Phase Retrieval Measurements of Antenna Surfaces Using Astronomical Sources

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Abstract

We present a novel technique for accurate measurement of the large-scale errors in an antenna surface using astronomical sources and detectors. Out-of-focus images of compact astronomical sources contain a wealth of information about the telescope optics. By characterising the surface as a sum of Zernike polynomials, it is possible to infer in a stable manner the surface of the telescope using an inverse-problem numerical technique. We report preliminary results using data from the 15-m James Clerk Maxwell Telescope and the 100-m Green Bank Telescope, and discuss the merits of this technique for measuring the large scale deformation of telescope antennas.

Introduction

Measuring the deformations of telescope antennas using microwaves (often called holography) is useful both for direct corrections of surface errors, and as an input into theoretical models of the telescope mechanics. Both of those are in turn invaluable for the recent generation of telescopes with actuator-adjustable, and in some case active, surfaces. Maximising the surface accuracy of existing and new antennas is of increasing scientific importance for two reasons: it increases the gain, so allowing detection of fainter compact sources, and it reduces the amount of power in the "error beam", so allowing higher dynamic range imaging of extended sources.

In the phase-retrieval approach to millimetre-wave holography, only the power pattern of the antenna is measured, usually at two or more different focus settings. The phase of the signal in the aperture is later recovered by numerical processing. This technique has been applied with considerable success on a number of large antennas, but usually only with artificial sources, i.e. transmitters on the ground or on spacecraft.

This paper describes the development of techniques for measuring surface errors with moderate spatial resolution by observing astronomical sources, using existing astronomical receivers on the telescopes. The new approach uses numerical fitting of a parameterised description of the surface errors, and of the amplitude of the receiver's illumination pattern. The technique is flexible. It can be adapted straightforwardly to various different observational techniques, including total power observations, and the various differencing schemes which involve movement of the secondary mirror ("beam switching") and/or primary mirror ("nodding"). The increasing availability of astronomical array detectors makes the mapping process particularly quick and efficient. In this short paper, we present preliminary results obtained for the James Clerk Maxwell Telescope (JCMT), and the 100-m Green Bank Telescope (GBT).

Description of technique

If we can measure both the amplitude and phase of the beam pattern in the far field, a simple Fourier inversion will give us the aperture function (this is *with-phase* holography). However, measuring just the power pattern will under-determine the aperture function (e.g. inverting the sign of the errors produces the same power pattern). We can break this degeneracy by measuring power patterns at a number of focus settings, which produces partially independent data sets.

A straightforward inversion is still not possible due to non-linearity, so we have employed a numerical fitting algorithm. We parameterise the surface in terms of a fixed number of coefficients of Zernike circle polynomial functions (see e.g. [1] for definition). Besides being orthonormal on the unit circle, they also have the advantage that by restricting the highest order used, the results are not sensitive to the poorly-constrained, small-scale errors on the surface. The results in this paper typically fit a model including terms up to radial order 7, which is a total of 36 terms: the smallest spatial scale contained in the model then corresponds to approximately one seventh the primary mirror diameter. The number of terms we can successfully derive is dependent on the signal-to-noise ratio of the dataset: for the data we have used so far, this is of order 200. Other free parameters in the model are the position and width of the primary reflector illumination (modelled as a Gaussian), the directions and sizes of the chopping and nodding motions, and optionally the coma error term introduced by the chopping of the secondary.

The best fit surface is then found by minimising differences between the observed and simulated maps, with appropriate weightings to take into account the noise. The noise is modelled as a sum of additive (thermal) and proportional-to-signal components. We use a public-domain Levenberg-Marquardt minimisation algorithm with numerically calculated derivatives [2], which we have found to be efficient and reliable for this problem. To have an independent check, we have also compared results using a downhill simplex minimisation algorithm. With reasonable quality data, we usually see good convergence and no local minima.

Any bright source of known shape is suitable for this method. Quasars are the natural choice at low frequencies, but at submillimetre wavelengths, planets are much brighter. Because our technique uses a fitting algorithm, it is possible to take account of any extension of the source (e.g. the planet's disc) if it is accurately known.

We have performed several simulations of the technique, by generating synthetic data and deriving estimates of the surface from them. These have allowed us to validate the robustness of the method, and allowed us to estimate the optimal size of the defocus term to use, and the signal-to-noise required to measure a given number of Zernike terms. The full results from these simulations will be presented in a future paper.

RESULTS AND DISCUSSION

The James Clerk Maxwell Telescope

The JCMT is a 15-m submillimetre telescope with conventional Cassegrain optics, covering the atmospheric transmission bands from 150 GHz to 1.5 THz (2 mm to 200 μm wavelength): its target surface accuracy is around 22 μm. We used the SCUBA bolometer array to make several broadband continuum measurements of the out-of-focus beam. Typically, we observed an in-focus map, plus maps with the secondary mirror defocused by ± 1.0 mm. All of them employ both rapid chopping of the secondary mirror by $c = 35$ arcseconds in azimuth, plus slower nodding of the primary, generating a triple-beam observation: the power pattern is then effectively convolved with a function $2\delta(x) - \delta(x-c) - \delta(x+c)$. The observations were done at 850 μm and 450 μm simultaneously, although the latter were not usually of high enough signal-to-noise ratio to be useful. We used both quasars (3C279) and planets (Mars and Venus) as our sources, and each map took approximately 3 minutes to make. The results of one set of these observations is shown in figures 1 and 2. These measurements were done before the recent campaign to improve the surface of the JCMT and are broadly in agreement with the expected deformations and measurements using conventional holography.

The Green Bank Telescope

The GBT is a 100-m off-axis paraboloid telescope, designed for frequencies up to around 100 GHz. We have been kindly provided with one set of three beam maps at 2.5 cm wavelength from the GBT, which used the methanol maser in W3 as a source. The defocus term at the GBT is more complicated then that of the JCMT (where it is a simple radial function) due to the off-axis geometry. We have therefore used a raytracing package to calculate the phase change due to movement of the secondary, which in this case was about 8 cm. As this was a spectral line observation, it was observed in total power mode without the need for chopping. The strength of the source meant the noise characteristics were very different to the SCUBA observations, with proportional noise dominating over additive noise over much of the map. Our calculated apertures and an example out-of-focus beam map are shown in figure 3. As can be seen from the figure, the surface is in impressively good shape for observations at around 2cm wavelength.

CLOSING REMARKS

This technique for measurement or large-scale surface errors has several benefits. Most importantly, it allows measurement of the surface at many different elevation angles, so allowing the measurement of gravitationally-induced deformations, which should be mainly large scale. The technique is also low cost both in terms of money and time: it uses existing instrumentation, and the maps can usually be made in short periods, usually less than half an hour of observing time. In addition, as receivers are upgraded and made more sensitive, the technique benefits from automatic increases in speed and

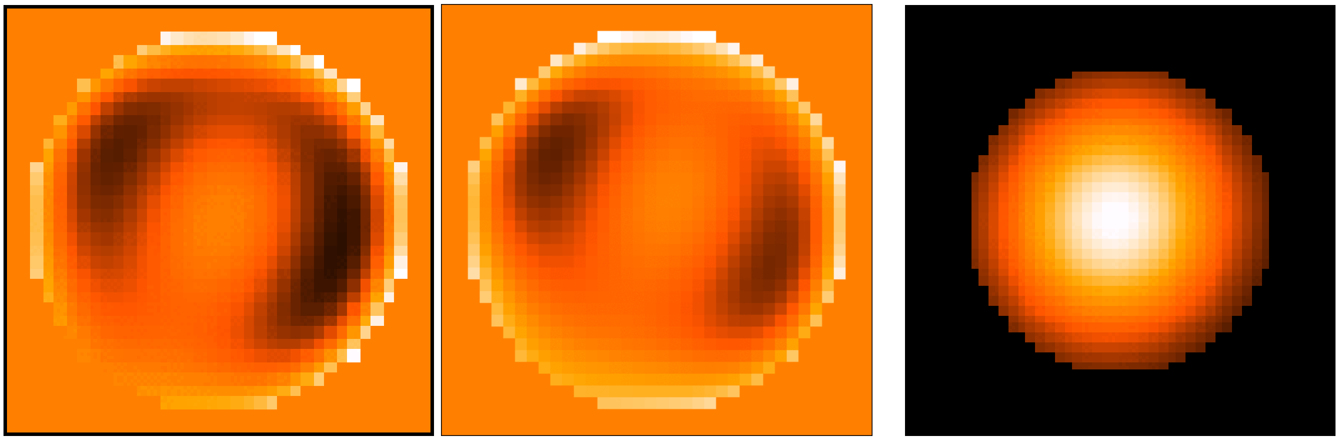

Figure 1: The inferred aperture function from SCUBA/JCMT maps taken on 01/01/2002; Left and Middle: Phase map (black to white represents a π path difference) ; Middle: Phase map from a second set observations taken on the same night, demonstrating reproducibility of the technique; Right: Amplitude map.

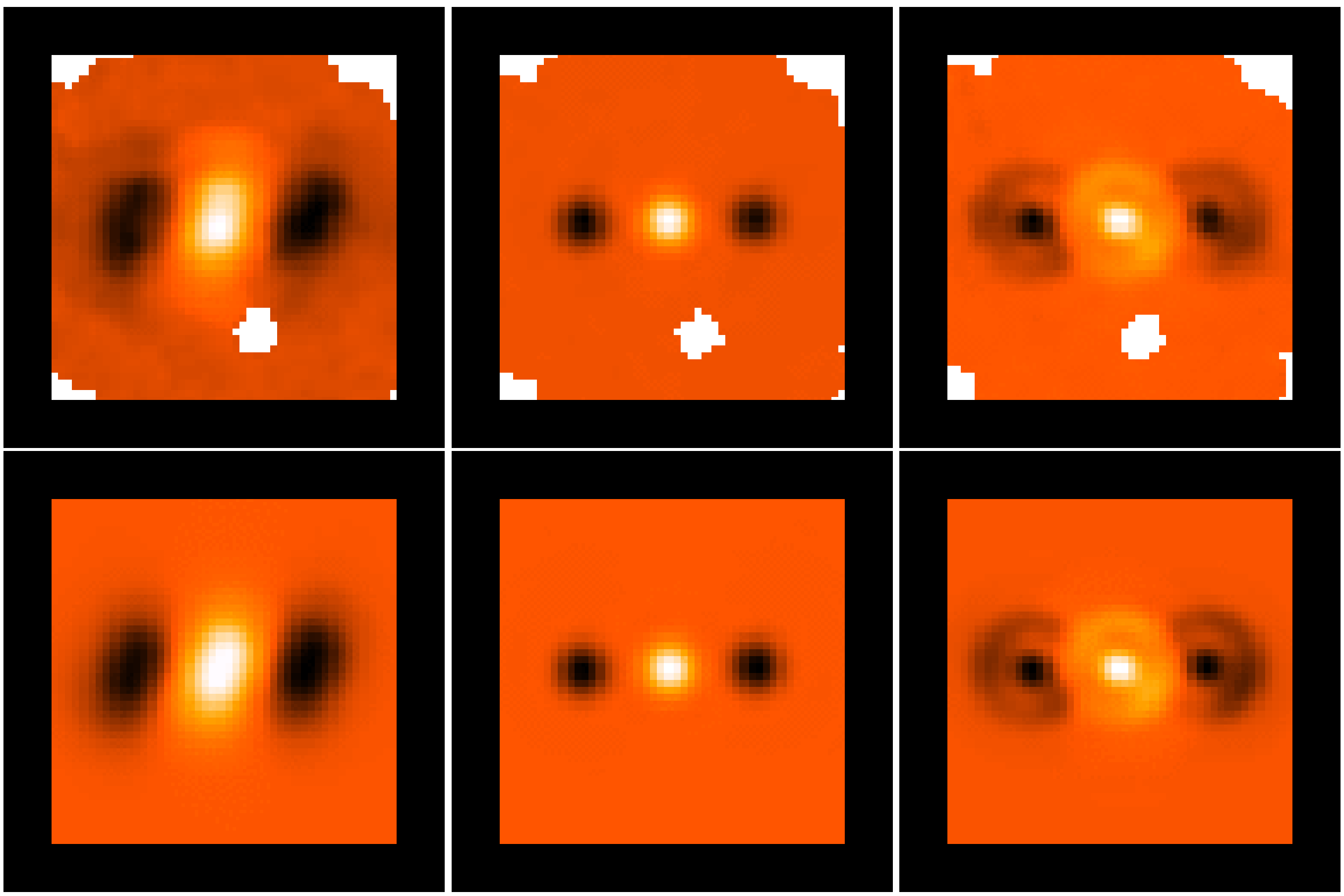

Figure 2: Top row: three SCUBA/JCMT maps of 3C279 used in the analysis, from left to right: focus -1.0 mm, in focus and focus +1.0mm. The white patch is due to a noisy bolometer which has been flagged as bad. Bottom row: Simulated beam maps corresponding to the best fit surface.

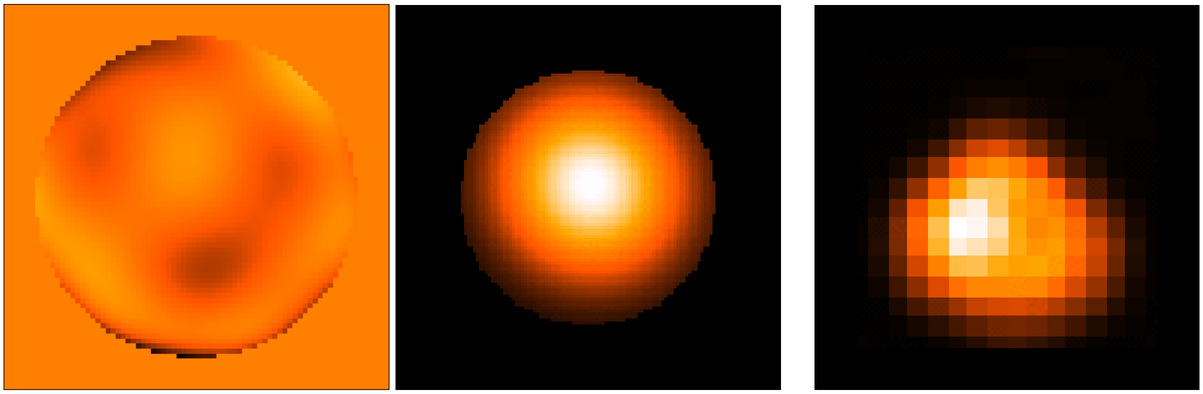

Figure 3: Calculated aperture function for the GBT; Left: phase, Middle: amplitude, Right: an example of an out-of-focus map

accuracy. The technique is most likely to be useful when used as an extra diagnostic of antenna behaviours in conjunction with a conventional transmitter-based holography system which measures accurately the small scale errors.

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References

[1] Born and Wolf. *Principles of Optics*, chapter 9. Pergamon, 1970.

[2] STARLINK, http://www.starlink.rl.ac.uk/star/docs/sun194.htx/node40.html. *Public domain algorithms library*.

Further information on our holography work, details of other measurements and more detailed plots are available at http://www.mrao.cam.ac.uk/ bn204/oof.html.