WMAP Polarization

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WMAP Details

Angular resolution (FWHM)	48, 37, 29, 20, 12	arcminutes
Frequency Coverage	23, 33, 41, 61, 94	GHz (K,Ka,Q,V,W)
Sky Coverage	41253 (full)	square degrees
Multipole Coverage	2 - ~200	(sensitivity-limited)
Polarization Modulation?	limited	(see later)
Types of Detectors	coherent (HEMT)	-
Location	L2	space
Instrument NEQ*	520,532,515,618,743	$\mu K\ s^{1/2}$
Current limit on *r***	<0.43, <0.20	(WMAP, WMAP+BAO+SN)
Status	9 years of operation	(funded)

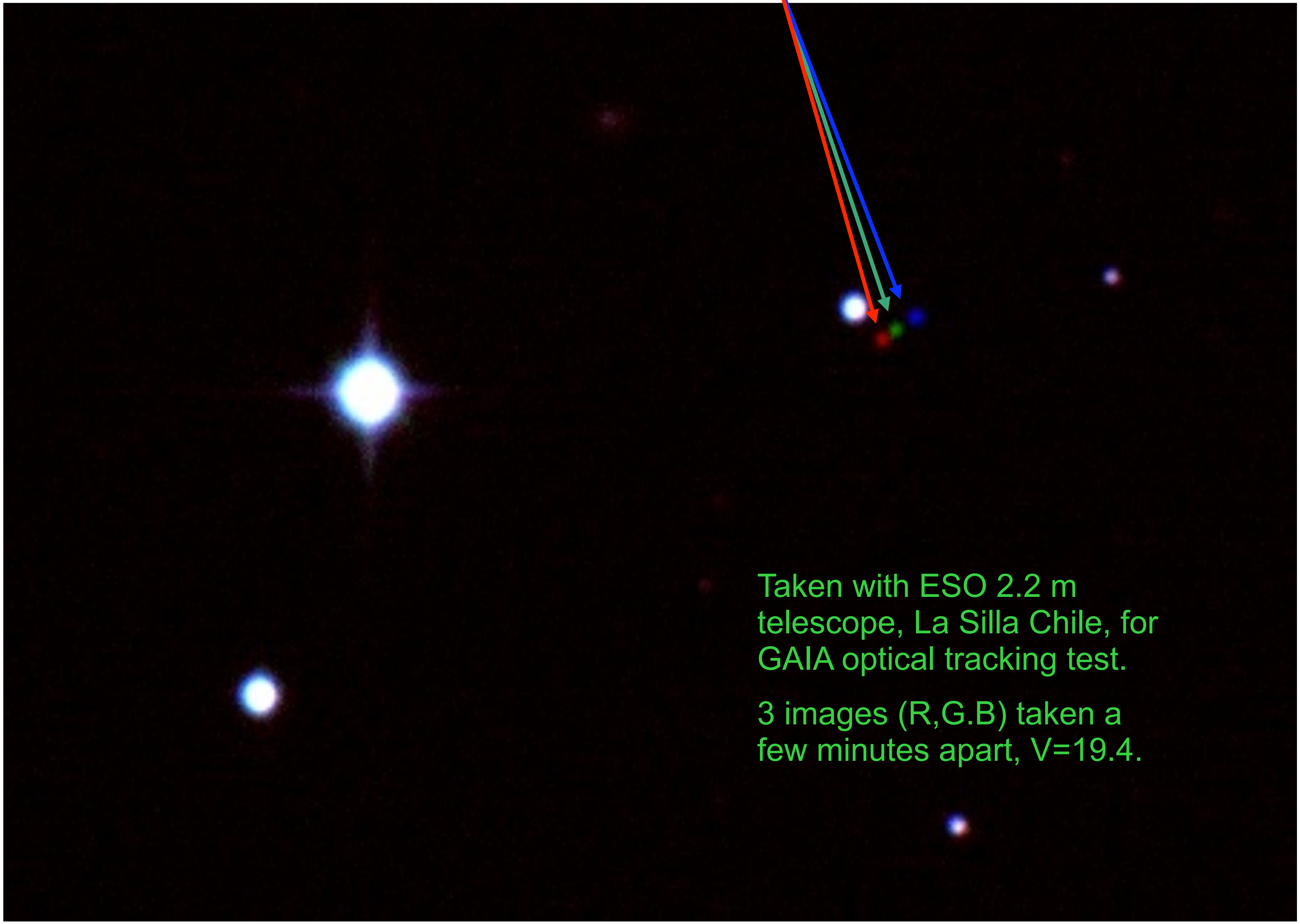
* Based on measured noise per differential observation. Co-added results for Q, V, W bands.

**Current *r* limits based on 5-year TT spectrum shape - approaching confusion limit of *r*~0.1 for TT.

Cleaned TT spectrum based on template-cleaned V+W data and Q+V+W-based residual source subtraction.

Data rate: 8 channels @ 128 ms, 8 @ 102.4 ms, 8 @ 76.8 ms, 16 @ 51.2 ms for 9 years.

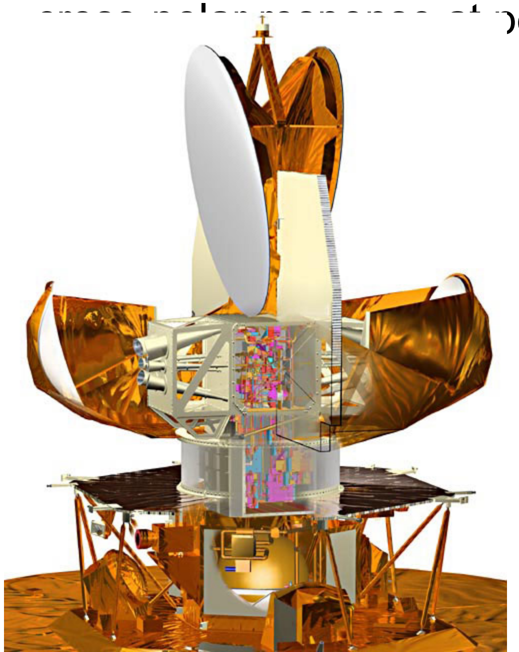
WMAP @ L2

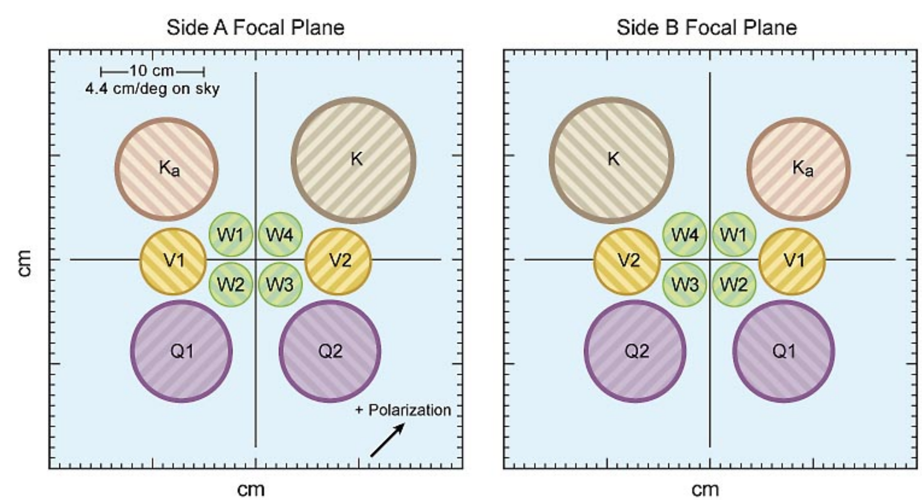

Taken with ESO 2.2 m telescope, La Silla Chile, for GAIA optical tracking test.
3 images (R,G.B) taken a few minutes apart, V=19.4.

WMAP Optics - I

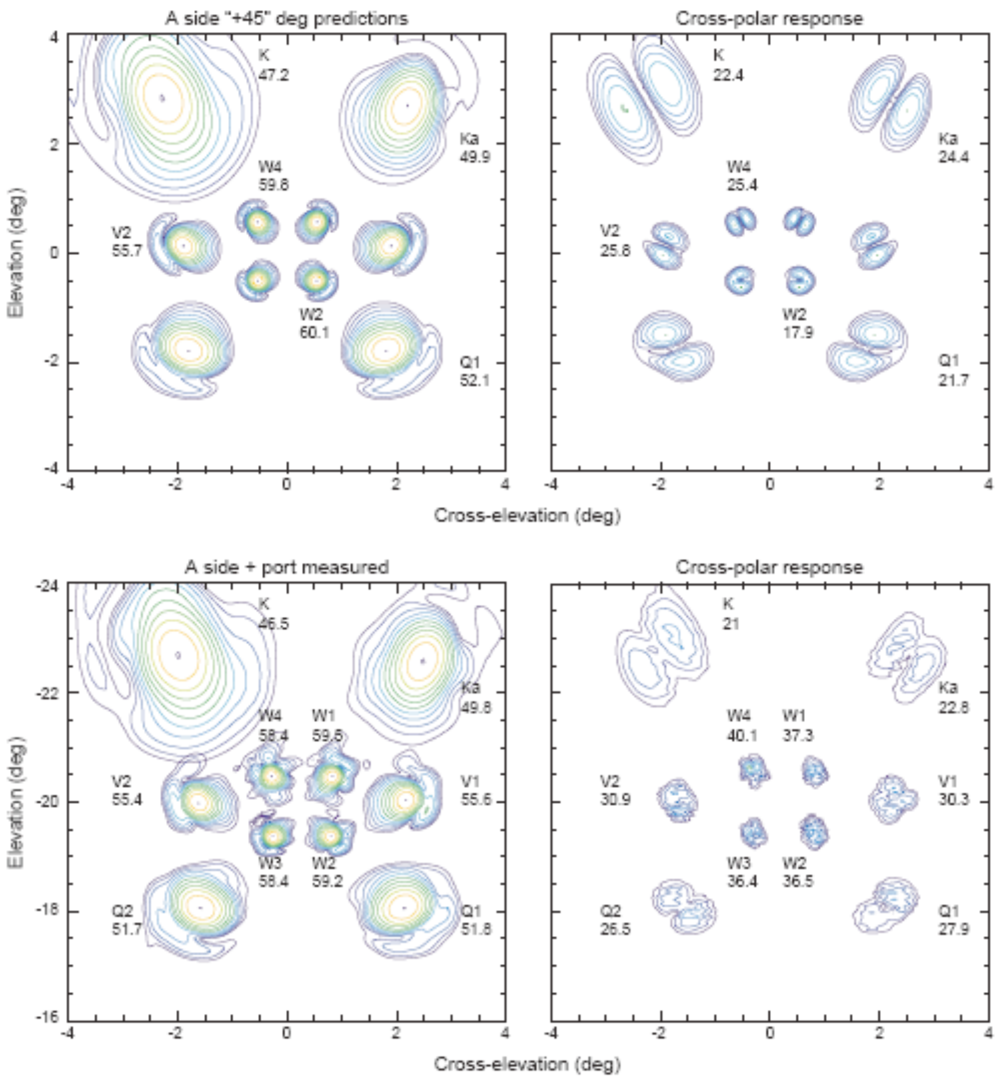
- Back-to-back Gregorian telescope:
  - 1.4 x 1.6 m primaries, shaped
  - composite construction: Korex honeycomb core, carbon-fiber face sheets, VDA (2.5 um) / SiOx (2.2 m) coating
- 10 corrugated feeds per side:
  - 1 ea @ K, Ka (profiled); 2 ea @ Q, V, 4 ea @ W band (extended)
- Ortho-mode Transducers (OMTs):
  - splits polarization response to 2 separate radiometers
  - polarization angles measured by metrology to ±0.2°, by radiometry to ±1.0°
  - cross-polar response at peak of main beam: < -25, -27, -24, -25, -22 dB (K-W)

Page et al., ApJ, 585, 566





WMAP Optics - II



- Modeled vs. measured beam response:
  - A-side optics
  - Broadband response (from 12 frequencies)
  - Data taken in warm chamber, pre-flight
  - In-flight optics are more distorted and required further modeling to establish -40 dB tails

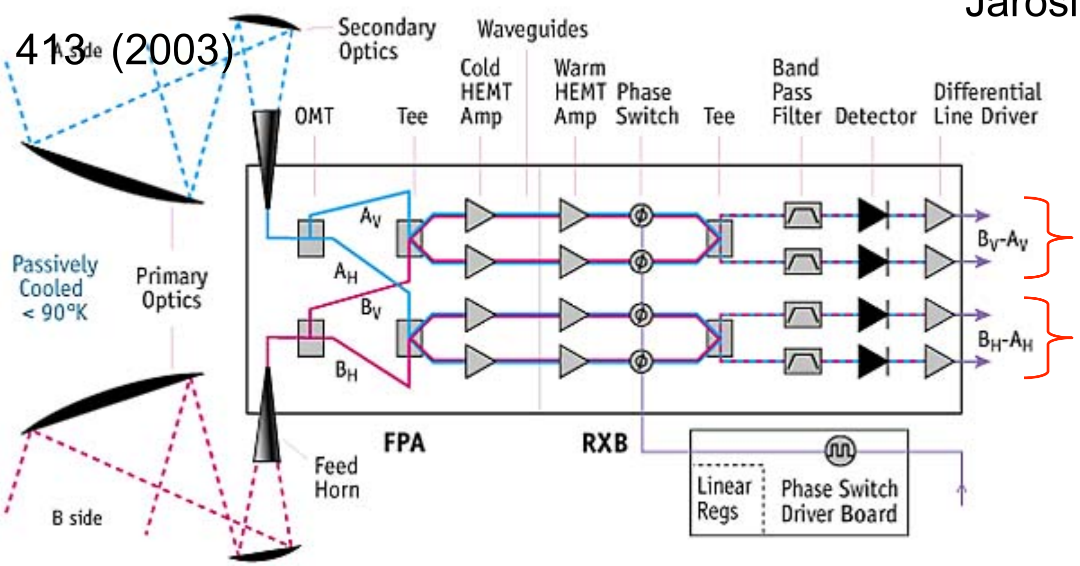
Jarosik et al., ApJS, 170, 263 (2007)

Hill et al., ApJS, in press (2008)

WMAP Radiometers

- Differential, pseudo-correlation, polarization-sensitive:
  - 2 sky ports (A side and B side),
  - phase-matched HEMT amplification,
  - polarization measured by separate radiometers
- Signal modulation:
  - 2.5 kHz phase switch after warm HEMT; mitigates 1/f noise, does not modulate polarization signal,
  - 0.464 rpm spacecraft spin; modulates polarization, but P signal does not “spin flip” like T signal does due to A/B side OMT orientation
  - 1.0 rph spacecraft precession

Jarosik et al., ApJS, 145, 413 (2003)



radiometer 1

radiometer 2

WMAP Pointing Accuracy

- WMAP spacecraft frame primarily determined by star trackers
  - Pointing reconstruction better than 5 arcsec in tracker frame.
  - Tracker mount flexes ~1 arcmin (on an annual time scale) relative to feed frame due to thermal flexure of spacecraft top deck. Effect is modeled with an accuracy of ~0.1 arcmin.
  - Instrument lines-of-sight measured with respect to spacecraft frame by centroiding Jupiter observations. Accuracy also ~0.1 arcmin per beam.

- Beams differenced in polarization measurement (radiometers 1 and 2) are always launched by the same feed, so are always relatively co-aligned.

In general, optical and pointing imperfections (which convert E mode to B mode) are subdominant for WMAP due to our relatively low signal-to-noise. We currently see no hint of B-modes after foreground cleaning. Larger concern is aliasing of T to E.

WMAP Band Definition

- Set by combination of HEMT gain profile and band definition filter
  - Will in general be slightly different between two radiometers (i.e., polarization channels),
  - Signal response per radiometers calibrated to CMB dipole with 2.7K blackbody spectrum,
  - Sky signals with different spectrum (i.e., foreground signals) will produce a spurious polarized response,
  - Distinguish from sky polarization by modulating polarization angle (see next)
  - Include a “spurious” sky map in the sky model

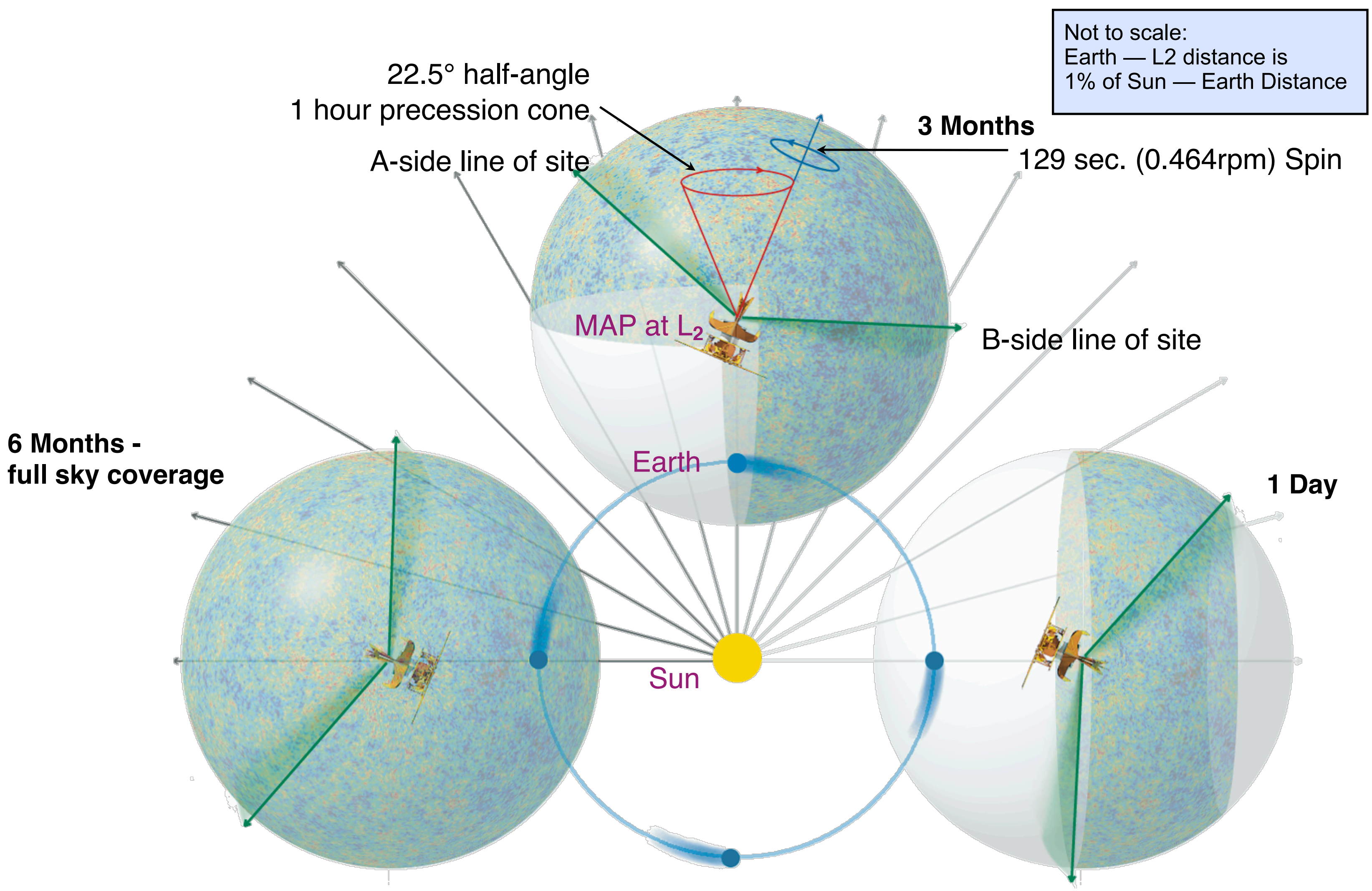
Jarosik et al., ApJS, 145, 413 (2003)

TABLE 11
MAP RADIOMETER BANDPASS PARAMETERS

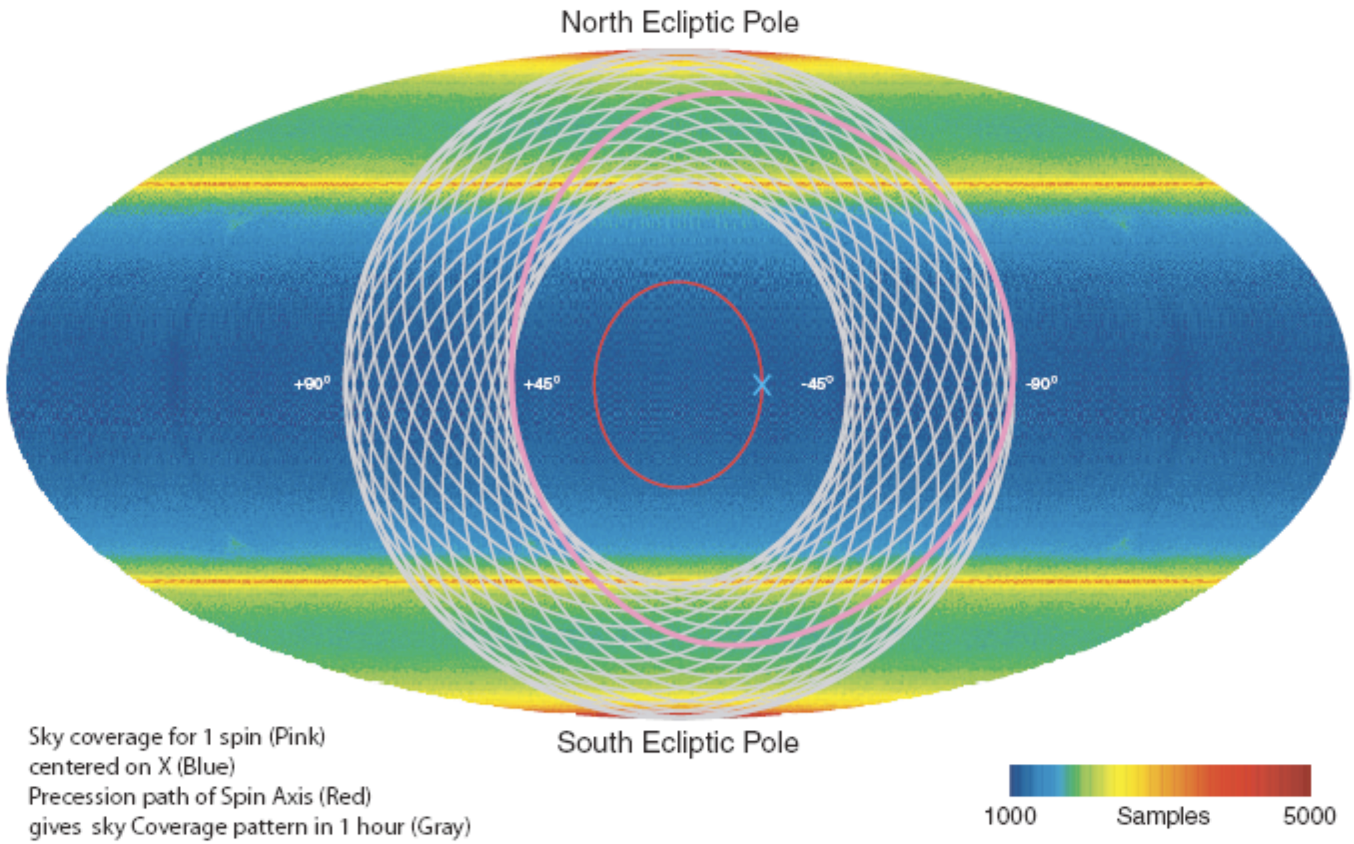
Radiometer	ν_{avg} (GHz)	c_1	c_2	$\Delta\nu_{eff}$ (GHz)	ν_{th} (GHz)	dT_{th}/dT_{RJ}
K11	22.29	-2.43E-03	2.78E-03	5.26	22.36	1.013
K12	23.12	-2.35E-03	2.83E-03	4.09	23.18	1.014
Ka11	32.78	-1.58E-03	1.75E-03	6.75	32.84	1.028
Ka12	33.12	-1.85E-03	2.06E-03	7.04	33.19	1.029
Q11	40.71	-1.85E-03	2.10E-03	8.62	40.79	1.044
Q12	40.81	-1.48E-03	1.70E-03	7.66	40.88	1.044
Q21	40.16	-1.58E-03	1.78E-03	7.55	40.23	1.043
Q22	40.92	-1.53E-03	1.78E-03	7.68	40.99	1.044
V11	59.20	-2.13E-03	2.20E-03	8.37	59.32	1.095
V12	61.10	-2.00E-03	2.23E-03	12.53	61.22	1.101
V21	61.61	-1.95E-03	2.22E-03	12.81	61.72	1.103
V22	60.63	-2.12E-03	2.35E-03	11.66	60.75	1.099
W11	93.60	-2.02E-03	2.20E-03	20.81	93.71	1.249
W12	93.18	-1.69E-03	1.82E-03	18.30	93.27	1.247
W21	93.49	-1.47E-03	1.57E-03	16.54	93.58	1.248
W22	94.27	-1.37E-03	1.48E-03	16.54	94.35	1.253
W31	92.36	-1.35E-03	1.44E-03	16.70	92.44	1.242
W32	93.32	-1.30E-03	1.37E-03	16.15	93.39	1.247
W41	94.24	-1.67E-03	1.83E-03	18.76	94.33	1.253
W42	93.09	-1.58E-03	1.68E-03	17.73	93.18	1.246

Worst case

WMAP Scan Strategy - I

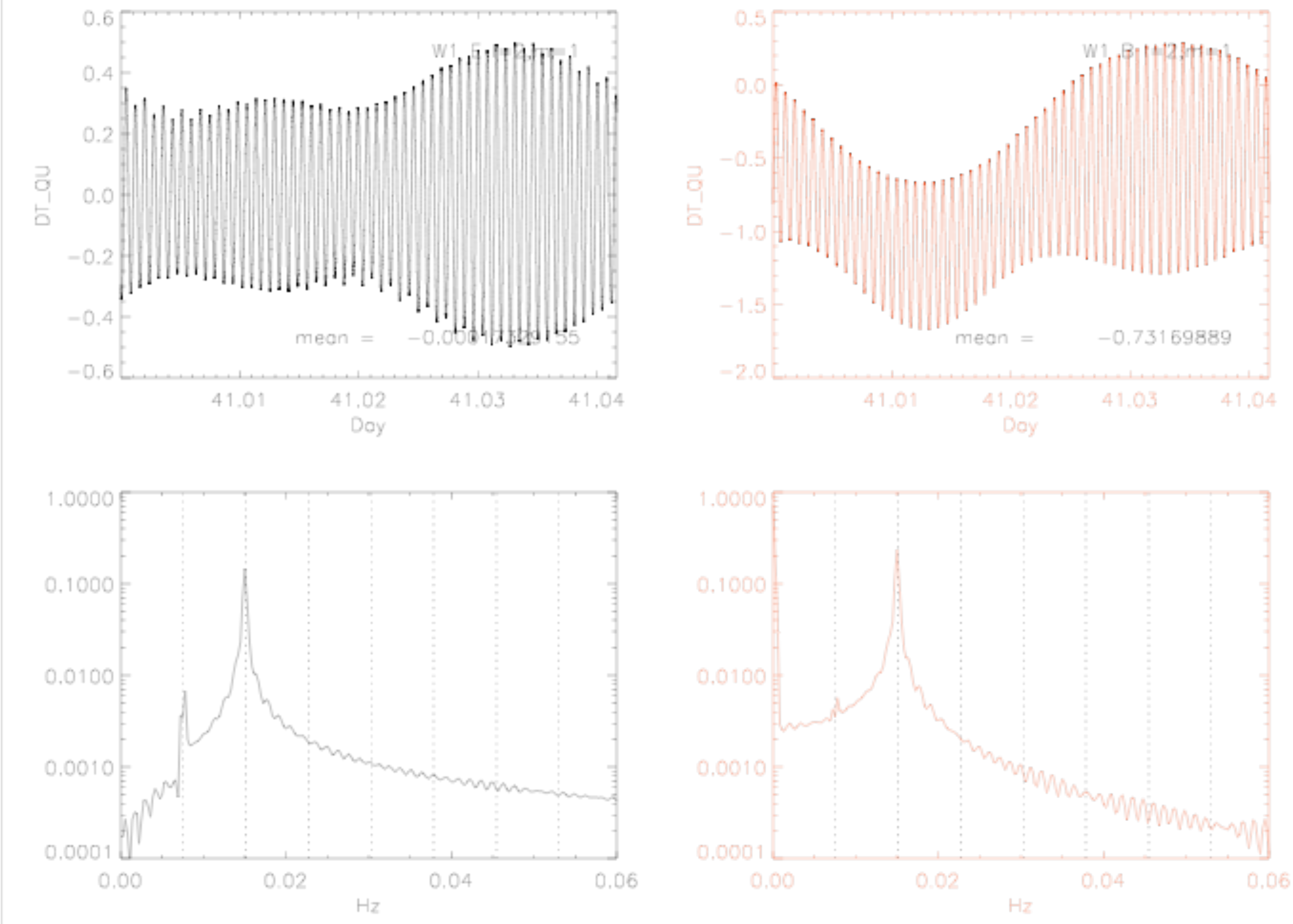


WMAP Scan Strategy - II

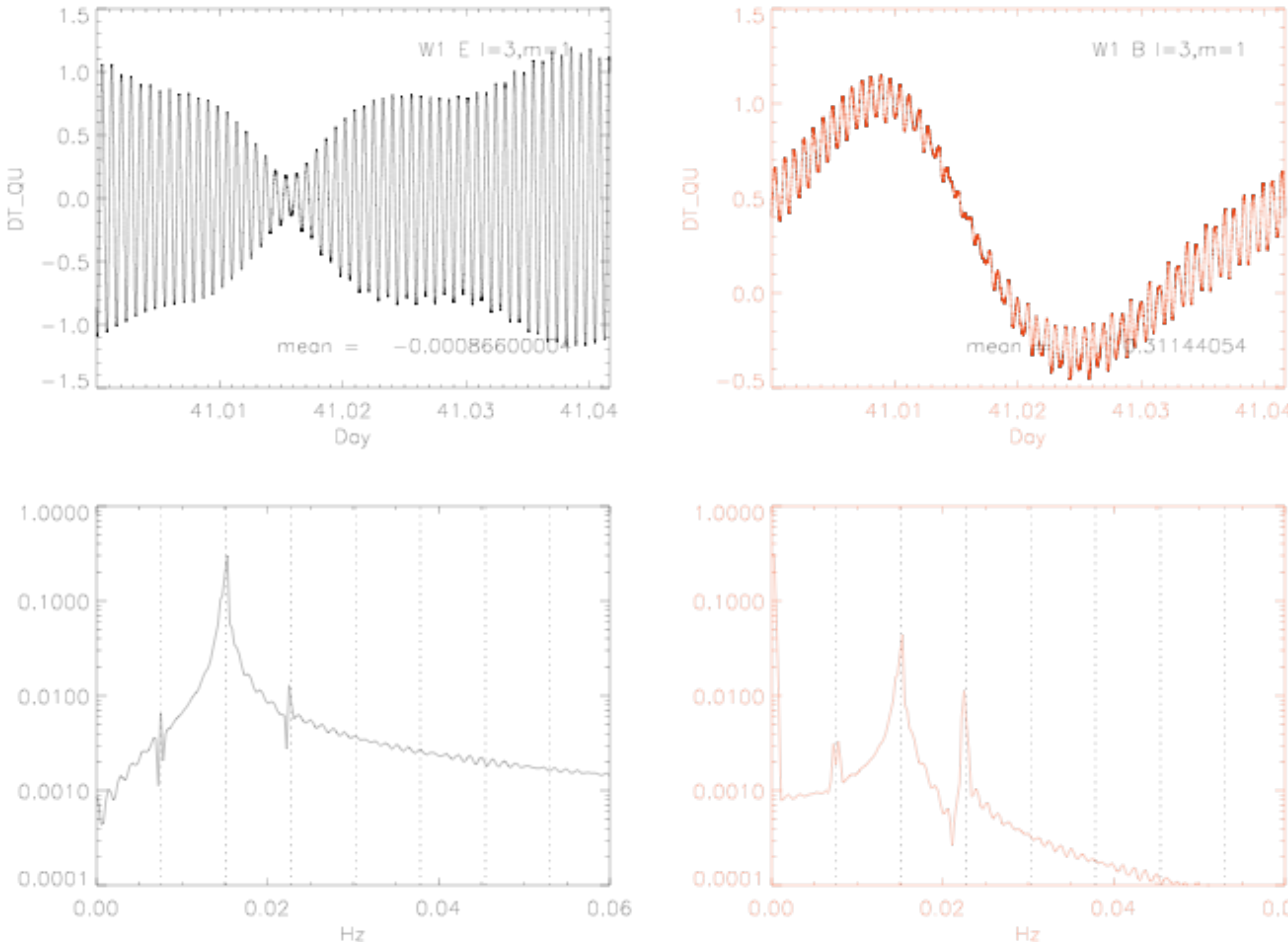


- Polarization angle modulation:
  - Ecliptic plane: ±22.5° once per hour in middle of annulus (slow),
  - Ecliptic poles: ±180° over 6 month period (very slow)
- Polarization signal modulation:
  - Complicated, depends on spherical harmonic mode (see next)

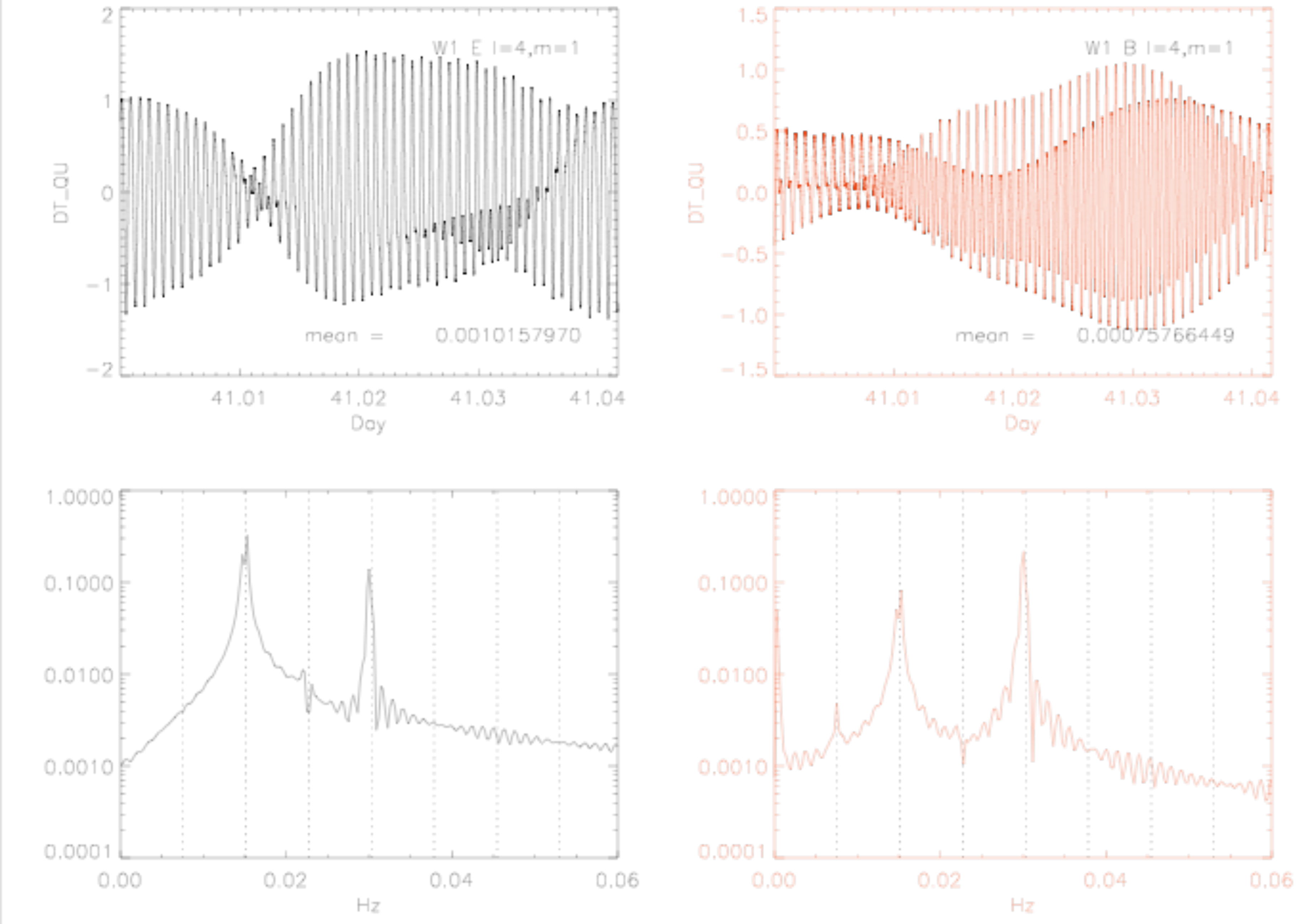
WMAP Polarization Modulation: *l*=2



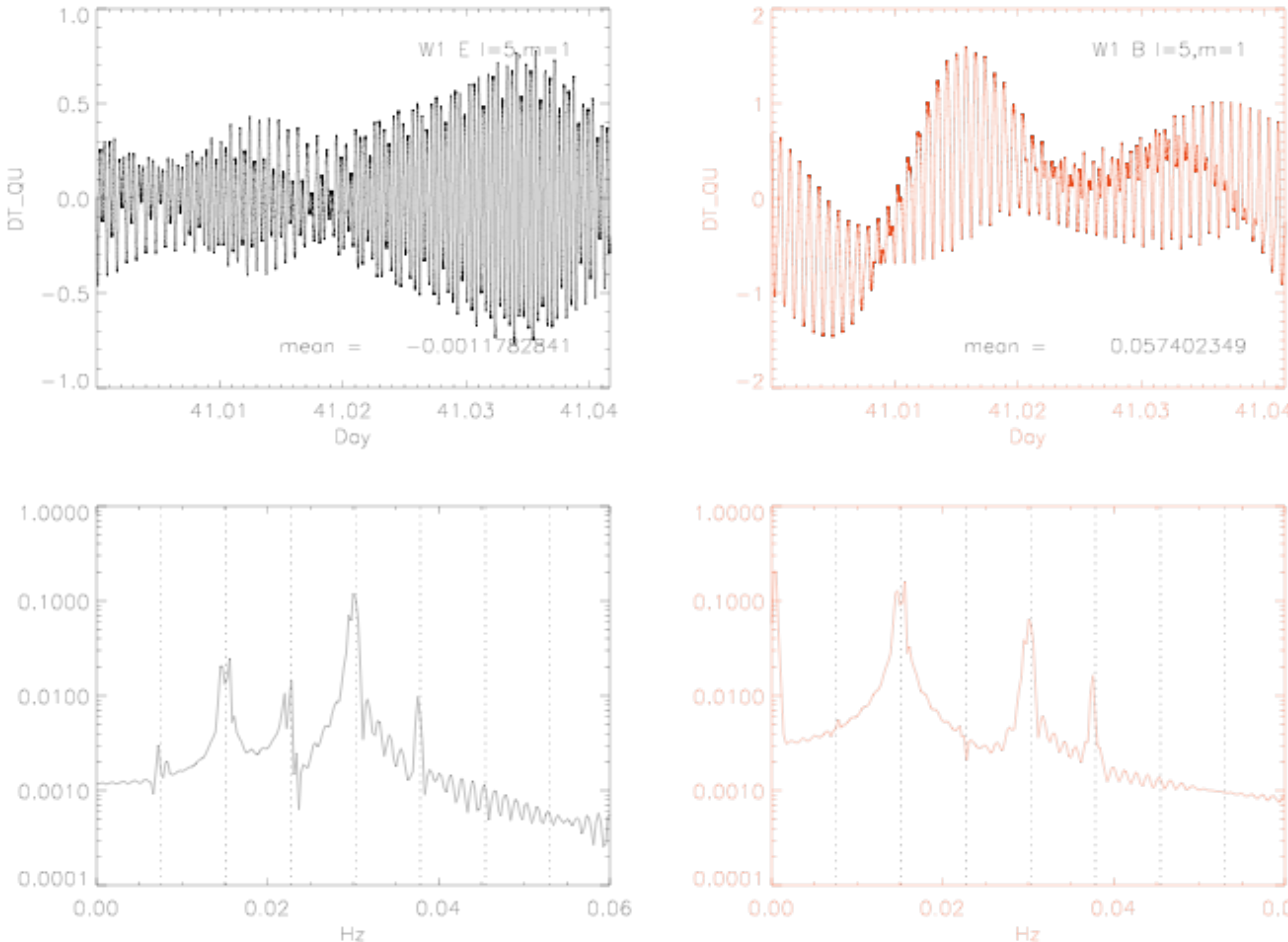
WMAP Polarization Modulation: *l*=3



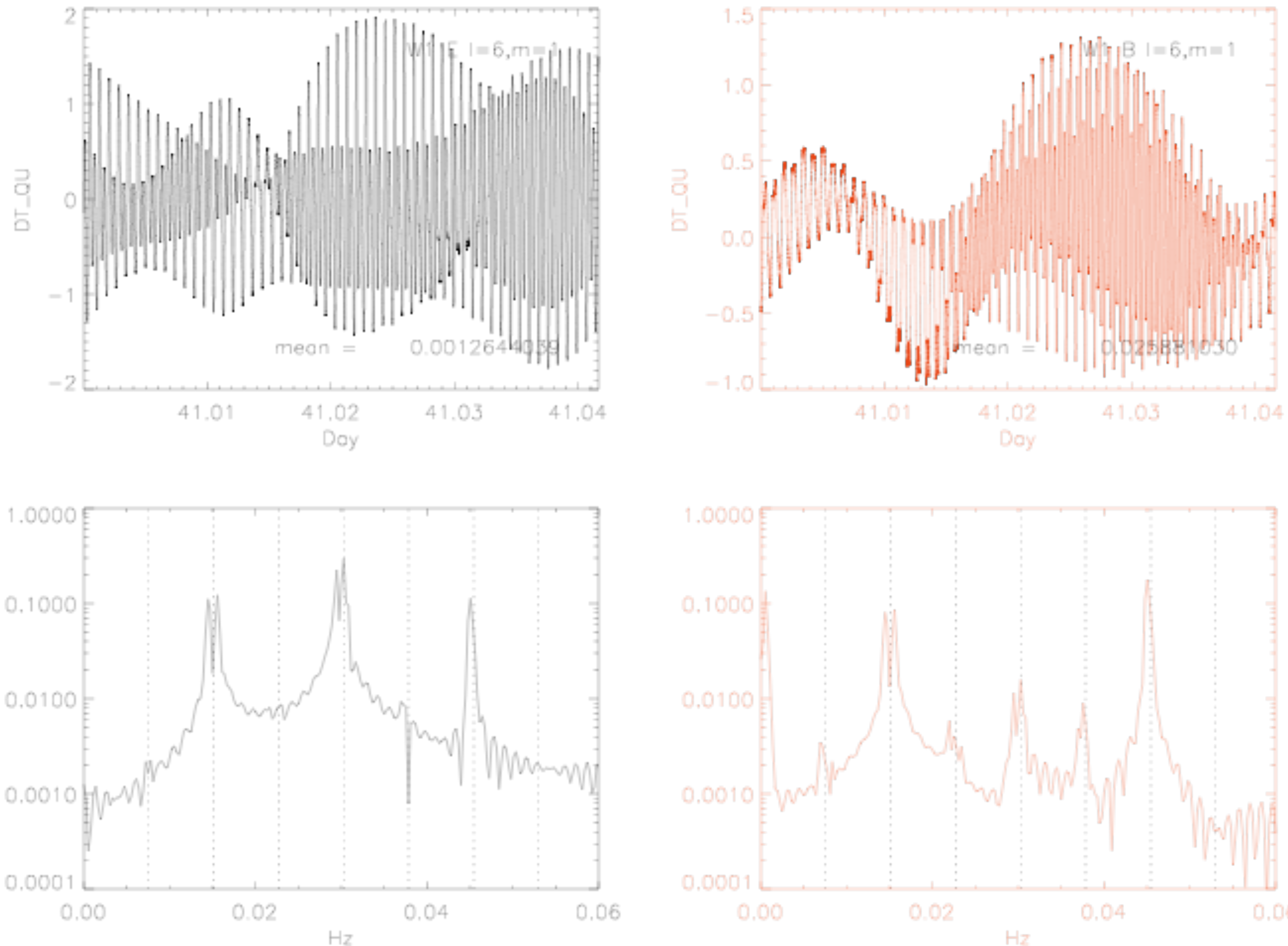
WMAP Polarization Modulation: *l*=4



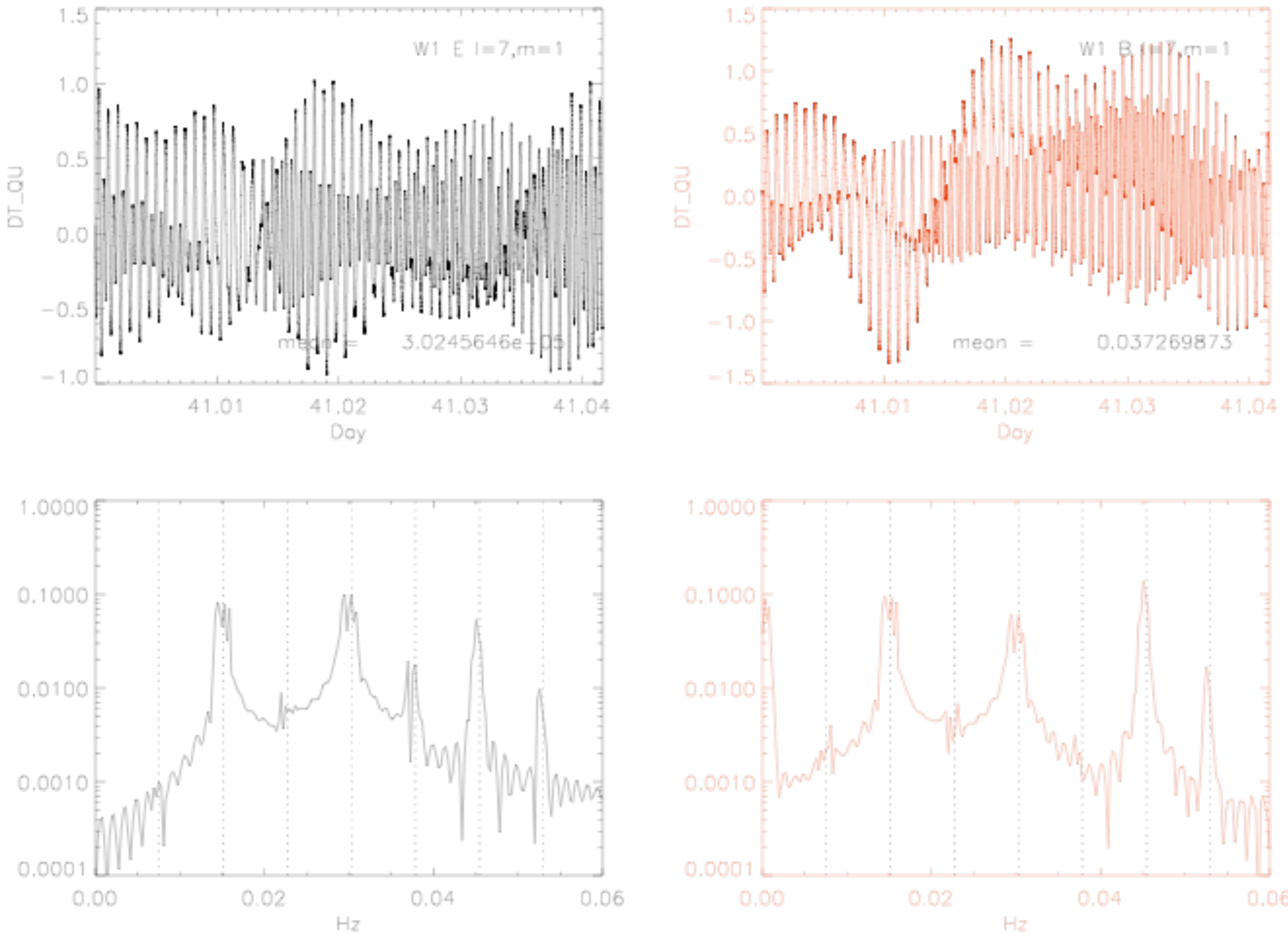
WMAP Polarization Modulation: *l*=5



WMAP Polarization Modulation: *l*=6



WMAP Polarization Modulation: l=7



WMAP Signal Modulation: Comments

- Radiometers 1 and 2 measure (ignoring loss imbalance):

$$d_1 = \Delta T + \Delta P \qquad \Delta T = T_A - T_B$$

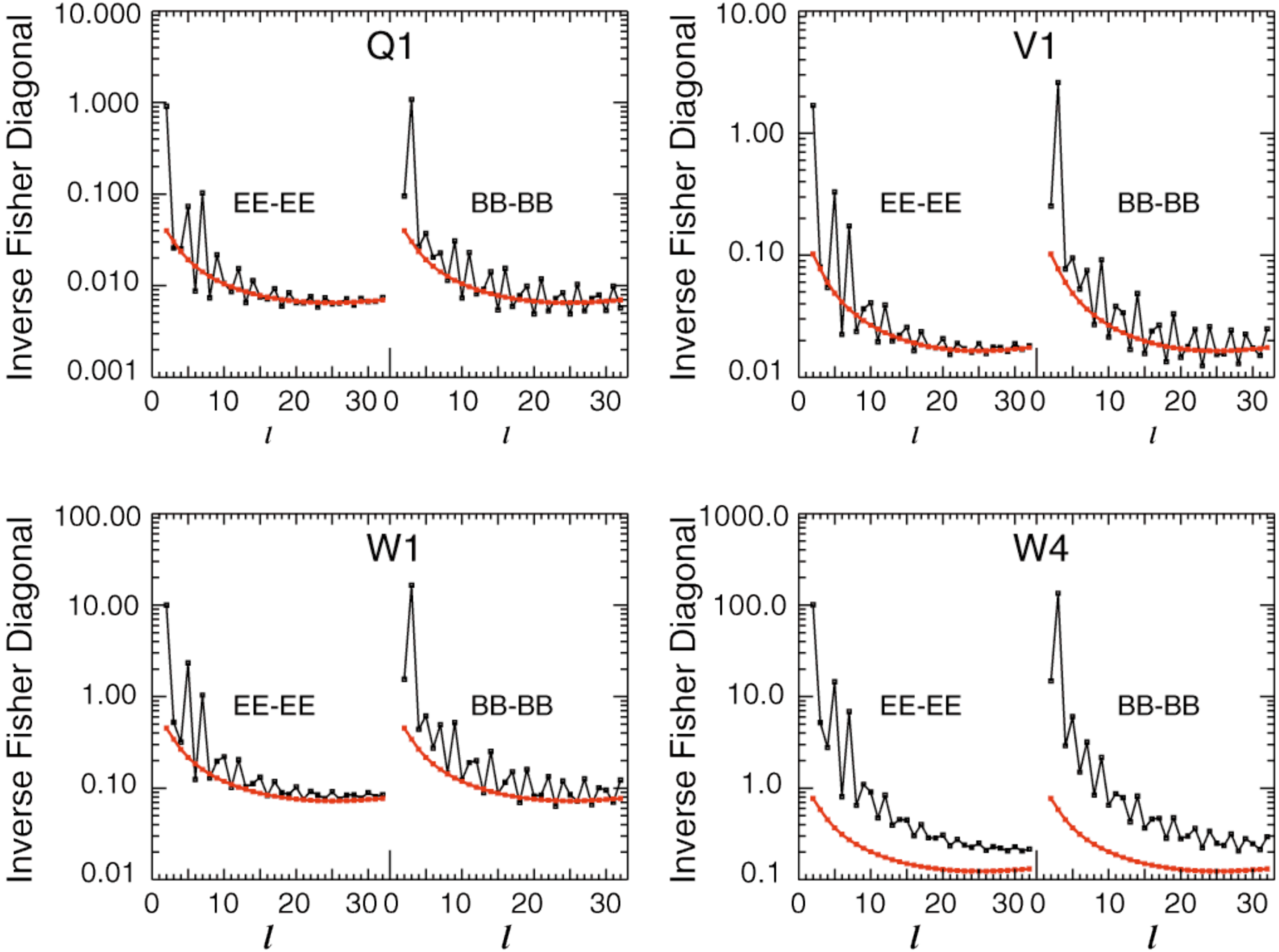
$$d_2 = \Delta T - \Delta P \qquad \Delta P = f(Q_A, U_A, \alpha_A) - f(Q_B, U_B, \alpha_B)$$

- The term ΔT changes sign on spin flip, but in general, ΔP does not, so the polarization measurement is more sensitive to offset (or baseline) variations than the temperature measurement is, especially *l*=3 BB.
- 1/f noise is a stochastic form of baseline drift. The 1/f noise model must be accurately propagated from the time-ordered data to the sky maps:

$$\Sigma^{-1}(p_1, p_2) = M^T N^{-1} M = \sum_{t_1 t_2} M(t_1, p_1) N^{-1}(t_1, t_2) M(t_2, p_2)$$

- MUCH effort has been expended to carry this out for WMAP. We produce a pixel-pixel inverse covariance at low sky map resolution (Nside = 16). We propagate this to power spectrum estimation using both pseudo-C_l and maximum likelihood methods.

WMAP Power Spectrum Errors



Black – errors computed using full pixel-pixel covariance

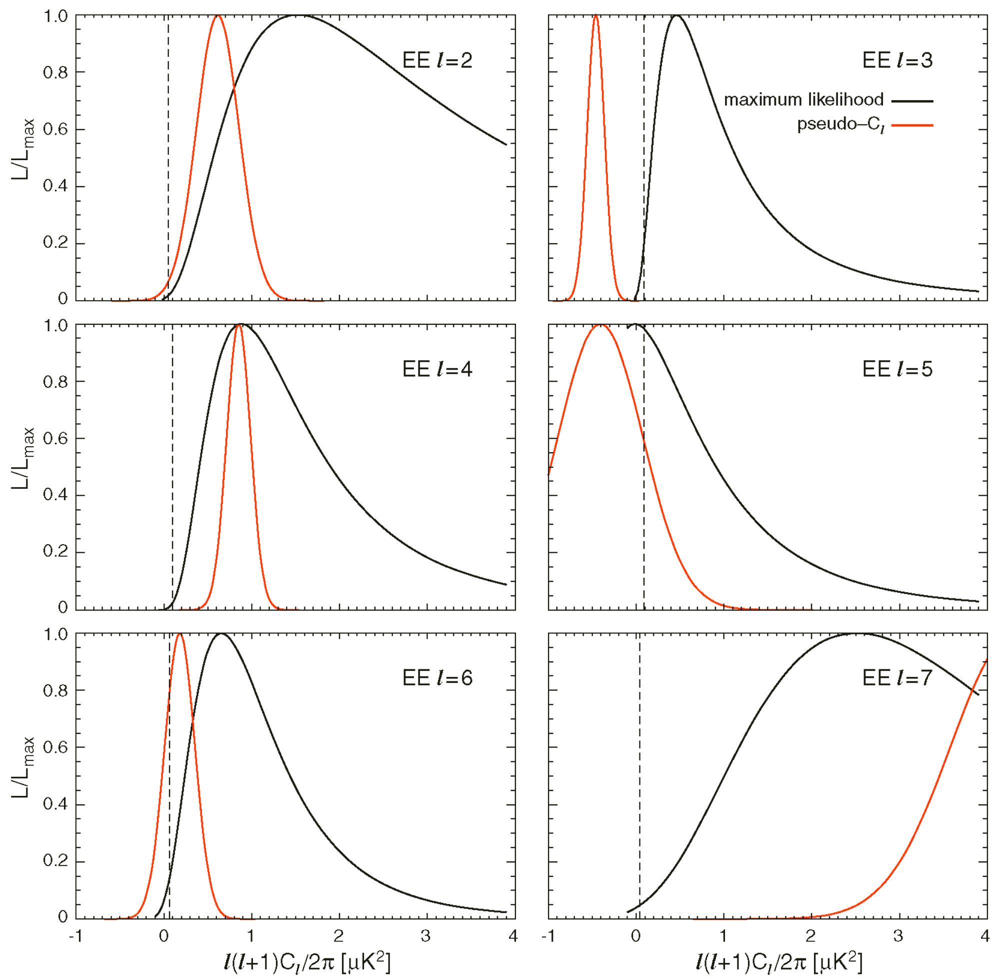
Red – errors computed assuming sky map noise is diagonal (no pixel-pixel covariance)

Sawtooth structure mostly arises from scan geometry. 1/f noise elevates the overall level.

Page et al. ApJS, 170, 335 (2007)

How Well do the Errors Work?

- Very well for Ka, Q, V bands, as measured by year-year scatter. (K band is used as a foreground template.)
- Very well for W band for *l* > ~10.



Reasonably well for W band, l<10 with some exceptions:

- *l*=2,3 BB: too much year-year scatter. Sign of baseline problems??

- *l*=7 EE: spot-on year-year scatter, but a "significant" co-added result (see left)

WMAP Systematic Error Table

Systematic	Effect	Notes
Cross-polar beam	$E \rightarrow B$	sensitivity-limited
Polarization angle errors	$E \rightarrow B$	“
Pointing errors (on Q/U)	$E \rightarrow B$	“
Main beam asymmetry (before differencing)	$dT \rightarrow B$	cross-polar?
Sidelobes	$dT \rightarrow B$	Barnes et al, ApJS, 148, 51 (2003)
Instrumental polarization	$dT \rightarrow B$	see 1/f noise
Relative calibration errors	$dT \rightarrow B$	subdominant to baseline errors
Pointing errors before differencing	$T \rightarrow B$	n/a
Gain drift before differencing	$T \rightarrow B$	see relative calibration
Optics and spillover T variations	$dT_{opt} \rightarrow B$	Hinshaw et al., ApJS, submitted
Scan modulated cold stage variations	$dT_{CS} \rightarrow B$	subdominant to optics variations
Band shape errors, including modulator effects	foregrounds $\rightarrow$ B	potentially significant to B modes, modulate polarization angle
Others?	“noise” $\rightarrow$ E,B	offset/baseline drifts

The End

Issues/Lessons/Concerns

- For a deployed experiment, what lessons were learned?

Polarization signal modulation is critical!

Instrument and Observing Strategy

Please describe the following items, as well as anything else we need to know to understand how you're going to make polarization maps

- Optics
- band definitions
- polarization selection
- Polarization modulation
- Scan strategy
- Pointing reconstruction (accuracy)