
ALMA Test Interferometer Project Book, Chapter 5.

Holography System

Darrel Emerson
Antonio Perfetto
Last modified 2000-February-14

Revision History
1998-11-10: Added specifications summary table, project time scale table and section/sub-section numbering.
2000-02-14: Modified to reflect the recommendations of the holography system PDR and to comply with the ALMA Test Interferometer Project Book.

Summary

This chapter describes the hardware and software requirements for a holography system that will be used to measure the first ALMA dishes. The objectives of holographic measurements are (1) to determine the primary reflector rms deviation from the ideal parabolic shape and (2) to generate a list of adjustments for each point on the dish that can be calibrated mechanically in order to achieve the best surface accuracy. The holography system will be compatible with both the US and European prototype antennas. Table 5.1 summarizes the main specifications and requirements for the ALMA holography system. This system will be designed, built and tested during the ALMA D&D phase. The main milestones are shown on Table 5.2.

Table 5.1 - Holography System Specifications and Requirements.

Single Dish Holography	
Item	**Specifications**
Measurement Accuracy (rms)	10 microns
Measurement Resolution	Approx. 10 cm
Holographic Map Sizes	Grids of 257*257, 129*129 and 65*65 points
Measurement time	About 1 hour
Holography Hardware	Land Beacon Transmitter Prime Focus Dual Channel Receiver Digital Back-end (A/D, DSP and Data Storage systems) Specifications: tbd
Interferometric Holography	
Requirements: Interferometric holography requires that most of the ALMA systems be operational.	

Table 5.2 - Holography Milestones.

Holography Hardware Design Review	March 1999
Deliver Holography System Software	March 2001
Deliver Holography System to Antenna Test Site	March 2001

5.1 Introduction

Holography will be used to measure the first ALMA 12 meter dishes, soon after they are first installed at the VLA site. The requirements are a measurement accuracy (rms) of 10 microns, and a resolution on the surface such that several independent points are available for each panel. In practice, this means the dish should be sampled at about 10 cm intervals. This in turn means that a 12 meter dish will need to be measured by about a 120*120 array of points. In practice, most holographic maps will probably be made at 256*256 or 128*128 points, with occasional measurements at 64*64 points. There is no requirement for the data to be measured on a 2^N grid - in fact an odd number of points, giving a symmetrical grid with the center point on the bore sight, is advantageous. For example, measurements on the Kitt Peak 12 Meter Telescope used a grid 129*129 or 65*65 points.

Note that, unlike standard single dish astronomical measurements, holographic measurements record complex pairs at each sample in the sky plane, rather than just a single total power value. This implies that Nyquist sampling is defined as (lambda/D) radians, rather than (lambda/2.D). D is of course the dish diameter, and lambda the wavelength at which holographic measurements are being made. The number of complex data points (e.g. 129*129) mapped in the sky plane, giving the complex antenna beam pattern, equals the number of data points (for example 129*129) describing the complex antenna illumination pattern.
So, the total angular extent of the necessary beam map is simply calculated, once the holographic wavelength, dish diameter, and necessary sampling interval on the dish surface are determined. For example, if a wavelength of 3.33 mm (90 GHz) is chosen, lambda/D for a 12 meter dish becomes 0.000275 radians, or about 57 arc sec. If a grid 257*257 is needed, the total map extent becomes 257*57" or about 4 degrees. In practice a little oversampling is always necessary, by perhaps 20%; in this example a sampling interval (after gridding) of about 46" would be appropriate.

Holography will be carried out in 2 distinct modes. In both cases, the aim is to produce a complex beam pattern - that is to say a map of relative amplitude and phase of the antenna being measured.

a. Single dish observations: the phase reference for the measurement of complex antenna pattern will be provided by a small feed looking towards the transmitter, behind the main dish feed, at the prime focus of the antenna. The antenna will be scanned back and forth over the source, to map its detailed, complex beam pattern.
b. Interferometric observations: this will use a pair of antennas, with one antenna tracking the source and providing the phase reference for the second antenna. The second antenna will scan back and forth across the source, to produce a 2-D map of its own complex beam pattern.This will allow antenna surface measurements over a range of elevation angles, but because of more limited signal-to-noise ratio, there will be an inevitable tradeoff between precision of surface

measurement and less frequent sampling along the antenna surface. This measurement also requires two antennas to be fully operational, with correlator and phase-stable LO distribution. Frequencies of ~86 and ~240 GHz will be used.

Case (a), the single dish mode, is in general a little more complex because of the necessary calibration procedures. Case (b), the interferometric mode is closer to a normal, astronomical mode of observing. In what follows, only the single dish mode, case (a), is considered.

5.2 Holography Hardware

5.2.1 Choice of observing frequency

The precise frequency is not critical. Holography measures physical distances; the lower the frequency, the smaller the phase change corresponding to a given distance, and so the higher the signal-to-noise required. If the frequency is too low, diffraction effects (diffraction shadows around the feedlegs, and diffraction around the central antenna blockage) can become significant. The lower the frequency, the larger the area on the sky around the boresight which has to be mapped, for a given linear resolution on the dish surface; this may ultimately present difficulties to the antenna drive and control system, in order for it to be possible to make a sufficiently large map in a reasonable amount of time.

The required signal-to-noise ratio and dynamic range requirement both increase inversely with frequency. At too low a frequency, the needed dynamic range can become a serious problem, and even small cross-talk between the two receiver channels (dish feed and reference horn) can introduce serious errors.

If the frequency is too high, then ambiguities can arise in the measures of the dish surface; fundamentally, holography cannot distinguish between a patch on the dish surface lambda/4 too high, or a patch 3*lambda/4 too low. At the frequency becomes higher, several factors cause the signal-to-noise ratio to become worse - receiver noise temperatures are higher, and the available signal power may become less. Interestingly, the antenna capture area of the reference feed does not vary with frequency; the beam solid angle needed for a given resolution on the dish surface decreases with the square of frequency, exactly as the beamwidth of an antenna with constant physical size. The physical size of the reference feed approximates to the limiting physical resolution of the final holographic map of the dish surface.

The ideal frequency is probably around 90 GHz. Ideally a signal source would be in the far field, but this is not essential. Several groups have achieved excellent holographic measurements of mm-wave or submm-wave telescopes using an artificial beacon a few km or even a fraction of km distant. For the reasons mentioned above, frequencies below 30 GHz are probably not suitable. Unfortunately, no satellite beacon transmissions suitable for ALMA holography have yet been identified. Also, all suitable mountain tops near the ALMA test site (VLA) present an unacceptably small elevation angle (< 2 degrees). The next best solution is to have the land beacon mounted on a tower, a few hundred meters from the antenna being measured. The near-field correction to the measurements is an important issue, but as demonstrated by other groups, a manageable one.

5.2.2 Frontend

The single-dish holographic measurements will be made, at least initially, with a prime focus receiver. For the duration of the measurements the holography receiver box will be mounted at prime focus instead of the normal subreflector. The main advantage of prime focus holography is that potential measurement uncertainties resulting from inaccuracies of the subreflector are avoided. The holography frontend will have two feeds; the first, mounted close to the true focal point, will illuminate the dish in the normal way. (Note however that for holographic measurements it is advantageous to over-illuminate the antenna; G/T optimization is not an issue for holography.) The second feed will point away from the dish, along the boresight of the antenna; this feed serves to provide the reference signal for the holographic system. The beamwidth of this reference feed should be somewhat larger than the maximum anticipated holographic map - for example, 5 degrees. Note the comment above that, in this receiver arrangement, the ultimate physical resolution on the dish surface approximates to the physical size of the reference feed, whatever frequency is chosen for measurements.

Both feeds have independent mm-wave mixers. The independent mixers will be fed from a common local oscillator source. The two resultant i.f. signals will be fed independently to the backed processor, which will be mounted in the antenna cabin. Temperatures, and hence phase drifts, in the two mixer and i.f. chains, with their cables, should be well matched to avoid measurement errors.

5.2.3 Backend

The measurements will be made on a CW signal. To optimize signal-to-noise ratio, a receiver bandwidth of perhaps 100 Hz will be used. The two IF signals will be filtered to a few kHz of bandwidth, then digitized directly. A DSP card will perform FFTs on the data samples to produce a spectrum with perhaps a few Hz resolution. The peak signal (amplitude and phase) will be chosen and stored for later analysis. Data from the main beam (the telescope feed) need to be sampled often enough to match the holography on-the-fly mapping rate. Something like 10 ms will probably be appropriate. The reference channel, with its much larger beam, should be integrated later in the data reduction software, to improve signal-to-noise ratio; this will reduce its effective data rate by about 2 orders of magnitude. However, at the raw data stage, it will also be sampled and stored at up to the 10 ms rate

5.2.4 General Telescope System

In order for holography observations to be possible, much of the telescope system needs to be fully operational. The most critical area is the telescope pointing; this has to be well understood and reproducible before any holography observations can be attempted. Proven observing techniques sufficient to check the telescope pointing frequently during a holography map will be needed. The telescope control system must already support high speed mapping operations, especially the on-the-fly mode. The holography mapping mode will be a variation of conventional on-the-fly observing; for instance, boresight pointing, amplitude and phase calibrations will be needed throughout a holography map - every mapping row, or perhaps every few rows depending on the stability of the system. The ability to make, analyse and apply pointing measurements quickly, in the course of a holography map, is an important requirement.

5.3 Holography Data Reduction Software

The data reduction will take raw data from disk, which has been observed in the on-the-fly mode, and will ultimately produce a list of adjustments, calibrated in microns, for each adjustment point of each panel of the dish.

The raw data for one holography map will consist of from 30 to 513 map rows. Each row may have up to about 5000 data samples. Each sample may be a complex spectrum of one to a hundred points.

Each data point will have associated co-ordinate information. The sampling along each row will be up to 10 times greater than the Nyquist rate for the telescope, while the sampling interval between rows will be perhaps 20% more frequent than the corresponding Nyquist rate. At the start and end of each map row, or in general after *n* map rows, there will be a calibration measurement taken on boresight. The basic observing grid will probably be in an azimuth-elevation system, with respect to the transmitter.

5.3.1 The steps in the data analysis will be:

a. >From each point in the spectrum, the complex data will be interpolated to a regular, 2-D grid. Either before or after the interpolation, some algorithm will choose the strongest point of the spectrum, reducing the spectrum to a single complex number.
   This regular grid will be an antenna-based co-ordinate system, significantly different from the original Az-El offset co-ordinate system. Note that the FFT-pair relationship between antenna far field beam pattern and aperture illumination is a function of the sine of the angular offset from boresight, rather than simply of angle. Since the holography map may extend over as much as 5 degrees, this begins to become a significant correction.
b. The gridded data will be calibrated in amplitude and phase, based on the boresight measurement at the beginning or end of each of the *n* map rows and assuming a gradual drift in gain and instrumental phase with time.
c. Phase corrections will be applied to the gridded data, to bring the antenna reference field close to the plane of the antenna surface. This is analogous to a refocus operation.
d. Amplitude and phase corrections will be applied to the gridded data, to allow for the complex antenna response of the holography reference feed.
e. Some tapering may be applied to the gridded data, to reduce the sidelobes of the point spread function after the FFT.
f. A Fourier Transform is made of the gridded, corrected data. Note that in general the grid will not be 2^m points, and will usually be an odd number, to put the antenna boresight on a grid point at the center of the field before the FT. After the FT, the data represent the aperture illumination pattern, and the aperture phase pattern, of the dish.
g. After the FT, some correction needs to be applied to allow for diffraction fringes from the edge of the dish, from the feed-legs, and from the central blockage. The shadowed areas will also need to be masked out.
h. A feed displacement correction needs to be applied. This will be a sum of:
   1. A least squares fit to a 2-D linear gradient across the phase map. This corresponds to a systematic pointing error, if any, during the observations.
   2. A fit to an out-of-focus term. This corresponds to an axial out-of-focus term. It approximates, but is not exactly, a quadratic distribution across the antenna.
   3. Higher order aberrations, such as coma lobes causes by radial offsets in the holography feed mount.
i. The corrected phase map now corresponds to an estimate of the errors in the dish surface, normal to the wavefront. From the phase map, we need to derive the errors normal to the dish surface, at the panel mounting points. If feasible, some algorithm should take account in some way of the finite resolution of the holography map.
j. Taking account of some structural model of panel and backup structure deformations, a table of corrections needs to be calculated for use by the antenna adjuster crew.

During the holography measurement campaign, the maps will be observed at night while the temperature is stable, and differential panel adjustments will be made during the day. The overnight holography data needs to be analysed in time for the morning adjustment crew to take the panel adjustment correction tables.

It is also likely that unexpected problems will be found during the holography observations and data analysis. It is important that the software analysis system be sufficiently versatile that any of the above steps can be modified, or additional analysis algorithms can be applied, in a timely fashion. It should be possible to introduce some new step into the analysis with not more than about one hour of programming effort.

5.4 Work Plan

In order to accomplish the above plan, the basic steps are:

a. Define in detail the holography system specifications, including transmitter frequency, needed power and signal to noise ratios, front-end and backed requirements.
b. Continue the search for a suitable satellite beacon, which would complement measurements with a terrestrial transmitter.
c. Study the possibilities for single dish holography with astronomical sources (e.g. SiO masers). Coarse resolution holography may be possible on these sources, enabling large scale dish deformations as function of elevation to be studied.
d. Define in detail the design for the holography hardware, including transmitter, receiver front-end, correlator, DSP etc.
e. Define in more detail, in collaboration with the AIPS++ group, the specifications for data analysis software.
f. Define in detail the interferometric holography requirements. Interferometric holography will offer much higher signal-to-noise ratio on a given signal source, simply because the full 12 m aperture, rather than a broad beam reference horn, can be used to retrieve the phase reference signal. This will permit measurements using astronomical sources. However, more of the complete electronics system has to be operational reliably for interferometric holographic measurements to be useful - fringes have to tracked with high phase stability. In the much longer term, holographic measurements with the ALMA will probably become exclusively interferometric.
g. Define the timescales for all the above, taking into account antenna delivery schedules etc..