Systematics in the QUaD experiment

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Abstract. QUaD was a ground breaking CMB polarization experiment, achieving for the first time sufficient sensitivity to see the acoustic peaks in the E-mode power spectrum. Systematic effects as they relate to the data analysis are discussed including relative gain calibration and ground pickup. The observation of beam centroid offset between the two halves of the detector pairs is also described and an empirical model presented.

1. Introduction

The QUaD experiment was designed to measure the polarization anisotropy of the CMB at 100 and 150 GHz. It consisted of a Polarization Sensitive Bolometer (PSB; [1]) based receiver mounted on a 2.6 m Cassegrain radio telescope, and supported by the platform originally constructed for the DASI experiment [2]. This is an az/el mount with a third axis allowing the entire optics and receiver to be rotated around the line of sight (referred to as "deck" rotation). The secondary mirror was supported by a cone fabricated from polypropylene foam sheets (Zotefoam PPA30).

QUaD observed from the South Pole during the Austral winters of 2005, 2006 and 2007 and is now de-commissioned. Full details of the instrument have been published [3], as have science results [4–8]. This paper focuses on some systematic effects.

2. Relative Gain Calibration

The halves of each PSB pair measure orthogonal linear polarizations. In the QUaD system there is no rapid polarization modulation. The pairs of detectors are read out separately and differenced to measure polarization in the off-line analysis. Accurate gain matching is required before the differencing operation to prevent total intensity leakage into polarization. It is thus necessary that the relative gains be stable over the time period between measurement and application. In addition the detectors are DC sensitive so any differential baseline drift between the two halves of a pair will appear as false polarization signal.

Before PSB direct pair differencing experiments like QUaD were proven in the field skepticism was expressed that the necessary level of gain stability could be achieved. As described in [3] QUaD utilized active focal plane temperature stabilization. The relative gain of the detectors was measured every 30 minutes by performing an "elevation nod" — the telescope was moved up and then down in elevation angle by one degree injecting an atmospheric ramp into the data stream. Regressing this signal versus airmass for each detector yields the relative gain factor in volts/airmass. Figure 1 shows the relative gain timeseries for the first ten detector pairs. The

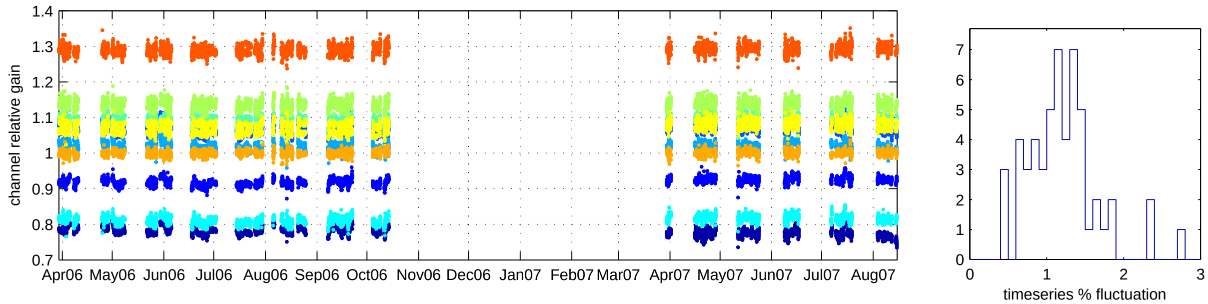

Figure 1. *Left:* the relative gains of the first ten 150 GHz detector channels as measured by elevation nods every half hour over two seasons. *Right:* a histogram of the percentage fluctuations of the timeseries at left including all channels. Reproduced from [5].

panel at right shows the percentage fluctuation of the timeseries with one histogram entry for each detector pair.

It is very important to note that random errors in the relative gain measurements average down over time and do not lead to systematic leakage of temperature into polarization — sometimes a given pair will leak T into $+Q$ and sometimes into $-Q$ leading to zero net leakage.

3. Pair Sum and Difference Timestream Data

Figure 2 shows a sample of timestream data taken while the telescope was scanning on the CMB field. Relative gain calibration has been applied and the sum and difference for each detector pair taken. In the top panel we see the rounded triangle wave azimuth scan pattern superimposed on top of the sidereal tracking rate. In the pair sum the common mode variation of the atmospheric signal with time is very substantial but is not strongly correlated with the telescope motion — it appears that we are seeing structured "clouds" blowing through the telescope beam faster than it scans. The pair difference timestream has dramatically less low frequency structure indicating that the atmospheric emission is largely unpolarized. The dark channels also show very little low frequency structure confirming that the pair sum signal originates outside the telescope and is not caused by, for instance, focal plane temperature instability.

Figure 3 shows the power spectral densities of the timestream data. We see that the low frequency structure seen in Figure 2 has the classic $1/f$ form at low frequencies. The cause of the "bump" at ~ 0.25 Hz is unknown. We do see a small increase in the pair difference noise at low frequencies. It is not clear if this is real or an artifact of imperfect relative gain calibration. Instead of using the elevation nod derived relative gains we can instead regress the A and B timestreams within a pair against one another. Doing this does slightly reduce the amount of pair difference $1/f$. There may be subtle effects going here due to passband differences and the differing spectra of the base thermal atmospheric emission versus that of the inhomogeneous (water line) component. However since the final maps are impressively free of temperature to polarization cross correlation and pass all jackknife tests we have not pursued this point further.

4. Ground Signal and Field Differencing

In initial QUaD observations it quickly became clear that ground pickup was a serious problem and we therefore adopted the commonly used lead-trail-field strategy. We scanned an area 0.5 hours wide in R.A. for half an hour before switching to the area 0.5 hours behind in R.A. The scan pattern in ground fixed azimuth/elevation coordinates was therefore repeated exactly half an hour later — see Figure 4. By differencing the lead and trail field data point-by-point in the

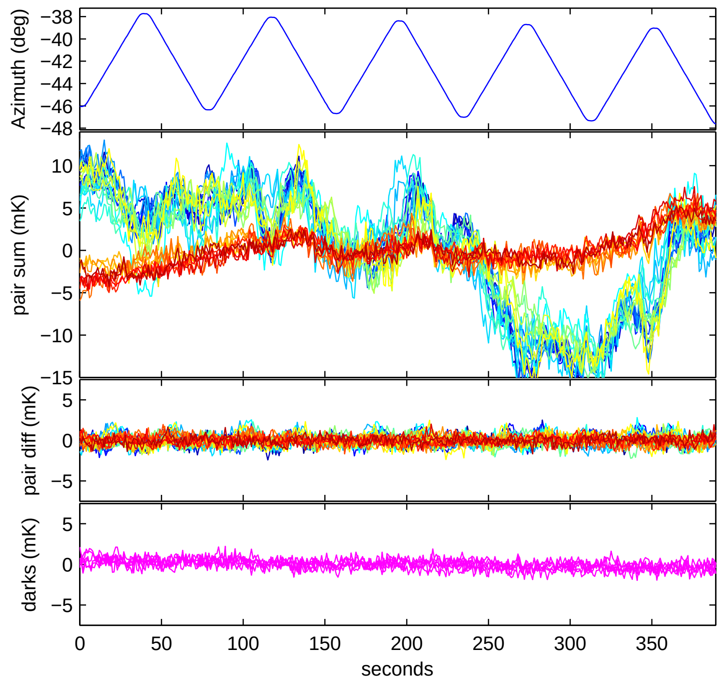

Figure 2. Timestream data for a sample scan set. The top panel shows the azimuth angle, and the middle panels the pair sum and difference detector timestreams with relative gain calibration applied; red/orange colors are the 100 GHz pairs, while blue/green colors are the 150 GHz. The bottom panel shows the dark channels. In all cases an approximate scaling to temperature units has been applied. For the purposes of this illustration the timestreams have been heavily low pass filtered (to ≤ 1 Hz). Reproduced from [5].

timestream ground signal which is constant over half an hour is removed and a difference map of the sky is obtained. Figure 5 illustrates the process.

In order to test for the presence of residual ground signal — or any other systematic contamination — we perform a further level of differencing. The data is split into pairs of approximately equal subsets each of which should contain the same sky signal (i.e. cover the same area of sky) but which are likely to contain different contaminating signal. The most powerful of these is our so called deck jackknife test in which the data subsets are the first and second halves of each day long data taking run. The run started at the same local sidereal time, and hence telescope azimuth angle, each day. The data halves were thus taken over completely different parts of the horizon, and in addition the entire telescope was rotated by 60 deg about the line of sight in the middle of the run. After taking the difference of maps made from the two data subsets we proceed to power spectra in the same way as for the un-differenced maps. Figure 6 shows the resulting power spectra — χ^2 tests show that the jackknife spectra are consistent with zero.

We can also difference the 100 and 150 GHz maps to look for evidence of foreground emission. Since the absolute calibration factor of both of these is determined by cross correlation with the same (150 GHz) B2K map what we are really testing here is if the maps have the same spatial form at both frequencies. While the CMB is expected to do so foregrounds are not — for instance synchrotron is known to have a spatially varying spectral index. As we see in Figure 7 the 100 and 150 GHz maps cancel impressively well.

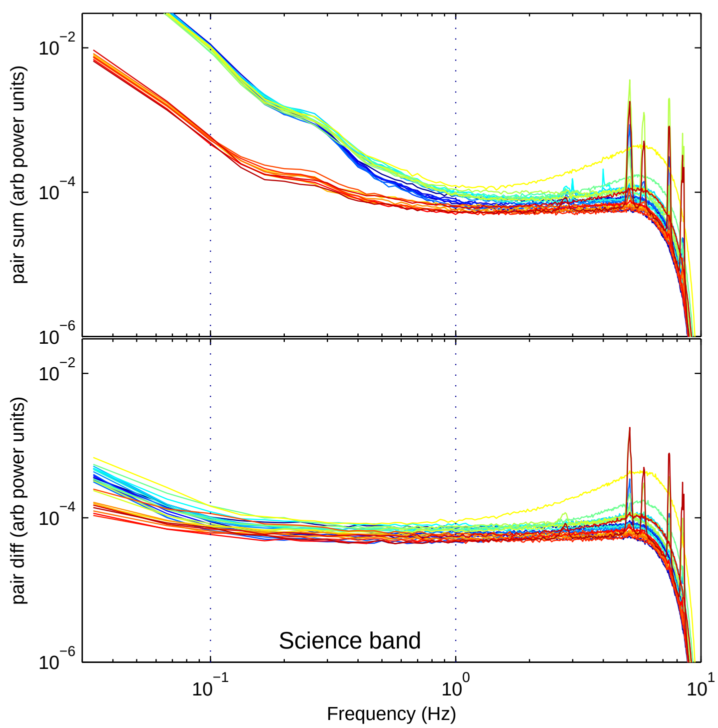

Figure 3. Timestream PSDs averaged over a single day of data. Pair sum and pair difference spectra are shown; red/orange colors are the 100 GHz pairs, while blue/green colors are the 150 GHz. Reproduced from [5].

5. Beam Centroid Offsets

The A and B halves of each detector beam should ideally have identical beam shapes on the sky. However as shown in Figure 8 in practice they are found not to do so. The principle effect is a centroid offset of ~ 0.001 deg — $< 5\%$ of the beam width in all cases.

This effect is repeatable between beam mapping runs and rotates when the telescope is rotated about the line of sight — i.e. it is a property of the telescope rather than due to polarization of the source. Additional evidence for this last statement comes from the fact that like aligned detector pairs do not see the same offset magnitude and direction. Figure 9 shows the repeatability.

An empirical model has been constructed which appears to fit the data well as illustrated in Figure 10. For bolo pairs oriented radial/tangential to the focal plane radial direction the A-B centroid offset is radial. For pairs oriented at 45 deg to the focal plane radial direction the centroid offset is tangential. i.e. For a half revolution of the A bolometer orientation starting from the radial direction, the A-B offset vector goes through a full revolution from inwards, to outwards and back to inwards again. This effect is not understood; reflections from the metallic surfaces of the primary and secondary cannot generate an offset of the observed magnitude. The feedhorns are axi-symmetric and aligned perpendicular to the bowl shaped focal plane surface so these also seem unlikely to generate an offset. This leaves the dielectric lenses. It might make sense for there to be an A-B offset for pairs oriented radially as A and B are then receiving light which strikes the lens radially and tangentially to its direction of curvature. However it is unclear how a pair arranged at 45 deg — symmetrically with respect to the lens curvature — can have a tangential centroid offset.

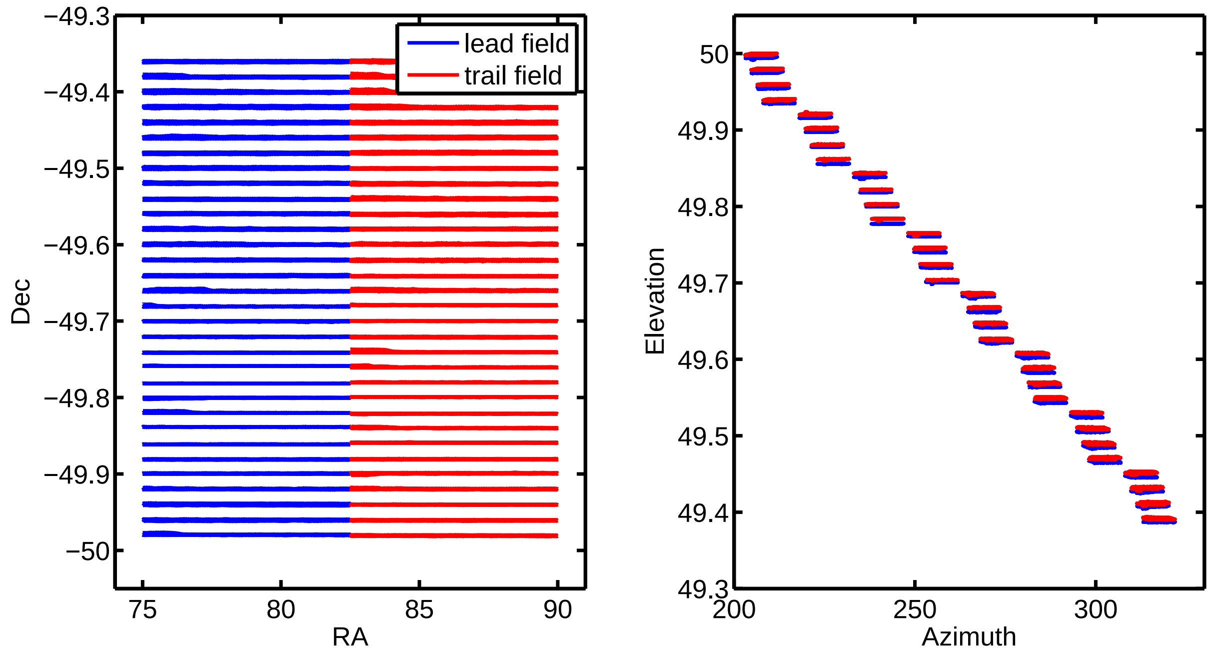

Figure 4. Telescope observation pattern over 8 hours. *Left:* in sky coordinates and *right:* in ground coordinates.

6. Conclusion

Some systematic related effects arising in the analysis of QUaD data have been described. After > 10 person years of effort the QUaD data remain imperfectly understood. In the final analysis systematic effects reduced the sensitivity of the results by only a small factor. However further increases in sensitivity will need to be accompanied by corresponding decreases in systematic effects to a) allow for the additional sensitivity to be fully exploited and b) to keep the analysis effort to < 100 person years.

References

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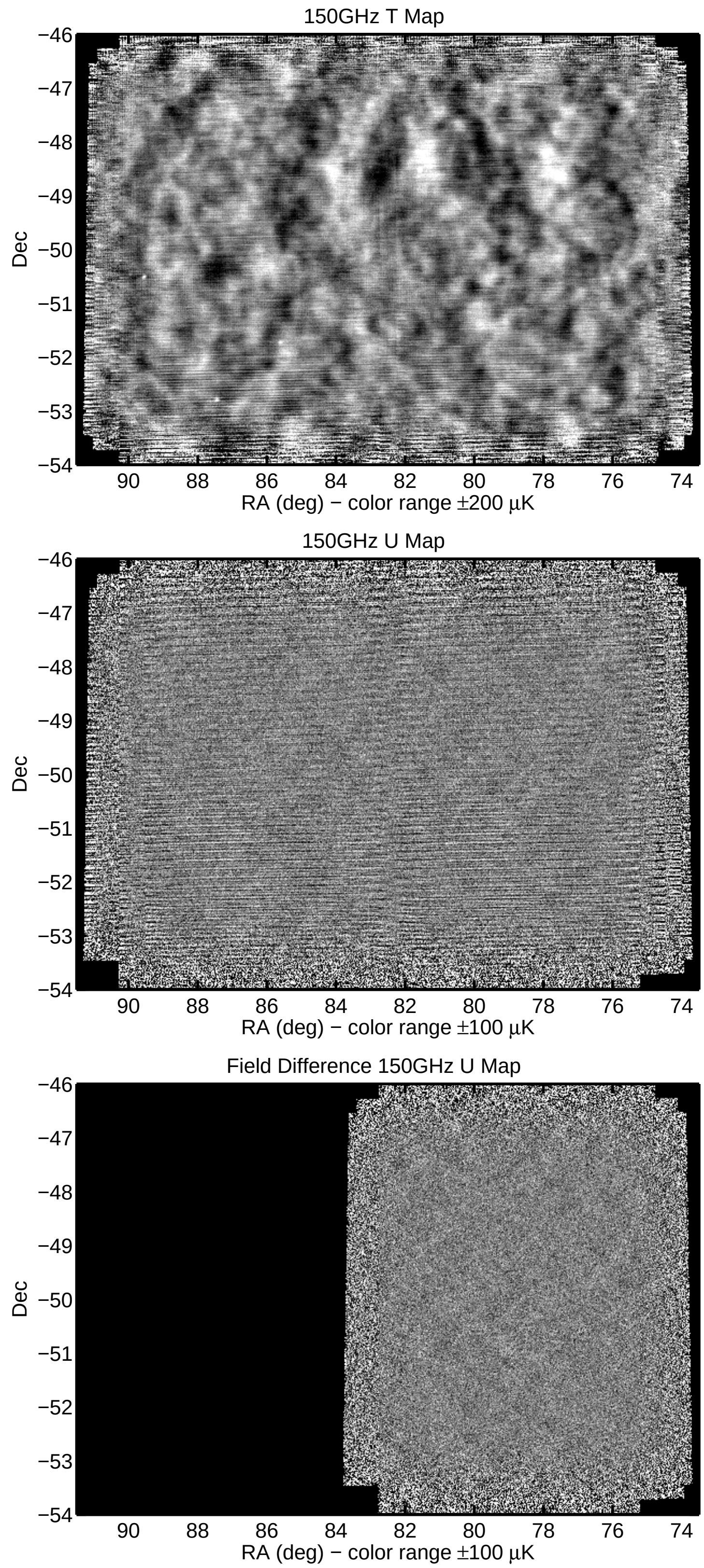

Figure 5. QUaD maps showing removal of ground contamination by field differencing. *Top:* 150 GHz total intensity map — ground contamination is evident as the diagonal stripes. *Middle:* in Stokes U the contamination dominates over the CMB and instrument noise. *Bottom:* field differencing is clearly effective at removing ground contamination.

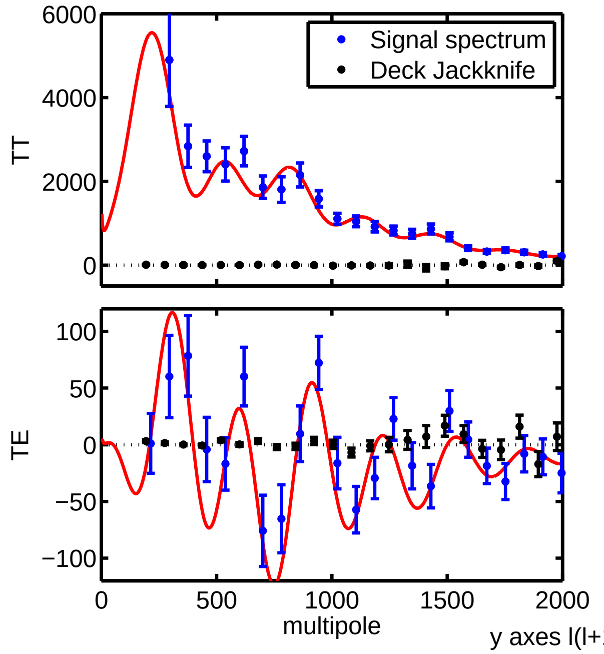

Figure 6. QUaD 150 GHz signal and deck jackknife spectra. The jackknife spectra are consistent with zero indicating no evidence for residual systematic contamination. (These points are identical to those published in [5].)

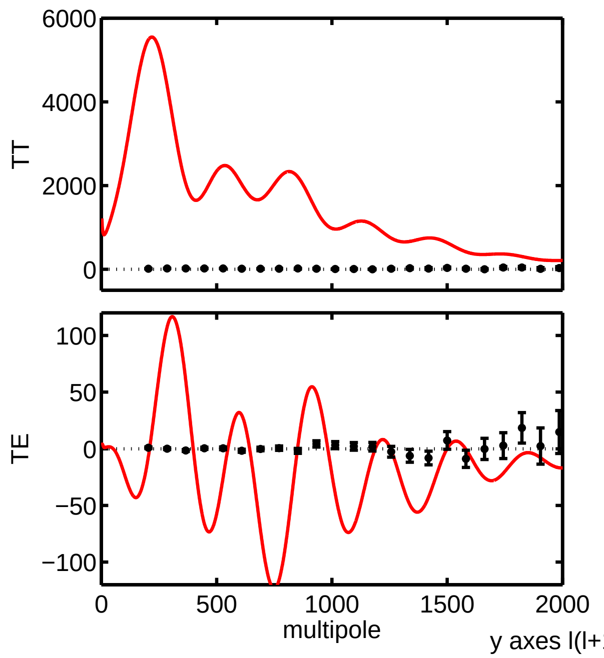

Figure 7. QUaD frequency jackknife spectra. All except the TT spectra are consistent with zero indicating no significant contamination of the CMB by foreground emission. (These points are identical to those published in [5].)

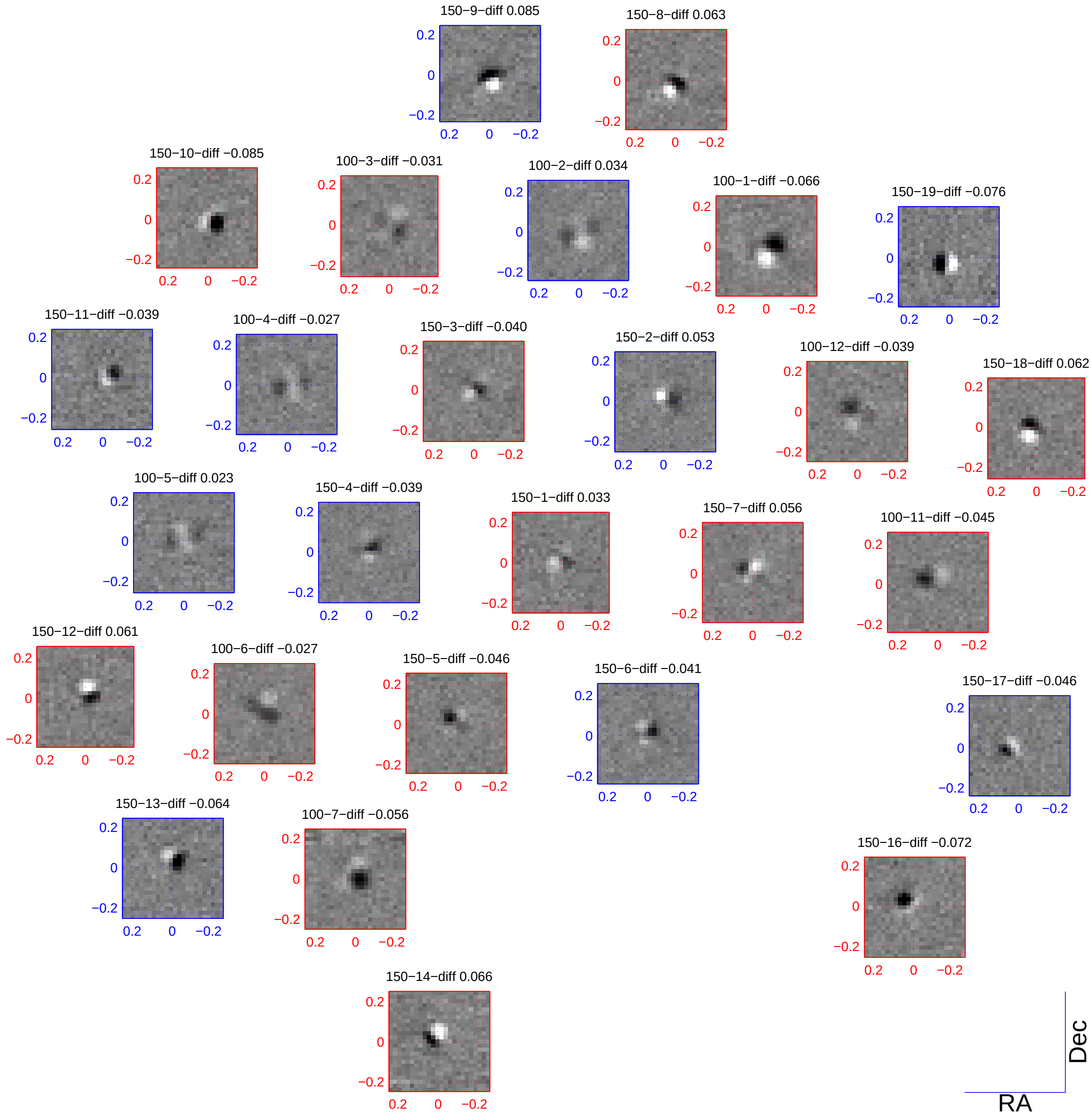

Figure 8. Pair difference maps of the bright galactic source RCW38. The numbers above each panel give the frequency band, detector pair number and the maximum value of the difference map as a fraction of the peak height of the un-differenced map — the color scale range is ±0.05 in these units. Note that many of the panels show a dipole form corresponding to centroid offset between the beams of the pair. The red and blue framed panels correspond to like aligned pairs of detectors.

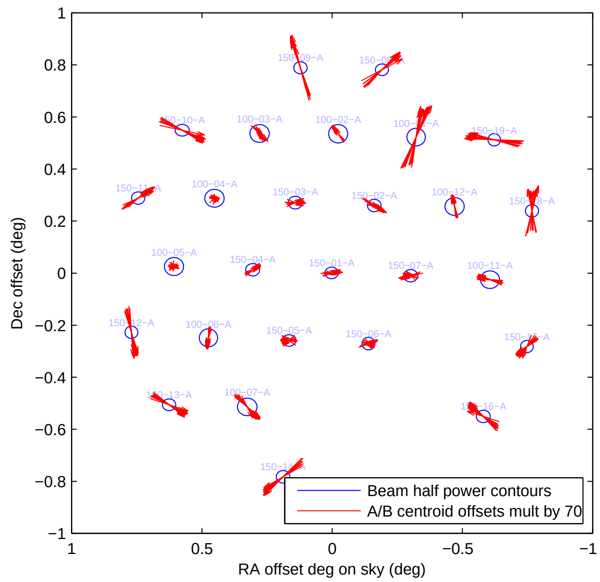

Figure 9. The red arrows show the centroid offset vectors between the two halves of each pair of detectors for eleven separate beam mapping runs on the source RCW38. The offsets are exaggerated by a factor 70 to make them visible. The blue contours show half power points of elliptical Gaussian fits to the beam maps — there are contours for each member of each pair but these are indistinguishable because the centroid offset is a tiny effect.

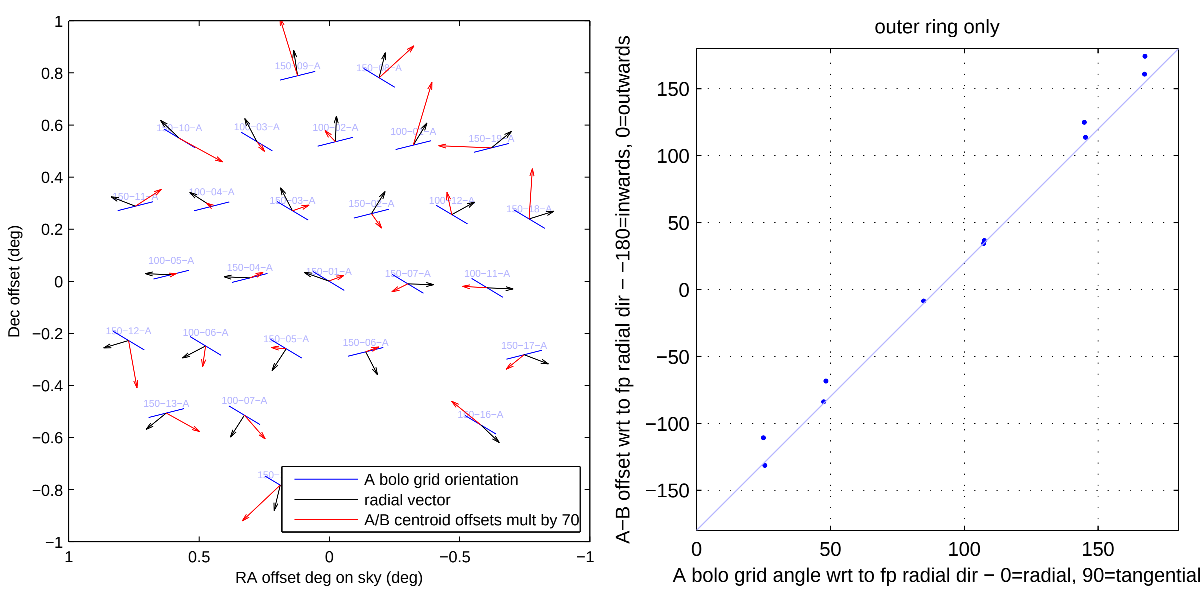

Figure 10. Centroid offset model. *left:* The mean pair centroid offset vector from Figure 9 is shown in red, the radial vector from the focal plane center is shown in black, and the A bolometer grid angle as projected on the sky is shown in blue. *right:* Scatter plot of the direction differences; the x-axis is the bolometer grid angle with respect to the radial direction (blue minus black at left), and the y-axis is the centroid offset direction with respect to the radial direction (red minus black at left).