WMAP: Experimental Sources of Systematic Error

Stephan Meyer
Kavli Institute for Cosmological Physics
University of Chicago

Instrument Design Philosophy

1. Control systematic effects from external sources (sun, earth, moon).
2. Control systematic effects from instrument by designing in extreme stability (temperature, voltage)

- Do this even at the cost of instrument sensitivity

Design Properties and Goals

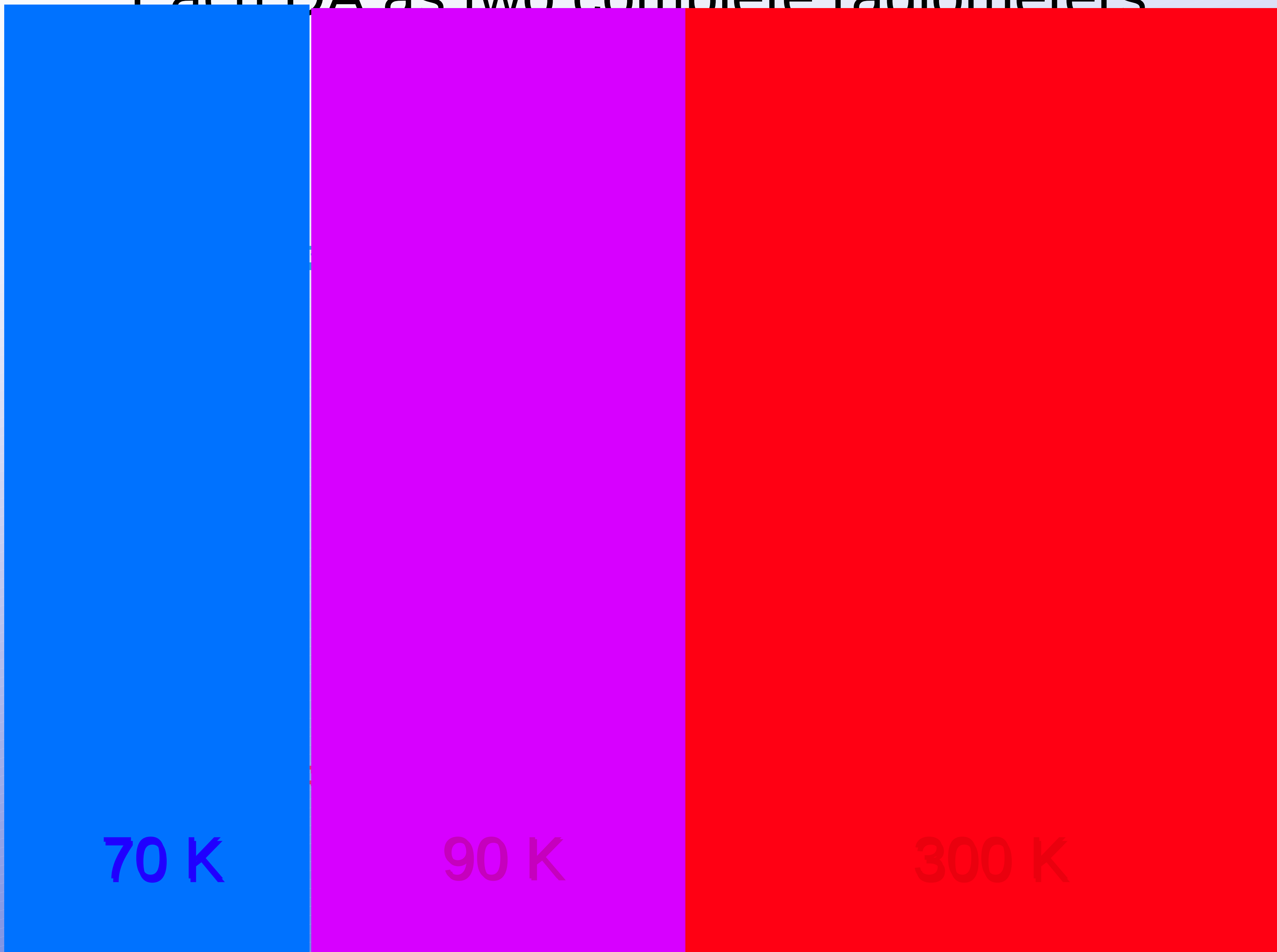
- Resulting design uses
  - differential radiometers
  - L2 orbit
  - passive cooling
  - 4 levels of modulation
  - complex scan pattern
- Design goal of 4 µK limit on systematic errors reached.
- No systematic corrections applied in data analysis of first year data

WMAP Parameters

- Frequencies: 23, 33, 41, 61, 94 GHz
- Beam size: 0.88, 0.66, 0.51, 0.35, 0.22 Degrees FWHM
- Primary modulation: 2.5 KHz
- Spin Frequency: 0.464 rpm
- Precession period: 1 hour
- Parameters, maps, and data are at http://lambda.gsfc.nasa.gov/product/map/

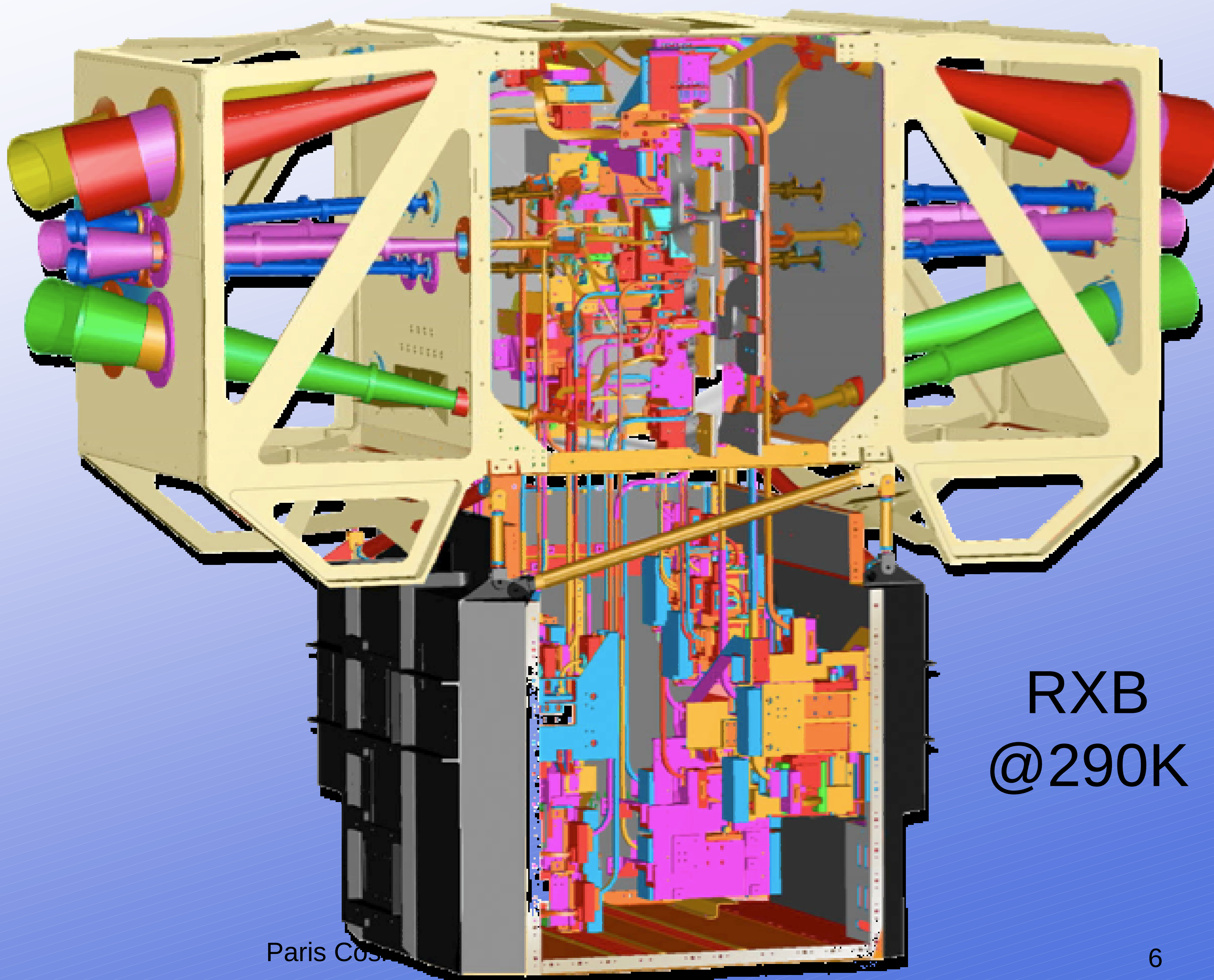
WMAP Pseudo-Correlation Differencing Assembly

Each DA as two complete radiometers



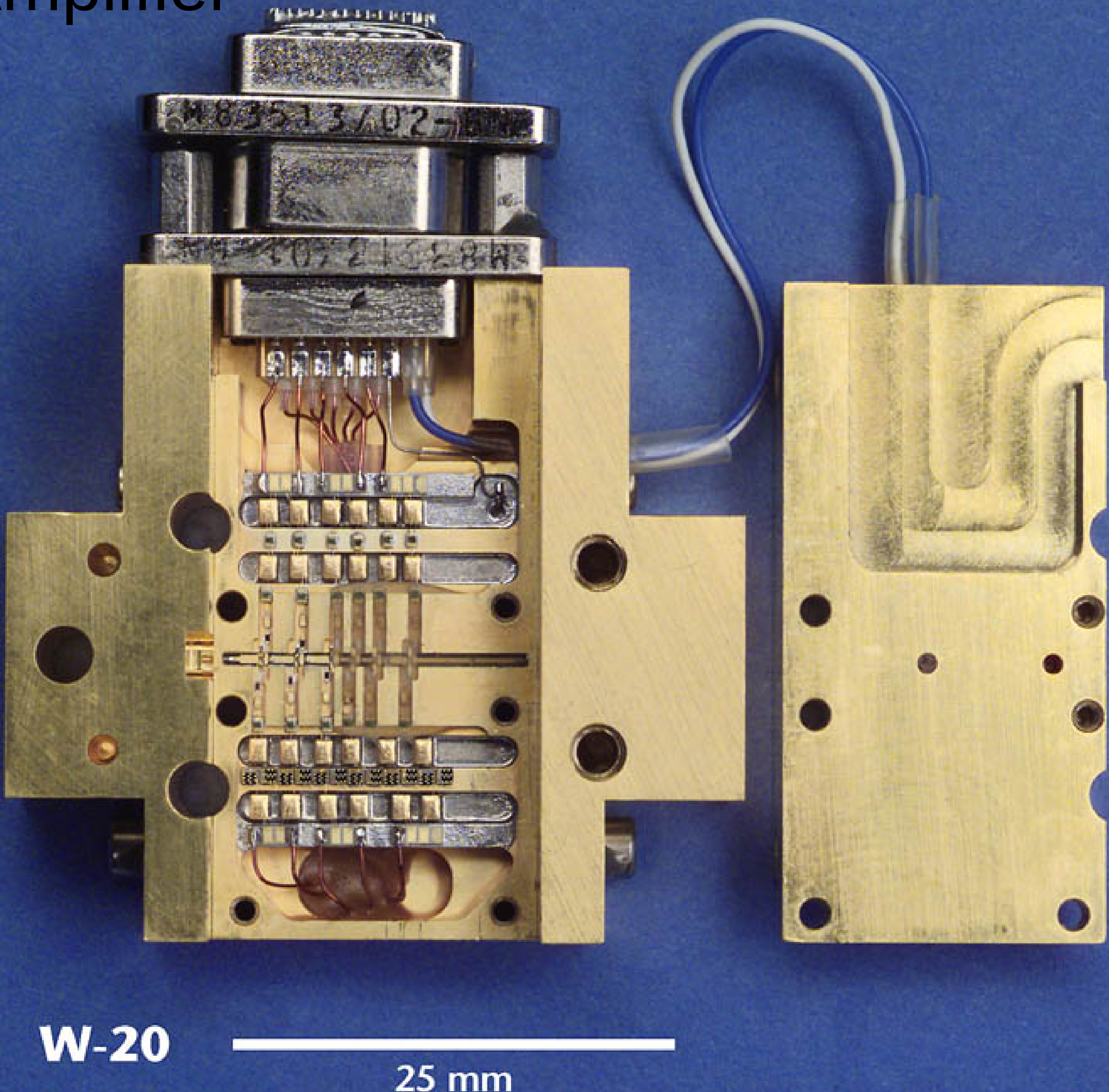
The *WMAP* Instrument contains 10 DAs

FPA
@90K

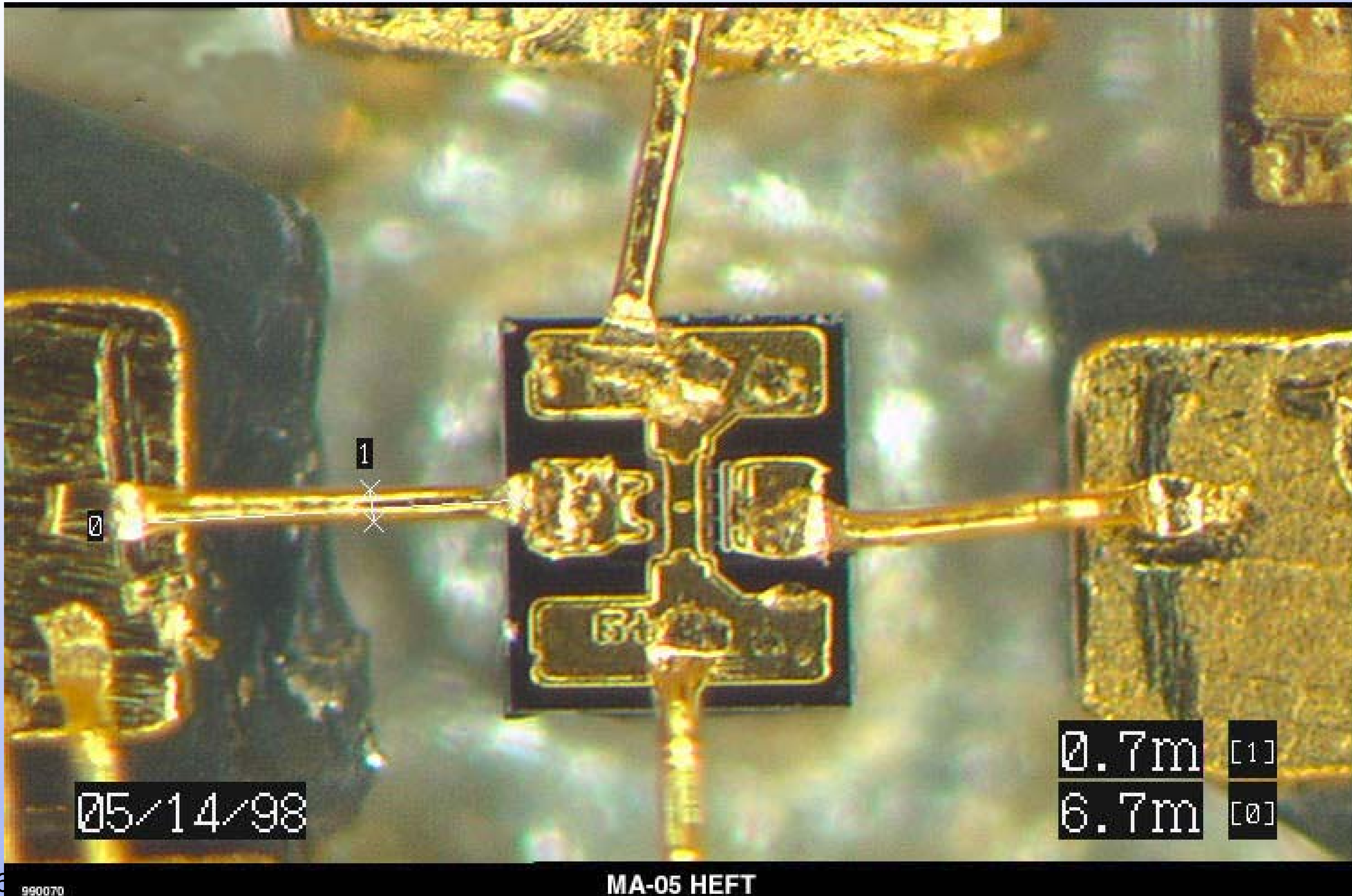


RXB
@290K

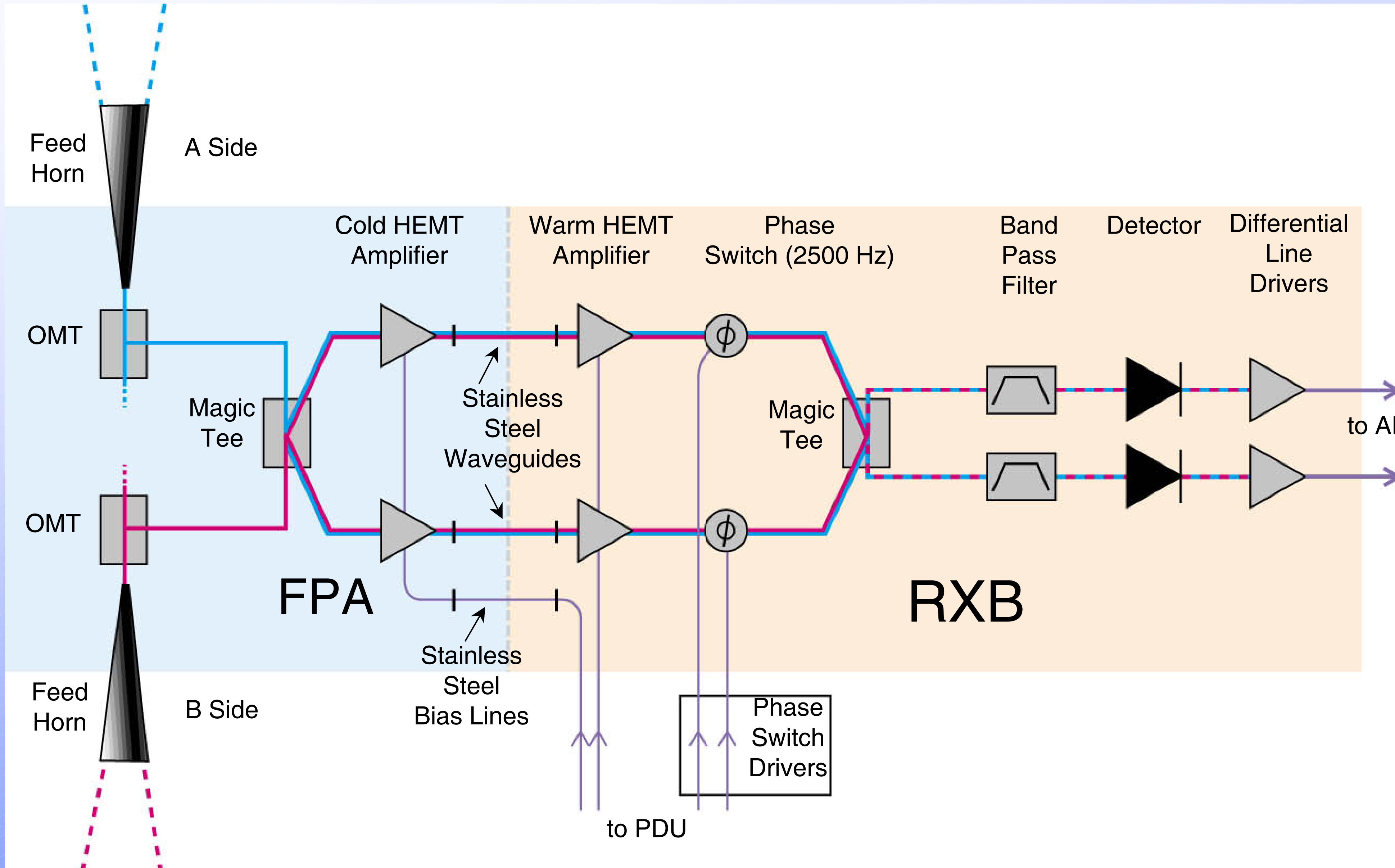
W Band Amplifier



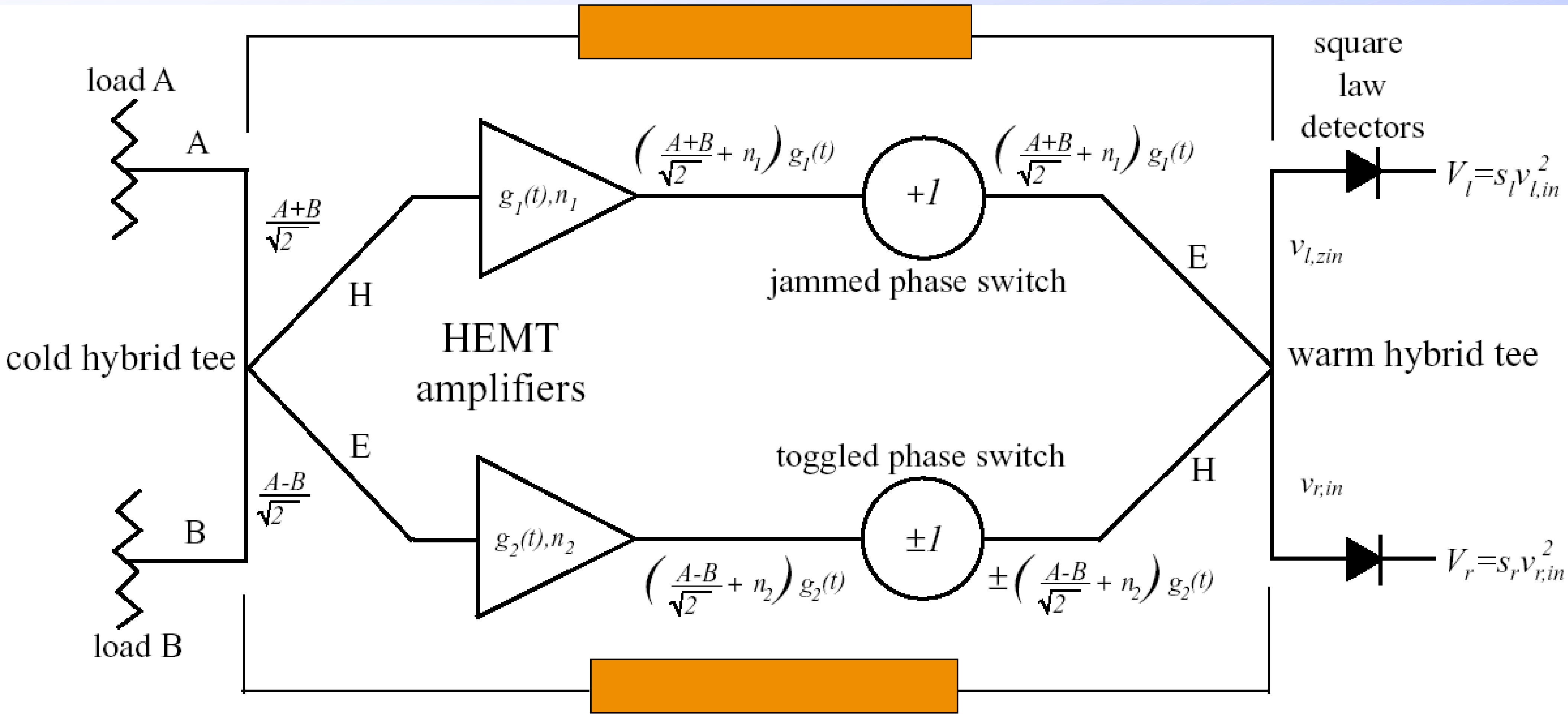
InP High Electron Mobility Transistor



MAP Pseudo Correlation Receiver



Simplified Radiometer Diagram



Electric Field Signal into Power Detector

$$v_{l,in} = \frac{1}{\sqrt{2}}\left(\frac{A+B}{\sqrt{2}} + n_1\right) g_1(t) \pm \frac{1}{\sqrt{2}}\left(\frac{A-B}{\sqrt{2}} + n_2\right) g_2(t)$$

$$v_{r,in} = \frac{1}{\sqrt{2}}\left(\frac{A+B}{\sqrt{2}} + n_1\right) g_1(t) \mp \frac{1}{\sqrt{2}}\left(\frac{A-B}{\sqrt{2}} + n_2\right) g_2(t)$$

$$\overline{A} = \overline{B} = \overline{AB} = \overline{n_i A} = \overline{n_i B} = 0$$

$$\overline{AA} \propto k_B \Delta\nu T_a$$
$$\overline{BB} \propto k_B \Delta\nu T_b$$

Voltage out of Power Detector

$$V_l = s_l v^2_{l,in} = \frac{s}{2}\left\{\left(\frac{A^2+B^2}{2}+n_1^2\right)g_1^2(t)+\left(\frac{A^2+B^2}{2}+n_2^2\right)g_2^2(t)\mp(A^2-B^2)g_1(t)g_2(t)\right\}$$

$$V_r = s_r v^2_{r,in} = \frac{s}{2}\left\{\left(\frac{A^2+B^2}{2}+n_1^2\right)g_1^2(t)+\left(\frac{A^2+B^2}{2}+n_2^2\right)g_2^2(t)\pm(A^2-B^2)g_1(t)g_2(t)\right\}$$

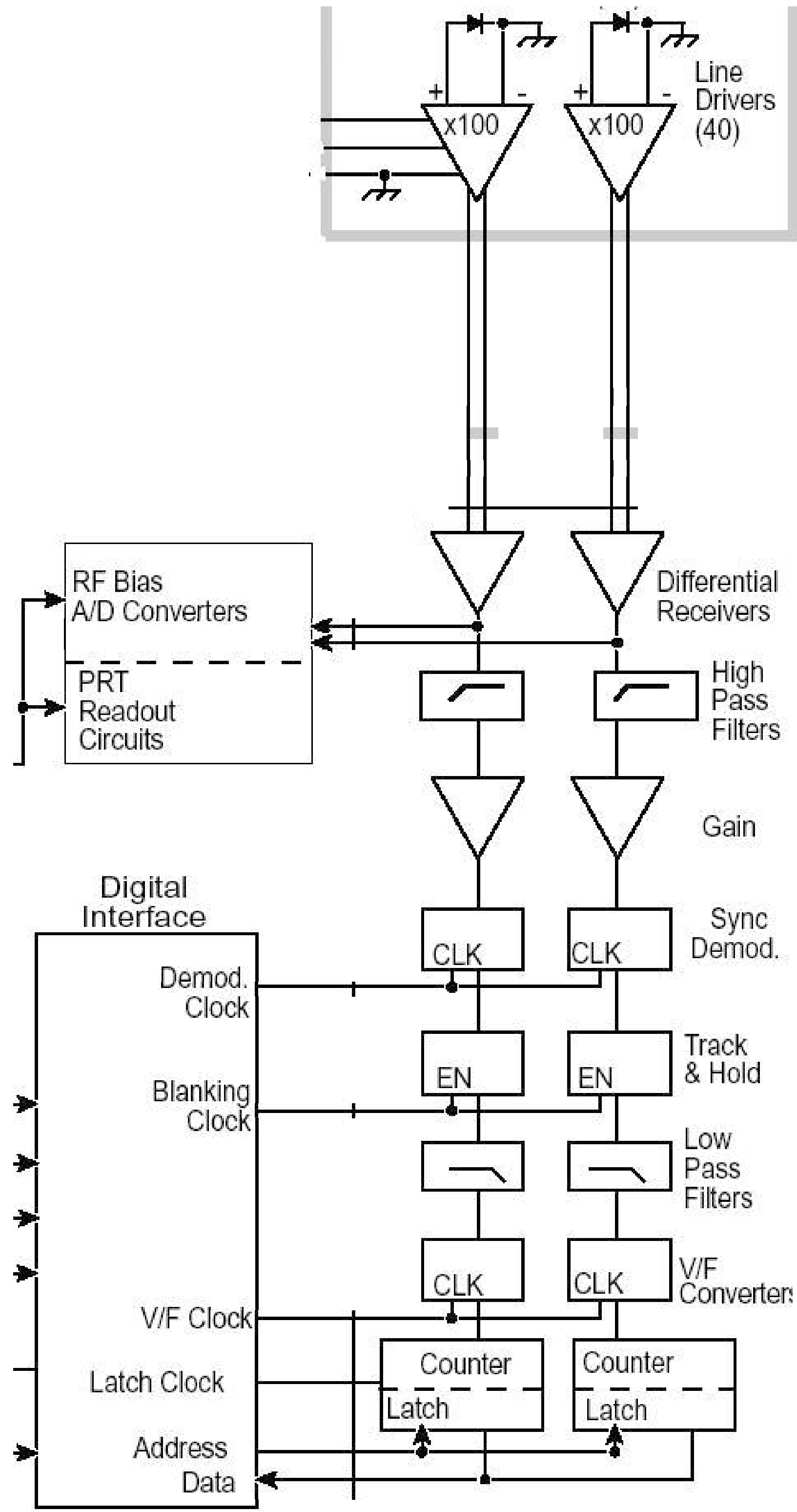
- A^2,B^2□$T_{CMB} < 3$K A^2-B^2 □ ™$T < 30$⌠K+ offset
- n^2 □ $T_{Sys} <$ 30K for K band and ~ 90K for W band

Leading terms are 10^6 larger than last term

Using the radiometer output

- The leading two terms out of the detector are between 10^5 and 10^6 larger than the last term.
- The amplifiers have gain variations, *g(t)*, with 1/f characteristics
- Differencing and locking detection can remove almost all of the first two terms

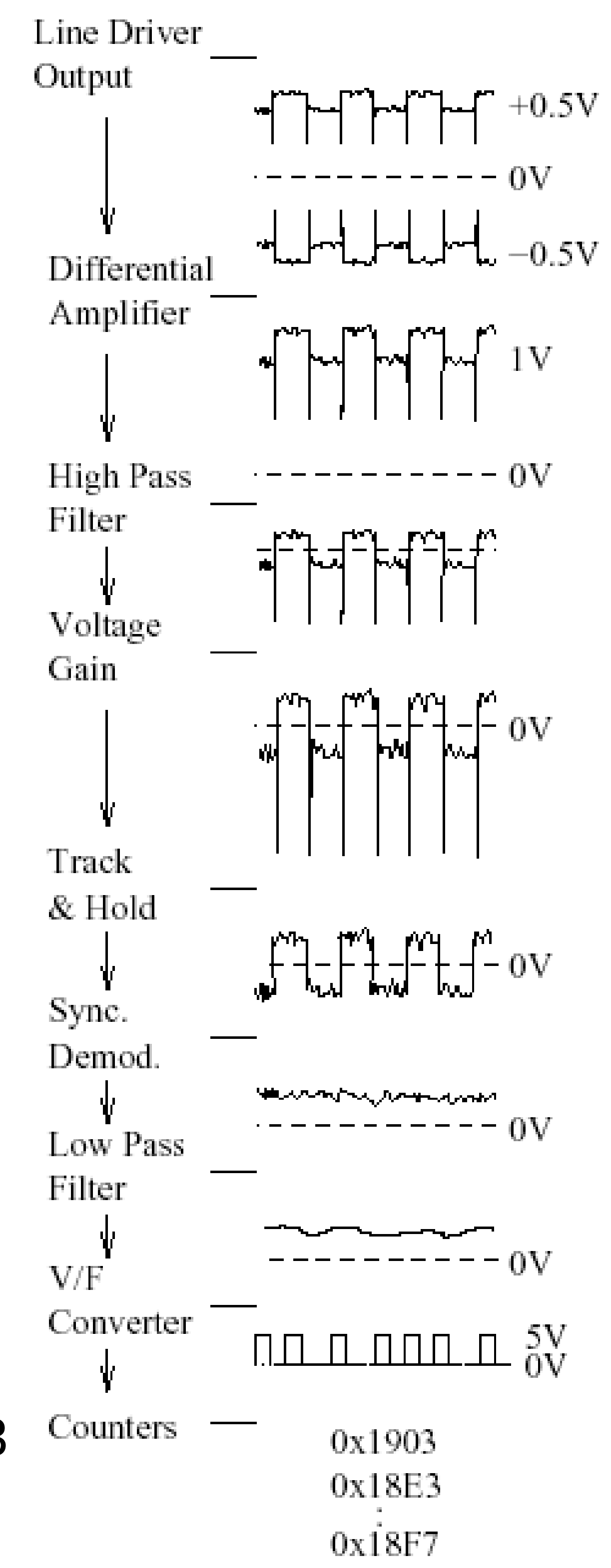
Post-Detection Signal Processing Diagram



Post-Detection Signal Processing

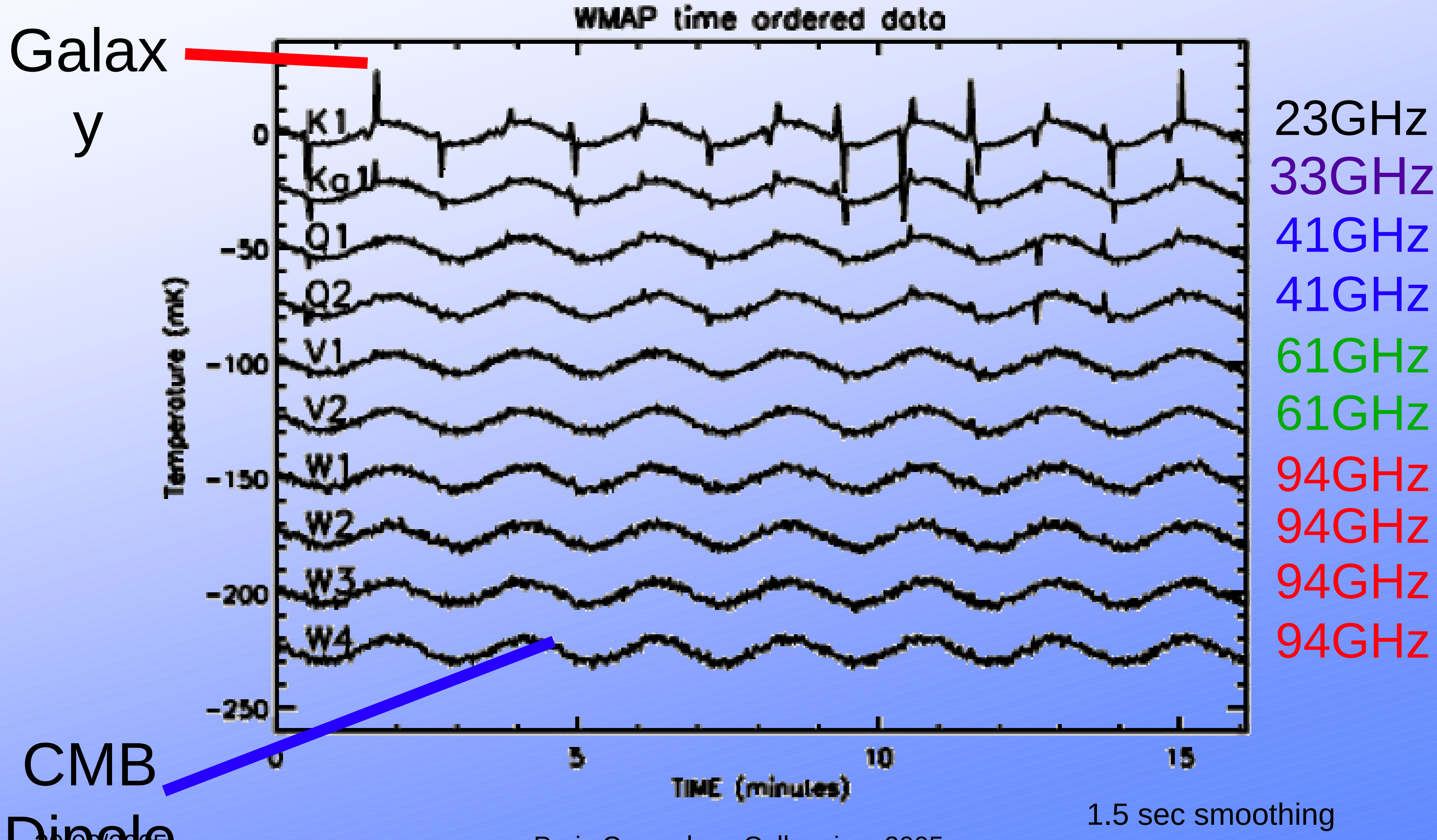
- Out of the detectors comes a signal with spikes on it during the phase switch transitions.
- AC coupling centers this on 0
- Track and Hold knocks out spikes
- Demodulation gives difference between A and B
- Low pass filtering makes it possible for ADC to integrate
- V/F ADC gives true integral of signal over windowing interval.
- Correlations between 25.6 ms samples are 2.6% becauase of low pass filter and -9% from V/F ADC.

Jarosik et al 2003



Timestream Data

Each line is the sum of the two signals from each DA



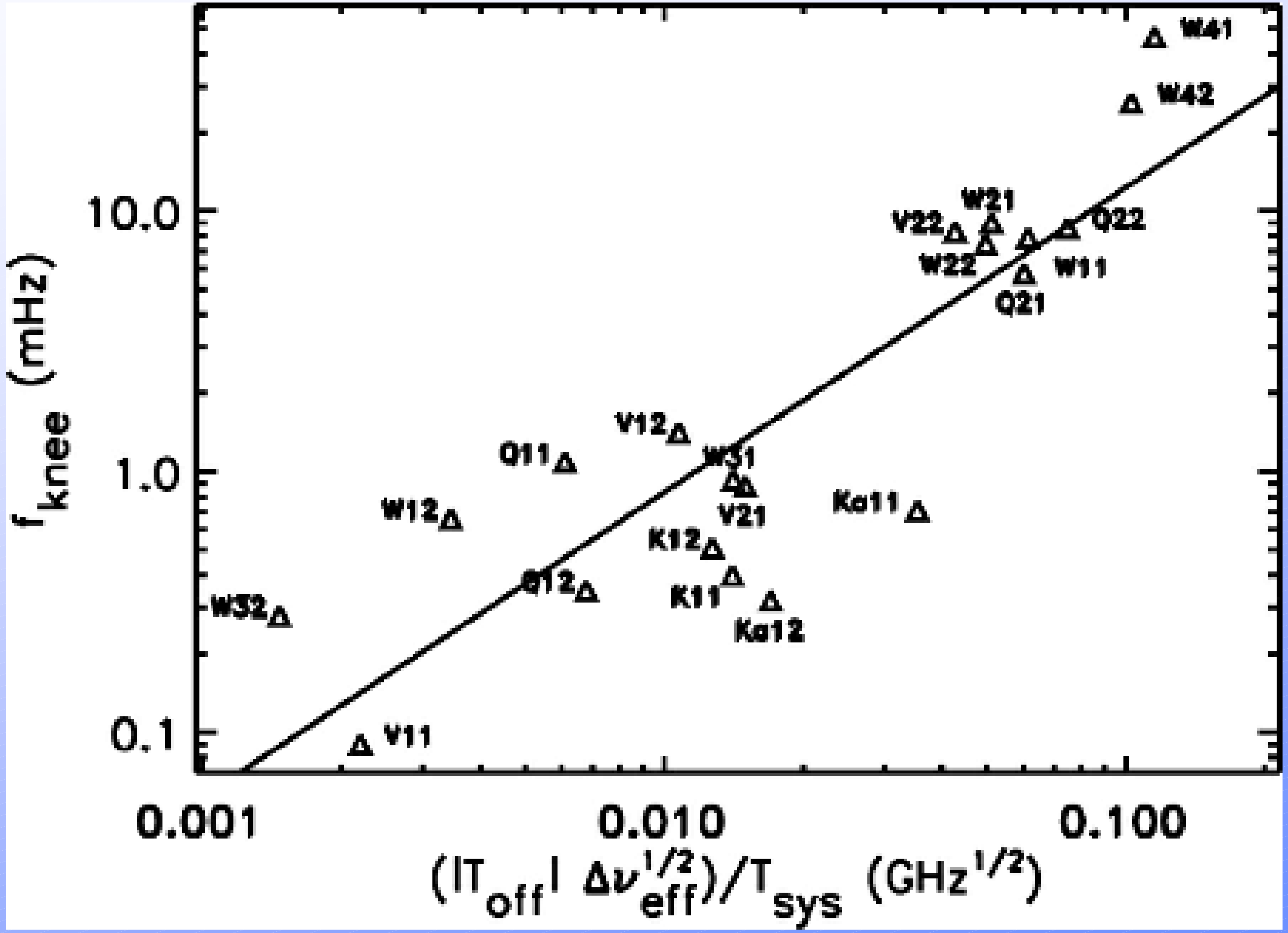
What could go wrong?

- Phase and amplitude mismatch of chains. The signal to noise depends on cos(θ)
- Cross-talk in cold hyrid tee (leads to about 0.2K offset in WMAP radiometers)
- Standing waves cause gain mismatch and gain flatness errors

WMAP Observation Strategy

- Differential radiometer moves 1/f knee to near 1 mHz.
- Primary modulation frequency (spin) higher then radiometer effective 1/f knee.
- Large area of the sky covered with the secondary modulation (precession) in relatively short time.
- Full sky coverage.
- Relatively uniform coverage.

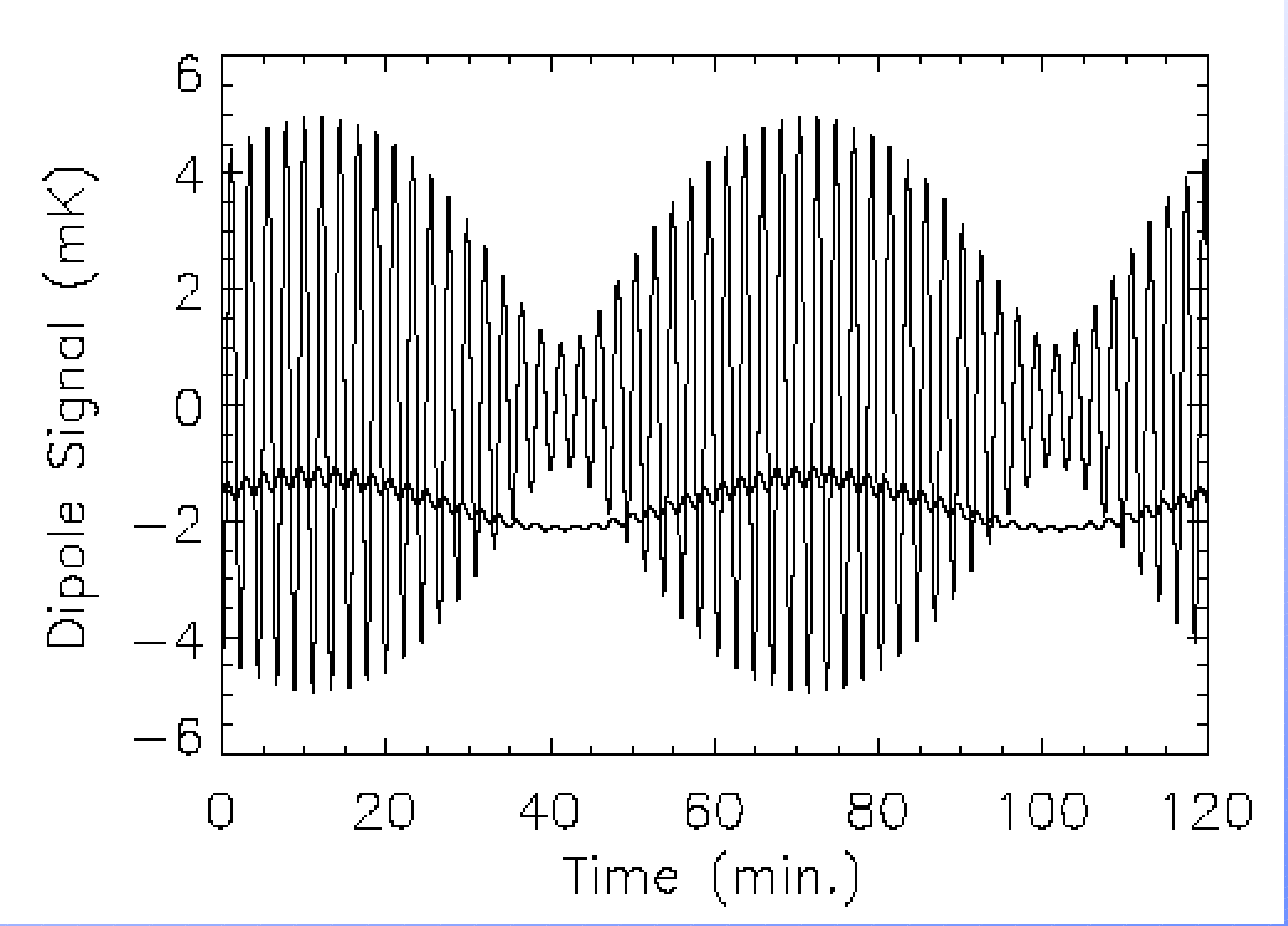
Radiometric offset and 1/f noise



Gain Imbalance

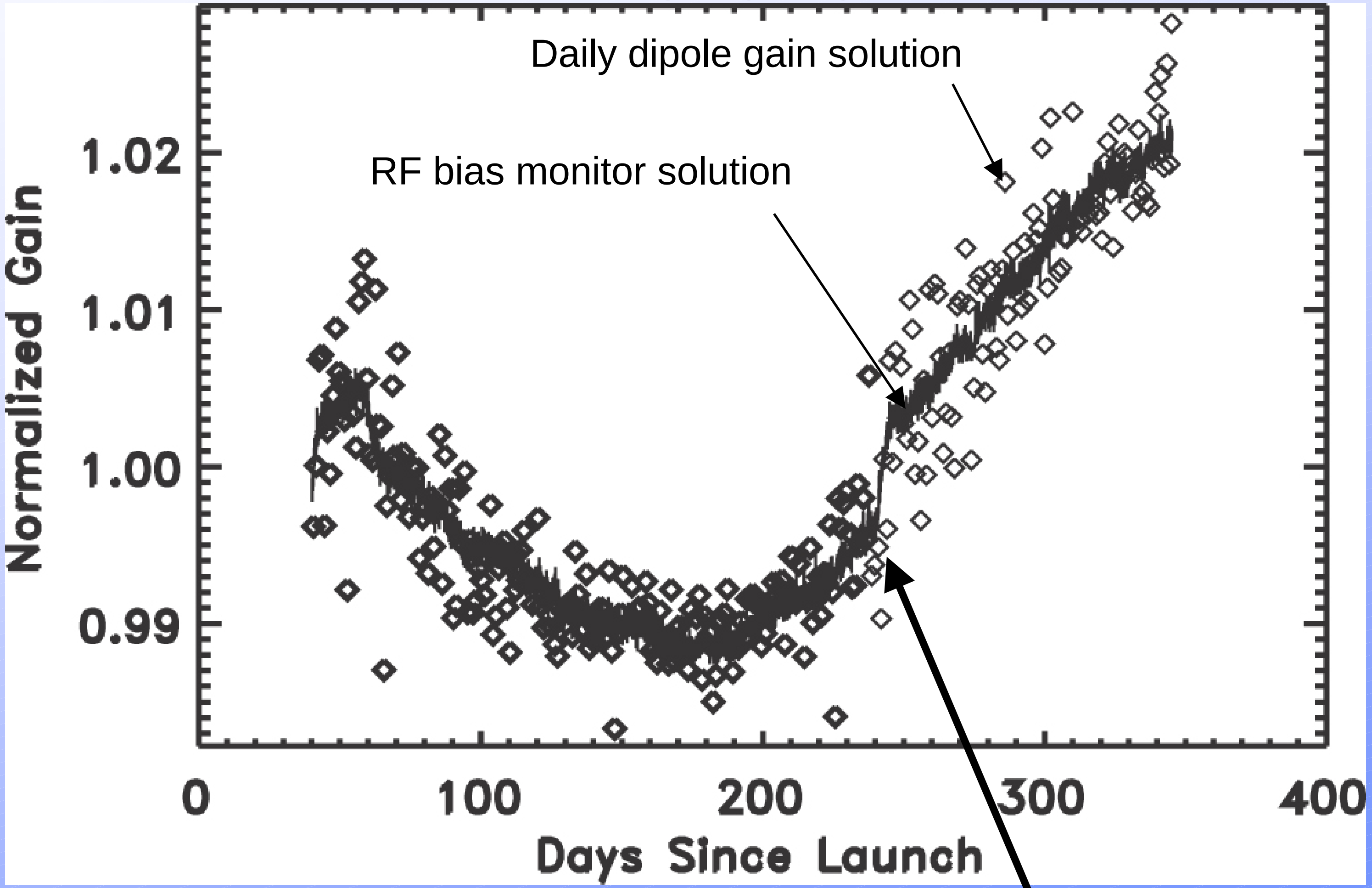
- Gain imbalance before hybrid tee promotes a common mode signal.
- Mostly canceled for T measurement. Not for polarization.
- Can be corrected using the common mode signal from dipole anisotropy.

Predicted Common-mode Response



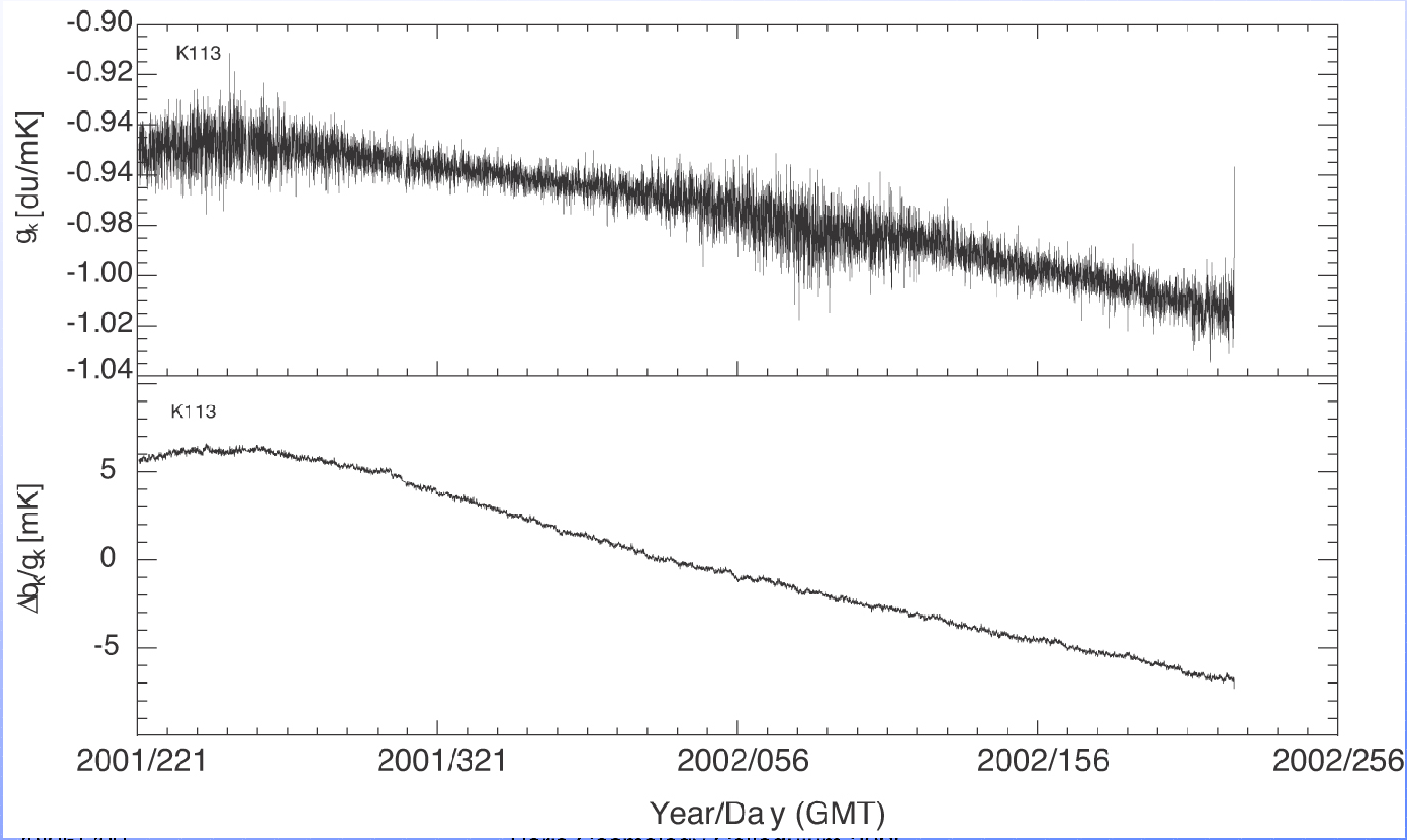
The gain imbalance in the two arms can be determined

Radiometer Gain Model



RXB temp change (0.5K) due
To spacecraft bus voltage shift

Achieved radiometer stability is high
Gain and Offset Over 1 Year Period



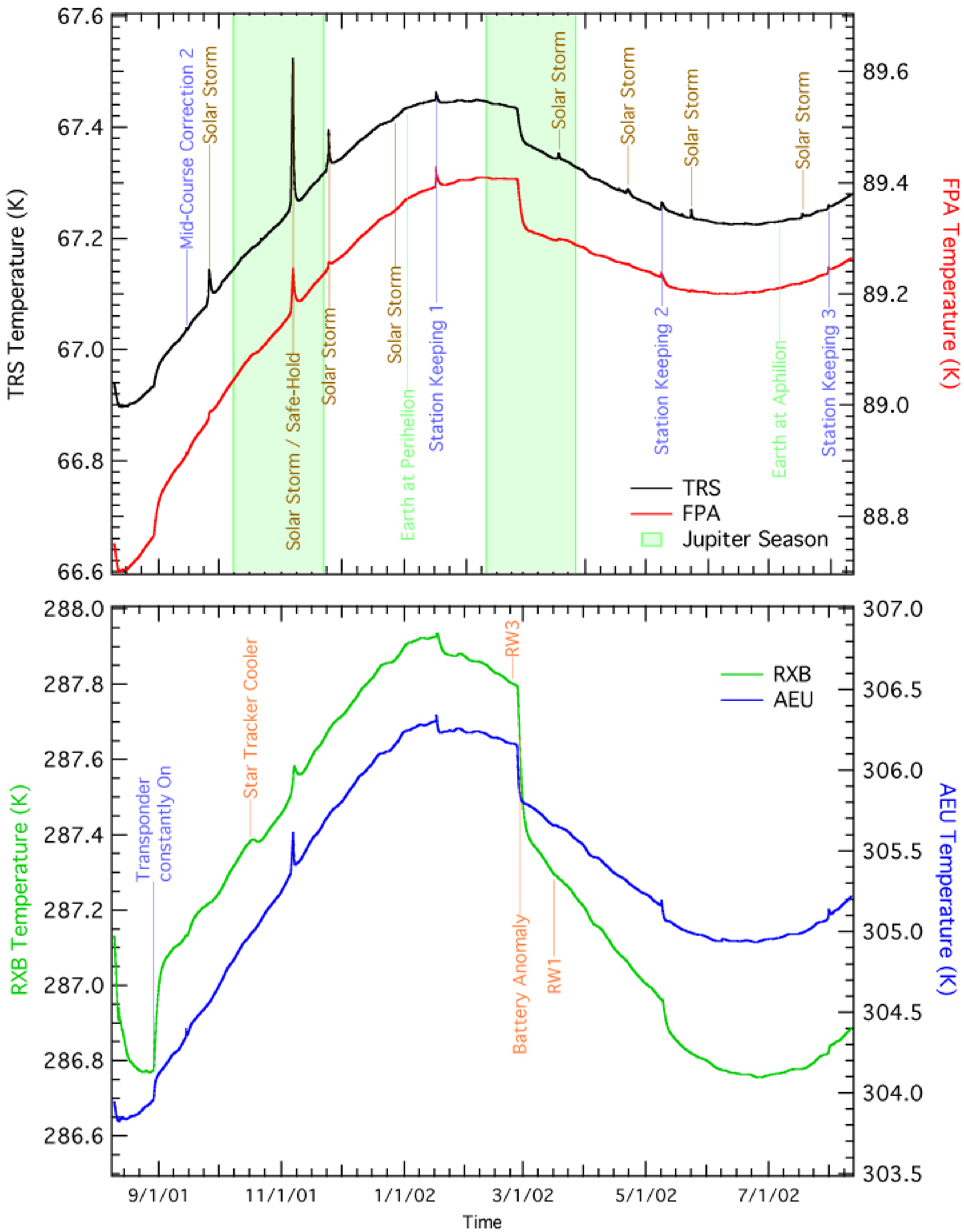
Estimating Sources of Systematic Errors

- Systematic errors are of two sorts:
  - Additive $P_{out} = P_{in} + \langle D(t)$
  - where ⟨=™P/™D is the susceptibility
  - D(t) is the time dependent driving function
  - Multiplicative $P_{out} = g(t)\, P_{in}$
- Driving function time dependence
  - Modulation synchronous
    - Does not integrate down with time
    - Assume different driving functions add with random phase
  - Random (integrates down with time)

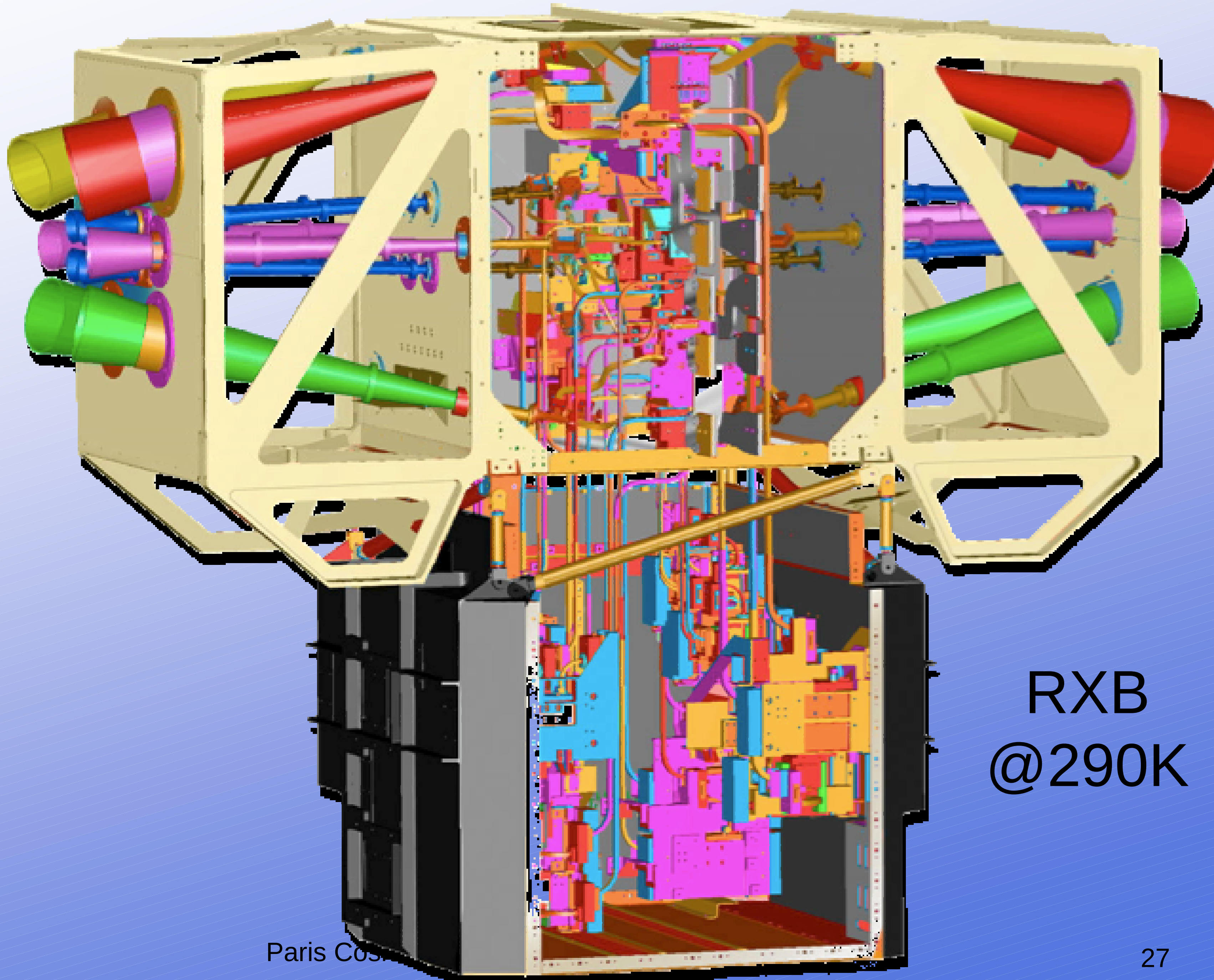
Radiometer Systematic Error Terms

Component	Susceptibility $\times$ Forcing function	Effect
Feed horns	$\epsilon \times \Delta(T_a - T_b)$	A
Orthomode transducer	$\epsilon \times \Delta(T_a - T_b)$	A
OMT - hybrid waveguides	$\epsilon \times \Delta(T_a - T_b)$	A
FPA hybrid tee	$(\epsilon_a - \epsilon_b) \times \Delta T$	A
FPA HEMT amplifiers	$dg/dx \times \{\Delta V_{gc}, \Delta V_{gf}, \Delta V_d, \Delta T, \Delta I_{LED}\}$	M
RXB HEMT amplifiers	$dg/dx \times \{\Delta V_{gf}, \Delta V_d, \Delta T\}$	M
Band definition filters	$dS_{21}/dt \times \Delta T$	A^*,M
Phase switches	$d(S_{21}(0^\circ) - S_{21}(180^\circ)/dx \times \{\Delta T, \Delta I\}$	A^*,M
Detectors	$ds/dT \times \Delta T$	M
Line drivers	$dg/dx \times \{\Delta V_{dd}, \Delta V_{ss}, \Delta T\}$	M
AEU	$\{dA_v/dx, dO_v/dx\} \times \{\Delta T, \Delta V_{bus}\}$	A, M
PDU	$\{dV_{gc}/dx, dV_{gf}/dx, dV_d/dx, dI_{LED}/dx\} \times \{\Delta T, \Delta V_{bus}\}$	

Instrument Temperatures During First Year Observations



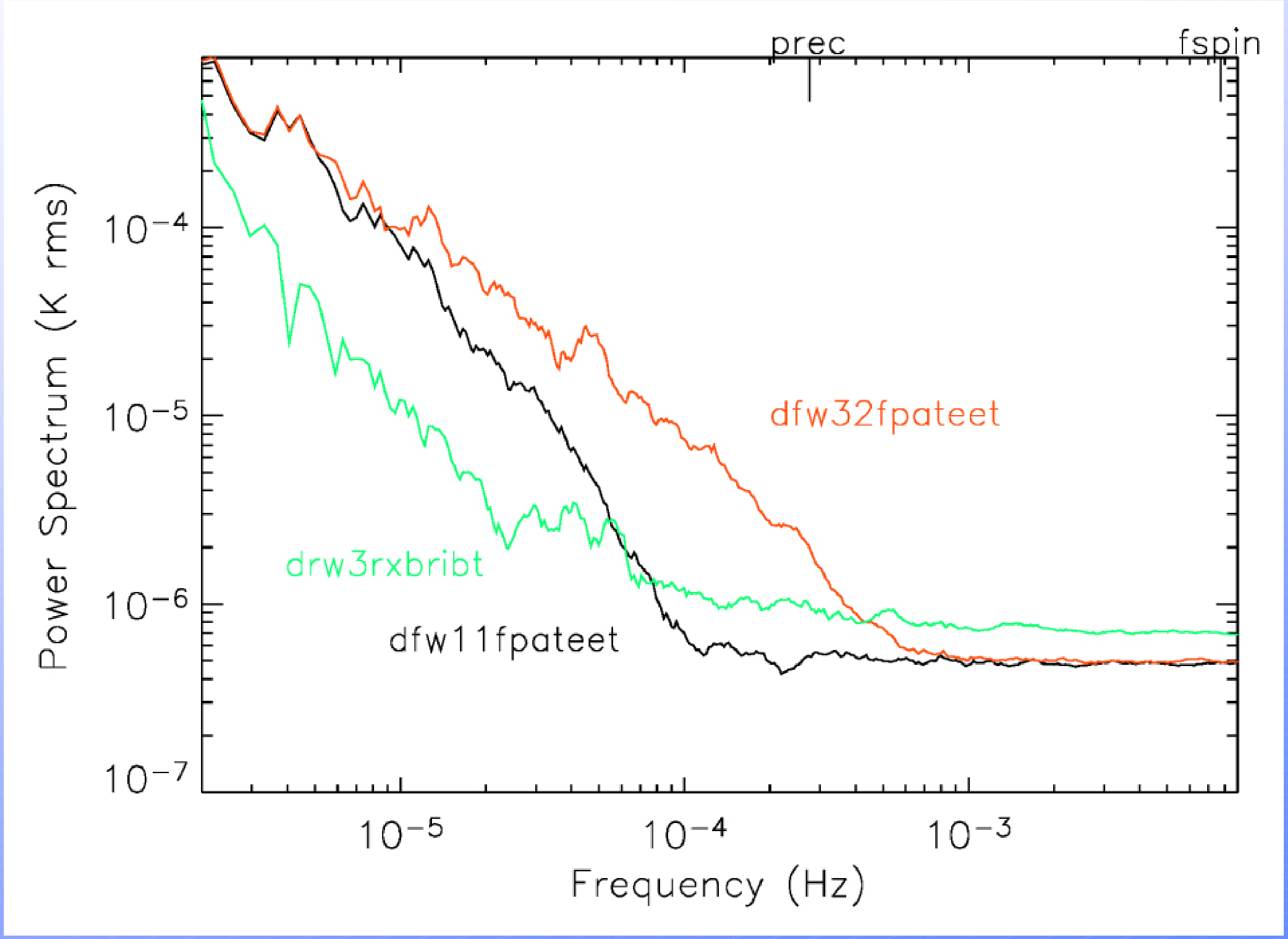
The warm part of the instrument is thermally suspended with time constant of a week.



FPA
@90K

RXB
@290K

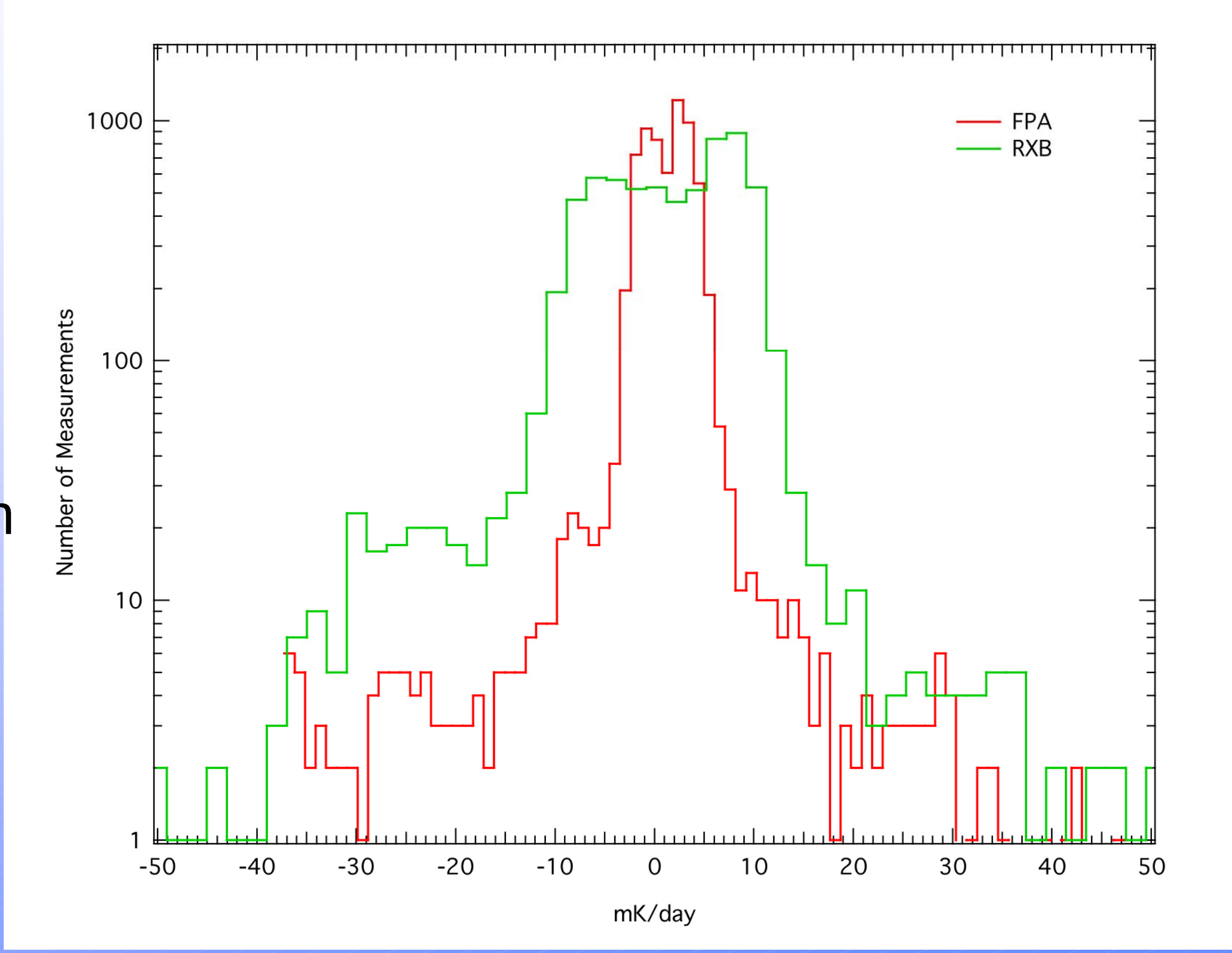
Temperature Powerspectrum



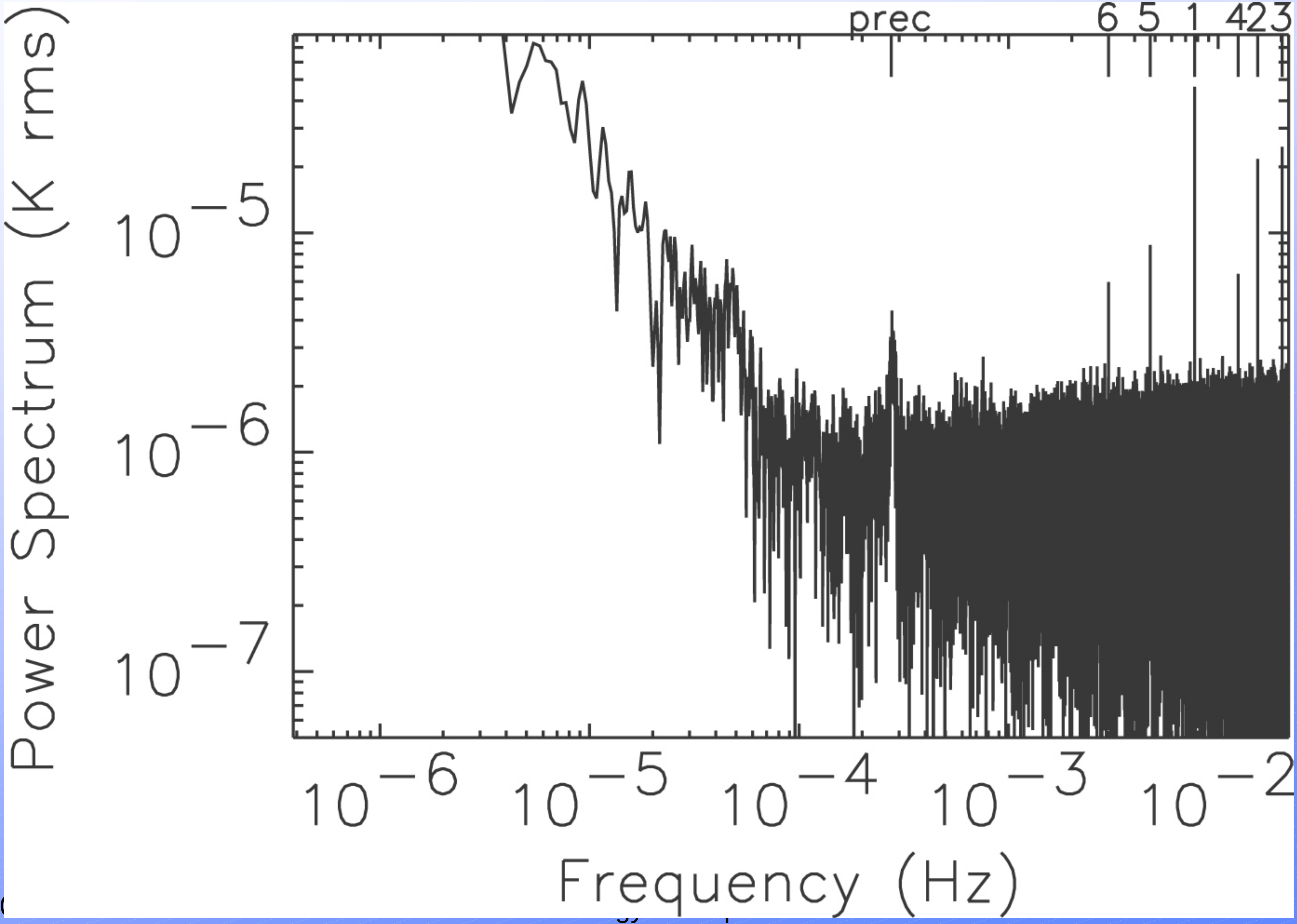
Temperature Drift Rates

Temperature differences are proportional to the drift rates.

Temporial variation in temperature differences drive systematics



Top of Reflector Power Spectrum



Characterization of optical instrument elements that can effect systematics

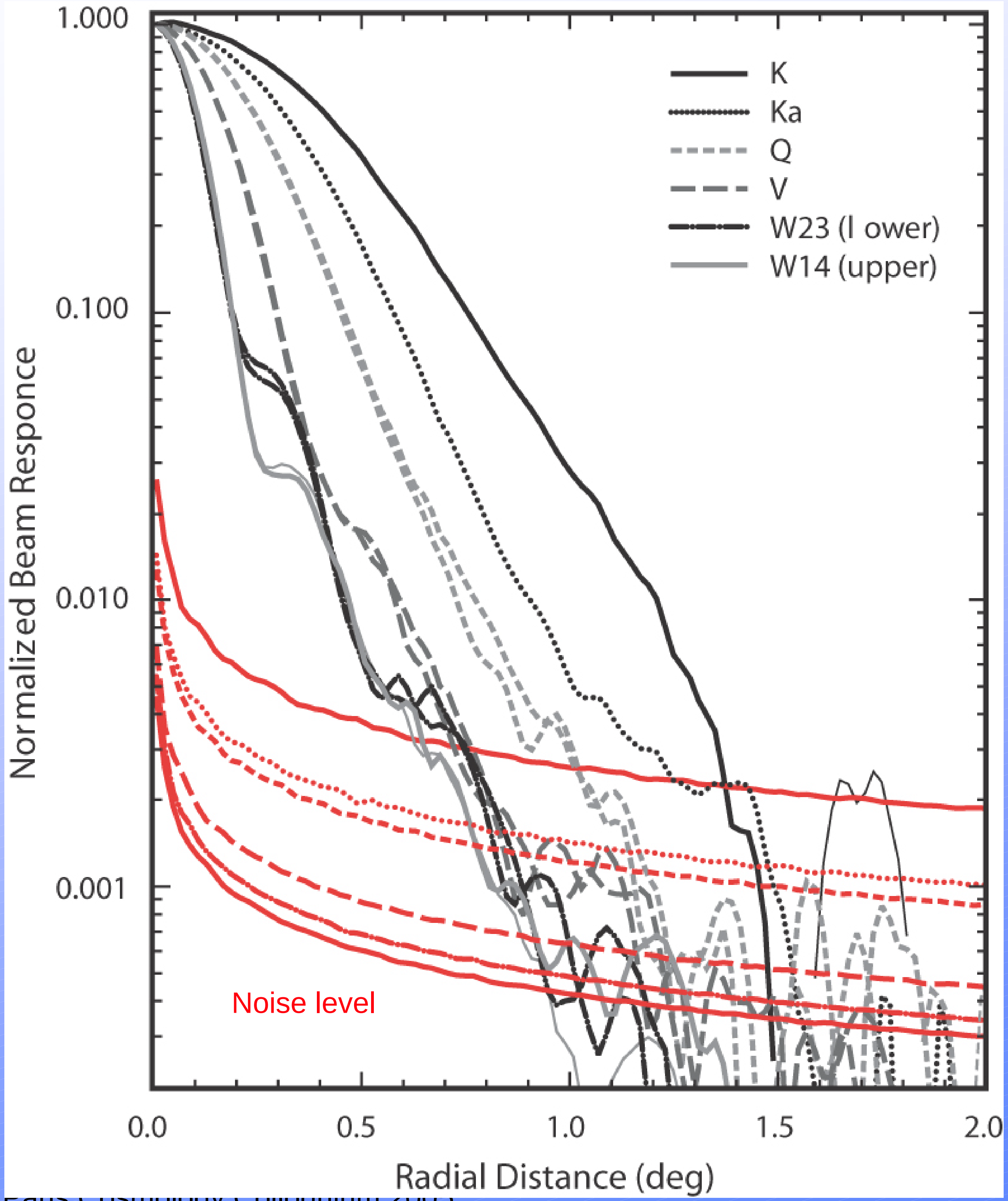
Window Function Determination

- Two methods to measure beam shape

1. Pixelize (2.4’) a Jupiter map.
2. Fit time ordered data (TOD) to Hermite functions centered on position of Jupiter.

- Both methods iteratively determine a centroid.
- The two methods agree within measurement uncertainty.

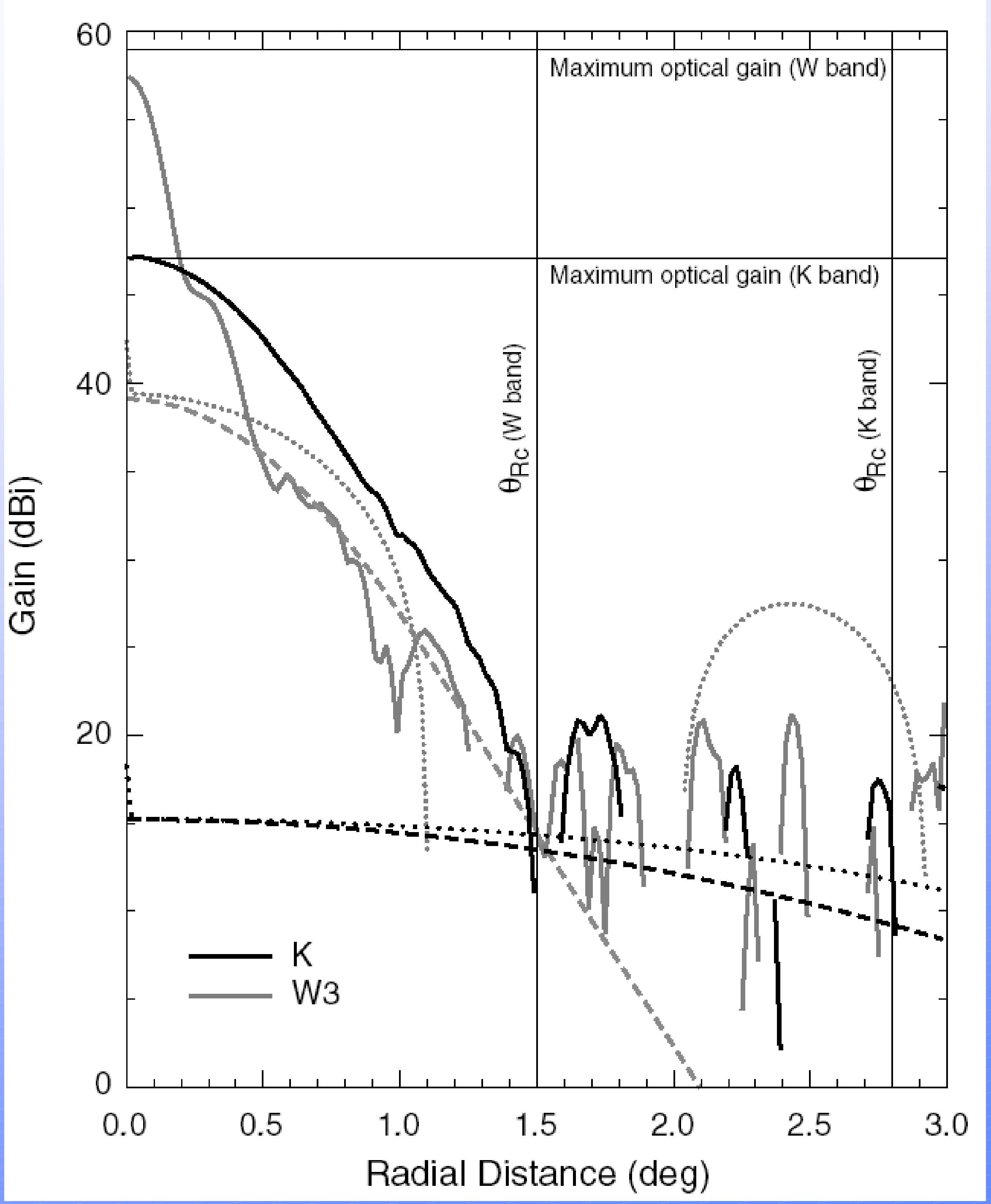
Normalized Symmetrized Beams



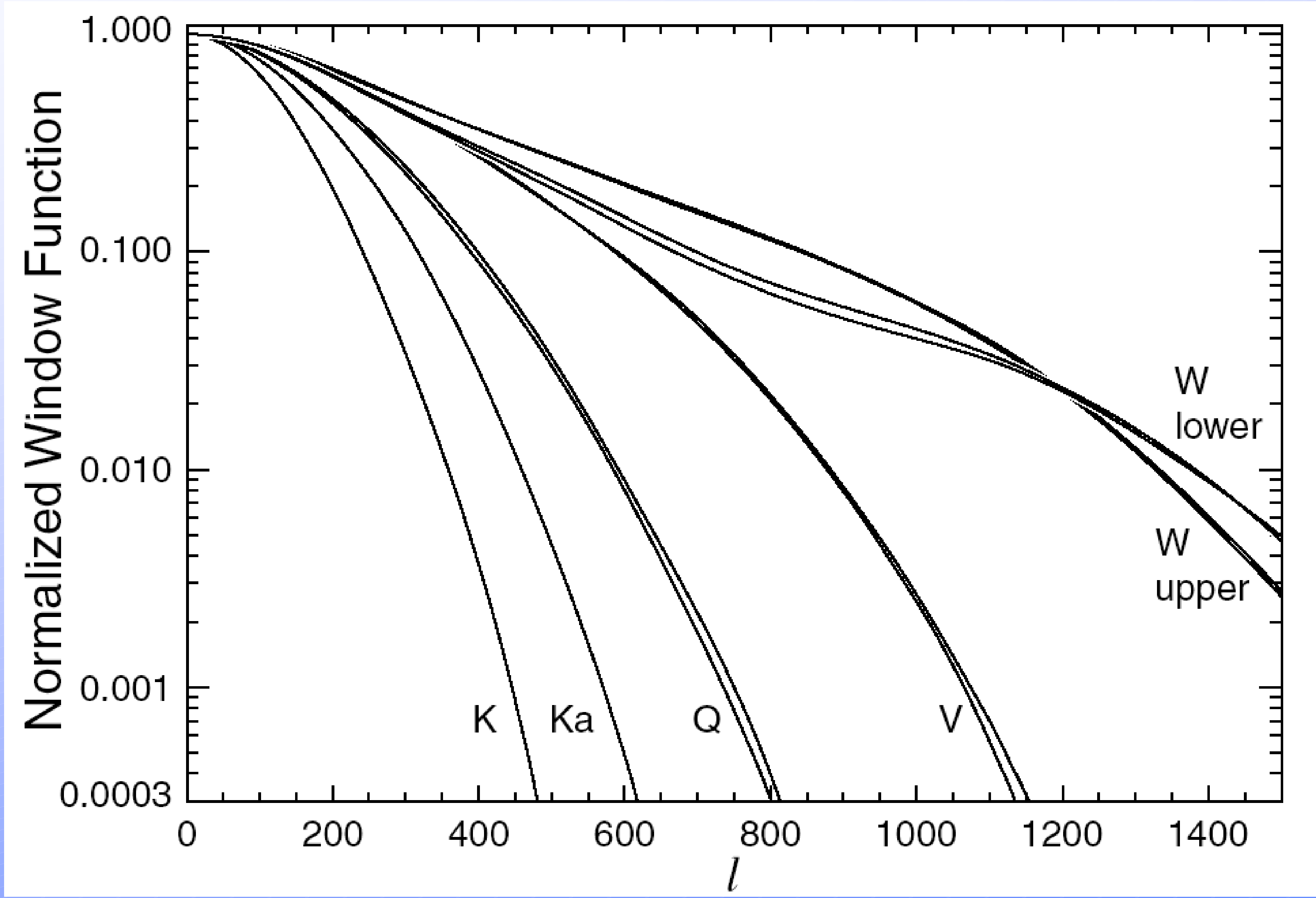
Relative Gain

- Calibration of WMAP is done using the change in the dipole due to the change of velocity of the satellite over the year. ($l=1$)
- Want to know absolute C_l over all l so we must be able to relate point source response to full beam response.
- Net uncertainty in total beam solid angle is about 2%.
- Beam uncertainties are propagated through all analysis.

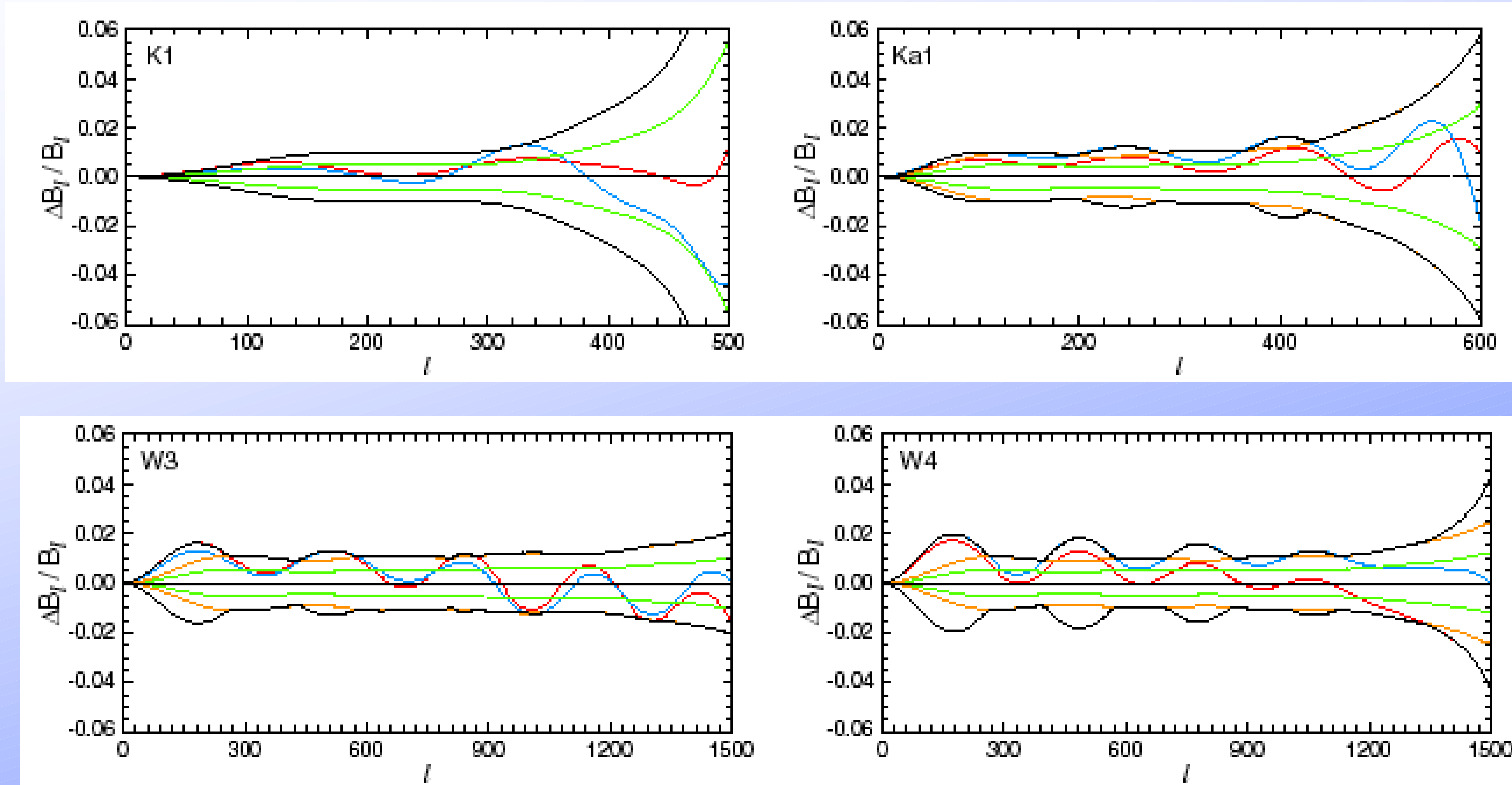
Contributions to Beam



Adopted Window Functions



Final Estimated Beam Uncertainty



Hermite statistical

2xHermite statistical

Fractional diff between Jup maps and Hermite

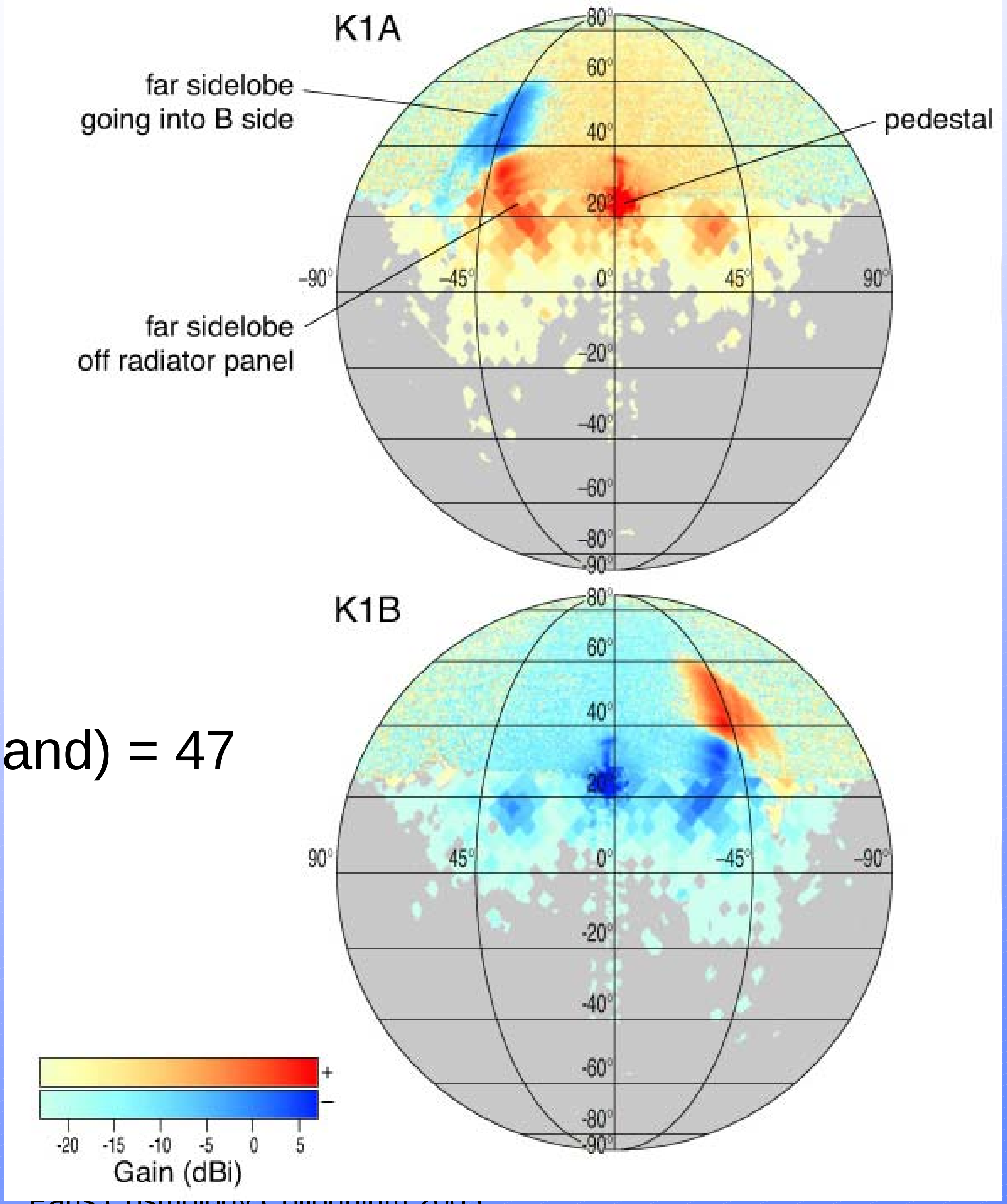
Adopted 1 ∫ beam transfer function uncertanty

Far-Sidelobe Determination

- Four sources of information used for sidelobe determination

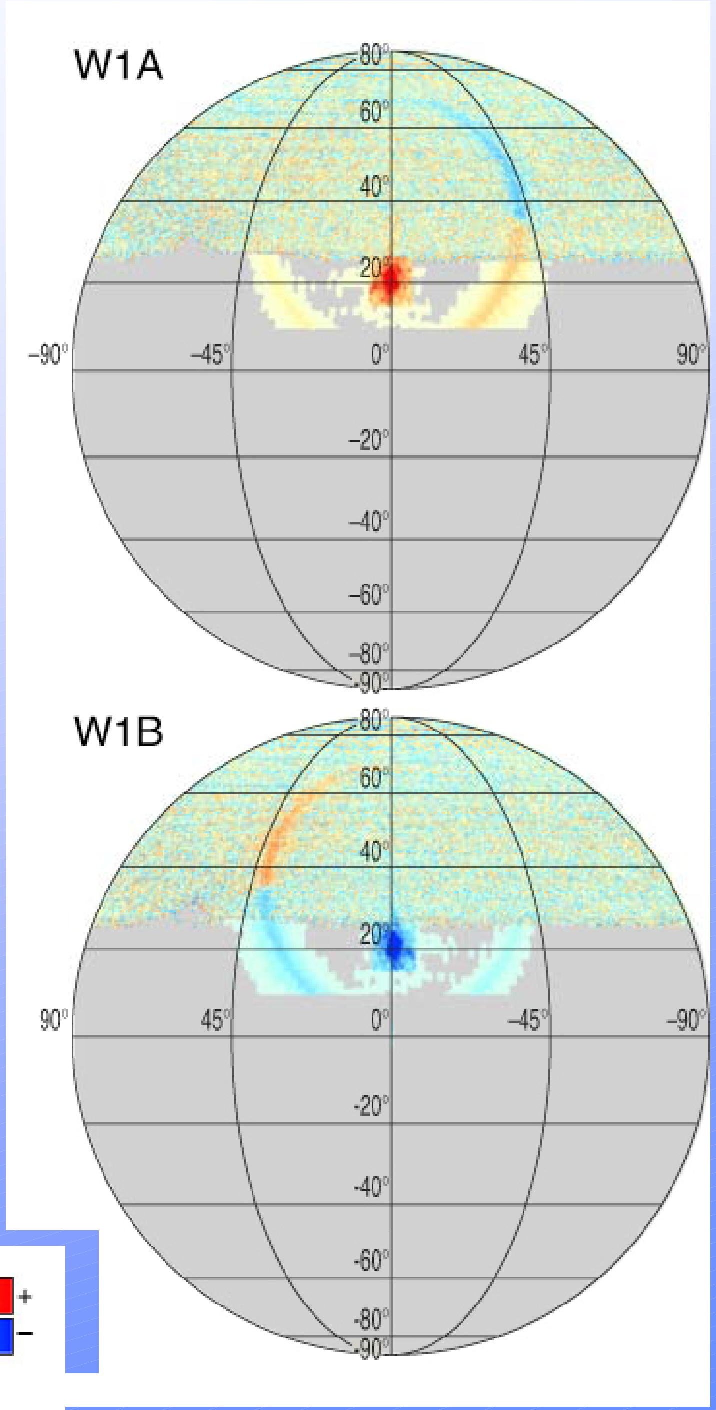
1. Anechoic chamber with 3m source telescope and reflections at -70dB. Model of 1/2 of reflector system is measured without full ground screens.
2. Outdoor range with full reflector system. Limited by noise floor at -100dB.
3. Moon during phasing loops. Moon about 2^{o} across but not full coverage.
4. Physical optics model.

K1 Sidelobe Pattern

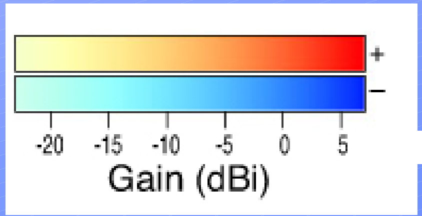


Peak Gain (K band) = 47 dBi

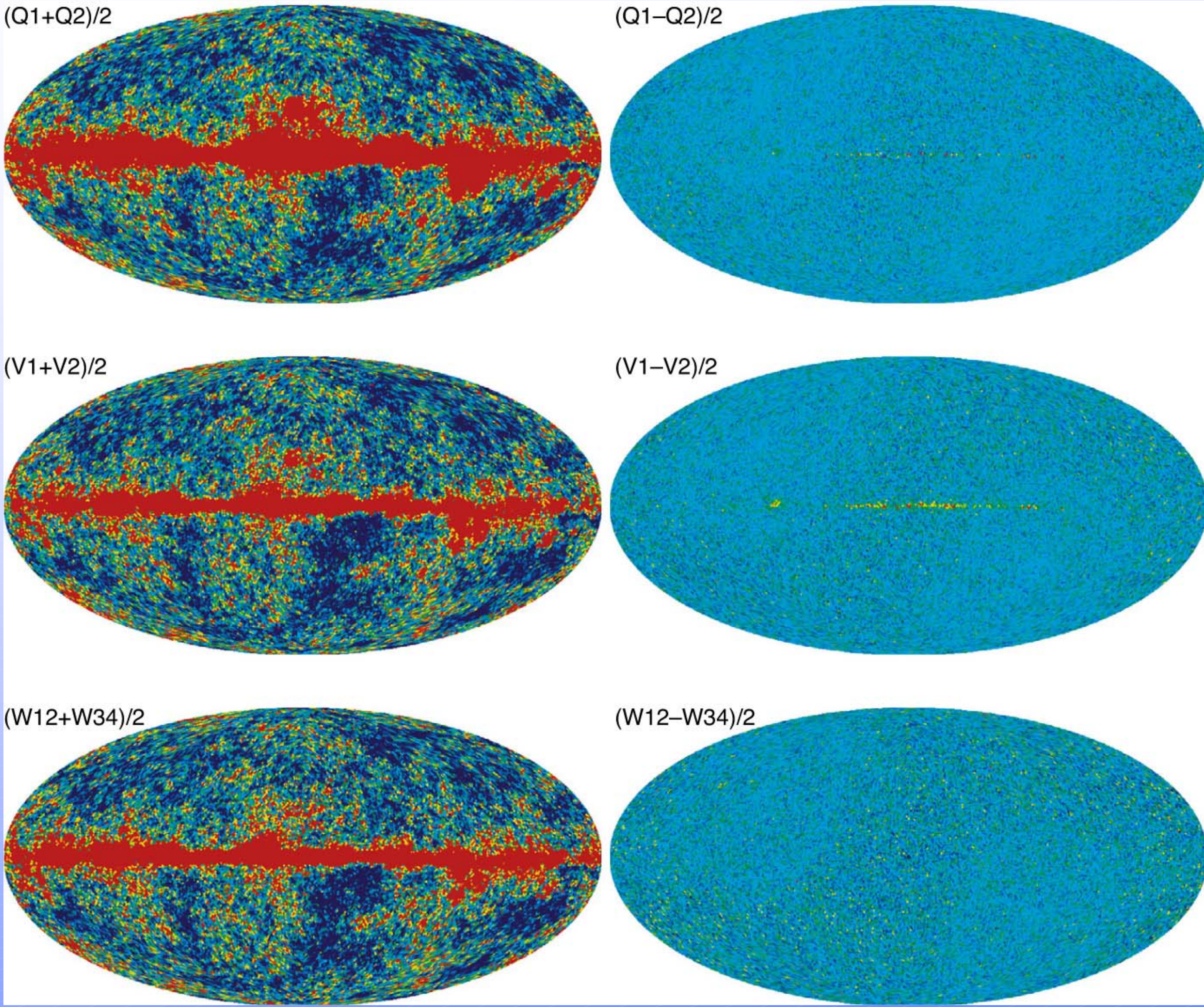
W1 Sidelobe Pattern



Peak Gain (W band) = 59 dBi



Sum and Difference Maps



Polarization Measurements

- Polarization measurements depend on difference between two radiometers
  - Gain imbalances, pass-band imbalance, beam sidelobe differences all effect the results.