9 μW. Details are given in Appendix A. This calculation assumes that the transmitter produces a plane wave at the antenna, as if it were in the far field, and that the receiving feed is at the far-field focal point. We know that these assumptions are not correct, but there are strong arguments that the result is nevertheless quite accurate. First, by re-focusing the feed to the appropriate near-field focal point we obtain nearly the same on-boresight signal as for a plane wave of the same amplitude. Second, assuming that we scan over the angular range needed to fully sample the field, the integrated power is independent of focus and nearness of field.

4.3.2 Multipath

One source of systematic error is multipath interference on the transmitter-receiver path. The vicinity of the path will be mostly empty, the obvious exception being the ground. Here we estimate the effect of the multipath reflection.

Given the geometry of Fig. 1, the specular reflection point from a smooth ground can be shown to be 263 m from the tower base, at which point the path difference (reflected minus direct) is minimized and equal to 2.30 m. The incident and reflected angles there are 10.75d. From the transmitter, this is nominally 2.6d below the center of the 12 m antenna, so the transmitting antenna's directivity provides little attenuation (about -3 dB at the planned beamwidth, see below). From the main receiver, it is more than 17d below the boresight at the lowest scan angle. The reflection point is very much in the near field of the 12 m antenna, and additional scattering from feed legs and other structures is likely, so a good estimate of the received power on the indirect path is difficult. For the reference channel, an ideal (uniform illumination) aperture horn of the planned beamwidth (4.6d) would be about -28 dB from boresight at this angle. Much more attenuation is expected because of polarization mismatch (see discussion in next section).

Coherent interference of -30 dB in either the signal or reference channel would produce a maximum phase error of 1.8d, which corresponds to 15μm at our wavelength. If the phase of the interference varies randomly over the raster, as is likely, then the average effect on any pixel of the resulting surface deviation map (120x120 pixels) will be about 0.12μm.

The minimum path difference of dx=2.30 m implies that the phase difference changes by one cycle for a frequency change of $df=c/dx$ = 130 MHz. For other reflection points, a smaller frequency change is needed to "wash out" the effect of the reflection. This sets the tuning range needed to mitigate the interference, should it prove to be a limitation.

4.4 Hardware configuration; design parameters

The geometry and frequency choices described above lead to the design parameters given in Table 3 and discussed further below.

Table 3: Design Parameters

Primary frequency	104.0	GHz
Secondary frequency	78.9	GHz
Tuning about each frequency	>130	MHz range, <1 MHz steps
Range	300	m
Transmitter height above ground	50	m
Transmitter height above elev axis	43	m
Nominal polarization (xmtr and rcvrs)	vertical	
Receiver processing bandwidth	10	kHz
Integrating time per measurement	12...48	msec (nominally 48 msec)
[Derived:]		
Scan angle for 0.1 m resolution	2.18	deg at 78.9 GHz (+-1.09)
	1.65	deg at 104.1 GHz(+-0.83)
Minimum scan angle	2.29	deg due to near field geometry
Transmitter beamwidth at -3 dB	4.6	deg (twice antenna angle@xmtr)
Transmitter antenna gain	33	dB
Transmitter EIRP	>20	µW
Transmitter power to antenna	>10	nW
Reference antenna beamwidth, -3 dB	4.6	deg (twice scan range)
Main antenna feed beamwidth, -3 dB	128	deg [-3 dB edge taper]

Polarization: Vertical polarization is chosen to minimize the effects of ground reflection. For shallow angle reflections such as we will have in our geometry, and for typical ground conductivity and permittivity, most of the reflected wave is horizontally polarized. (See some brief correspondence on this topic.)

Bandwidth: Since we are operating in the large-signal regime, the average SNR is only weakly dependent on the bandwidth. But the digital processing speed required is proportional to bandwidth, favoring a small value. On the other hand, a large value permits a frequency tracking error between receiver and transmitter. The 10 kHz value is a reasonable compromise.
Integrating time: Achieving the desired resolution in 30 min observing time corresponds to 56 msec per measurement. To achieve accurate synchronization with antenna motion, integration should be tied to the 48 msec system timing signal. With 48 msec integrations and some overhead for antenna turn-arounds and boresight calibrations, the 30 minute mapping time can be achieved. The minimum transmitter power calculation (Appendix A) assumes 28 msec integrations. The minimum integration time should be somewhat smaller, to allow for faster mapping if higher-than-minimum SNR is available. Long integrations, if desired, can be implemented in MC or analysis software.

Scan angle: The scan angles in Table 3 are calculated as if the received signal were a plane wave. In fact, at moderate scan angles where a plane wave signal would be far down in the sidelobes, significant near-field signal will still be received. To avoid losing the information in this signal, a geometrically-determined minimum scan angle should be used, regardless of the desired resolution. This is the angle at which a cylindar whose diameter is equal to the antennas's and which is parallel to the antenna's axis just grazes the transmitter. We find that this is slightly larger than the scan angles calculated for plane waves.

Beamwidths: The transmitter's -3 dB beamwidth is chosen, somewhat arbitrarily, to be twice the angle subtended by the antenna. This makes the signal at the antenna edge about -0.75 dB lower than at the center, slightly reducing the sensitivity to reflector deformations near the edge. Making the beamwidth larger would increase the chance of multipath interference, and would also reduce the transmitting gain and thus the SNR. This leads to a gain of 33 dB.
The reference antenna's -3 dB beamwidth is chosen to be twice the scan angle, or about 4.6 deg. This will reduce the gain at the scan edges by 0.75 dB, slightly reducing the transverse resolution; again, a larger beamwidth would reduce the gain everywhere and thus the SNR.

5.0 Error Budget

An overall error budget is summarized in Table 4.

Table 4: Error Budget

Thermal noise	5 µm rms (at minimum xmtr pwr)
Feed phase pattern knowledge	5 µm peak (critical)
Reference antenna pattern knowledge	<1 µm (insensitive)
Multipath interference	0.4µm (-20 dB, random phase)
Frequency error	0
Near field correction error	unknown
RSS (except near field correction)	7.2 microns

Appendix A: Transmitter Power Calculation

ALMA Holography, SNR and power requirements

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Assumed hardware parameters:

Receiver pre-correlation bandwidth	B	10 kHz
System temperature, each receiver	T	3200 K (1600K DSB)
Frequency	f	92 GHz (λ=3.26mm)
Antenna diameter	D	12 m
φ_{3dB} = .01556°		
Range	R	300 m
Transmitter EIRP	P	TBD

Measurement requirements:

Transverse resolution	Δ	0.1 m
Surface displacement accuracy	δz	5 µm
Total measuring time (OTF scanning)	t	<30 min

Derived Paramters:

Scan angle θ 1.867^o $(+-0.934^o)$
$\theta = (\lambda/D)(D/\Delta)$

Number of measurements K 180^2
$K = (sD/\Delta)^2$, oversampling factor $s=1.5$

Integrating time per measurement τ 27.8 msec
$t = \tau K$ + overhead, allowing 100% overhead.

Reference antenna diameter d 50 mm
-3dB beam = $2\theta = \lambda/d$

Analysis:

Reference antenna power rcvd P_r (1.736e-9 P)
$P_r = (1/16)(d/R)^2\ P$

Main antenna power rcvd on boresight $P_s(0)$ (1.000e-4 P)
$P_s = (1/16)(D/R)^2\ P$

Receiver noise power kTB 4.42e-16 W

On-boresight sig (corr output ampl) M_0 (4.167e-7 P)
$s(0) = \{P_s(0)\ P_r\}^{(1/2)}$

On-boresight noise σ_0 $[(1.59e\text{-}22W)(P)]^{\{1/2\}}$

$\sigma^2 = [kTB + P_r + P_s(\alpha)]\ kT / \tau$
where α is scan angle, $-\theta/2 < \alpha < \theta/2$.
Can neglect kTB term for any P>1 μW.

Average noise over map:

$P_s(\alpha) = P_s(0)\ [J_1(\pi\alpha\ D/\lambda) / (\pi\alpha\ D/2\lambda)]^2$

Noise dominated by P_s term until power is down by 50 dB. That happens when $J_1(2x)/x > 3e\text{-}3 \Rightarrow x > 31.7 \Rightarrow \alpha > 20.2\lambda/D$. Outside there, the P_r term dominates.

Off-boresight noise (P_r term) σ_1 $[(2.76e\text{-}27\ W)(P)]^{\{1/2\}}$

Very conservative estimate: With sampling every $0.75\lambda/D$ (s=1.5), there are about $\pi\ 27^2 = 2270$ samples where the P_s term dominates. Thus, there are 180^2-2270 = 30,130 samples where the P_r term dominates. Of those where P_s dominates, take the inner 4 to be σ_0, the next 25 to be 10x lower, and the rest to be 100x lower, in accordance with the envelope of $J_1(x)/x$.

$$\sigma_{avg}^2 = [(4+25/10+2241/100)\sigma_0^2 + 30130\ \sigma_1^2] / K$$

$$= 9.084e\text{-}4\ \sigma_0^2 = (1.444e\text{-}25W)\ P$$

This is actually the noise from a single, real correlator. For complex correlation, we need to increase this by 2 times.

Finally, from [1] eqn (30):

$$\delta z = .044\ (\lambda/sD)^2\ D^2\ K^{\{1/2\}}\ \sigma_{avg} / (\lambda\ M_0)$$

$$= .044\ \lambda/s^2\ K^{\{1/2\}}\ (\sigma_{avg} / M_0)$$

$$= .044\ (3.26mm)/2.25\ 180\ \{2(1.444e\text{-}25W) / P\}^{(1/2)} / 4.167e\text{-}7$$

$$= (2.754e4\ m)\ \{(2.888e\text{-}25W) / P\}^{(1/2)}$$

For $\delta z = 5\ \mu m$, this implies $P = 8.76\ \mu W$.

References

[1] D'Addario, L., 1982, "Holographic antenna measurements: further technical considerations." 12M Telescope Memo No. 202, NRAO, Charlottesville, Nov 1982.

[2] International Telecommunications Union, Handbook On Radio Astronomy. ITU, Geneva, 1995.

[3] Scott, P. F. and M. Ryle, 1977, "A rapid method of measuring the figure of a radio telescope reflector." MonNotRoyAstrSoc, v 178, pp 539-545.

[4] Rahmat-Samii, Y., 1984, "Surface diagnosis of large reflector antennas using microwave holographic metrology: an iterative approach." Radio Science, v 19, pp 1205-1217.

[5] Morris, D., 1985, "Phase retrieval in the radio holography of reflector antennas and radio telescopes." IEEE Trans. Antennas & Prop., v AP33, pp 749ff.

Table 3.4.2-1 Example Surface Accuracy Budget

Error Source	RMS Error
Panels	
Manufacturing *(Including measurement errors)*	8.5 µm
Aging	2.0 µm
Gravity	4.0 µm
Wind	4.0 µm
Absolute Temperature	4.0 µm
Temperature Gradients	4.0 µm
Total Panel (RSS)	**11.8 µm**
Backing Structure	
Gravity (Ideal)	5.5µm
Gravity (Departure From Ideal)*	3.0 µm
Wind	2.0 µm
Absolute Temperature	2.0 µm
Temperature Gradients	2.3 µm
Aging	2.0 µm
Total Backing Structure	**7.5 µm**
Panel Mounting	
Absolute Temperature	2.0 µm
Temperature Gradients	2.0 µm
Panel Location in Plane	2.0 µm
Panel Adjustment Perpendicular to Plane***	2.0 µm
Gravity	3.0 µm
Wind	2.0 µm
Total Panel Mounting (RSS)	**5.4 µm**
Secondary Mirror	
Manufacturing	5.0 µm
Gravity	2.0 µm
Wind	2.0 µm
Absolute Temperature	2.0 µm
Temperature Gradients	4.0 µm
Aging	3.0 µm
Alignment	3.0 µm
Total Secondary Mirror (RSS)	**8.4 µm**
Holography**	
Measurement	10.0 µm
Total Holography (RSS)	**10.0 µm**
Other Errors not Included Above	**2.0 µm**
TOTAL (RSS)	**20.0 µm**

* *Departures from ideal such as member true size, manufacturing, modeling accuracy, etc*

** *AUI is responsible for the precision adjustment of the primary surface.*

*** *AUI is responsible for the panel adjustment perpendicular to plane of the primary surface (fixed at 2.0 µm).*

Figure 1: Signal Path Geometry