A Preliminary Analysis of the Correlation Scales of Wavefront Errors of the GBT Using the Moon

Bojan Nikolic, Dana S. Balser & Richard M. Prestage

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Abstract

Observations of the GBT error beam are performed using the Moon to explore the spatial scales in the aperture plane over which the dominant wavefront errors are correlated. Models of the wavefront errors are produced on different spatial scales to generate the expected telescope beam as it passes across the Moon. The models are consistent with the observations when the rms error is slightly larger than 250 μm and when the error is on panel-sized scales.

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History

51.0 Original draft (Bojan Nikolic)

51.1 Add abstract; minor corrections (Dana S. Balser)

1. Introduction

Current measurements of the overall aperture efficiency of the GBT at a wavelength of 7 mm indicate that the surface efficiency, in the best conditions, is of the order of 65%, which corresponds, via the Ruze (1966) equation to RMS wavefront error of 365 μm. Decreasing these errors will both improve the efficiency of observations at these wavelength and make observations at shorter wavelengths worthwhile.

We do not yet, however, know exactly what the main cause of the wavefront errors which lead to this value of surface efficiency.

We have measurements or estimates of several possible contributions to this overall wavefront error. The manufacturing panel wavefront error was 70 μm, increasing to possible 100 μm under the influence of gravity (F. Schwab, priv. com). An estimate for the sub reflector wavefront error contribution is also around 100 μm (F. Schwab). OOF holography observations described by Nikolic et al. (2006), suggest that the wavefront errors on large spatial scales (20-metre or so) are of the order of 160 μm RMS under the best conditions. Taking all of those in account still requires approximately 300 μm RMS wavefront error from an unidentified source.

A very useful clue to this source would be to identify the scales in the aperture plane over which these dominant wavefront errors are correlated. To place further constraints on the correlation lengths of the wavefront errors we have made measurements of the GBT error beams using the Moon as the source, following to a large extent the experiments of Greve et al. (1998).

2. Observations

Observations of the Moon were carried out in March 2005 under the project code TPTCSOOF_050324. We observed using the Q-band receiver operating at 7.3 mm and the DCR. A total of 12 good scans across the moon were made, four of which were done while a 1 mm RMS randomisation of the surface was applied. The scans range between 71–82.

Data were extracted directly from the engineering data files and the only calibration consisted of dividing by the cal diode signal, i.e., the observations are in the units of the cal signal. Two sample scans are illustrated in Figure 1, showing the normal surface and the surface when an 1 mm randomisation is applied. The scans discussed here were all done in the azimuth direction.

Because of the very high antenna temperature when the telescope is pointed at the moon, some gain compression may be expected. This is confirmed by investigating the amplitude of the cal signal, shown in Figure 2, which shows a change of around 10–15% when the beam crosses the moon.

3. Analysis

3.1. Method

The approach for the analysis was to make reasonable models for the wavefront errors due to panel-to-panel miss-alignment and to compute the expected telescope beam and, from this, the expected total power as it is scanned across the moon.

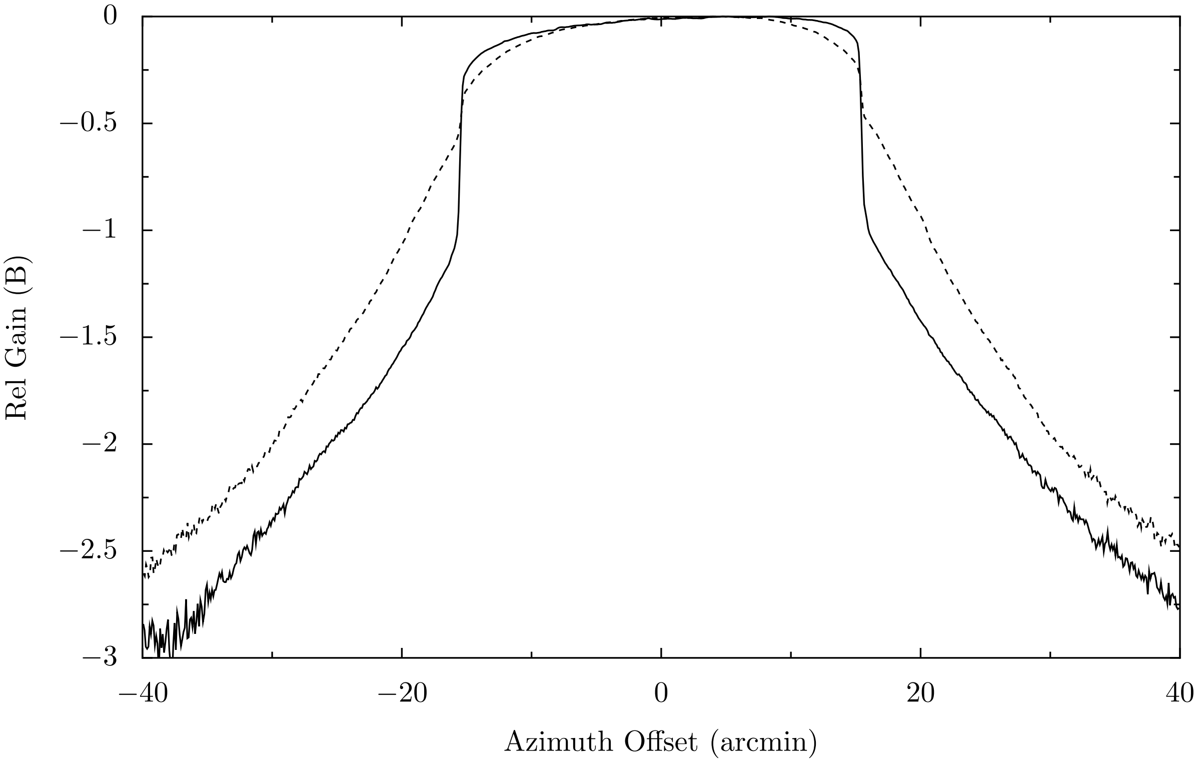

Fig. 1.— Observed total power received (with constant baseline subtracted) for scans across the Moon with the nominal surface (full line, scan 75) and with the surface with 1 mm randomisation (dashed line, scan 79).

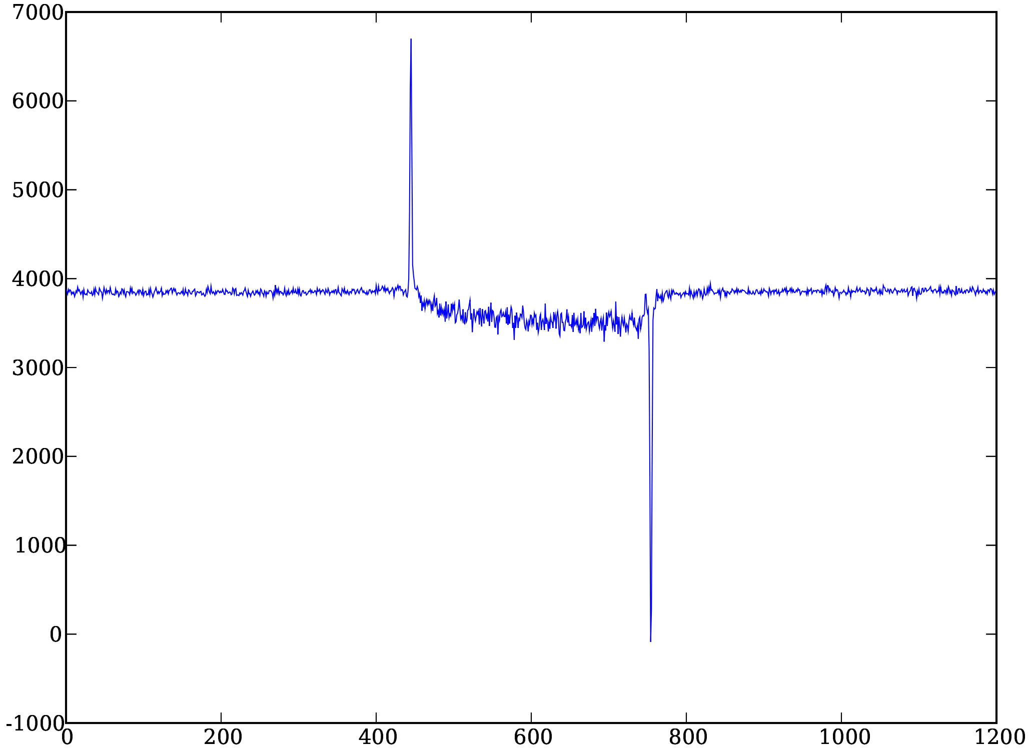

Fig. 2.— Strength of cal diode signal as function of record number during a scan across the moon.

The modelling procedure begins by calculating the distribution of the scalar electric field in the aperture plane. The size of the maps used was 1024×1024 pixels with critically sampled pixels.

The wavefront errors, that is the phases of the electric field, were modeled as square patches of constant phase. In most of the experiments shown below, the patch sizes are of $1.6 \times 1.6\,\mathrm{m}$, while individual pixels were eight times smaller.

These patches represent individual panels, and to model random panel mis-setting, these patches were given random phases so that the total map rms phase error was as desired. No attempt was made to place these patches in an arrangement corresponding the arrangement of the GBT panels; rather, they were placed in a simple rectangular grid. The rectangular grid gives a wrong azimuthal structure to the model beam and therefore model Moon scans but we expect the effect is very small.

The aperture plane illumination was modeled as a 100 m diameter truncated Gaussian with 14dB taper at the edge.

The far field power response pattern of the telescope was then calculated from the FFT of the aperture field distribution. This does appear to lead to a fair amount of ringing (see Figure 3) which should be investigated.

Once the beam pattern has been calculated, it is easy to convolve this with the brightness distribution of the Moon to obtain the expected received power as the telescope scans. For the results presented below, the assumed Moon brightness distribution was simply uniform, which is correct for the new Moon. The moon was in fact almost completely full when the observations were taken. Some investigation has shown that this only has an effect on the accuracy of models within an arcminute or so of the Moon edge.

3.2. Results

The question we are addressing is, primarily, are the observed Moon scans consistent with $\approx 250\,\mu$m RMS error at scales of individual panels? This question can be immediately attacked by comparing the observed Moon scans with a model scan that has a surface RMS of 250 μm, as shown in Figure 4.

In Figure 4 we note:

- The large error beam slope is modeled with the correct slope and approximately the correct amplitude for offsets 15 to 30 arcmin from the centre of the moon.
- The agreement at the smallest radii is not exact – this is due to assuming that the moon is uniformly illuminated.
- The agreement at large radii is poor because the model flattens out. The flattening of the model is unphysical and is due to aliasing and numerical effects. It should be disregarded.

For comparison, we also compare the observations with 350 μm and 150 μm surface RMS in Figures 5 and 6 respectively.

To find out how convincing it is that the observed scans are consistent with panel-sized phase distribution errors rather than perhaps ‘medium-sized’ errors, we have repeated the same experiment with much

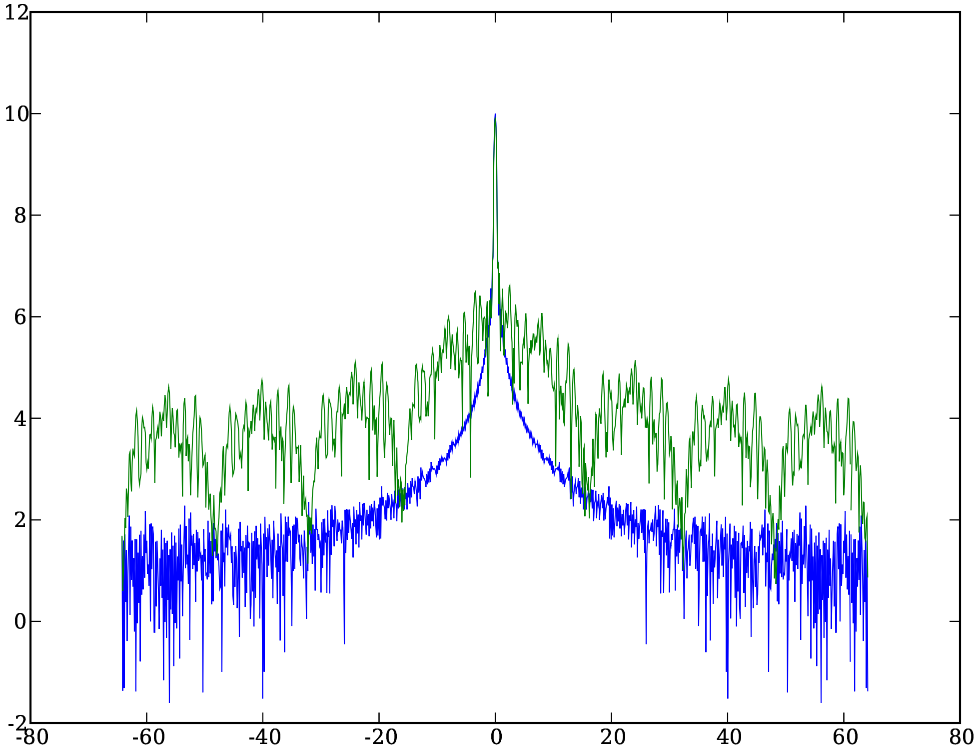

Fig. 3.— Cuts through the ideal beam (blue) and a beam with 250 micron panel-to-panel error (green).

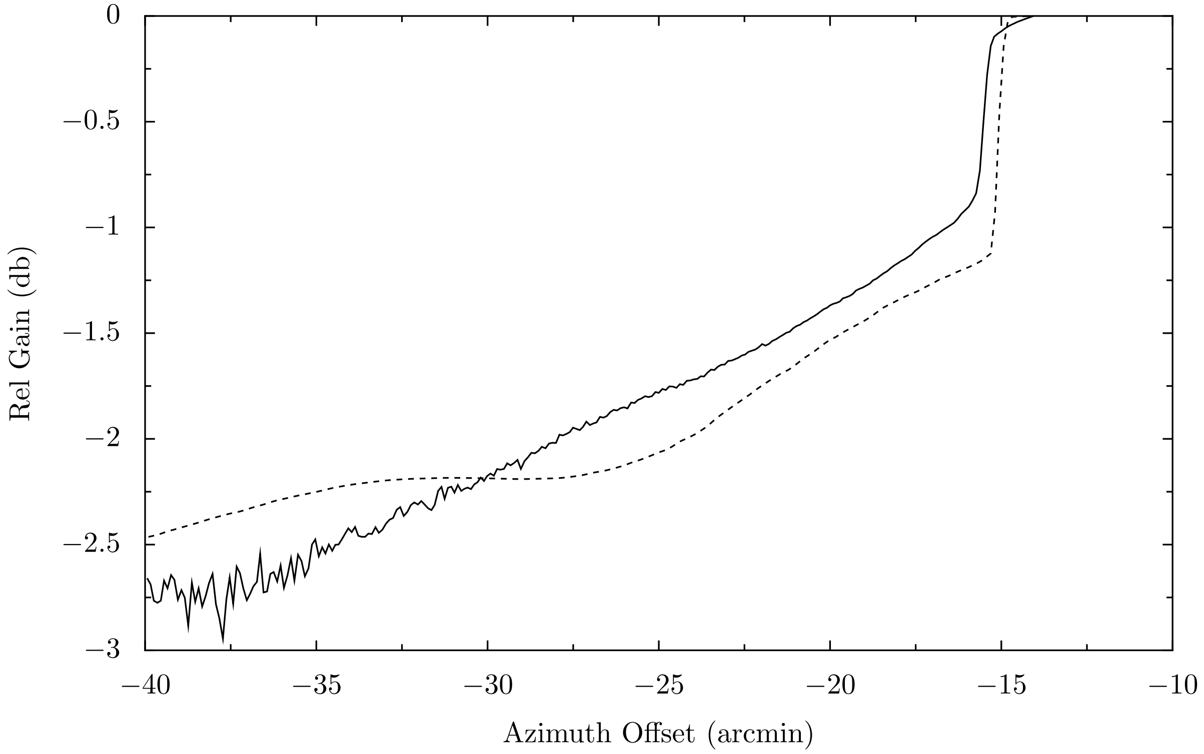

Fig. 4.— Comparison of the observed total power (full line) and expected total power (dashed line) assuming a panel-to-panel rms of 250 μm and phase patch size of 1.6 m. (Note y-axis label should be Bells rather than dB, same for other plots).

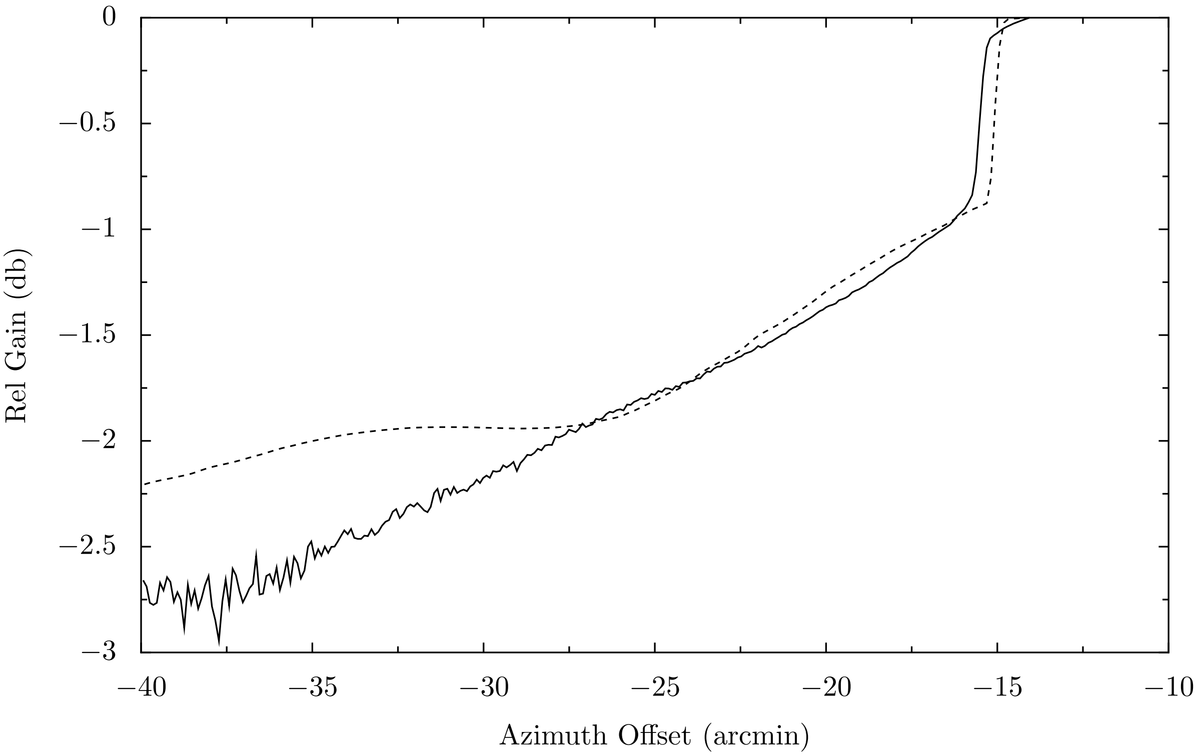

Fig. 5.— As Figure 4, but for 350 μm panel-to-panel rms.

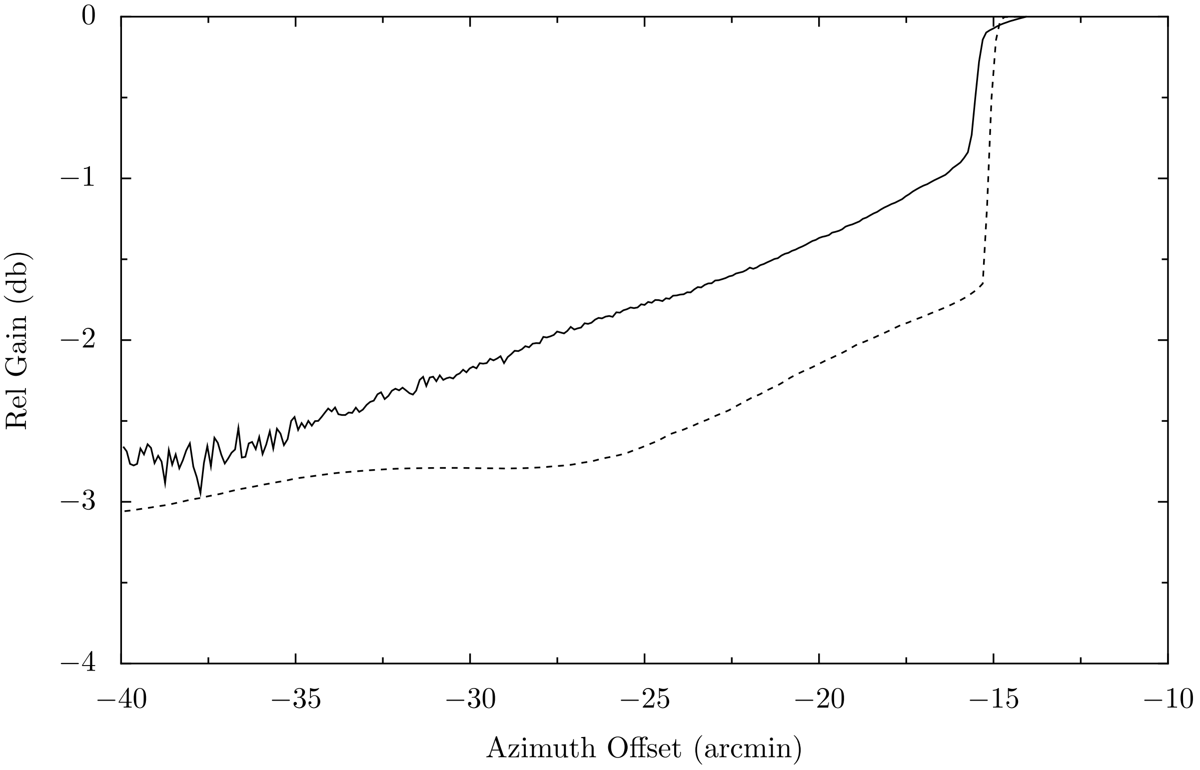

Fig. 6.— As Figure 4, but for 125 μm panel-to-panel rms.

larger phase patches, corresponding to 6.4 m square in the aperture panels. This corresponds to three or so panels. The expected observed scan is shown in Figure 7. It can be seen in the figure that the morphologies as well as magnitudes of the observed and model data are clearly different.

As a further test we have also analyzed the Moon scans done when the surface was randomized. The magnitude of this randomization was 0.5 mm half-path RMS. Therefore we expect total errors to be 560 μm RMS i.e., 500 μm and 250 μm added in quadrature. The model and observed data are compared in Figure 8. Good agreement can be observed (up until 30 arcmin, where the aliasing sets in).

4. Discussion and Conclusions

This preliminary analysis has several shortcomings.

- No accounting for the large scale structure was made. This will, however, only show up at small radii from moon edge.
- No accounting for spillover efficiencies were made. This may change the normalization of the model curve somewhat.
- There is the aliasing problem at large radii. Experiments with larger maps show that this largely goes away.
- There could be significant gain compression when pointing at the moon. This may also affect the relative normalization of the small-scale error beam.
- The Moon is assumed to be uniform. I have implement an approximation for this but it does not substantially alter the main results.

The results obtained nevertheless may be interpreted in the following way.

First of all it is clear from the observed data by themselves that the GBT has a broad error beam. The error beam is measurable up to 25 arc minutes away from the edge of the Moon. The similarity between the Moon scans performed with the nominal and randomized surfaces suggests that the error beam is on scales appropriate for actuator mis-adjustments.

Secondly, the calculated models scans can be made to agree closely to observed scans. This is most true when the error RMS is somewhat larger than 250 μm RMS and when the error is on panel-sized scales. The best-fitting RMS value is probably subject to taking into the account the spillover efficiencies. From the models it can be seen that, however, it is quite unlikely it is close to 125 μm RMS. From Figure 7, it can also be ruled out that the errors are on super-panel scales.

The close agreement between the model and observations for the randomized surface in the critical radius range between 17 and 30 arcminutes from Moon centre is an encouraging sign for the accuracy of the modeling procedure.

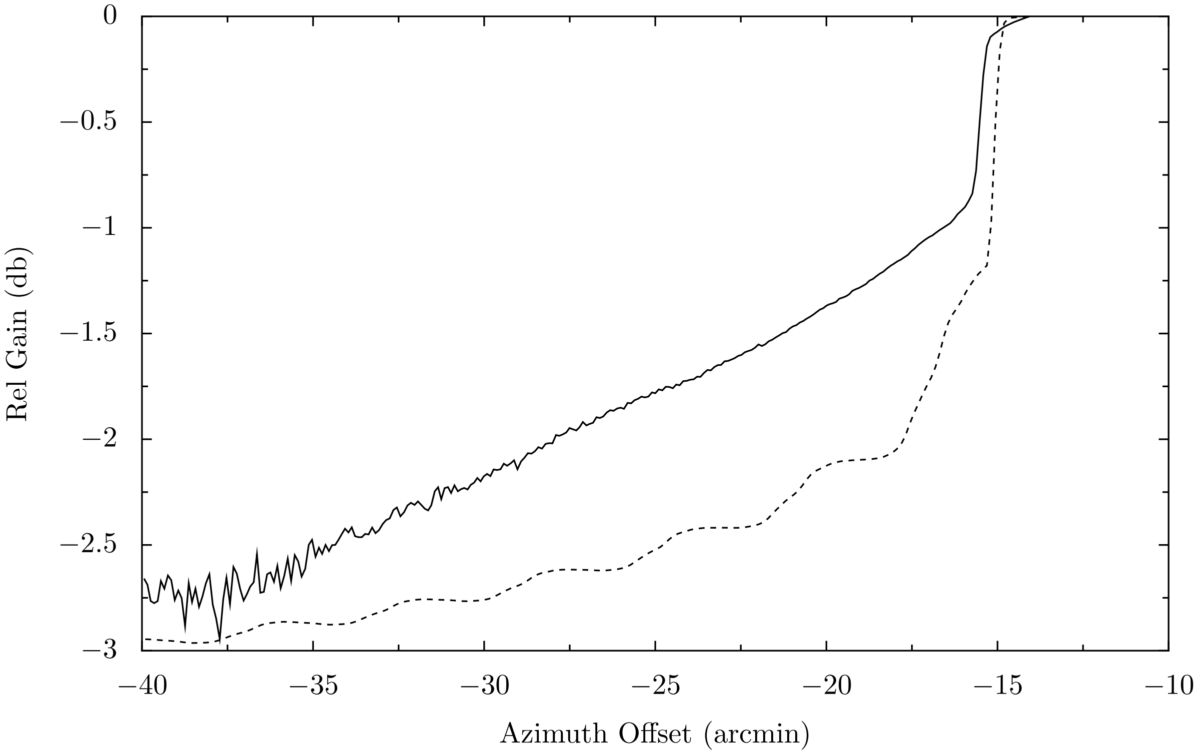

Fig. 7.— Comparison of the observed moon scan (solid line) and a model with 250 μm RMS but 6.4 m phase patches (e.g., these could be ‘medium-scale errors’).

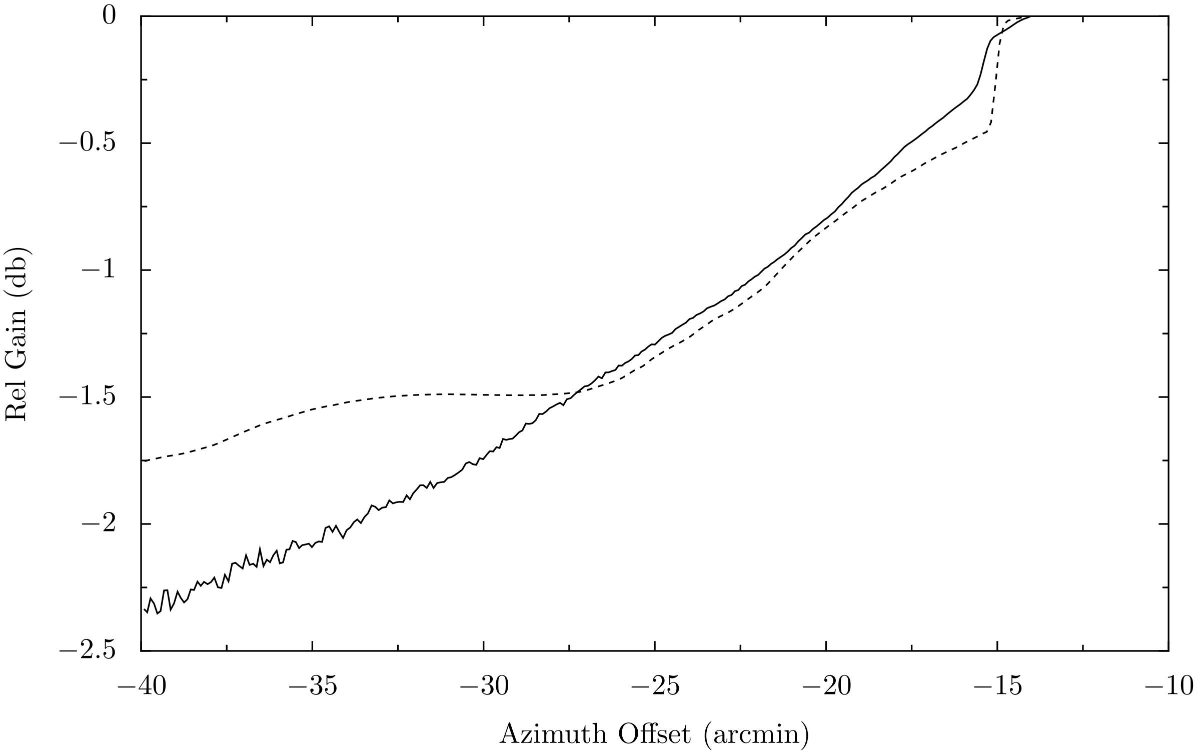

Fig. 8.— Comparison of the observed scan for the randomised surface and the appropriate model (560 μm RMS).

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