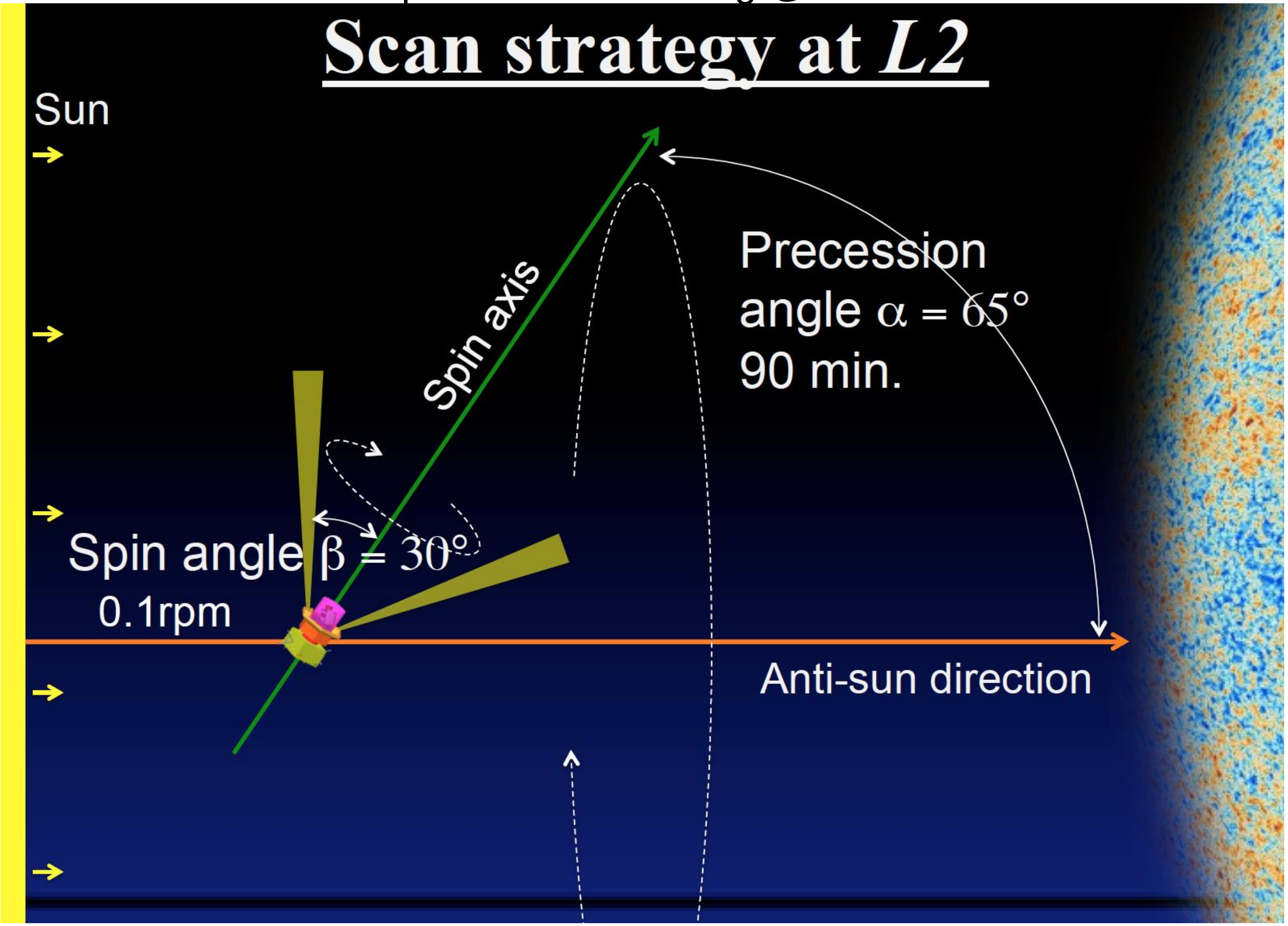
Optimization of the LiteBIRD Scan Strategy

S. Uozumi (Okayama Univ.) for the LiteBIRD Phase-A1 working group
2017 Apr-20th JPS meeting @ Osaka Univ.



- Those nominal scanning values had been first defined on 2015-Feb MDR (Mission Definition Review.)
- However we come back to decide scan parameters because international review(2016) pointed more consideration on revisit time.

Scan Strategy (from a view of scientific output)

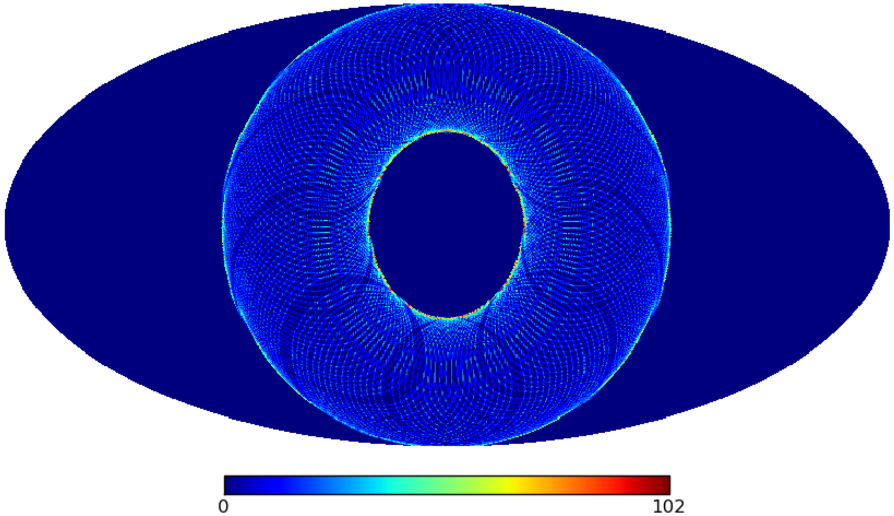
- **The strategy should be determined from the science points of view.**
- **We are working on an option w/o HWP: we think the w/o HWP option can also cover a part of the w/ HWP option (if it fails) in systematic uncertainties.**
- Elements to decide the strategy used in the current study :
  - Hit uniformity
  - Cross link values.
  - Revisit time and Jack-knife test (null-test) availability
  - Spin / precession rate determination based on
  - 1/f noise mitigation (w/o HWP)
    - Test with realistic simulation

Main topic of this report

- **Two candidates determined (will be explained in later slides) :**
  - Large-α option : α=65^{o}, β=30^{o}
  - Small-α option : α=45^{o}, β=50^{o}

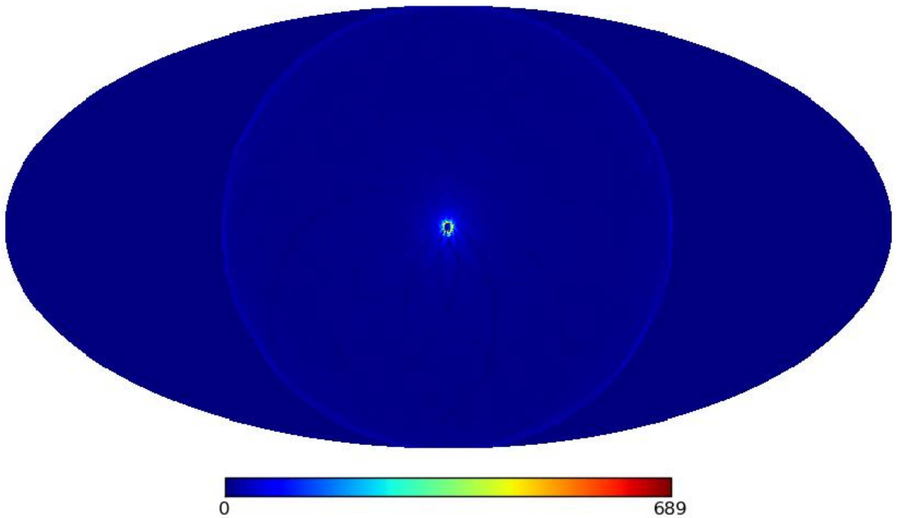
two candidates of scanning angle configuration (reported at previous JPS meeting)

Large-α ($\alpha>\beta$) option :



$\alpha=65^o$, $\beta=30^o$, $\alpha+\beta=95^o$,
precession time=1.51 hrs,
spin revolution rate=0.1 rpm

Small-α ($\alpha<\beta$) option :



$\alpha=45^o$, $\beta=50^o$, $\alpha+\beta=95^o$,
precession time=1.51 hrs,
spin revolution rate=0.1 rpm
Smaller hole ($\alpha\sim\beta$)

Note : we have limitations :
- On precession time from ADR recycling … 30 hours
- On spin rate from mechanical limit … ~ 0.3 rpm

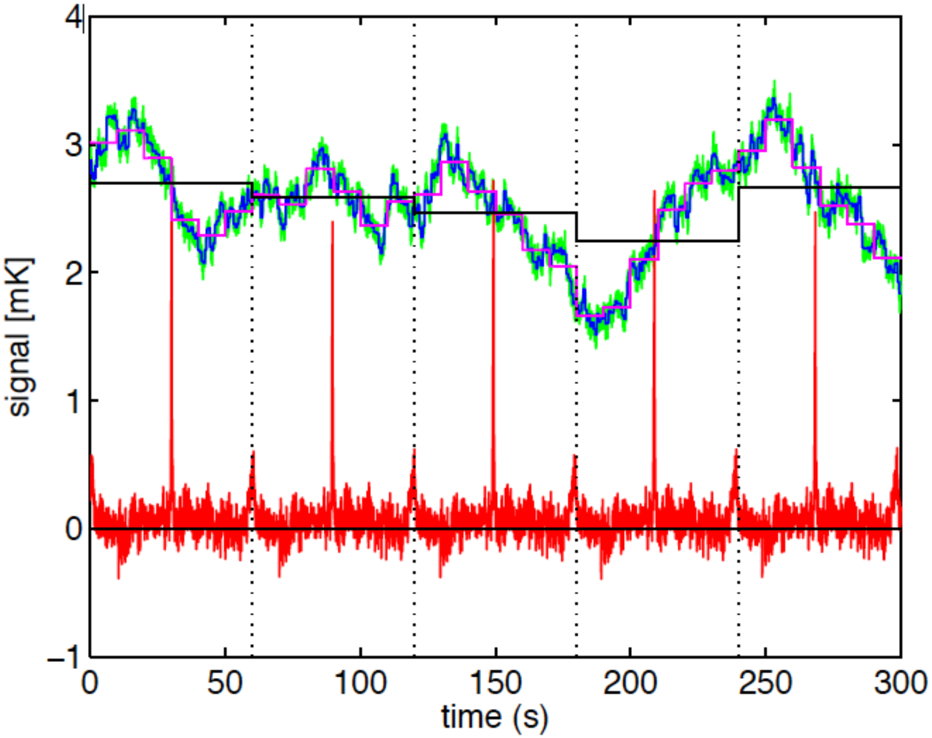
A list of items related with the scan strategy

Items	Alpha=65/Beta=30	Alpha=45/Beta=50	Comments
Cross links	○	○	Large-α is slightly better than smaller-α
Hit uniformity	Larger hole, smaller RMS	Smaller hole, Larger RMS	
Revisit time uniformity	△ (larger gaps in Δt dist.)	○	Hole size also affects to revisit time
1/f noise mit. w/o HWP	△	△	No specific difference, but depends on spin rate
Thermal (External Interfaces)	**Earth+moon to 4K**: 0mW **Sun to outer shell**:794W **Shadow**: TBC	**Earth+moon to 4K**: 0mW **Sun to outer shell**: 911W **Shadow**: TBC	Light from earth/moon, Heat radiation plates, Shadow around the aperture <u>Values for α=65 are in the case of on Lissajous orbit , no orbit dependencies when α=45</u>
Thermal (Internal Interfaces)			Optical system support structure, Thermal Interfaces among the cold mission components, Thermal distribution
Optics	**Baffle requirements**: h>300mm	**Baffle requirements**: h>300mm	Side-lobe, Support Structure, Stray light <u>Values for α=65 are in the case of on Lissajous orbit , no orbit dependencies when α=45</u>
Solar panel	Requirement: > 3894 W	Requirement: > 4990 W	Sizing
Telemetry			Antennas for X/S bands
Thruster/propellant	**Propellant**: 542.0kg (Lissajous)	**Propellant**: 255.9kg (Halo)	Position of Thruster, amount of propellant
Reaction Wheel			Specification
HWP			Position/Angle
Refrigerators	2ST×3 + JT×2	2ST×3 + JT×2	Positions, Interfaces, Thermal conduction, Vibration
Focal plane detector			Thermal interfaces, Length of harness
Cost			
mass	**4K shell + absorbers + mag shield**: 83.3kg	**4K shell + absorbers + mag shield**: 89.4kg	<u>Values for α=65 are in the case of on Lissajous orbit , no orbit dependencies when α=45</u>

Destriper+mapmaker – MADAM

https://arxiv.org/pdf/0907.0367v2.pdf
https://arxiv.org/abs/astro-ph/0412517

- Separate noise into high frequecy white noise + lower frequency 1/f noise.
- 1/f noise is modeled by step function (Legendre function also available)
- “baseline length” of the step function of sky pixel resolution are the key tuning parameters according to first paper.



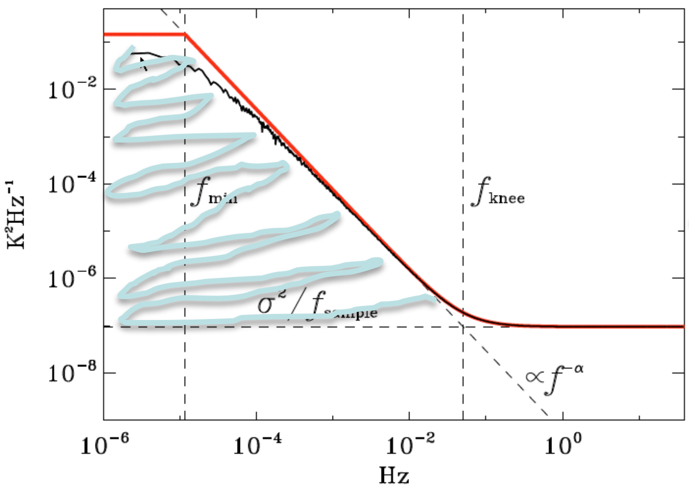
- Sort of CMB signal, white noise, 1/f noise are disentangled by a sort of math (first paper eq. 4-8)
- Revisiting gives constraints to shape of the 1/f noise

Scheme

Fourier-translation
to frequency domain

Toast : white + 1/f noise generation
With configurad scan strategy, noise par, etc.

Time-Ordered-Data



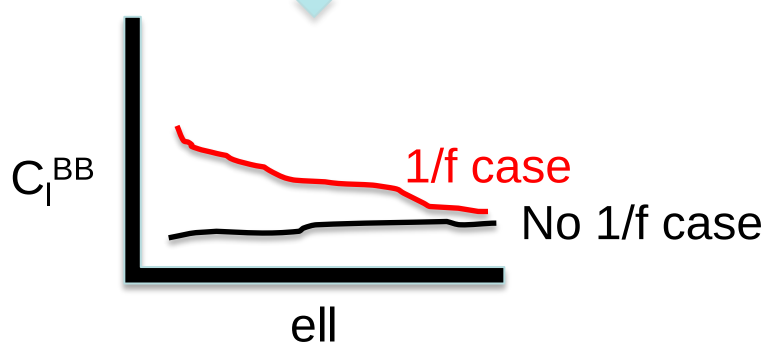
MADAM : destriper + map-maker

Time-Ordered-Data

Sky-map

Map-to-power spectra converter
(hand-made)

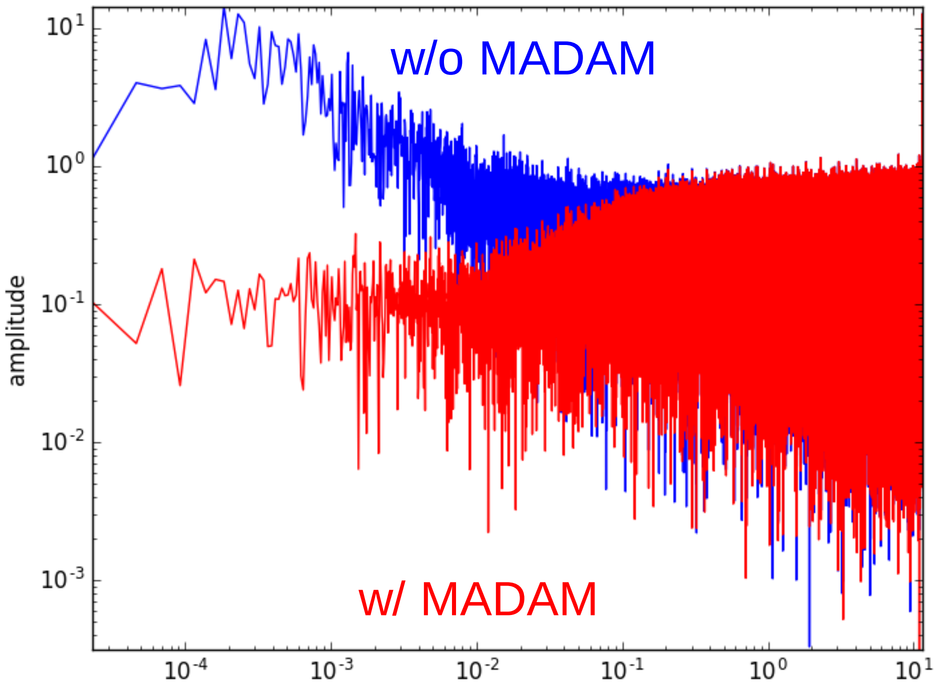
- Happy if 1/f part is eliminated



- Evaluate how 1/f noise afffects
  To power spectra
- Happy if 1/f+MADAM matches
  with no 1/f case

Frequency-domain evaluation (1-day data)

Large-alpha case



Nominal parameters:

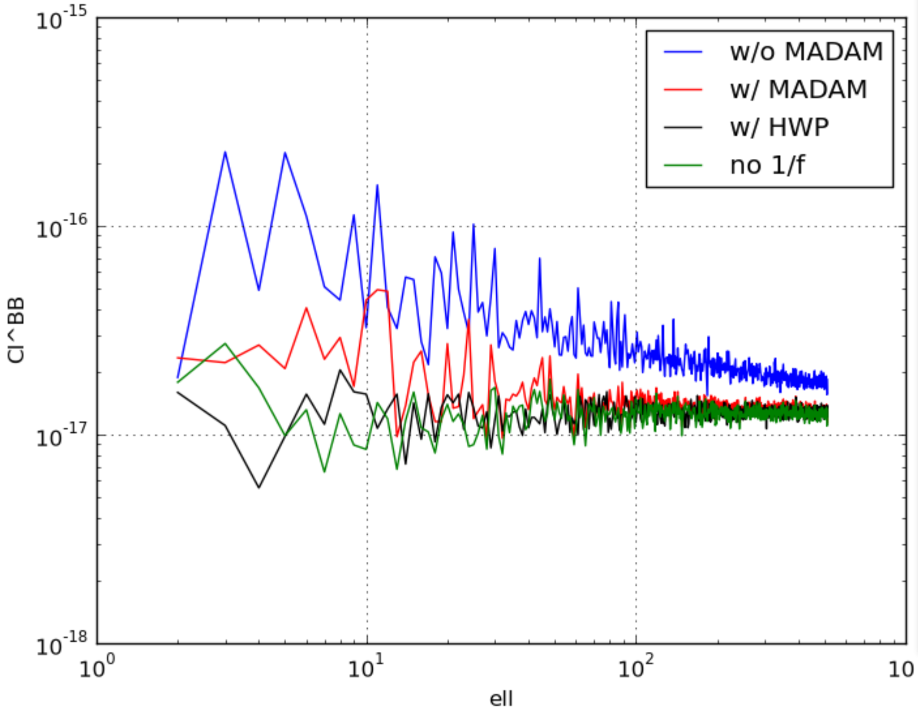
White + 1/f noise only
Large-alpha case
fknee = 0.05 Hz
alpha = 1.5
fmin = 1day^{-1}
Baseline = 1 sec.
Nside=1024
Spin = 0.1 rpm

… with large/small-alpha case
(prec. angle α=65^o, 45^o)

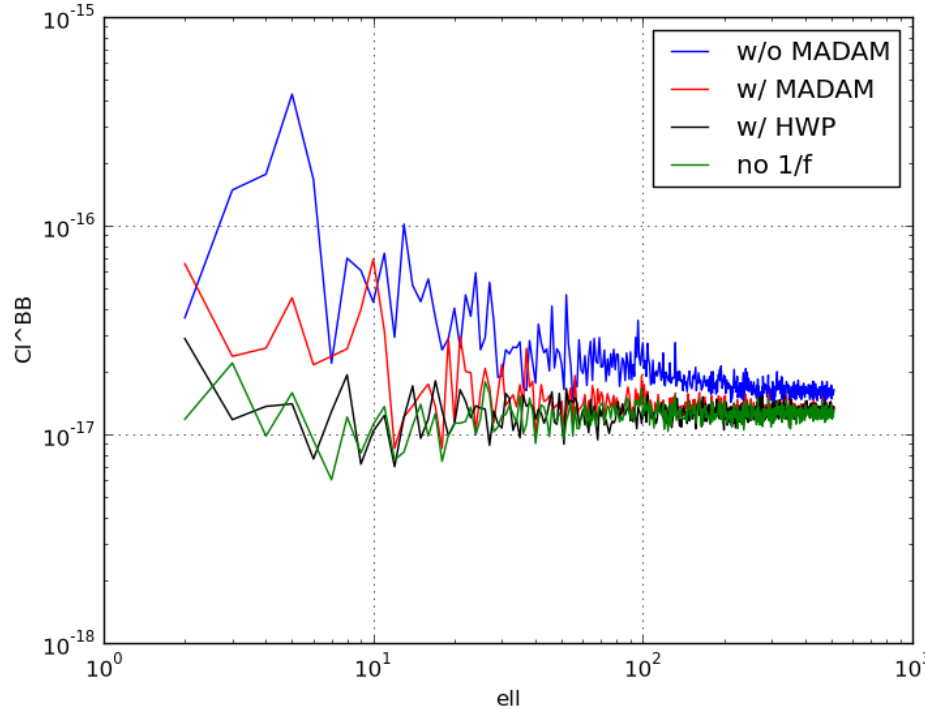
By MADAM destriping, 1/f part is totally gone in this view!!

Power-spectra evaluation (1yr-data)

Large-alpha option



small-alpha option

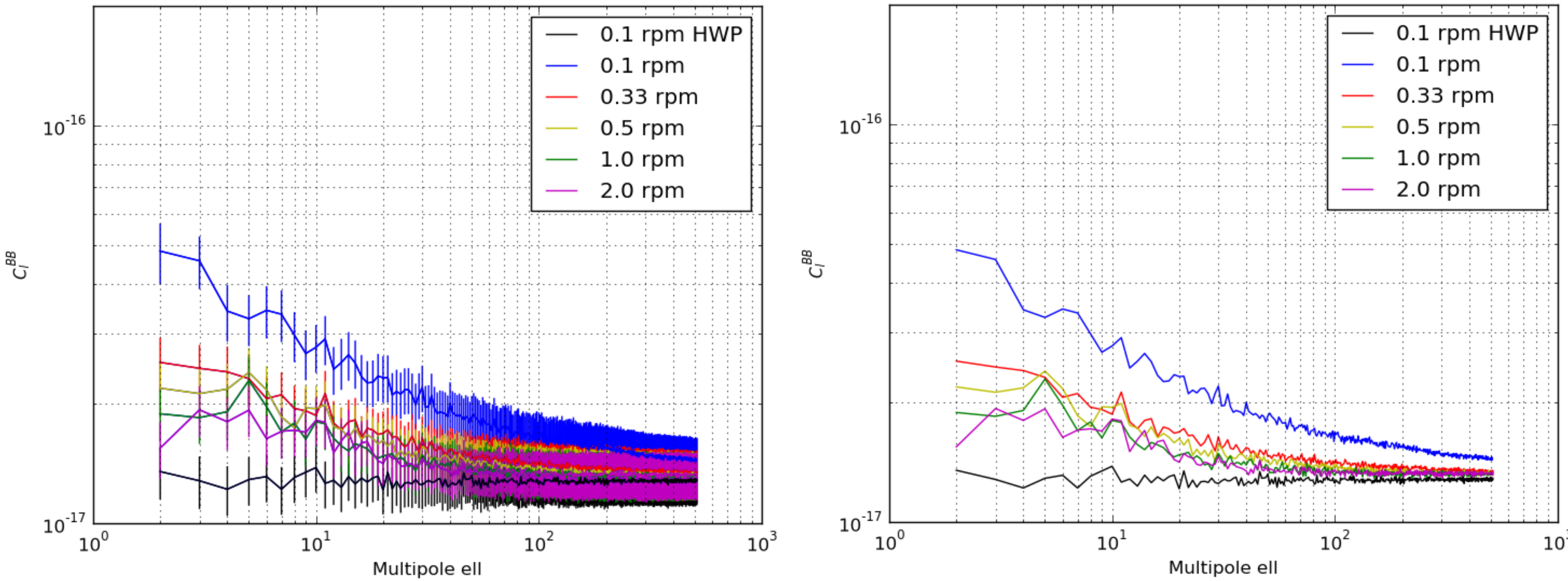


MADAM w/o HWP shows somehow reasonable performance to eliminate 1/f noise effect. (a bit better for large-alpha option?)

1/f noise mitigation by spin

- Case A : f_{knee} = 0.05 Hz, α = 1.0, sampling rate = 23 Hz, precession time = 93 mins.

Mean of 60 noise MC trials
Same plots but w/ or w/o error bars

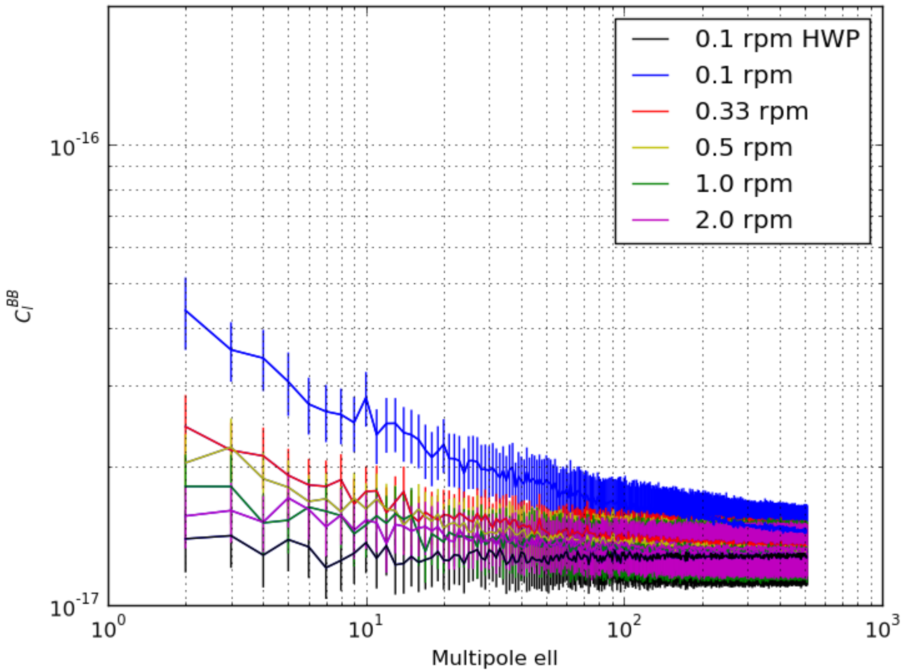


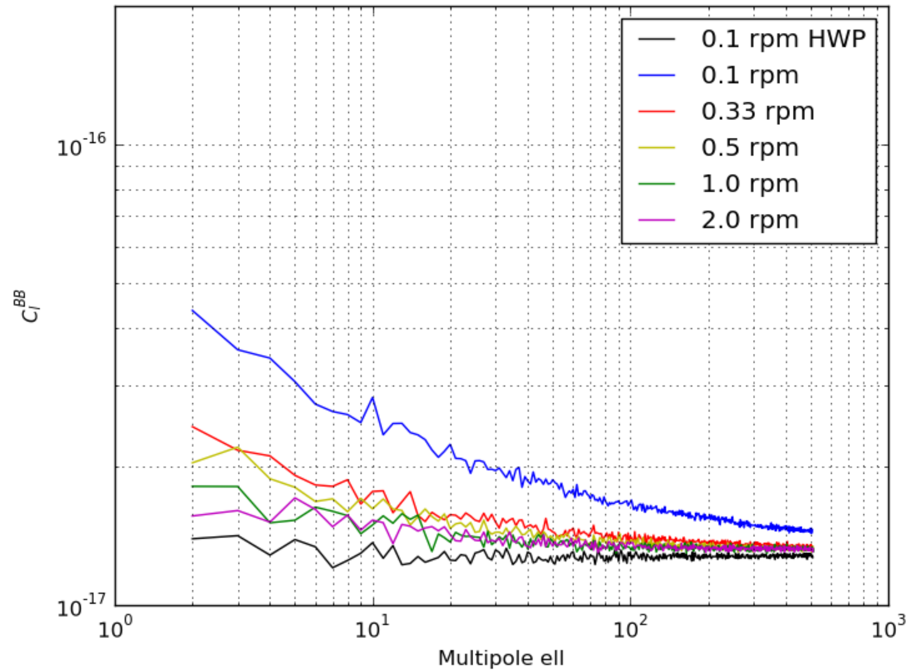
- Advantage to increase spin from 0.1 to 0.3 rpm
- No significant gain in > 0.3~0.5 rpm

1/f noise mitigation by spin

- Case B : f_{knee} = 0.05 Hz, α = 1.0, sampling rate = 23 Hz, precession time = 24 hrs (1440 mins).

Mean of 60 noise MC trials
Same plots but w/ or w/o error bars



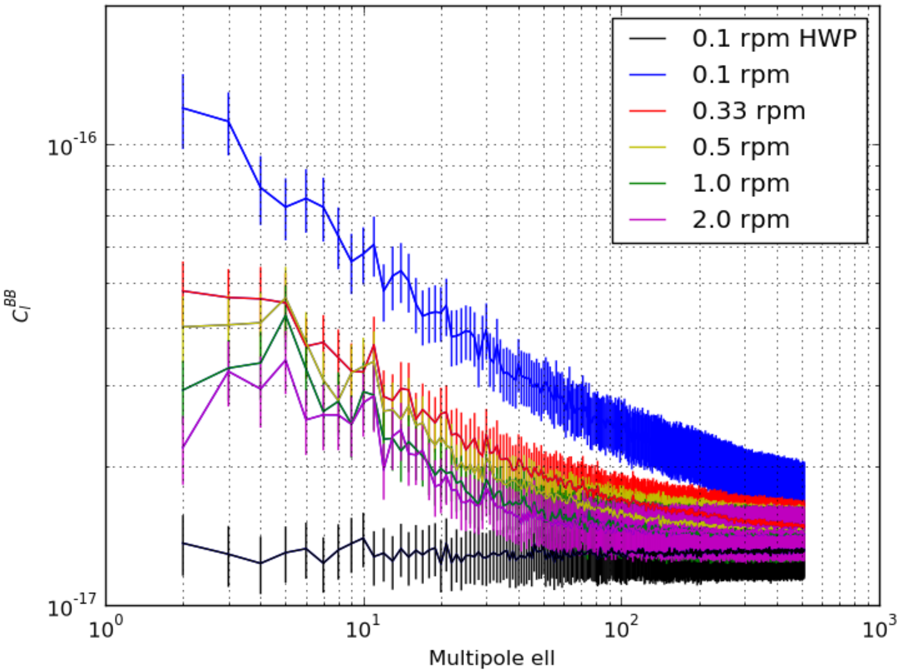


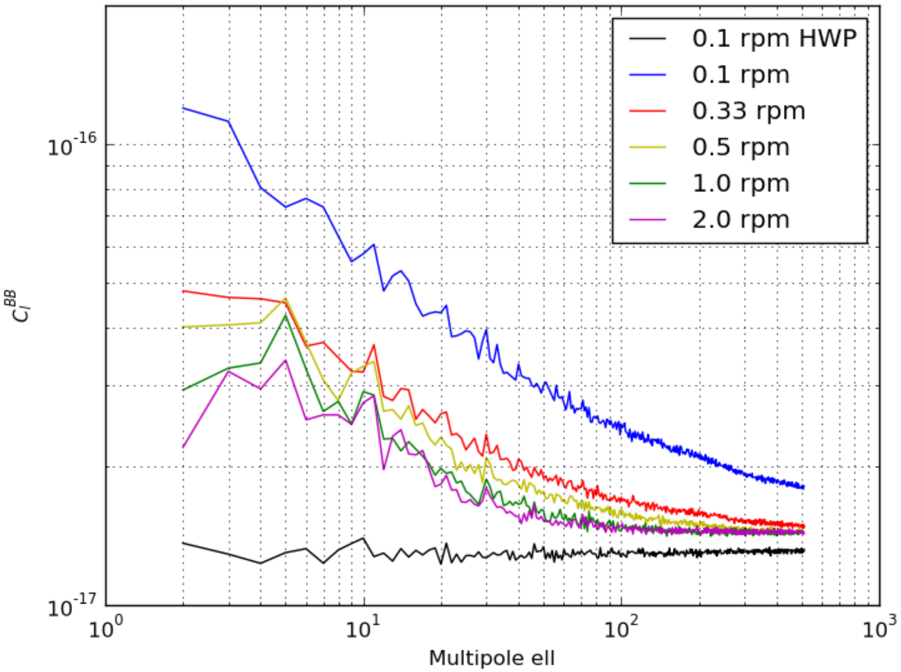
- No visible difference with precession time 93 mins and 24 hrs.
- No significant gain in > 0.3~0.5 rpm

1/f noise mitigation by spin

- Case C : f_{knee} = 0.15 Hz, α = 1.0, sampling rate = 23 Hz, precession time = 93 mins.

Mean of 60 noise MC trials
Same plots but w/ or w/o error bars





- Large f_{knee} largely affects 1/f noise effect
- Advantage to increase spin from 0.1 to 0.3 rpm
- No significant gain in > 0.3~0.5 rpm

Summary & Conclusion

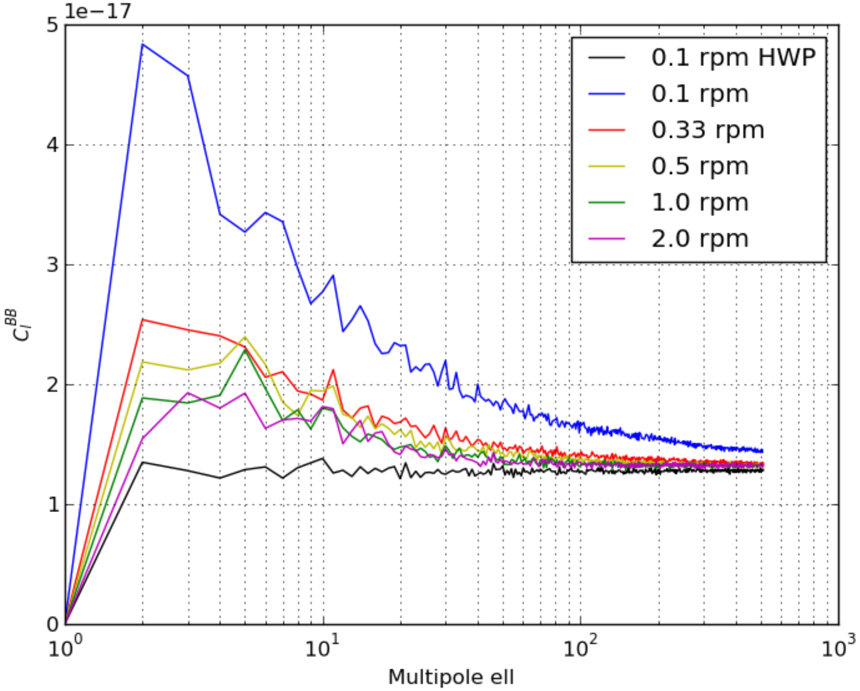
- To determine the scan strategy, we need “reasonable” consideration of scientific & mechanical & cost-mass issues.
- For scientific view :
  - Two candidate configurations determined
  - 1/f noise is affected by spin rate, but not precession time
  - Suggested spin rate is 0.3-0.5 rpm
- Cost & mass are also important driver, but need estimation by company for quantitative
- Based on those, we should judge which scan strategy option is more reasonable.

Supplements

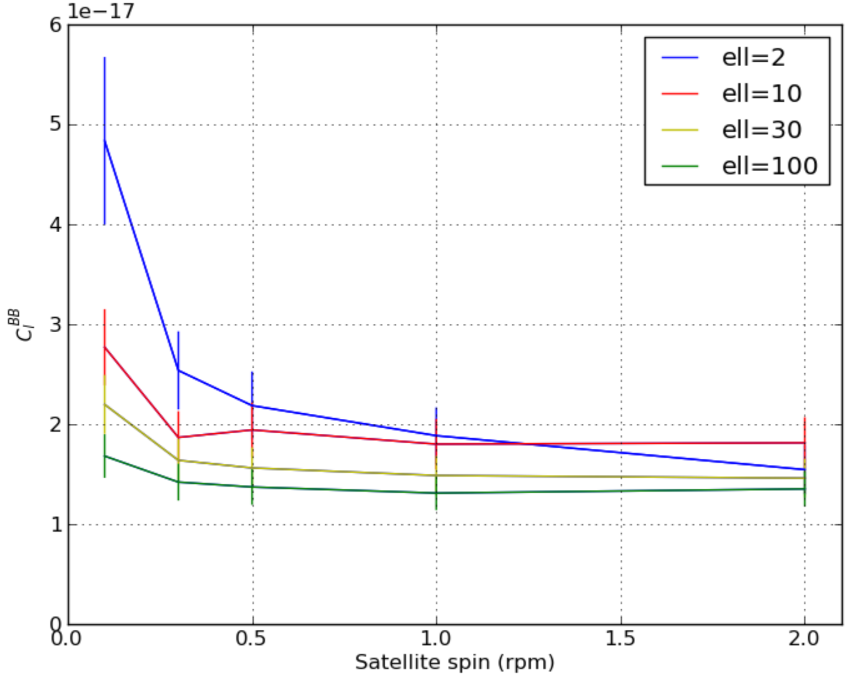
1/f noise mitigation by spin

- Case A : f_{knee} = 0.05 Hz, α = 1.0, sampling rate = 23 Hz, precession time = 93 mins.

Linear scale



Spin rate dependence of C_l^{BB}

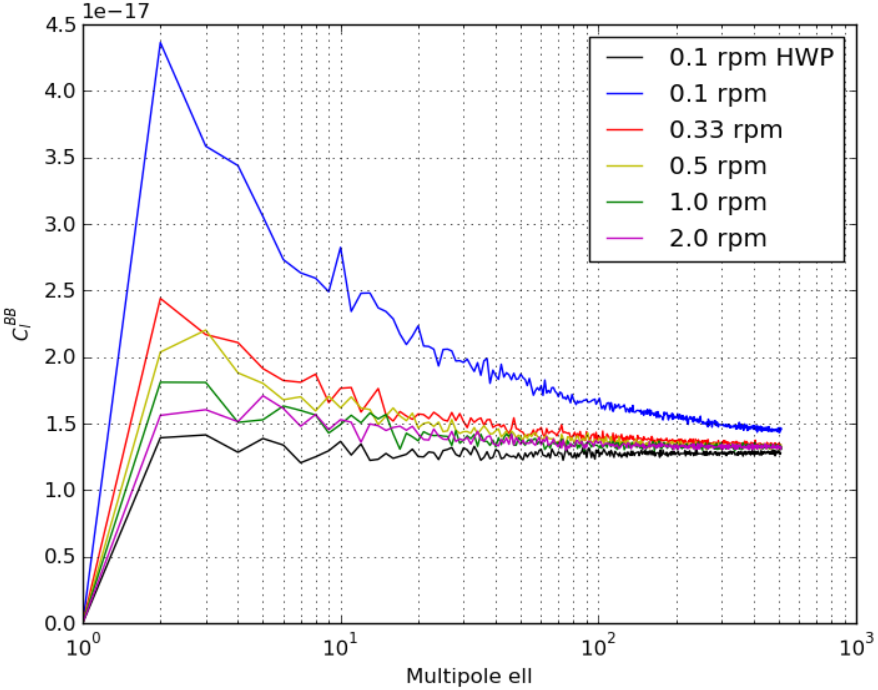


- Lines with different spins do not distribute linearly (saturation effect seen)
- No significant gain in > 0.3~0.5 rpm

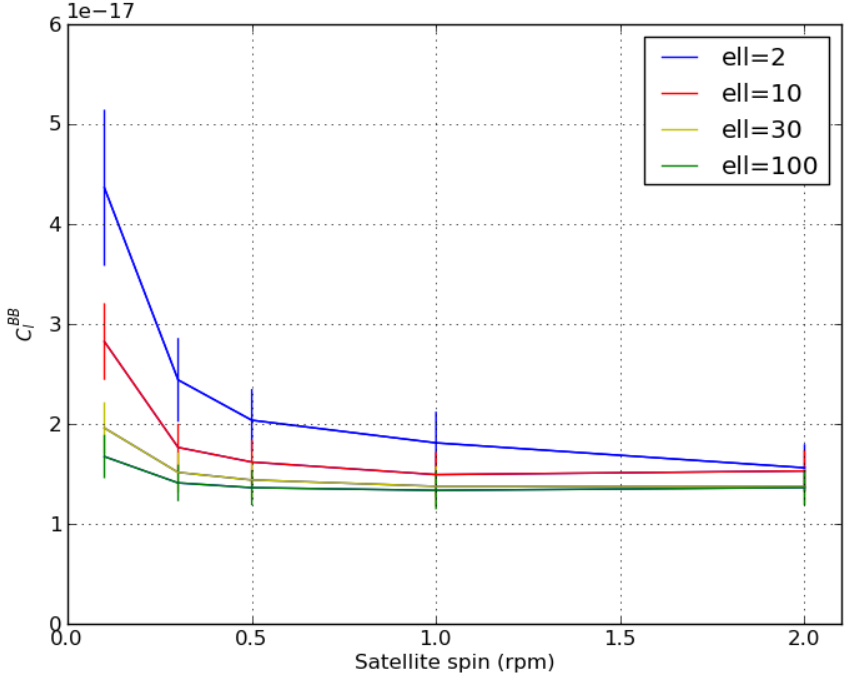
1/f noise mitigation by spin

- Case B : f_{knee} = 0.05 Hz, α = 1.0, sampling rate = 23 Hz, precession time = 24 hrs (1440 mins).

Linear scale



Spin rate dependence of C_l^{BB}

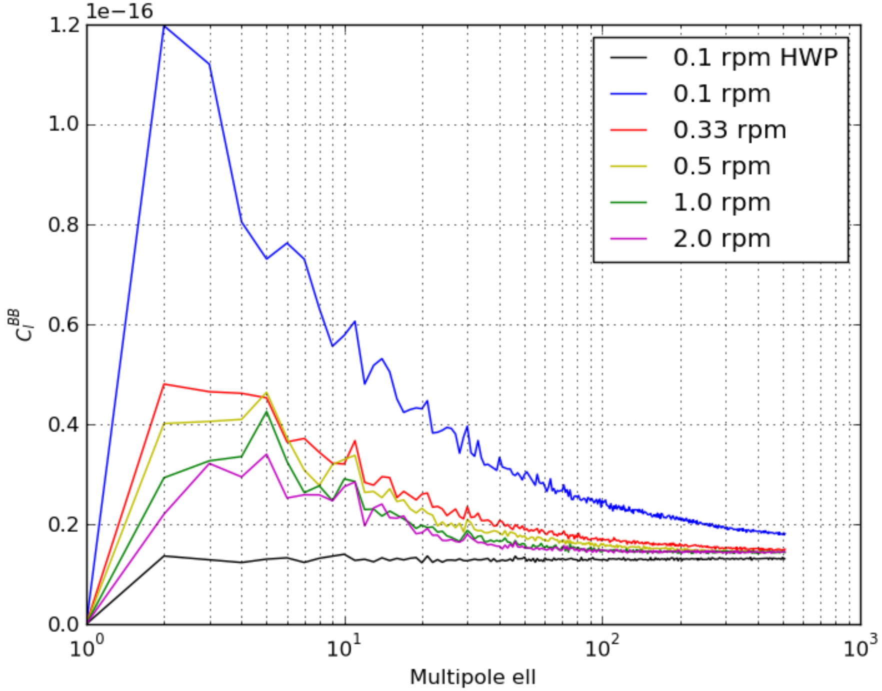


- Saturation effect also seen in long precession time.
- No significant gain in > 0.3~0.5 rpm

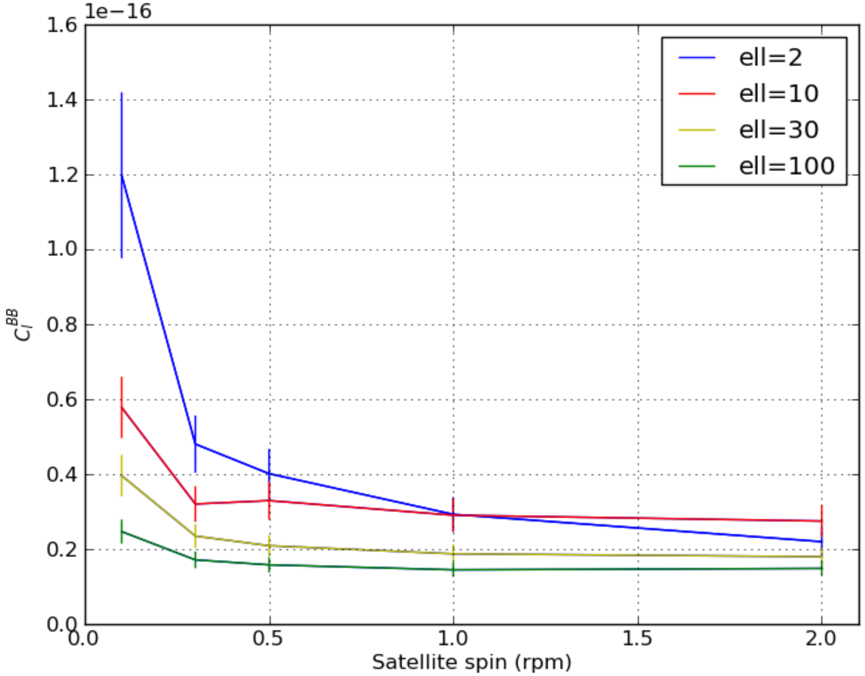
1/f noise mitigation by spin

- Case C : f_{knee} = 0.15 Hz, α = 1.0, sampling rate = 23 Hz, precession time = 93 mins.

Linear scale



Spin rate dependence of C_l^{BB}



- Tendency of saturation is same with case A and B
- No significant gain in > 0.3~0.5 rpm

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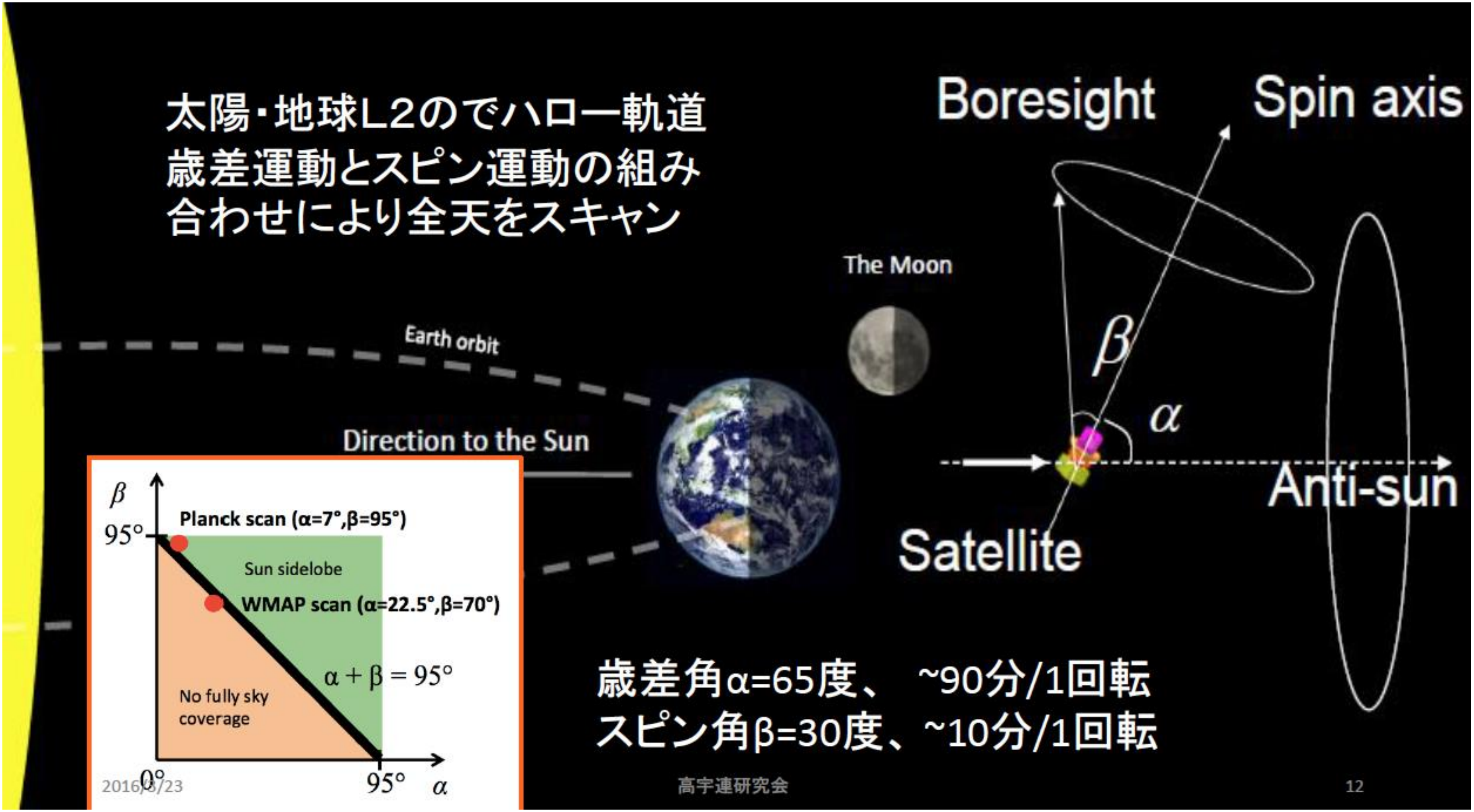
2017 Jan-23th B mode from space WS @ Montreal



Some more thoughts

- Sampling rate (relates to time constant)
- Precession time & spin rate optimization?
- Practical method of glitch removal?
- Stepped precession option?
- Large-β works better for gain calibration?
- What combinations of Jack-knife (null-test) works for various expected or unexpected syst measurement ?

  (refer BICEP2 arXiv:1502.00608)
- ADR recycling loss (~15 %)
- Galaxy masking
- Katayama-san's option

  (moving precession axis)

TABLE 4
INSTRUMENTAL SYSTEMATICS

Systematic	Characteristic r
crosstalk	$\simeq 3.2 \times 10^{-3}$
beams (including gain mismatch)	$< 3.0 \times 10^{-3}$
EMI	$< 1.7 \times 10^{-3}$
cross polar response	$< 10^{-3}$
detector transfer functions	$< 5.7 \times 10^{-4}$
systematic polarization angle error	$< 4.0 \times 10^{-4}$
gain variation $E \rightarrow B$	$< 5.3 \times 10^{-5}$
random polarization angle error	$< 5.0 \times 10^{-5}$
thermal fluctuations	$< 1.2 \times 10^{-5}$
ghost beams	$\simeq 7.2 \times 10^{-6}$
scan synchronous contamination	$< 1 \times 10^{-8}$
Total	$\simeq (3.2-6.5) \times 10^{-3}$

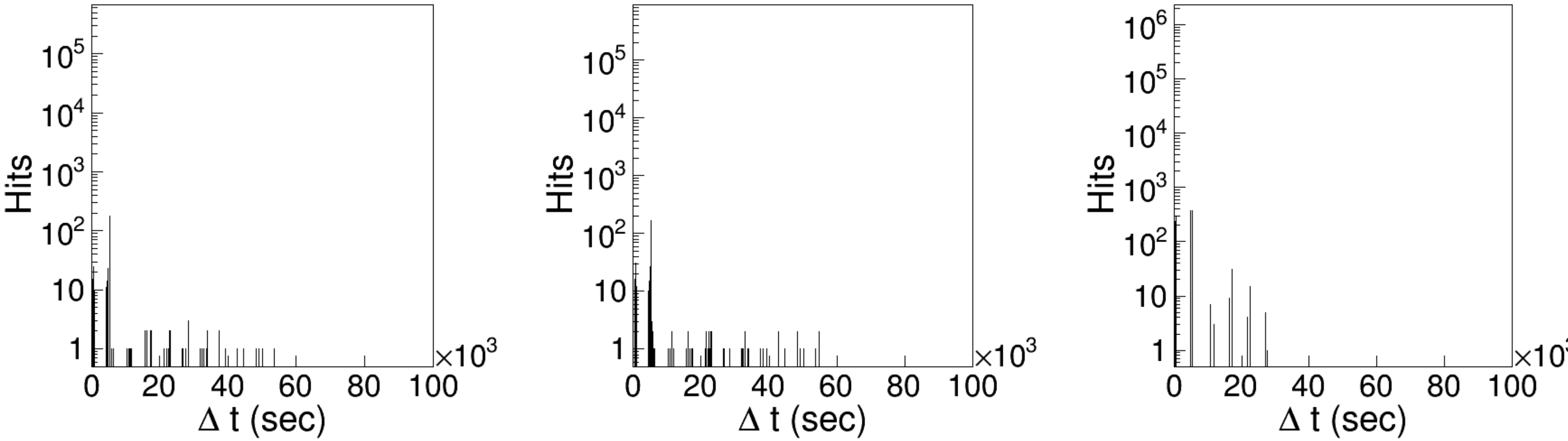
NOTE. — The comparable characteristic r of BICEP2's statistical uncertainty is $r = 3.1 \times 10^{-2}$.

Revisit time distribution (1-day timescale)

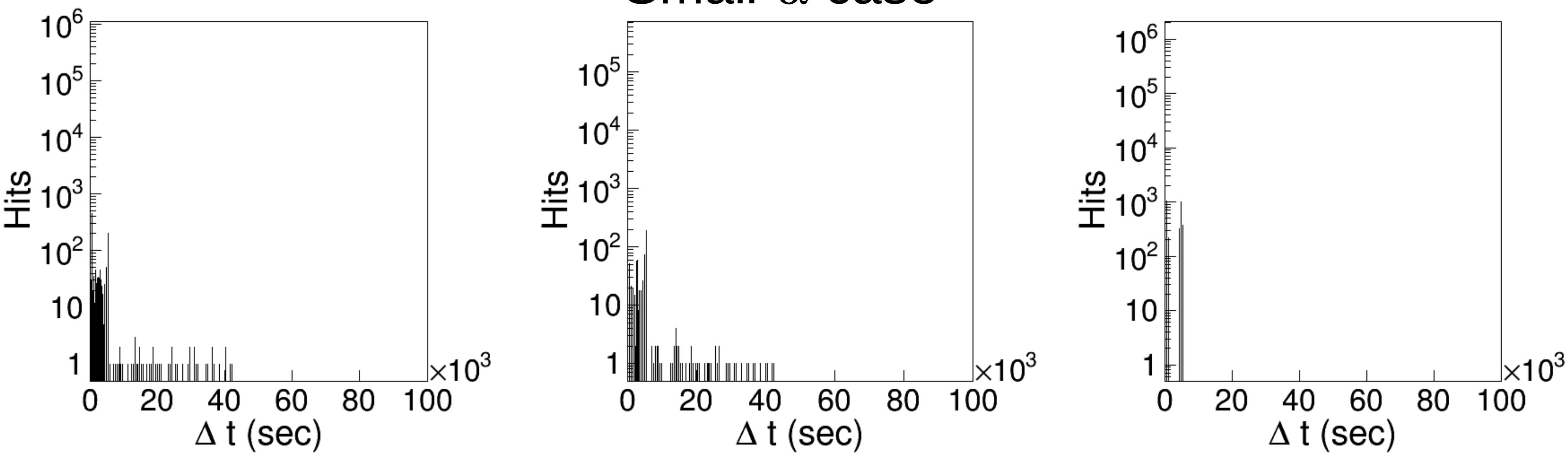
precession time = 1.51 hrs, spin rate = 0.1 rpm

Scan time = 1yr, full detector

Large-α case



Small-α case



Situation at Planck

- Planck has 60 rings at same place, stepped precession
- Long-time revisit (6 months), 5 sets of full-sky map in total
- Jack-knife worked in various situation
  - Short-term : cosmic ray glitch removal
  - Mid-term : destriping (1/f noise removal)
  - Long-term : time constant elimination (beam symmetrization)

    Temperature-to-polarization leakage correction
  - ADC non-linearity correction (appeard as gain variation)
- Almost of those are unexpected issues before launching, but rescued by enough amount of redundancy of data.

What we can think of for LB case?

- $\alpha+\beta\sim 95^{\circ}$ (Full sky coverage + avoid sun side-robe) … sacred
- Small cross-link … fundamentally important for polarization measurement
  Also works to symmetrize beam shape
- Destriping ... If possible, doing in several time scales is better
- Jack-knife availability for unexpected problem … with various time-scales

- What to do with cosmic-ray glitch removal?
  - Stepped precession? It has pros (easy to analyze) and cons (sparse scan, satellite stabilization)
  - Template removal method?
  - I suggest to keep both options in current phase
- Requirement for sensors … make time constant as short as possible
- In-flight time constant modeling? With cosmics or Jupiter?
- Small-β would work better for gain calibration (to catch CMB dipole in a short time)
- Single-detector mapping?

Table 1: Summary of systematics. The requirements are estimated so that each systematic item results in 1% of lensing B-mode spectrum in amplitude. The expected measurement errors are the obtained using simulations We categorize the individual systematics with and without HWP.

Id	types	Requirements	Exp. meas. error	Comments	w/ HWP	w/o HWP
1	Diff. gain	$< 0.002\%$ (bias, $\ell = 2$, a pair) $< 0.06\%$ (bias, $\ell = 200$, a pair) $< 0.04\%$ (rand., $\ell = 2$, a pair) $< 0.2\%$ (rand. $\ell = 200$, a pair) $< 0.04\%$ (bias, $\ell = 2$, array)	0.002% (per year) 0.4% (600 sec)	CMB dipole calibration yields 0.4% uncertainty for the diff. gain of a single pair. Meas. error assumes random diff. gain variation in time with 600 sec time scale without any obvious trend. Bias is assume to be stable. If the gain variation in time follows a function with the small number of parameters, the requirements can be less stringent.		√
2	Diff. beam point.	< 4 arcsec ($\ell = 2$) < 2 arcsec ($\ell = 200$)	2 arcsec @40 GHz	-30 dB meas. of beam using Jupiter that enter the beam accidentally during the scan.		√
3	Diff. beam ellipticity	$< 7\%$ ($\ell = 2$) $< 0.04\%$ ($\ell = 200$)	$\sim 0.1\%$	With -40 dB measurements of beam using Jupiter observation mode.		√
4	Diff. beam width	$< 0.8\%$ ($\ell = 2$) $< 0.2\%$ ($\ell = 200$)	$\sim 0.1\%$	With -40 dB measurements of beam using Jupiter observation mode.		√
5	Diff. side-lobe	< -40 dB	-40 dB	With -40 dB measurements of beam using Jupiter observation mode.		√
6.1	Near Side-lobe	< -40 dB	TBD	Near side-lobe is determined with a precision of less than -40 dB from the Jupiter observation mode.		√
6.2	Near Side-lobe	TBD	TBD	Need to check polarization of the near side lobe.	√	
7.1	Far Side-lobe	TBD	TBD	May be spin synchronous leakage from the sun and the center of galaxy.		√
7.2	Far Side-lobe	TBD	TBD	Need to check polarization of the far side lobe.	√	
8	HWP instr. pol. at $4f$	$< 0.03\%$	$< 0.03\%$	ABS team's achievement.	√	
9	Pol. efficiency	$< 1\%$	TBD	From ground calibration or C_ℓ^{EE} etc.	√	
10	Single. det. gain var. in time	$< 10\%$ (600 sec)	0.6%	From the CMB dipole calibration	√	√
11	Single. det. Abs. gain	Not considered hear, as the parity is conserved and no effect in E to B leakage			√	√
12	Pointing knowledge of bore-sight	< 3 arcmin	0.23 arcmin	Star tracker specification	√	√
13	Abs. pol. angle	< 1 arcmin	1 arcmin	Simulations with C_ℓ^{EB}	√	√
14.1	$1/f$ noise $f_{\rm knee}$	$f_{\rm knee}$(pairdiff.) $<$ spin rate	TBD	For a spin rate of 0.3 rpm, a naive requirement is $f_{\rm knee}$(pairdiff.) $<$5 mHz. This may need to be more stringent if we consider loss in S/N filtering. The requirement may be relaxed with a proper de-striper.		√
14.2	$1/f$ noise $f_{\rm knee}$	$f_{\rm knee} < 1$ mHz	TBD	The requirement of 1 mHz comes by setting 10% of the $1/f_{\rm knee}$ with respect to the white noise level at $\ell = 2$ with the spin rate of 0.1 rpm and $\alpha = 2$, where α is the slope index. The study in progress to assess the benefit of the destriping map making and the penalty by filtering.	√	
15	Cosmic ray glitches	TBD	TBD	Simulation estimation using de-glitching.	√	√
16.1	Band pass mismatch	TBD	TBD	Simulation estimation using. Spurious terms.		√
16.2	Detection efficiency dependence on the HWP rotation angle	TBD	TBD	This effect is basically mitigated by the $4f$ demodulation, as this effect appears as the $2f$ modulation.	√	

Parameters/strategies which (may) need to be considered for the scan optimization

- All-sky scan($\alpha+\beta=95^o$)
- Cross-link
- Hit uniformity

those had been dominant targets so far

- How useful is it for destriping?
- Stepped/continuous precession?
- Jack-knife availability

Revisit time optimization

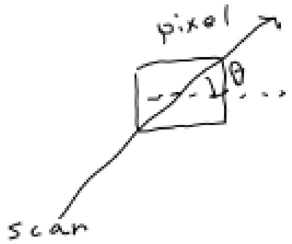
- ADR cycling (30 hrs) and its dead-time (15%)
- Galaxy masking (f_{sky}~0.5)
- Heat issues, mission-part structure … need assesment from optical / structure viewpoint
- Any synchronous effect with other devices
- Any others (e.g. data transfer rate)?

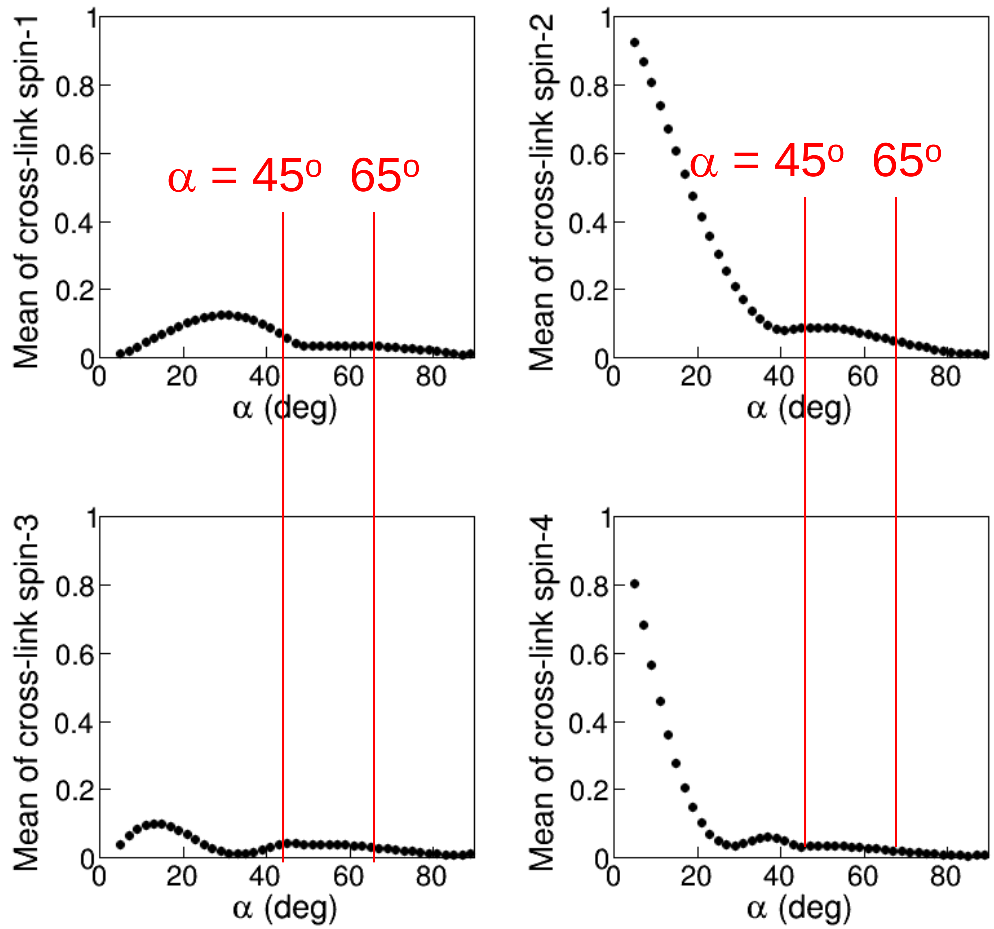
Cross-link with spin 1-4

Vary α under condition $\alpha+\beta=95^o$, precession time=1.51 hrs, spin revolution rate=0.3 rpm

$$\text{Cross-link (spin-2)} \equiv \langle \cos 2\theta \rangle^2 + \langle \sin 2\theta \rangle^2$$

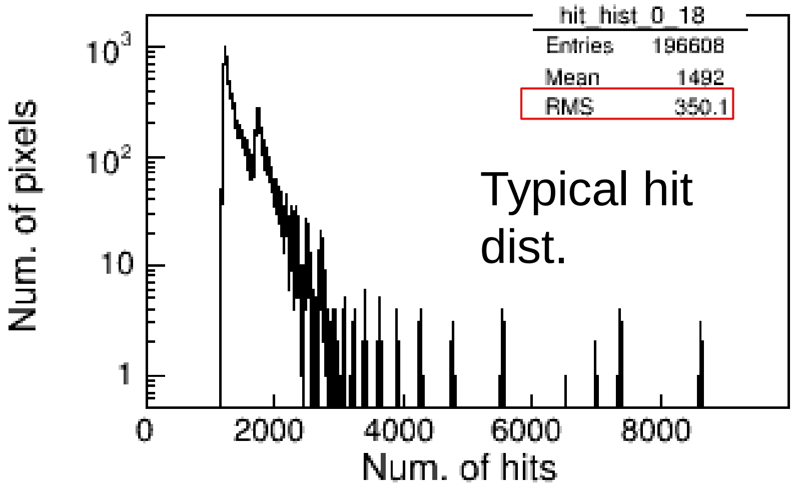
average over all hits

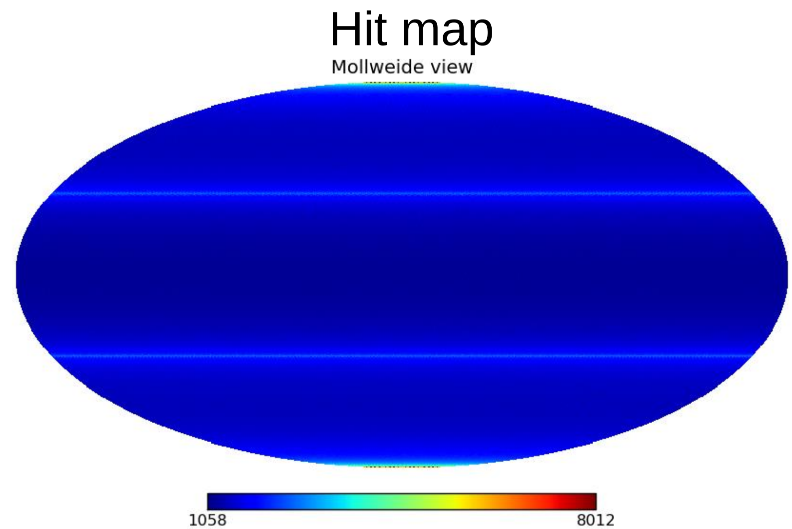


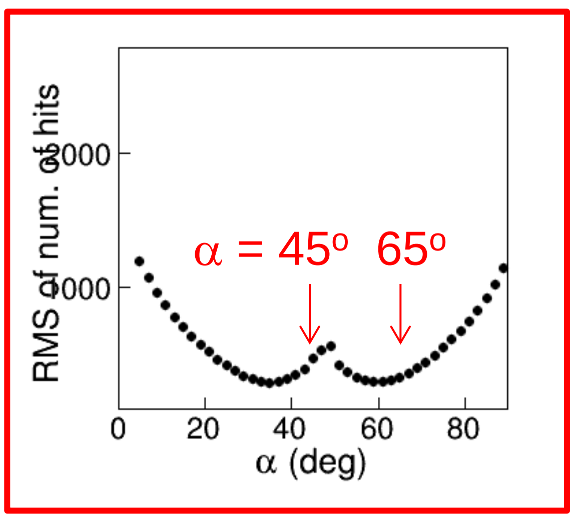


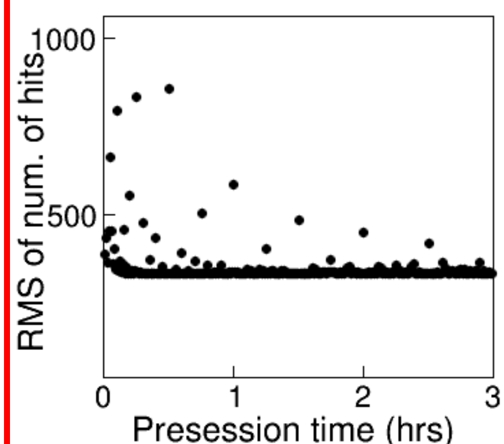
Both $\alpha = 45^o, 65^o$ seems to be OK concerning the cross-link.

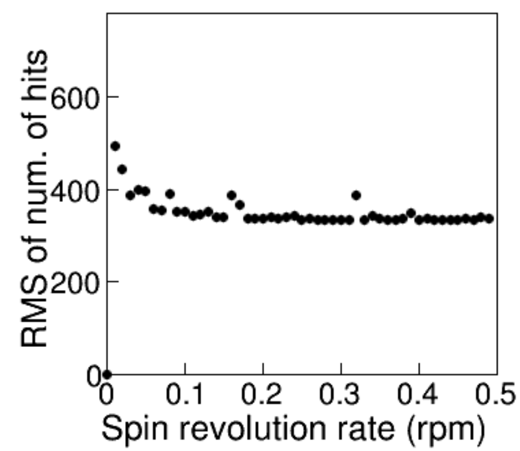
Hit uniformity (spin = 0.3 rpm)











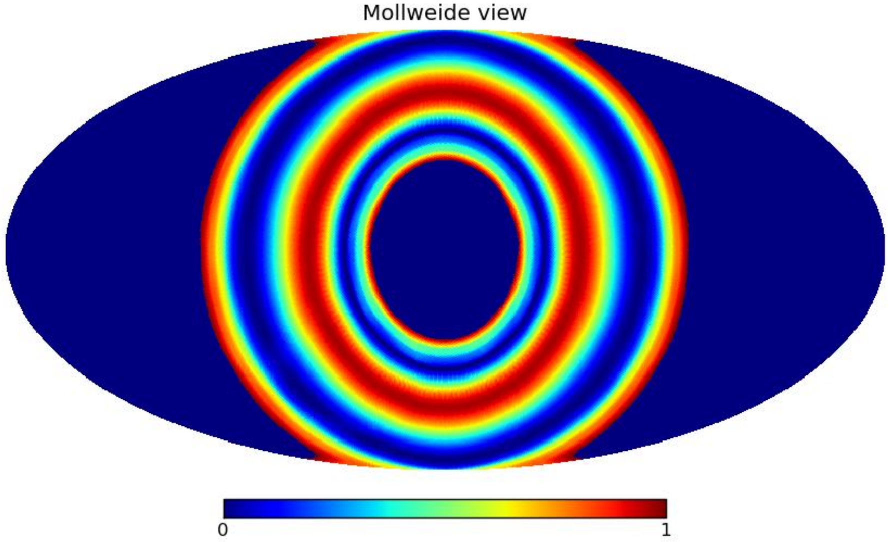
Hit unifirmity is comparable between small & large α cases.

Cross-link for Jack-knife (null-test)

One-day cross-link (spin-2) maps

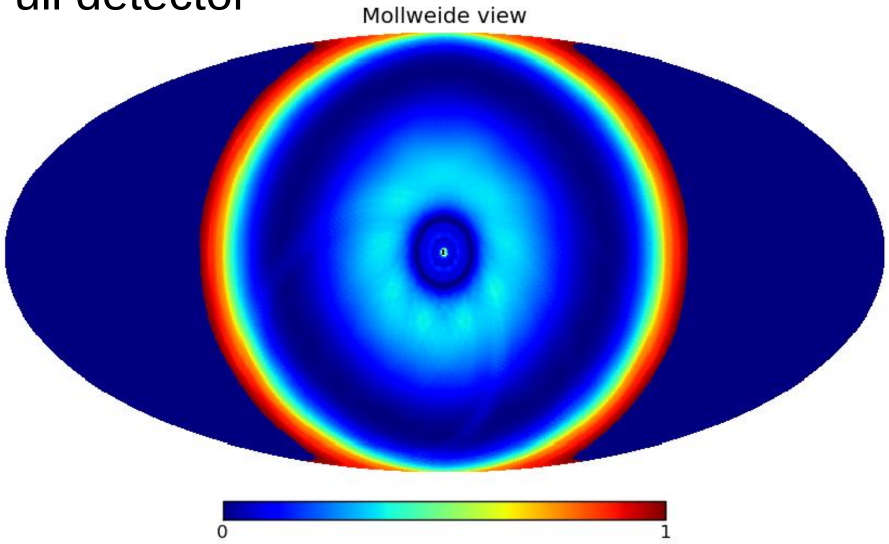
α=65^o, β=30^o

Full detector



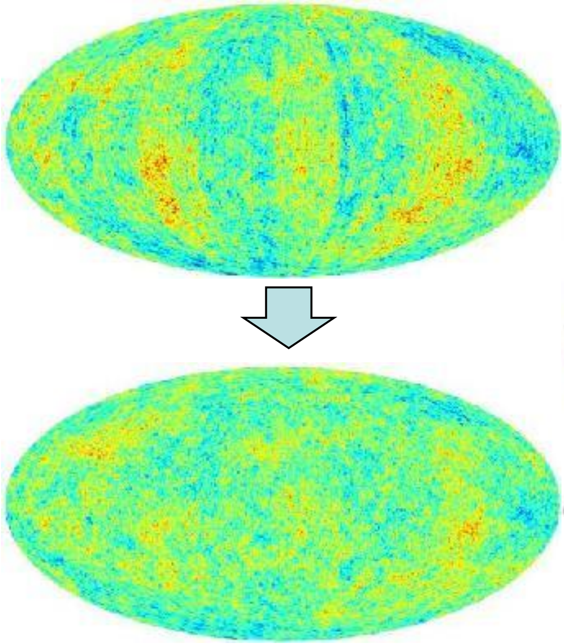
α=45^o, β=50^o

Full detector

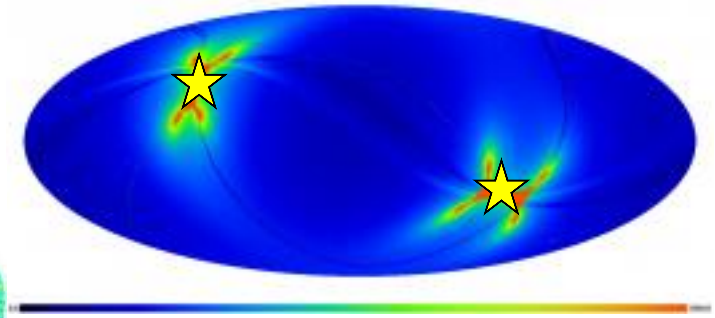


Destriping

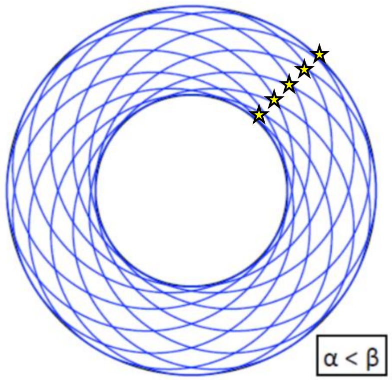
Planck case



Planck 1yr hitmap
Stars … Reference points

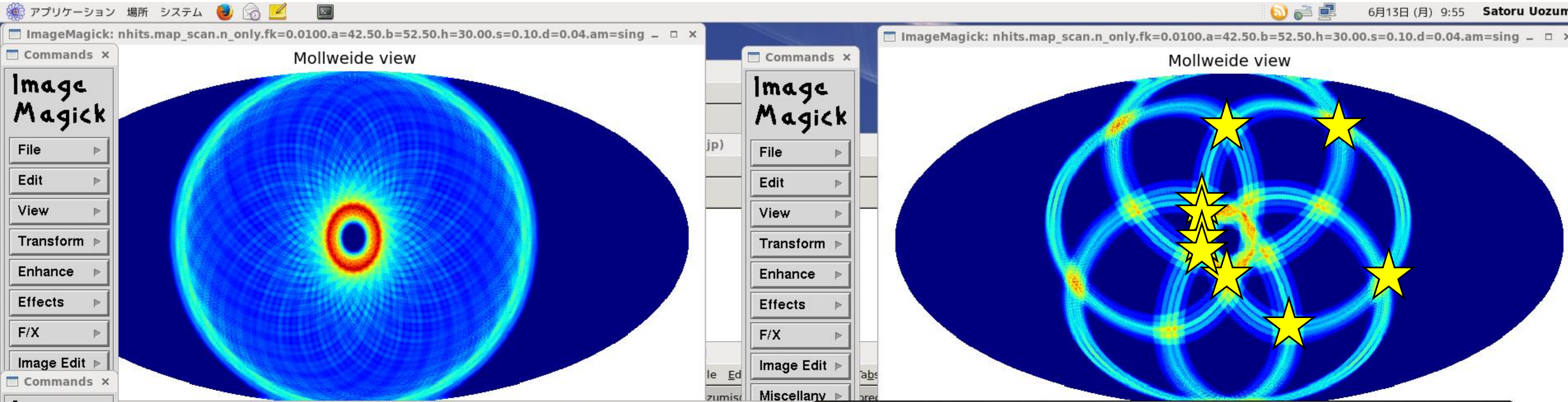


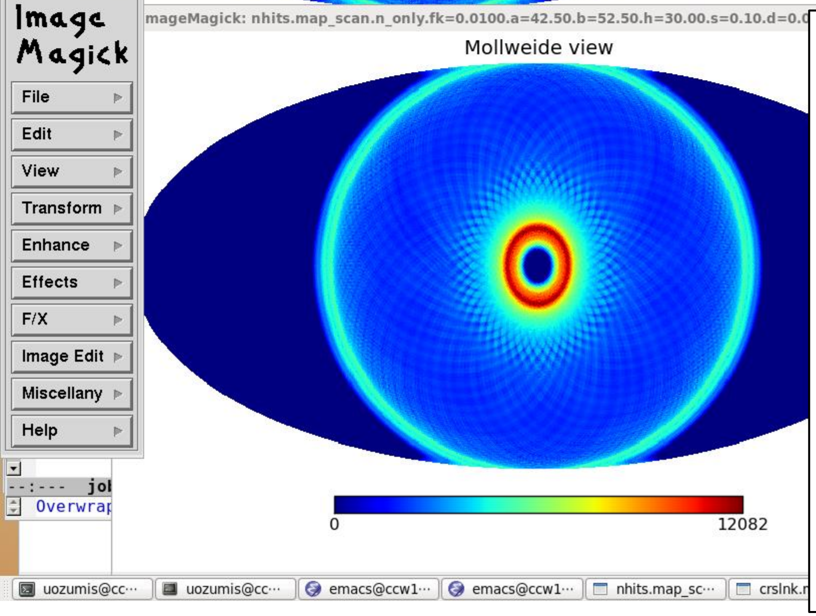
LiteBIRD case – an idea



- Remove 1/f noise by normalizing signal at reference points
- Actual procedure not yet established for LiteBIRD
- May need to perform simulation of destriping with different configurations :
  - Different α, precession times, spin rates
  - Stepped or continuous precession

Stepped precession?





- Stepped precession may useful for
  - Reduce white noise at reference points
  - Spin-based jack-knife test

- However it's still not clear how those works, how to optimize num. of steps.
  →Need to try realistic destriping analysis ?
- Any synchronous issue with the stepped precession?

An other option

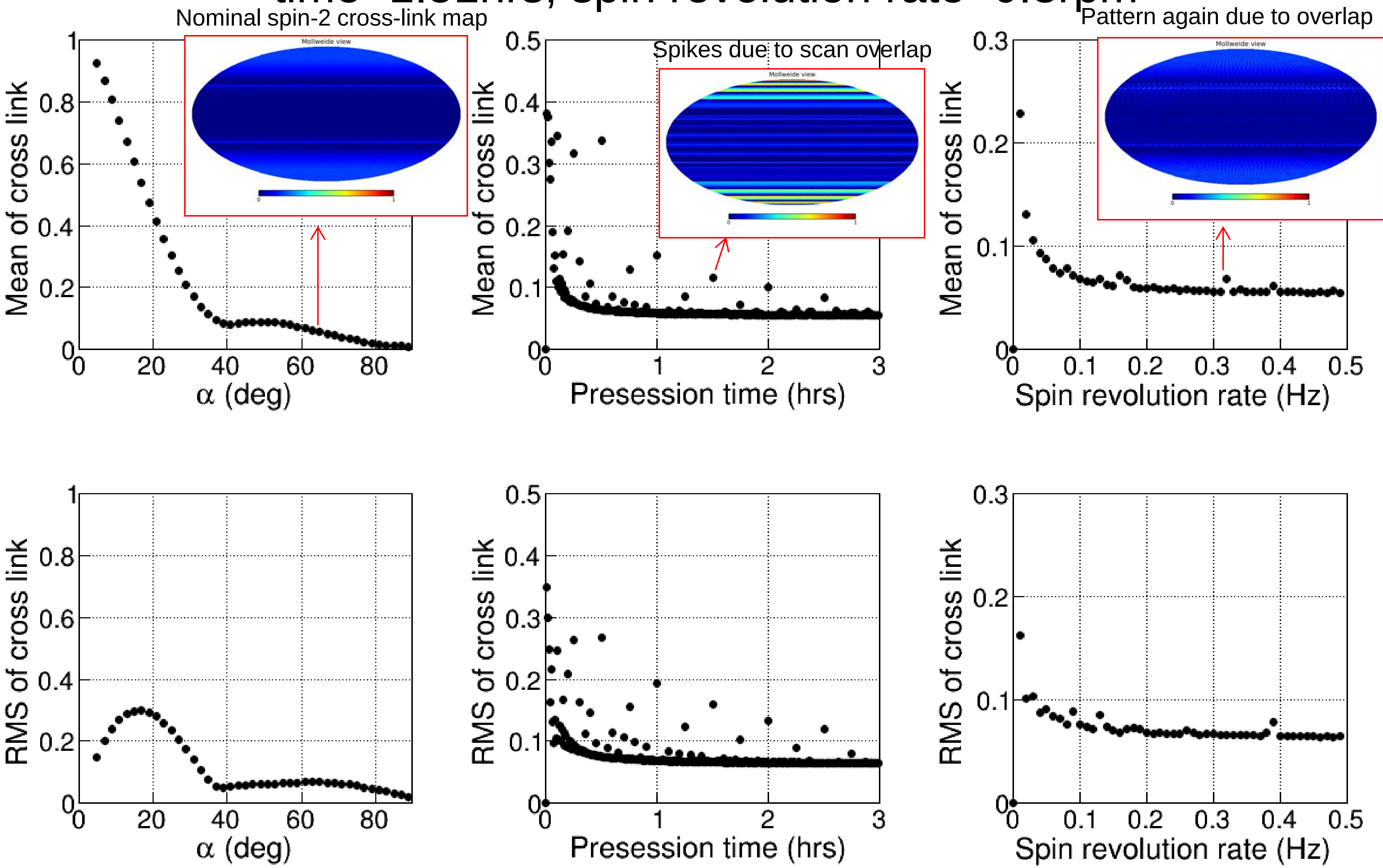
- Moving precession axis (Katayama-san)
  - Possibility to make α smaller

  - However it would make scan strategy complicated…
  - Configurations? (e.g. moving style, speed,etc…)
  - Feasibility for satellite structure ?

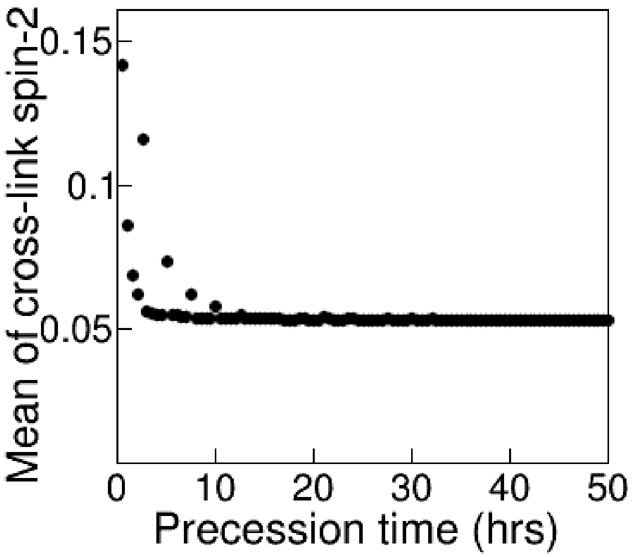
  - Would be good to keep in our mind until main strategy candidates will be established.

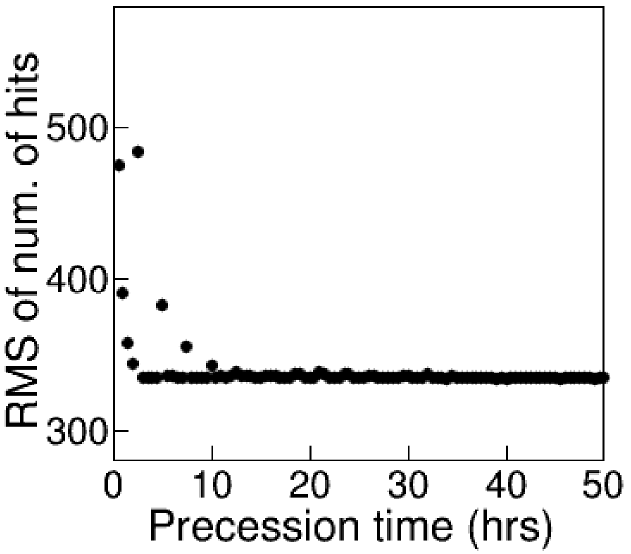
Comparison (spin-2 cross-link)

Nominal values : $\alpha=65^o$, $\beta=30^o$, $\alpha+\beta=95^o$, precession time=1.51hrs, spin revolution rate=0.3rpm



Longer precession time

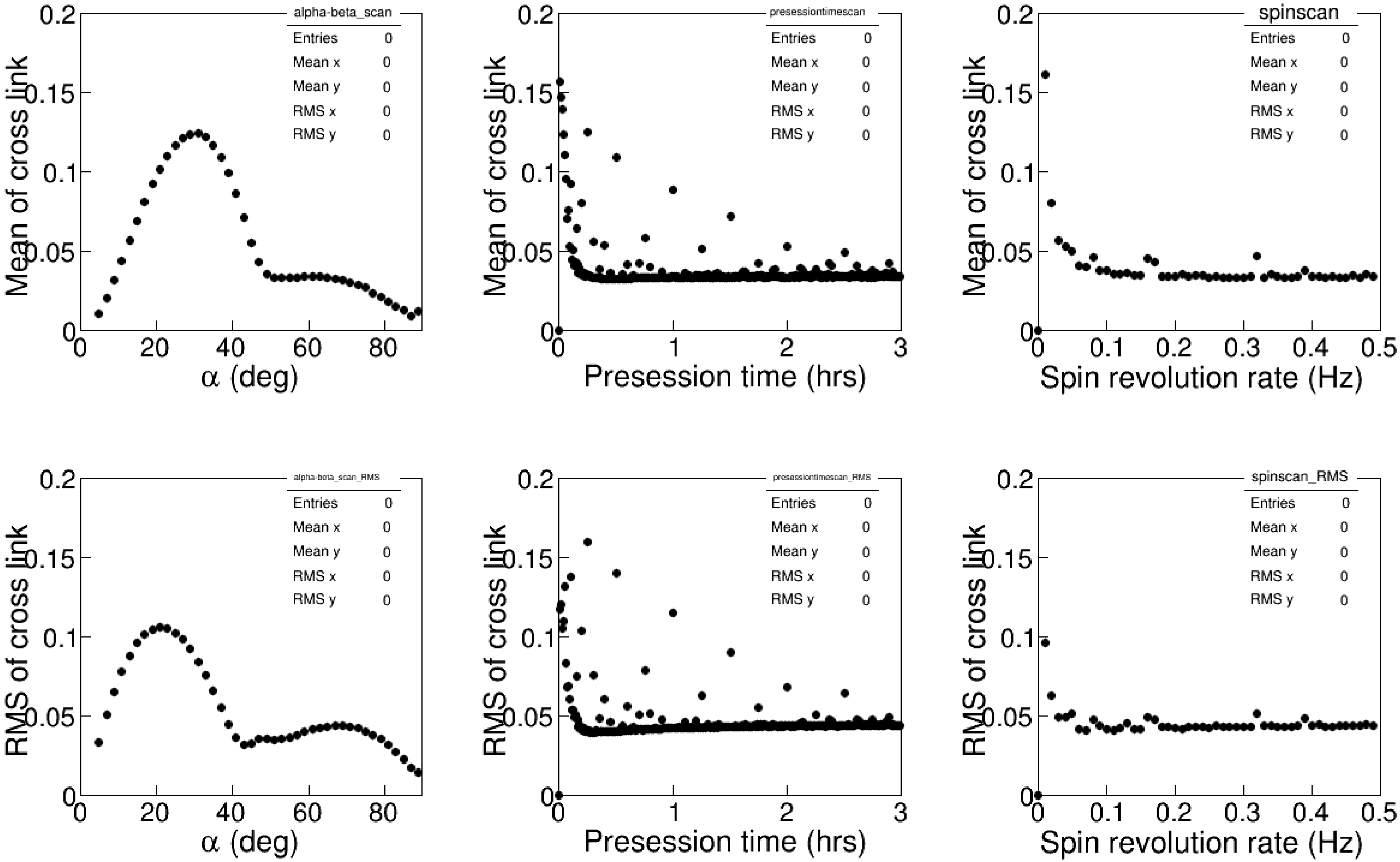




No significant dependence in long precession time range.

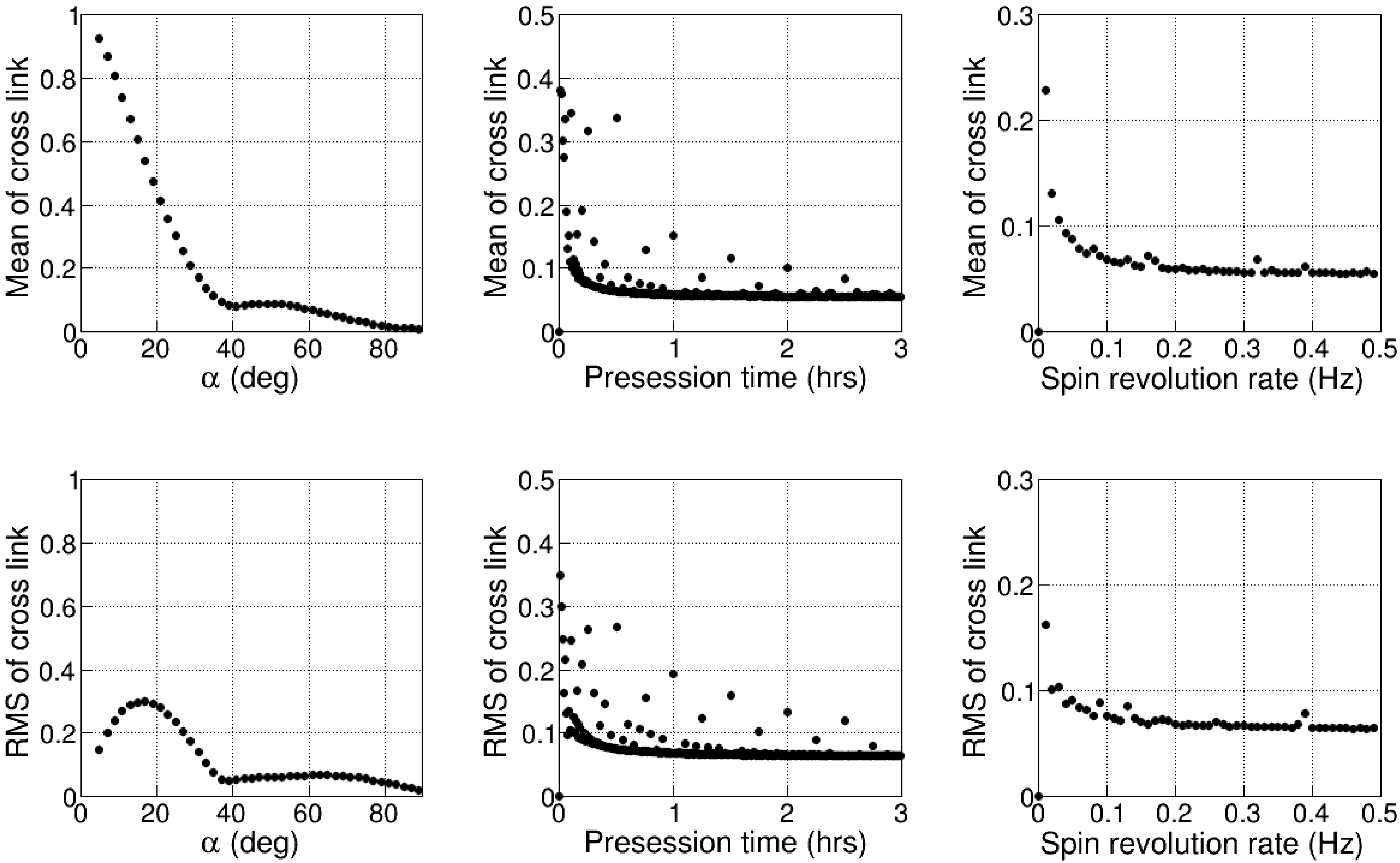
Scan results (spin-1 cross-link)

Nominal values : α=65°, β=30°, α+β=95°, precession time=1.51hrs,
spin revolution rate=0.3rpm



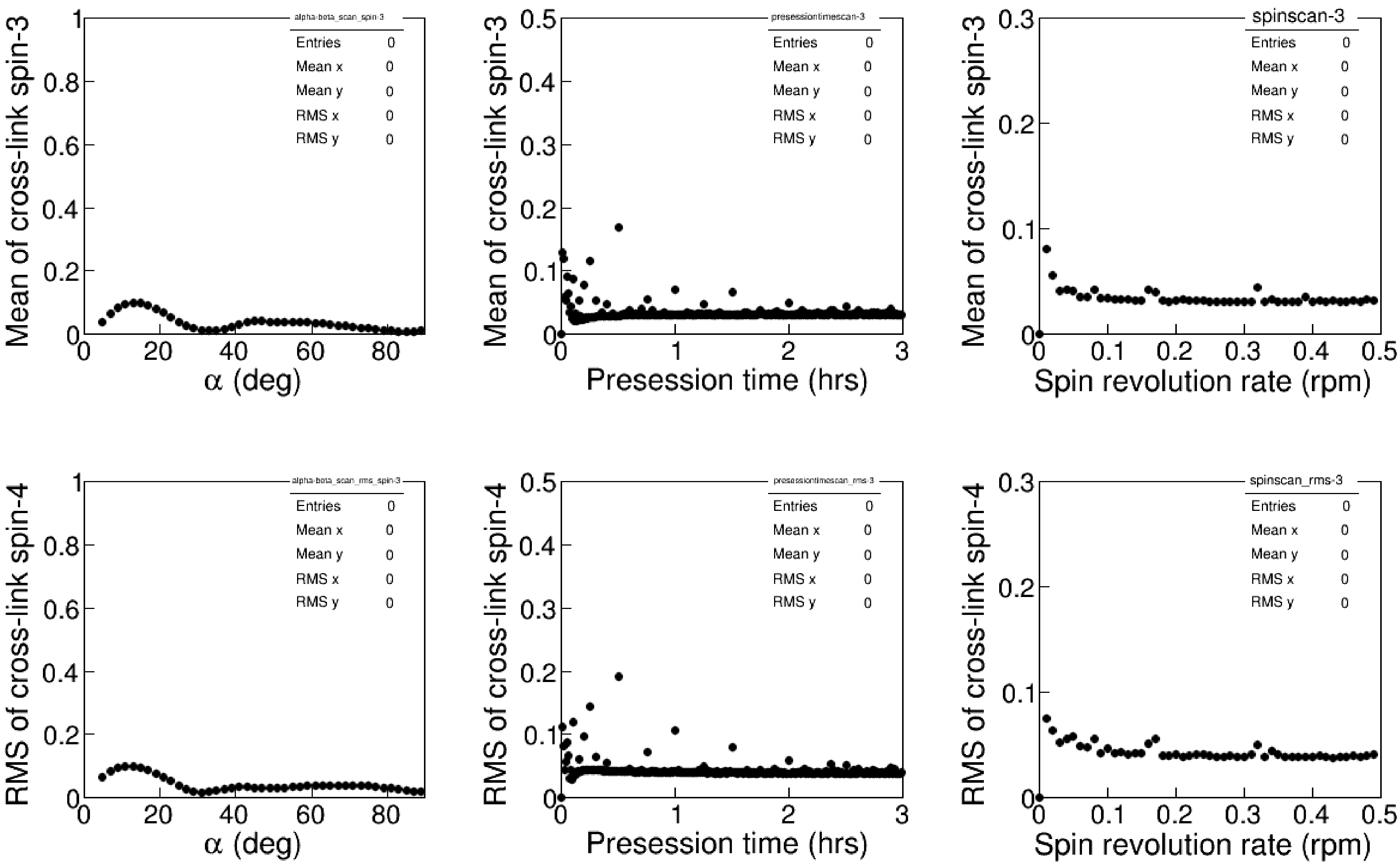
Scan results (spin-2 cross-link)

Nominal values : α=65^o, β=30^o, $\alpha+\beta$=95^o, precession time=1.51hrs, spin revolution rate=0.3rpm



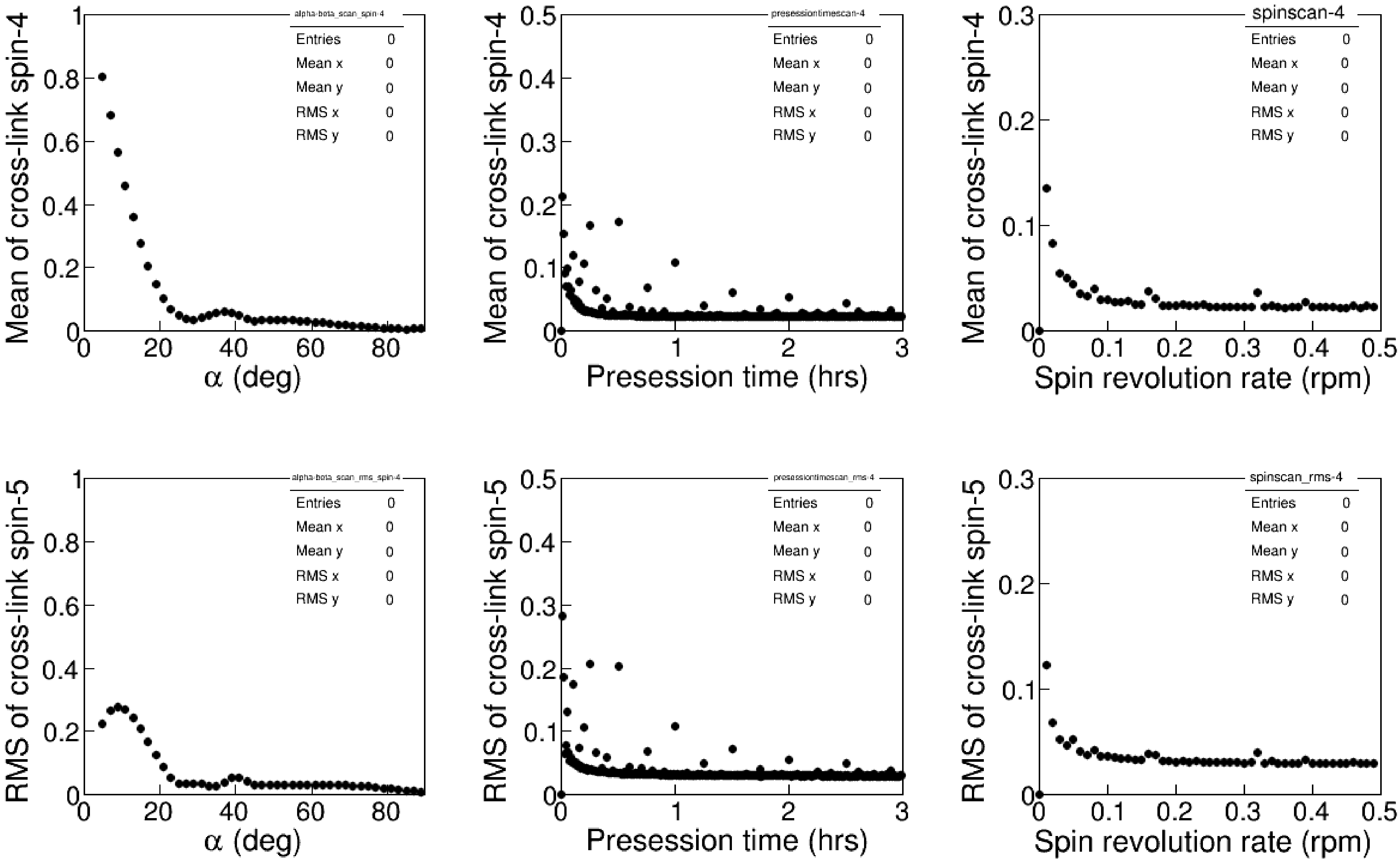
Scan results (spin-3 cross-link)

Nominal values : α=65º, β=30º, $\alpha+\beta$=95º, precession time=1.51hrs, spin revolution rate=0.3rpm

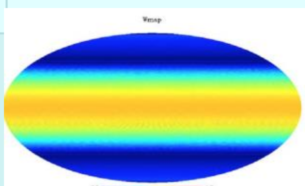
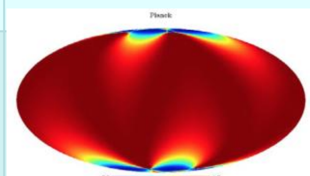
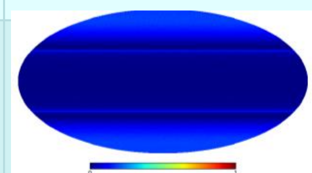
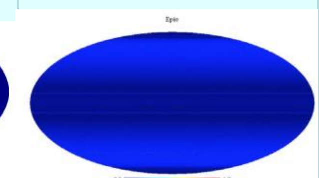
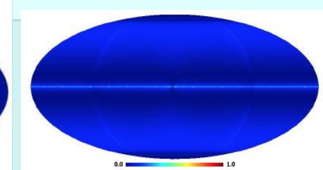


Scan results (spin-4 cross-link)

Nominal values : α=65°, β=30°, $\alpha+\beta$=95°, precession time=1.51hrs, spin revolution rate=0.3rpm

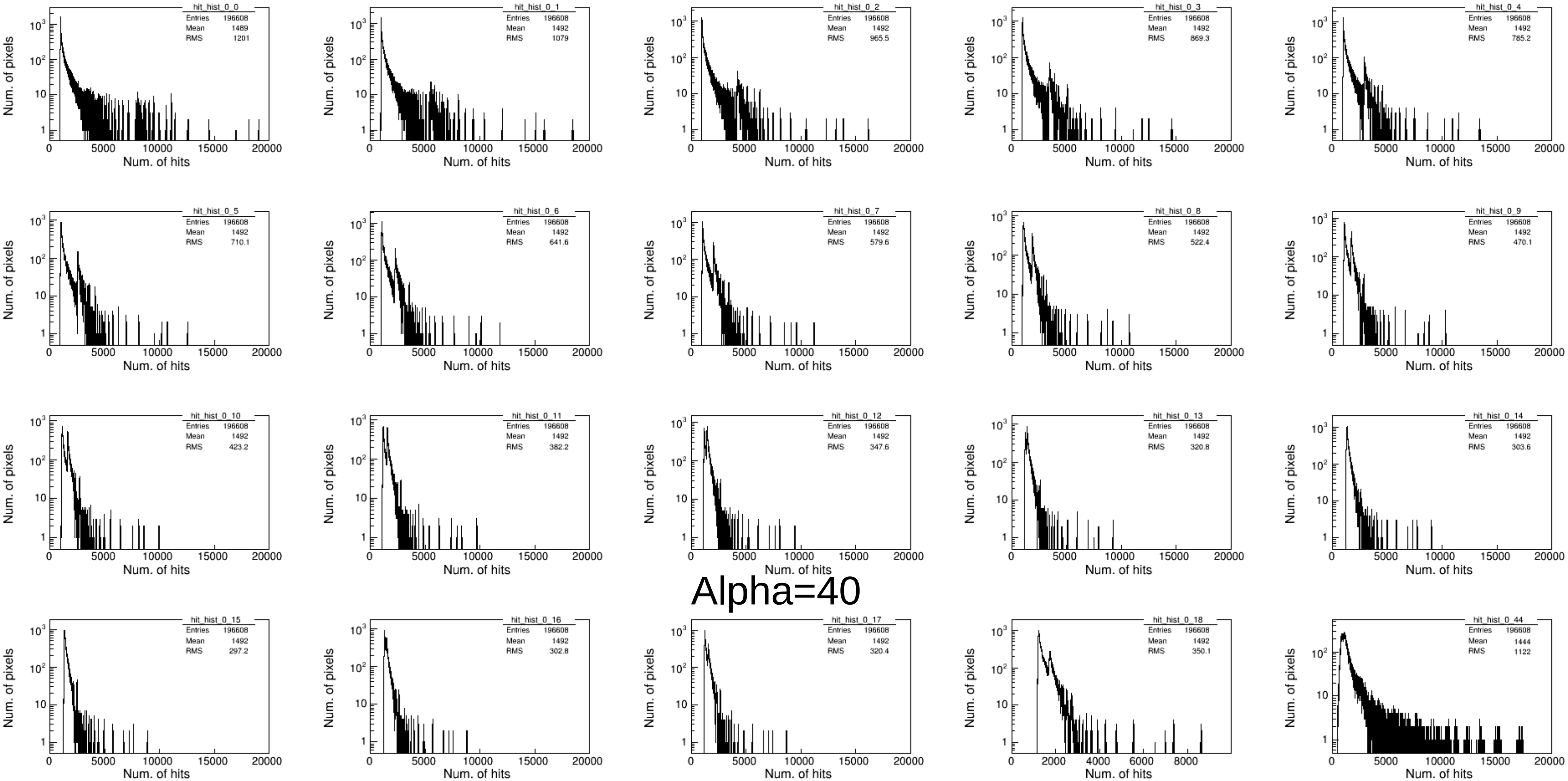


Scan strategy comparison

	WMAP	Planck	Litebird (fast spin)	EPIC	ESA M5 (arXiv:1604.02290)
Concept& Priority	Scan a pixel with many azimth angle, Comparison with COBE	Simplicity : Sun aspect angle constant to minimize thermal variation	Cross-link & Hit uniformity (+Jack-knife test?)	Cross-link & Jack-knife test	Cross-link (multi-spin)
Scan parameters	α=22.5º β=70º Prec = 1 hr Spin = 0.45 rpm	α=7.5º β=85º Prec = 6 months Spin = 1 rpm	α=65º β=30º Prec = 1.51 hrs Spin = 0.3 rpm	α=45º β=55º Prec = 3.2 hrs Spin = 1 rpm (option-?)	α=45º β=50º Prec = 40 hrs Spin = 0.4 rpm etc.
Cross-link map					
References/notes	http://map.gsfc.nasa.gov/mission/observatory_scan.html	https://wiki.cosmos.esa.int/planckpla/index.php/Survey_scanning_and_performance et al.	ADR heat cycle ~ 30 hrs	arXiv:0805.4207 0906.1188	arXiv: 1604.02290

Hit distribution (LiteBIRD spin=0.3rpm, varying alpha, beta)

Alpha=5 Alpha=7 …



全天面積 R=1として

$S = \frac{4}{\cancel{3}}\pi$

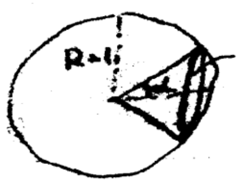
$N_{pix} = 12 \cdot 128^2 = 196608$ で割ると

$S_{pix} = S/N_{pix} \sim 2.13 \times 10^{-5}$ x 3

pixel を正方で近似すると

L_{pix} $\boxed{\text{pixel}}$ $L_{pix} = \sqrt{S/N_{pix}} = 4.62 \times 10^{-3}$ x sqrt(3)

これが隣りあう pixel のキョリ.



$\alpha = 65°$ で同天球に描く円周は

$L_{prec} = 2\pi \sin\alpha \sim 5.69$

これが間隔 L_{pix} で満たされれば良いので

precession 1つを spin が

$L_{prec}/L_{pix} \gtrsim 1231$ 回あれば /sqrt(3)

precessionは十分遅い。

spin rate $= 0.3$ rpm とすると (spin time 200秒)

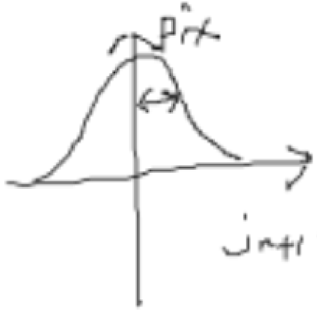
precession time $\gtrsim L_{prec}/L_{pix} \times 200$ sec

$= \frac{2\pi \sin\alpha}{\sqrt{S/N_{pix}}} \times 200$ sec ~ 68.54 hrs /sqrt(3) = 39.57 hrs

Simple statistical modeling ?

m pix $\quad T = \sum_{i=0}^{m} t_i$

$$t_i = \frac{T}{m} \qquad m = \frac{T}{t_i}$$



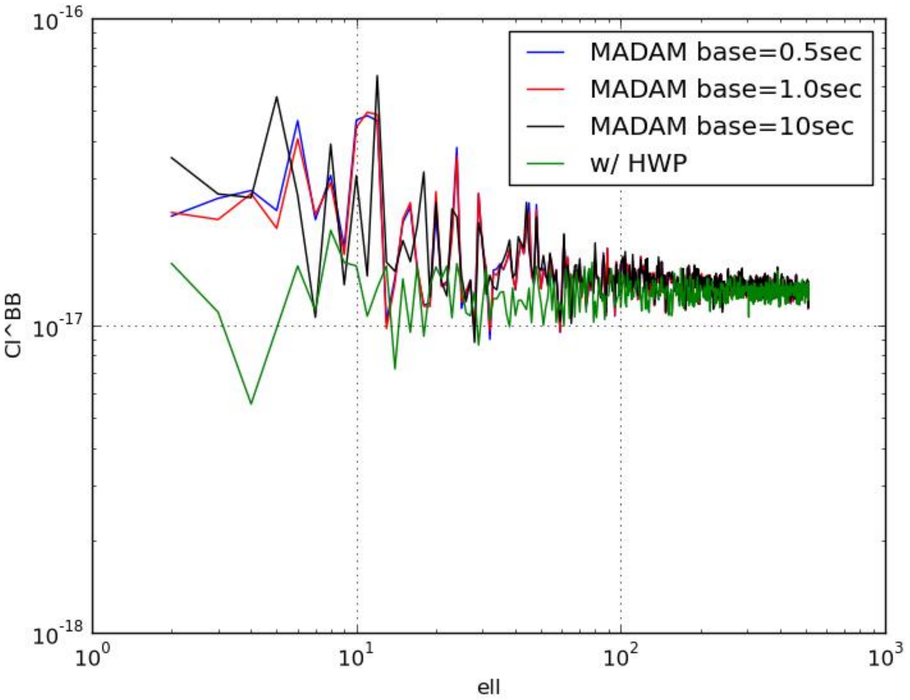
$$\sigma = \sqrt{2}\,NET/\sqrt{t_i} = \sqrt{2}\,NET\sqrt{\frac{m}{T}}$$

$j_{n+1} - j_n$

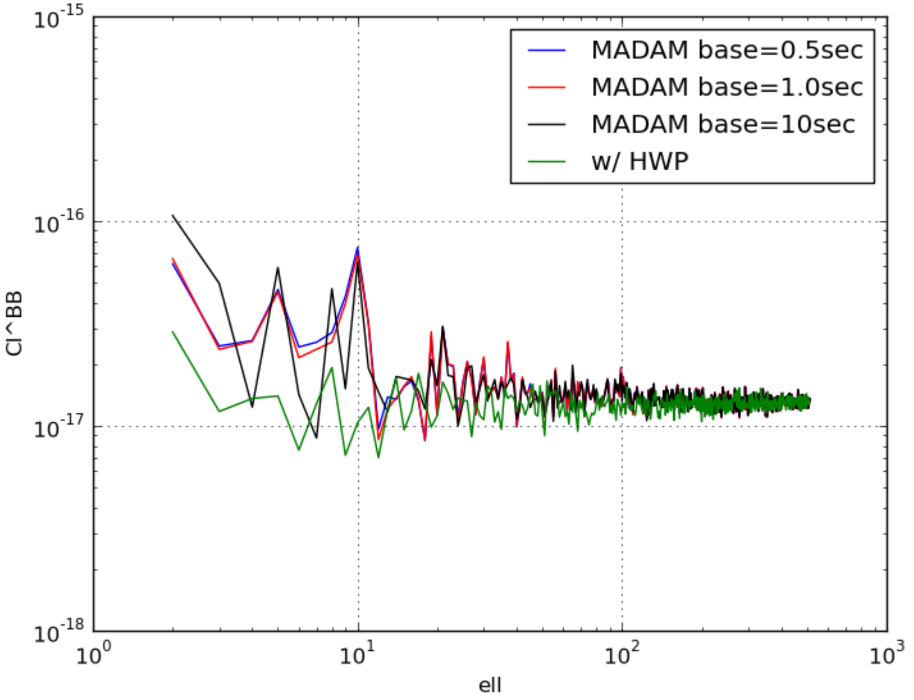
$$\Delta\sigma = \frac{\sigma}{\sqrt{2(m-1)}} = \frac{1}{\sqrt{2}}\sqrt{\frac{t_i}{T}}\,\frac{\sqrt{2}\,NET}{\sqrt{t_i}} = \frac{NET}{\sqrt{T}}$$

MADAM baseline scan

Large-alpha option



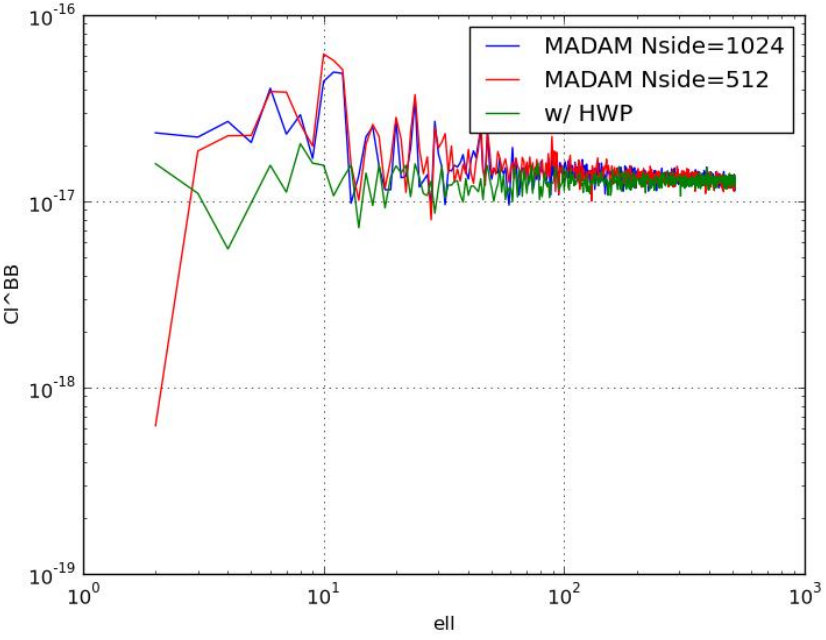
small-alpha option



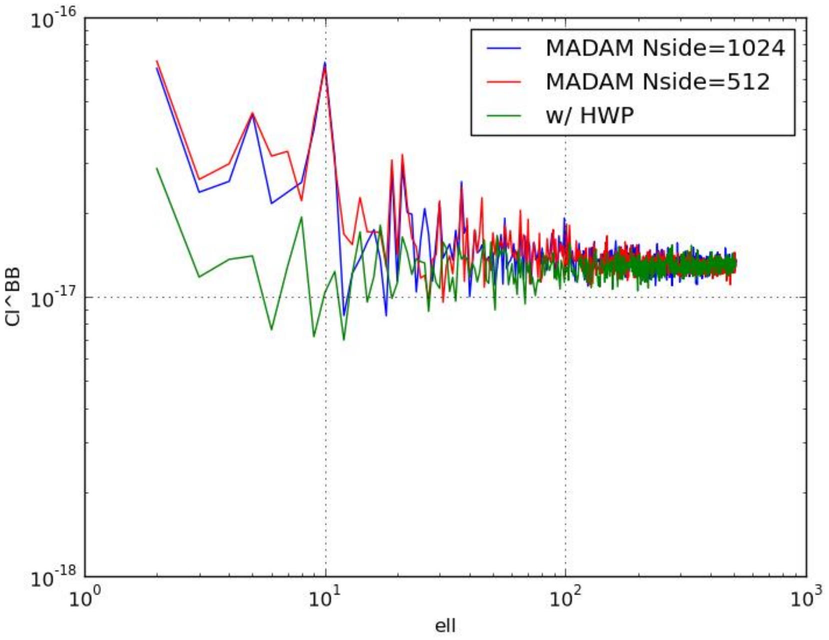
No much difference with baseline length among 0.5-10 sec
-> Omit from scan parameter list in the next iteration

MADAM resolution (Nside)

Large-alpha option



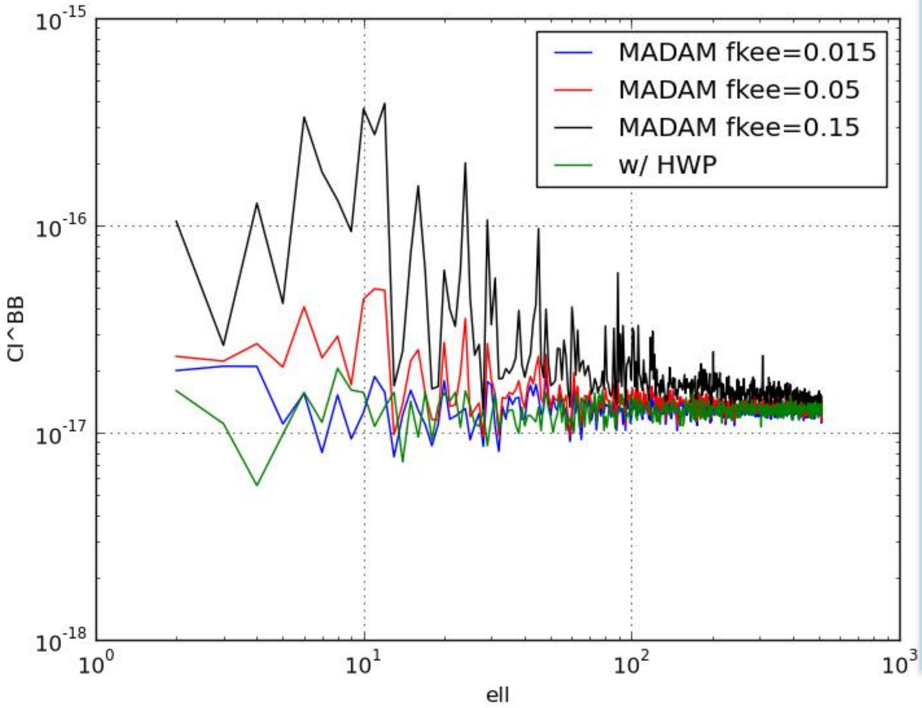
small-alpha option



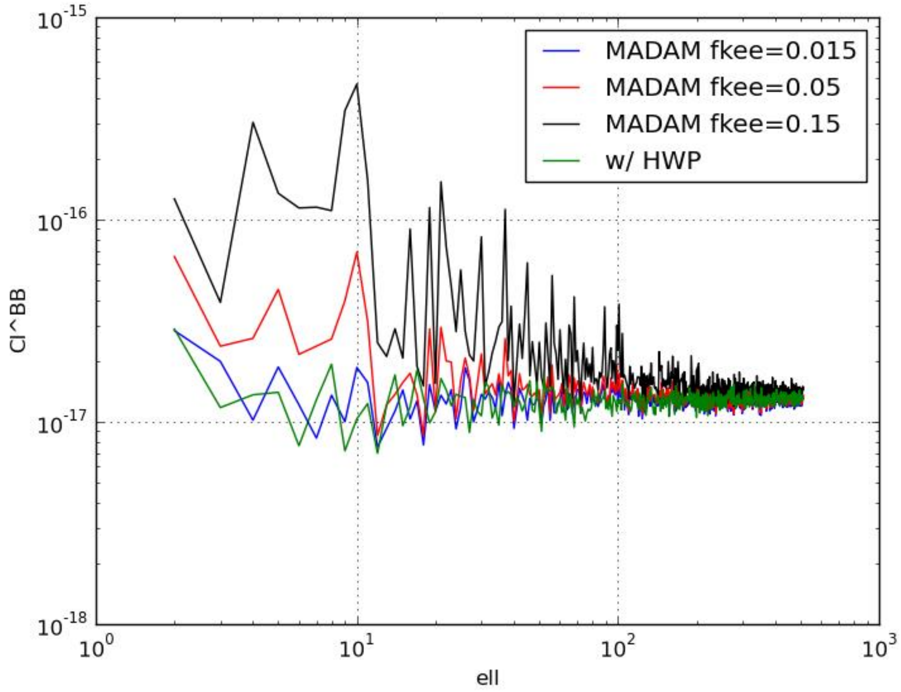
Somehow working, but a weird behavior observed.
Need more finer scan or more stat. for more understanding?

fknee scan

Large-alpha option



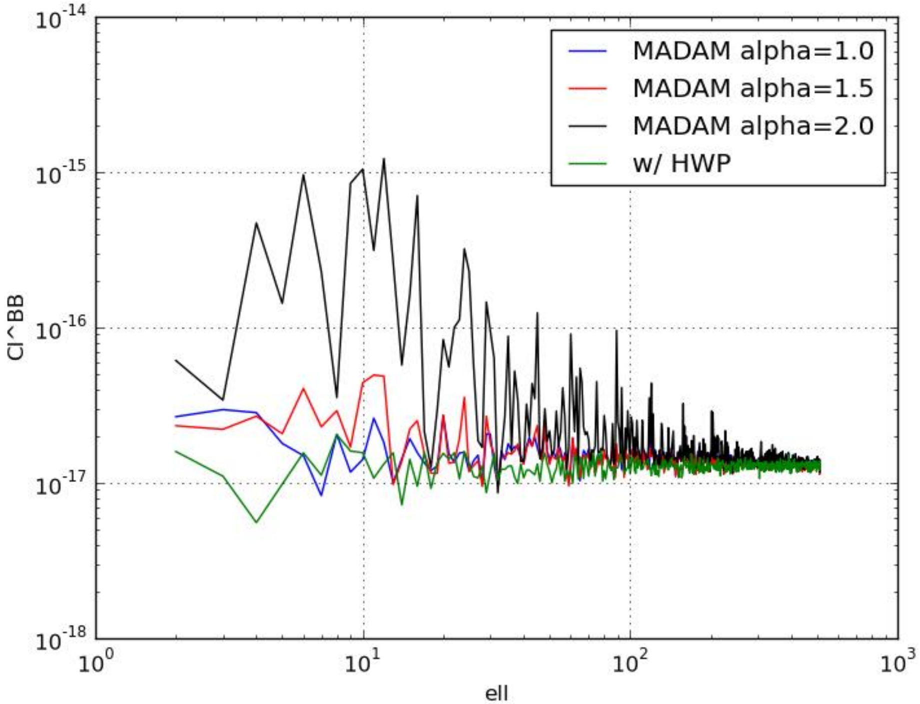
small-alpha option



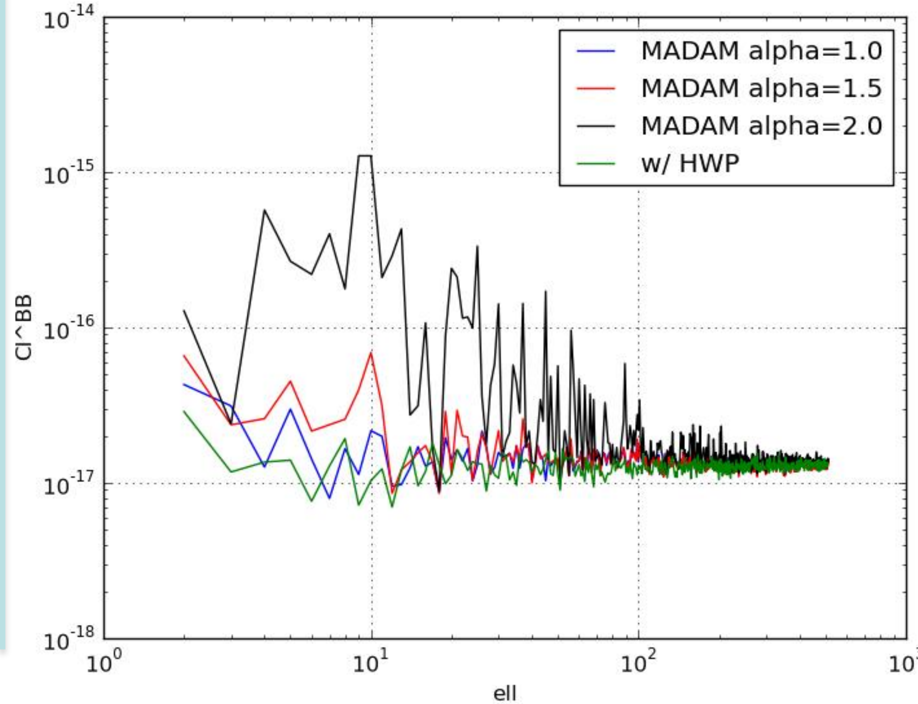
- Change on fknee 0.05 Hz -> 0.15 Hz makes big difference, while fknee < 0.05 Hz sh consistent results.
- Finer scan between fknee >0.05 Hz needed?
- What is the most reliable value of fknee we can have now?

Alpha (noise parameter) scan

Large-alpha option



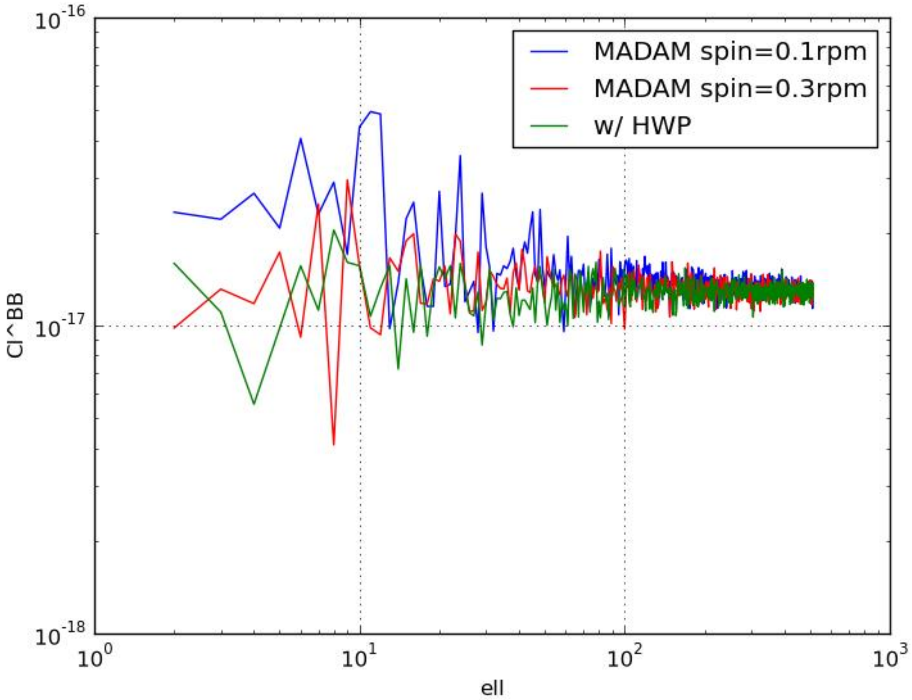
small-alpha option



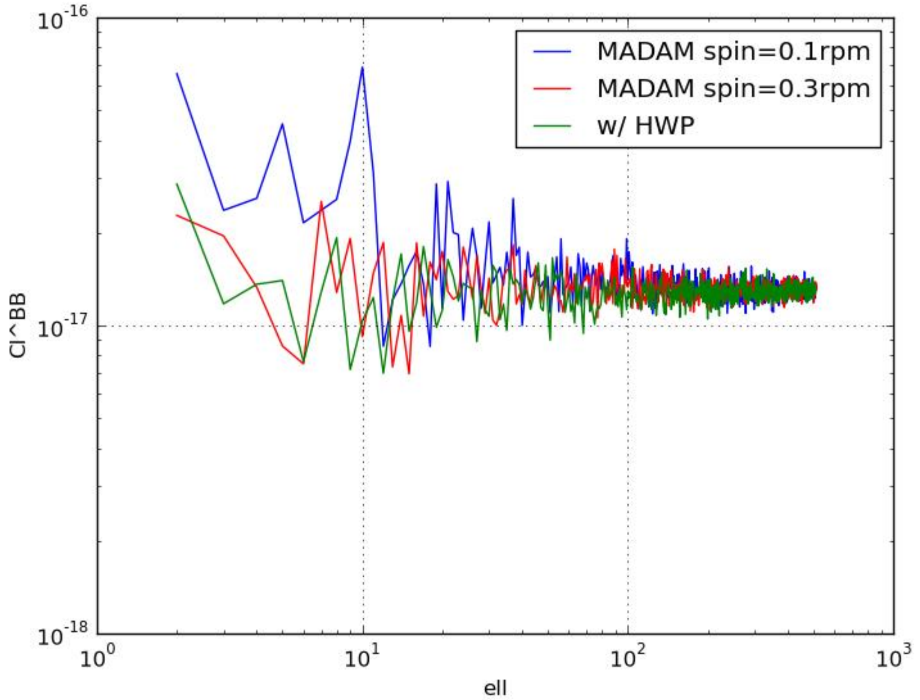
- Change on fknee 1.5 -> 2.0 makes big difference, while alpha < 1.5 show consistent results.
- Finer scan between alpha =1.5~2.0 needed?
- What is the most reliable value of alpha we can have now?

Effect of spin

Large-alpha option



small-alpha option



- In both large/small-alpha cases, spin=0.3 rpm shows consistently good result with the with the HWP.
- Worthwhile to do finer scan for spin=0.1~0.3, or faster?

Pixel ID (Npix=196608)