SURFACE MEASUREMENTS OF LARGE ANTENNAS AT HIGH ACCURACY

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ABSTRACT

The surfaces of large millimeter and submillimeter radio telescopes must be measured to very high accuracy in order for the panels that make up their surfaces to be adjusted to their optimum positions. The high accuracy requirement together with the large diameters of the primaries, makes mechanical surface setting impractical. This has led to the development of several measurement techniques. The one covered here is mainly the full-phase holography technique. But of some of the other techniques will also be discussed: Shearing holography, phase-retrieval holography, and laser metrology.

INTRODUCTION

In order to achieve an aperture efficiency of 50%, a radio telescope must have a surface accuracy of about $\lambda/16$ where λ is the observing wavelength. For example, the surface accuracy goal for the 100-m Green Bank Telescope (GBT) is 200 μm, the NRAO 12-m telescope has a surface accuracy of about 70 μm, the goal for the 50-m Large Millimeter Telescope (LMT) is also about 70 μm. And submillimeter telescopes such as the 10-m Heinrich Hertz Telescope (HHT), 10.4-m Caltech Submillimeter Observatory (CSO), and the 15-m James Clerk Maxwell Telescope (JCMT) require an even higher accuracy: 15 μm. It would be extremely difficult to obtain such accuracies mechanically.

FULL-PHASE HOLOGRAPHY

Full-phase holography has been used for many years on many antennas. It is the most mature of the above techniques [1]. It can achieve very high accuracy. We have used it to measure the figure of the HHT with a spatial resolution of about 20 cm to an accuracy of 12 μm rms. (This was the level at which the successive measurements repeated.)

This technique requires a transmitter to illuminate the antenna to be measured. The antenna is scanned across the transmitter to measure the beam pattern of the antenna. A reference antenna which also receives the transmitter signal is needed in order to provide a phase and amplitude reference. The output of the two receivers when combined gives both the amplitude and phase of the beam pattern of the antenna to be measured. This can be used to derive the amplitude and relative phase of the radiation reflected from points on the antenna surface when the antenna is pointed directly at the transmitter. An antenna with a perfect figure in perfect focus would have all these reflections in phase with each other. The amount that the reflections are not in phase measures the deviations of the surface from a perfect figure.

In order to achieve 20 cm spatial resolution over the primary of the HHT, the beam pattern had to be measured accurately at large angles off axis: 1.5 degrees (30 beam widths, full-width-half-max). This of course requires a transmitter strong enough to be detected so far off axis. Ideally, the transmitter should located above the antenna at a great distance. At the HHT, we were able to use a synchronous satellite, LES-9. But we were forced to do holography at a frequency lower than is ever used for astronomical observations at the HHT: 37 GHz. And we had to compete with other users of the satellite.

A more convenient arrangement is to use a transmitter located on a tower or mountain some distance away from the antenna. If the transmitter is not in the far-field, one must correct for this effect. One must also take care that there is no significant radiation that reaches the antenna from the transmitter due to reflections off structures on the ground. And the figure of the antenna will be that measured at an elevation lower than is used for astronomical observations.

While all the holography techniques give very accurate results, they do not allow one to measure the focal length of the telescope directly. Instead they tell one how to optimize the positions of the panels for whatever mean focal length the panels happen to define. If the focal length is not what was intended when the panels were fabricated, one will be led to bend the panels so as to achieve the erroneous focal length. At the JCMT, for example, the phase residuals in the first holography measurements formed a scalloped pattern, one scallop per panel. Since there were only three attachments points per panel, they could not be bent. But by assuming each panel had been fabricated to the same focal length, the focal length error was derived from the magnitude of the scalloping. The panels were then tilted to the correct focal length and when the holography measurement was repeated, the scalloped pattern was much reduced.

SHEARING HOLOGRAPHY

Shearing holography is an alternate method of measuring the focal plane pattern of a point source and so determining the surface errors of the telescope primary [2]. Instead of measuring the pattern's amplitude and phase directly, an interferometer is used to superimpose the on-axis (reference) pattern with an off-axis pattern. The resulting interference pattern is focused on a single-pixel detector. A grid of such measurements at different off-axis points can be used to derive the surface error map of the telescope.

An advantage of this technique over full-phase holography is that it does not require a monochromatic point source. And since only a modest frequency resolution $(\lambda/\Delta\lambda)$ of about 20 and only the power need be measured, the detector can be a bolometer. One can either use a narrow band filter to achieve this resolution or, by adding the capability of moving one of the flat mirrors in the interferometer to change the relative path length of the two arms of the interferometer, the interferometer can be used as a Fourier transform spectrometer.

Using this technique and Mars as the source, the surface errors of the CSO were measured to an accuracy of about 9 μm at a spatial resolution of about 60 cm across the primary [2].

PHASE-RETRIEVAL HOLOGRAPHY

Phase retrieval holography (also known as out-of-focus holography) is another alternate method of measuring the surface errors of a radio telescope [3]. An advantage of this technique is that it is done by simply comparing observations of a point source both in focus and after moving the telescope out of focus by a known amount. (In practise, one obtains more reliable results if one has observations at several different focus positions.) Like with Shearing Holography, the point source need not be monochromatic. That is, no special holography receiver or modifications to the telescope are required. Since there are no phase measurements made, the phase must be in effect retrieved in the analysis of the data. One disadvantage is that since no phase is measured directly, the problem is non-linear and one cannot solve directly for the surface error map. Instead, one must propose a model of the surface errors and find the best set of model parameters that will fit the data.

This technique has been used at the JCMT and has given promising results. The aperture was modeled using Zernike polynomials with about 30 terms. (See the poster paper by Nikolic, Richer, and Hills in this meeting for details.)

With both Shearing Holography and Phase-retrieval Holography, one need not use a transmitter but instead use can an astronomical continuum source (so long as it is not too extended). This has the advantage that the shape of the telescope primary need not be measured with the telescope pointing near the horizon as is the case with a measurement technique with a transmitter on the ground. A disadvantage is that one is limited by the signal to noise ratio one can achieve on the astronomical object. Even the brightest continuum sources cannot achieve the signal to noise one can obtain with a holography transmitter. So the size of the resolution element on the telescope aperture of the resulting surface error map, is larger than that normally achieved with a transmitter.

LASER METROLOGY

Another method of measuring the surface of an antenna is laser metrology. Laser rangers are used to measure the distance of retroreflectors mounted on the surface. A minimum of three laser rangers is needed to define the position of a retroreflector in three dimensions but more accurate results are obtained if there are more than three laser rangers. An advantage of this technique is that it can be done while the telescope is being used for normal observing. A disadvantage is that retroreflectors must be permanently mounted on the surface and their positions measured relative to the panels.

The GBT and the LMT plan to use this method to measure and correct the errors in their primaries in real time. Tests of the method for the GBT are promising, but an actual measurement of its surface via laser rangers has not yet been done. The measurement errors are expected to be under 100 μm but will probably be considerably larger than obtained via holography techniques.

REFERENCES

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