Summary of the current solar calibration in the QA2 process and its problems

“Interferometer”

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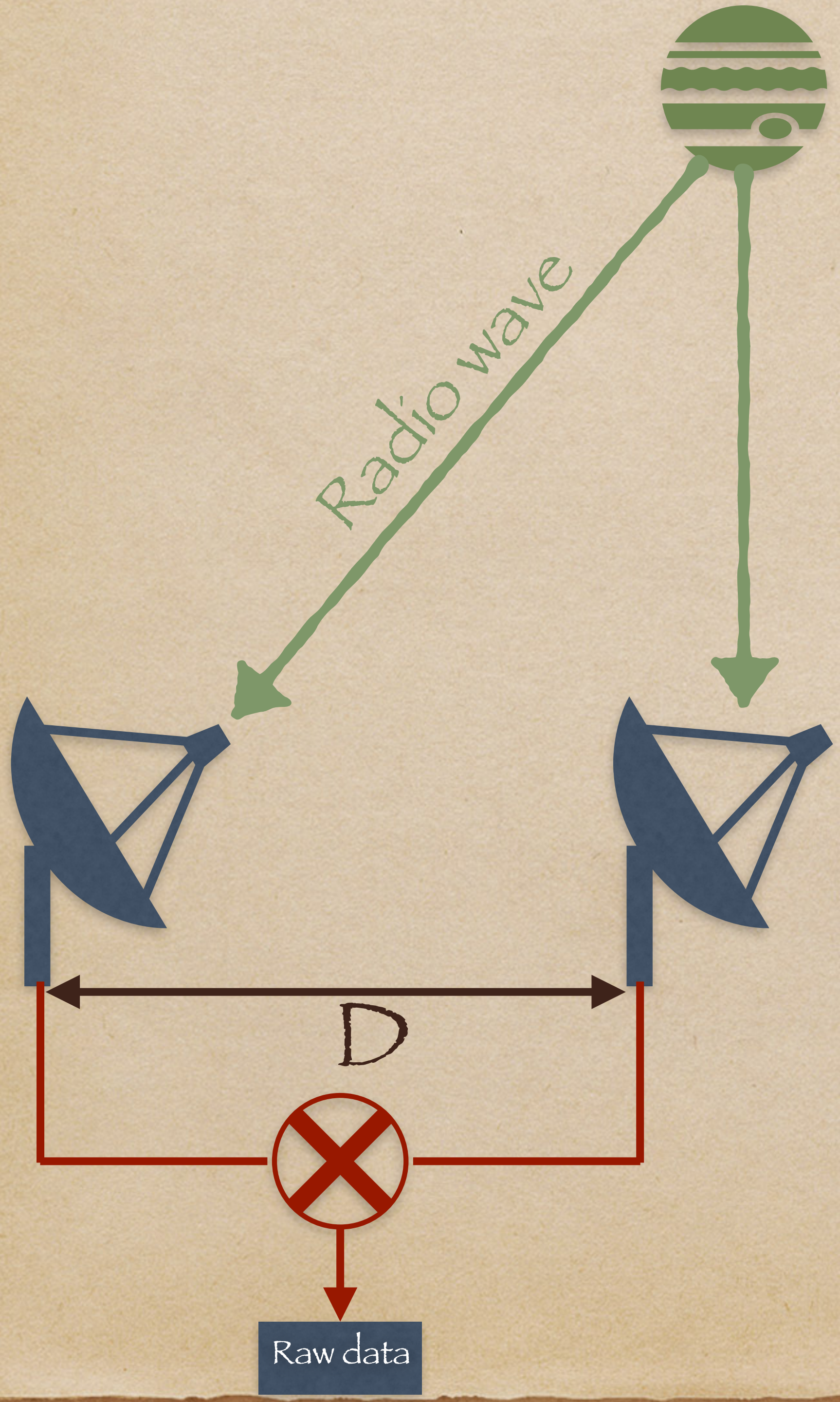
A radio interferometer is an instrument for obtaining Fourier components of the brightness distribution of the sky.



- From one pair (baseline) of two antennas, we can obtain one Fourier component.
- Fourier Series by Euler's Formula (1-dimension)
    - $f(x) = \Sigma C_n \cdot \exp(i2\pi D_n x/\lambda)$
        - n: ID of the Baseline
        - D_n: Distance between two antennas.
        - λ: Observing wavelength
        - $2\pi D_n/\lambda$: Spatial frequency
        - $C_n = r_n \cdot \exp(i\varphi_n)$: Complex Fourier coefficient
            - r_n: "Amplitude" / φ_n:"Phase"

But, the observed Fourier coefficients are not the actual values of the celestial target.

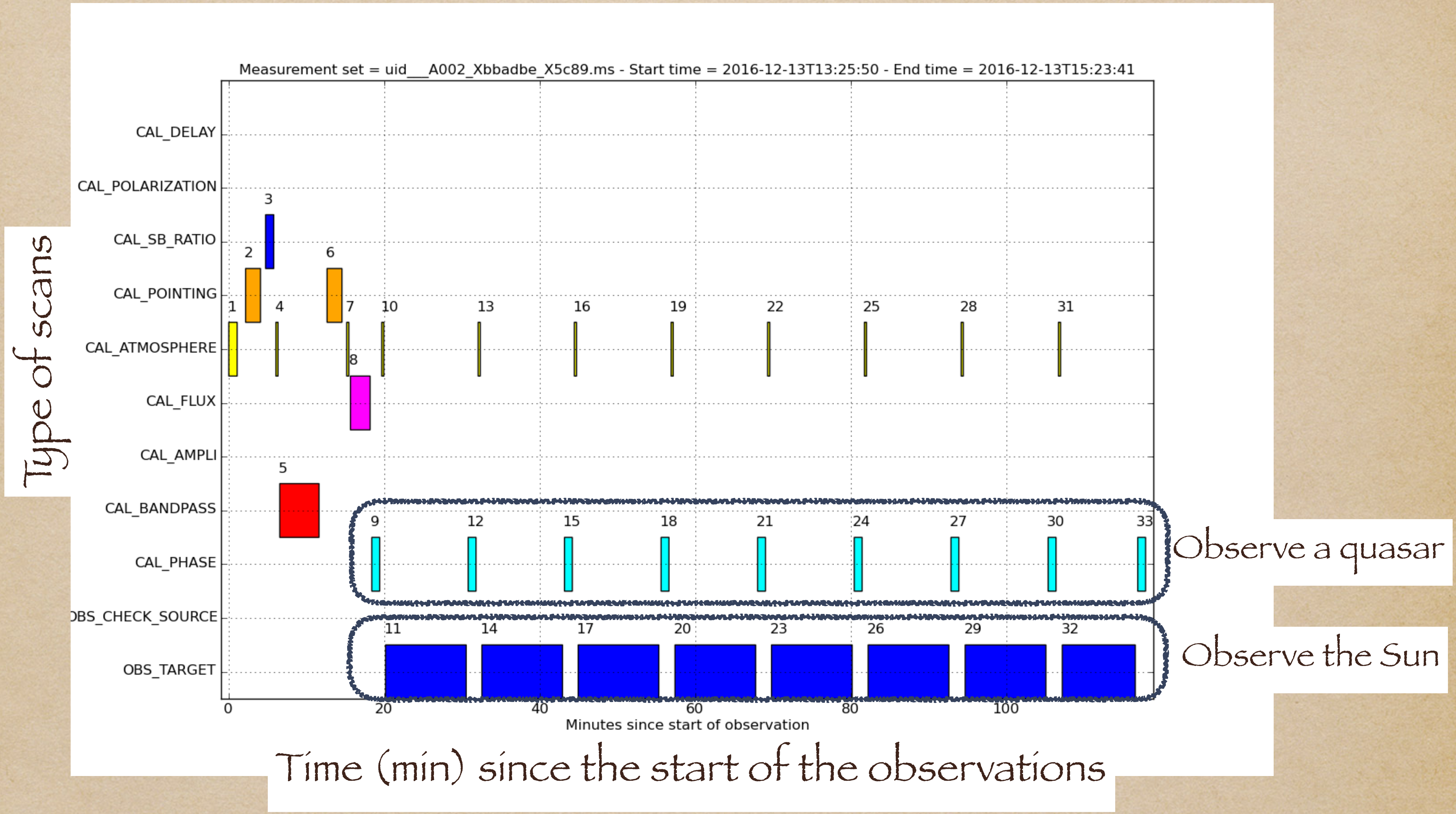
- The following things change the Fourier coefficients.
  - Earth atmosphere (especially, water vapor for mm/sub-mm wave)
  - Ununiformity and time variation of the antennas, receivers, cables, circuits, etc.
  - The error of the antenna location, and the deformation of the antennas.
  - etc. etc. etc.…
- "Calibration" of the interferometric data is to reduce such effects and obtain the true Fourier coefficients of the celestial target.
  - Actually, to obtain true "Amplitude" and "Phase" of the target, we measure the influences of the above effects and apply them to the raw data.

How to measure the influences? [Phase]

- All phases of the Fourier components of δ function are 0.
- "The δ function in the Sky" (=a point source) is a celestial object that is much smaller than the synthesized beam of the interferometer (= the spatial resolution of the interferometer).
- Therefore, the phase when observing a point source indicates the phase shift caused by things mentioned in the previous page.

To obtain the phase shifts, we observe a bright quasar near a scientific target frequently during an observation.

- Summary of an solar observation with ALMA



Type of scans

Observe a quasar

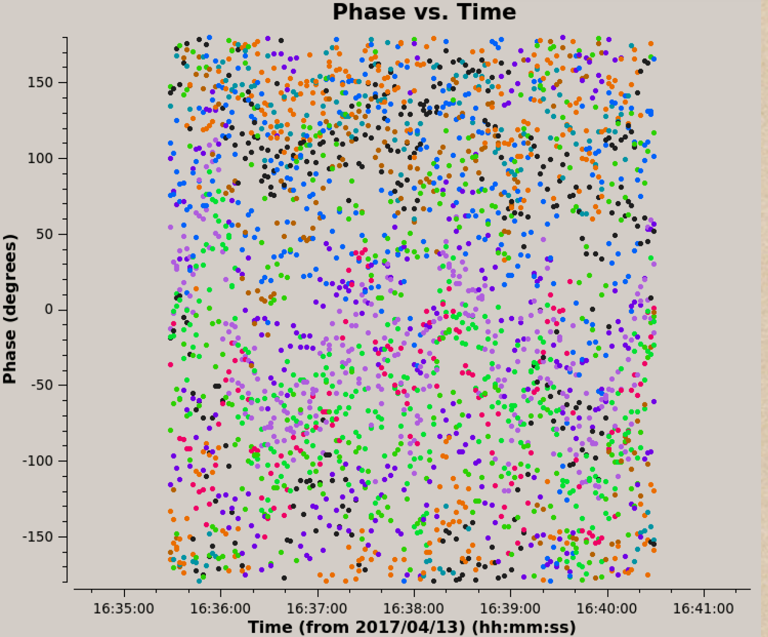
Observe the Sun

Time (min) since the start of the observations

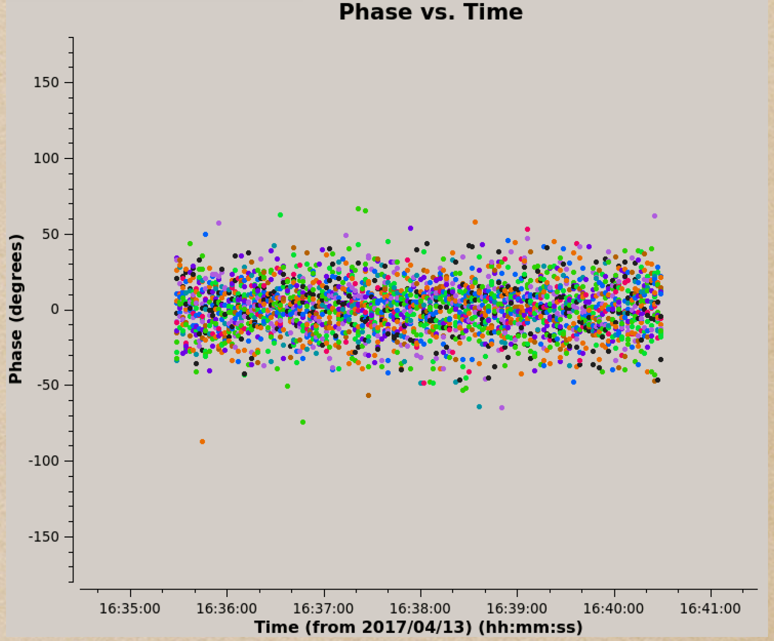
Phase shift varies in the time. So, we observe a phase calibrator (quasar) frequently.
100 GHz (Band3): every 10 mins, 239 GHz (Band6)/346 GHz(Band7): every 8 mins,

An example of phase shift & a result of the phase calibration

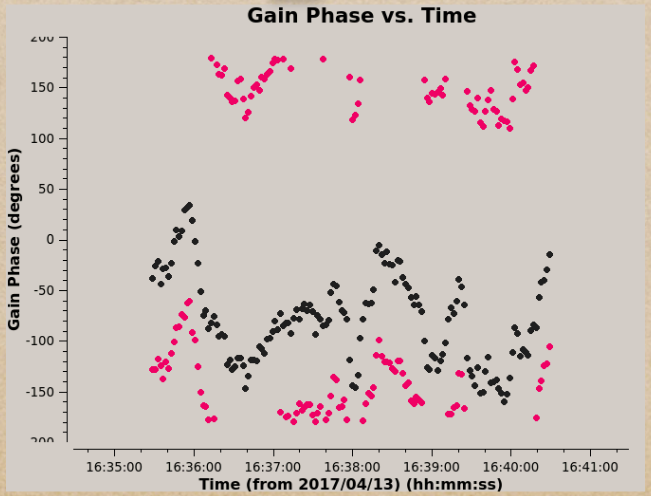
Observation of a quasar (bandpass calibration)



Each color indicates each baseline.



Each color indicates each baseline.



Black:XX

Magienda: YY

ex. The time variation of phase shift (DV01) during the bandpass calibration

Difficulty of the phase calibration for solar observations with ALMA

- Because the sensitivity of the receiver is reduced for observing the Sun, we have to select a bright quasar (>1 Jy) as a phase calibrator. Such bright quasars is not so many, especially in higher observing frequencies.

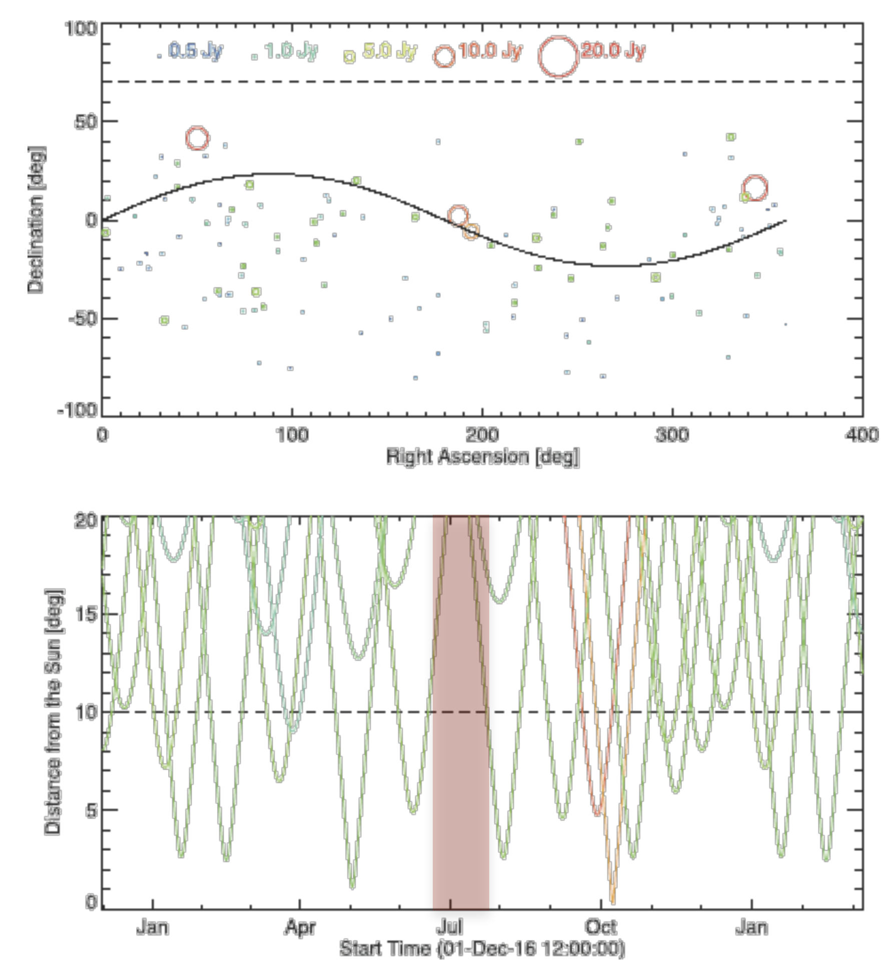


Figure 2 of Shimojo et al. (2017)
The bright quasars near the Sun
[>0.5 Jy at Band6]

- There is no bright quasar near the Sun around early July!!
- The brightness of a quasar varies in time. So, we have to revise the plot every Cycle.

How to measure the influences?

[Amplitude: 1] Method

- A raw data from the correlator is a "normalized" correlates coefficient(ρ). Hence, the data does not include information about the absolute value of Amplitude, include only the relative variation.

- To convert the normalized correlates coefficient to Amplitude (= Correlated Flux Density S_{cij}), we use the following relationships.

$$\rho_{i,j} = \frac{\sqrt{T_{ci}T_{cj}}}{\sqrt{T_{anti}+T_{sysi}}\sqrt{T_{antj}+T_{sysj}}} \Rightarrow S_{cij} = \frac{2k\sqrt{(T_{anti}+T_{sysi})(T_{antj}+T_{sysij})}}{\sqrt{A_{ei}A_{ej}}}\rho_{ij} = \rho_{ij}\sqrt{SEFD_i SEFD_j}$$

$$S = \frac{2kT}{A_e}$$

i,j: ID of an antenna
k: Boltsman constant
A_e: effective area of the antenna
S: flux density
T: output power from the receiver converted to temperature
"ant": power caused by a target (antenna temperature)
"sys": power caused by receiver itself & blank sky (system temperature)
"c": correlated component in T_{ant}

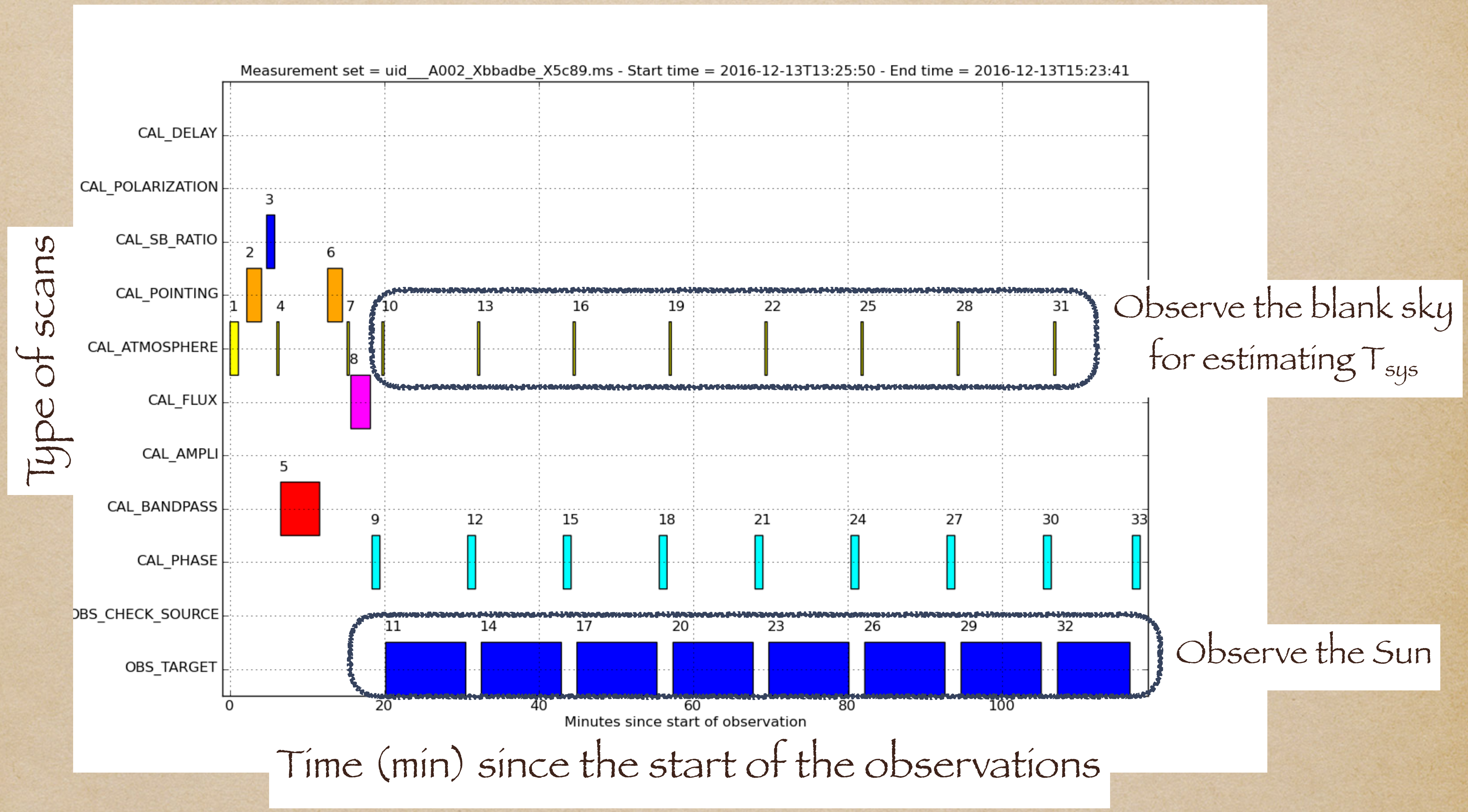
System Equivalent Flux Density

$$SEFD = \frac{2k(T_{ant}+T_{sys})}{A_e} \sim \frac{2kT_{sys}}{A_e}$$

$$\uparrow$$

$$T_{ant} \lll T_{sys}$$

- Summary of an solar observation with ALMA



Type of scans

Observe the blank sky for estimating T_{sys}

Observe the Sun

Time (min) since the start of the observations

T_{sys} varies in the time. So, we observe the sky near the target frequently.
100 GHz (Band3): every 10 mins, 239 GHz (Band6)/346 GHz(Band7): every 8 mins,

How to measure the influences?

[Amplitude: 2] ALMA's standard

- In the standard calibration script for non-solar QA2, we do not use the effective area of the antenna (A_e) for the amplitude calibration, and only Tsys is used as follows because "$T_{ant} \lll T_{sys}$" in most non-solar cases.

$$S_{cij\_nonscale} = \sqrt{T_{sysi} T_{sysj}} \cdot \rho_{ij}$$

- To establish the absolute flux scaling, comparing between the flux density of a bright quasar (=flux calibrator) recorded in the calibrator catalogue with the observed value ($S_{cij\_nonscale}$)of the same quasar, and estimating the factor for the flux correction.
    - Calibrator Catalogue: https://almascience.nao.ac.jp/alma-data/calibrator-catalogue

How to measure the influences?

[Amplitude: 3] For solar observations

- "$T_{ant} \lll T_{sys}$" is not valid, because T_{ant} of the Sun is larger than T_{sys}. So, we cannot neglect T_{ant} and have to use the following formula.

$$S_{cij\_nonscale} = \sqrt{(T_{anti} + T_{sysi})(T_{antj} + T_{sysj})} \cdot \rho_{ij}$$

- To calculate the above , we estimate T_{ant} for all antennas, all spectral windows, all correlations (XX and YY), and all sub-scans (every 30 sec for single-pointing, every 7 sec for MOSAIC).
  - Since we have to use the data from the SQLD for the estimation, we assume that T_{ant} is the same in all channels of a spectrum window.
  - Due to the process of estimating T_{ant}, the standard calibration of QA2 for solar interferometric data takes longer than one night, in present.
- The processes after calculating $S_{cij\_nonscale}$ are the same as those for non-solar data.
  - In most solar cases, a bandpass calibrator is used as a flux calibrator.

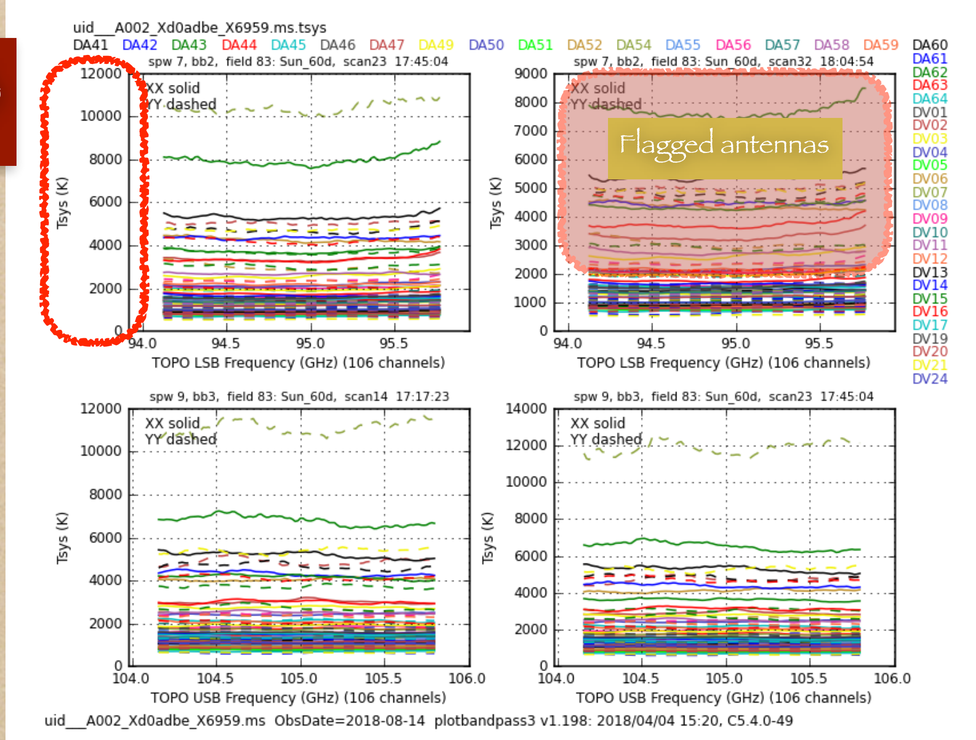
The list of the current issues in the standard calibration in QA2 of solar interferometric data

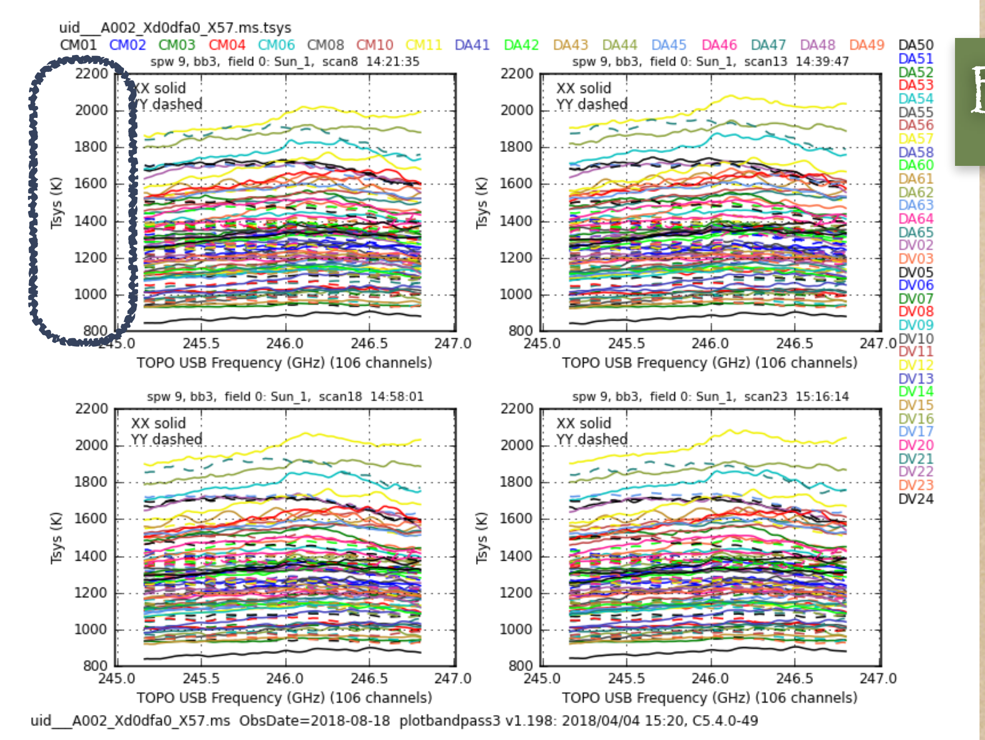
1. Anomaly of T_{sys} in Band3.
2. Large variation of T_{ant} in a sub-scan.
3. Asymmetry of the brightness difference between XX and YY.
4. How to establish the flux calibration between spectrum windows?
5. The inconsistent of the flux calibration method between interferometric and single-dish observations.

- 4 and 5 are closely related to the single-dish calibration.

1. Anomaly of T_{sys} in Band3.

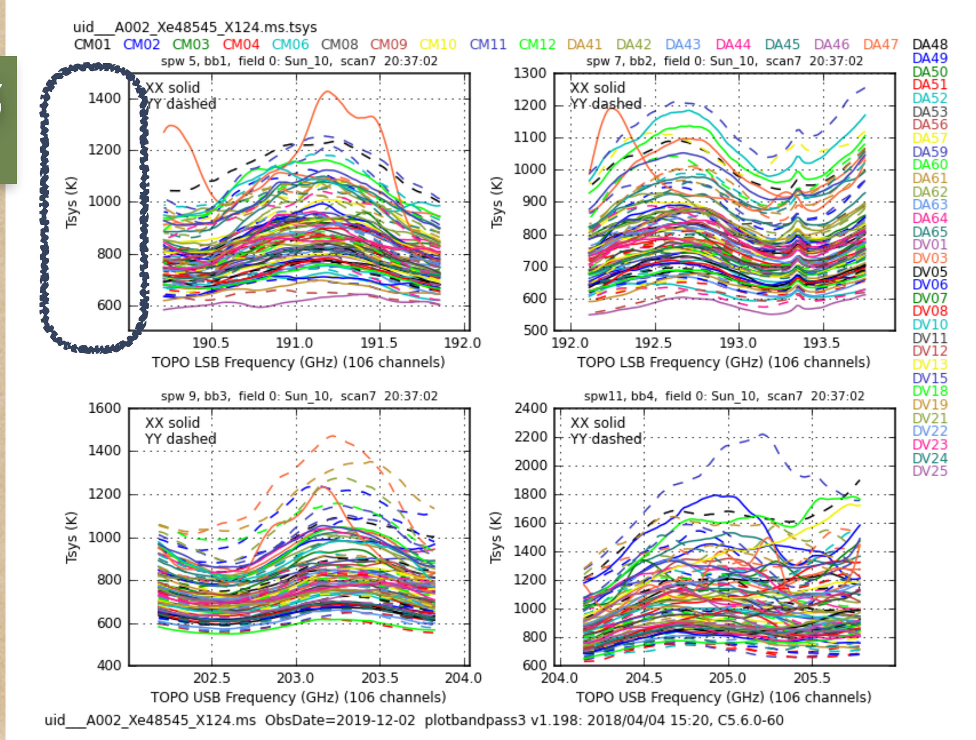
Band3





Band6

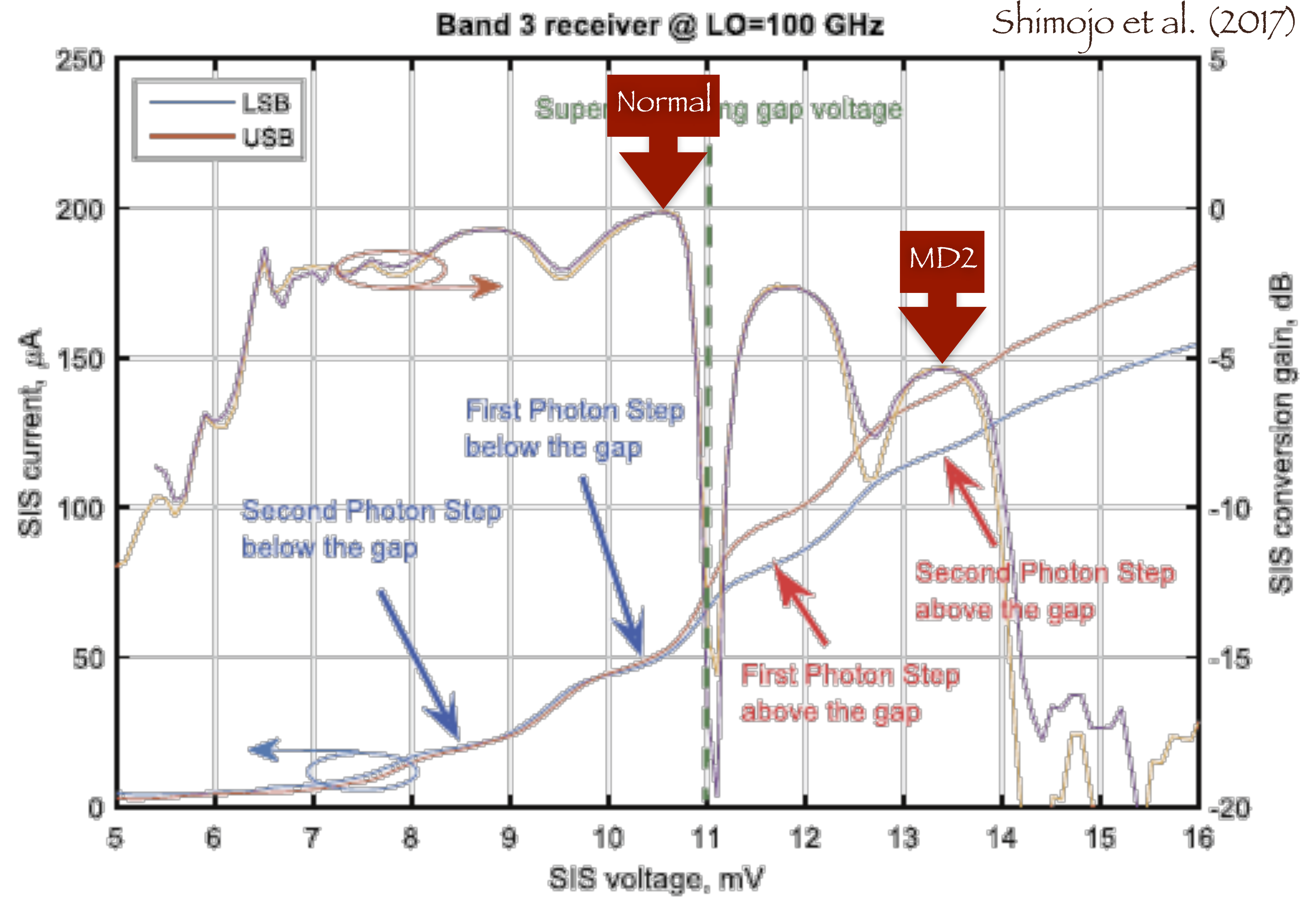
Band5



- The number of the flagged antennas by the anomalous Tsys in Band3 is always larger than that in the other bands (~ 5 antennas in Band3).
- It might be caused by the unstable of the MD mode.
- The optimization of bias voltage and LO power for Band5 should be applied to Band3 too?

The Band3 receiver's gain profile as a function of the SIS bias voltage

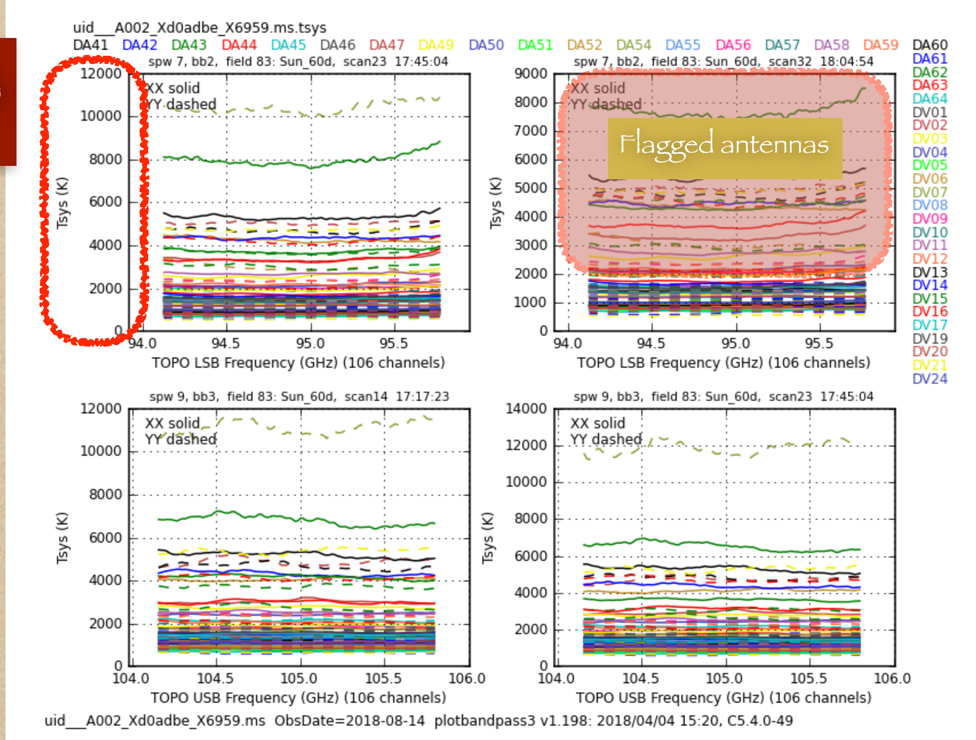
It is a typical (average) one. The profile of each SIS mixer is different a bit.



Shimojo et al. (2017)

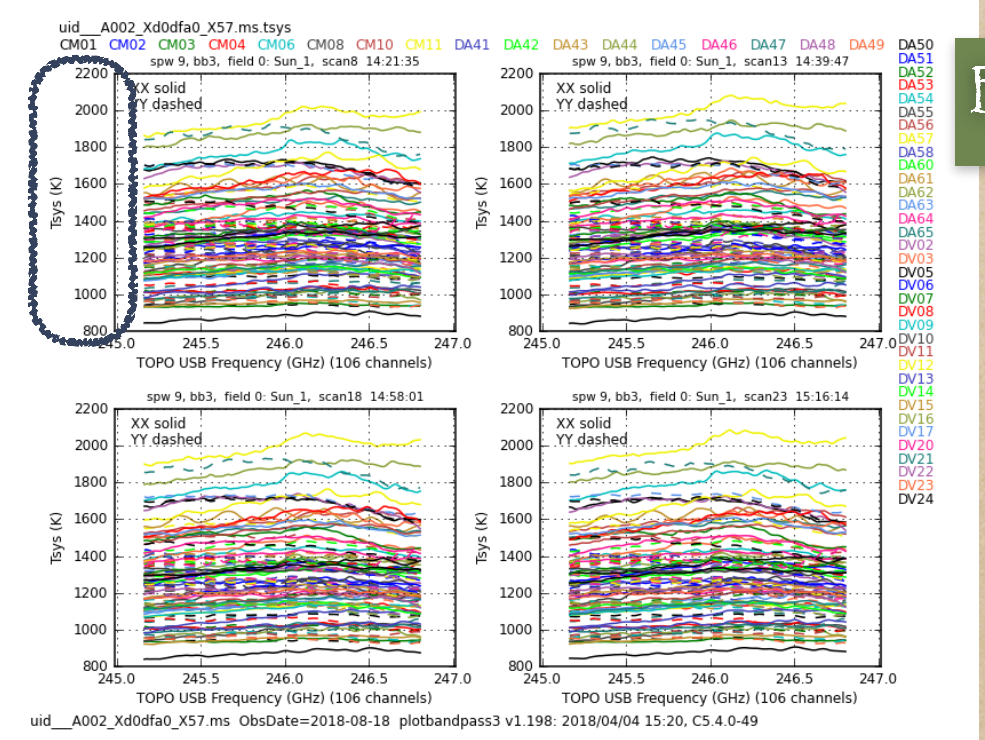
1. Anomaly of T_{sys} in Band3.

Band3

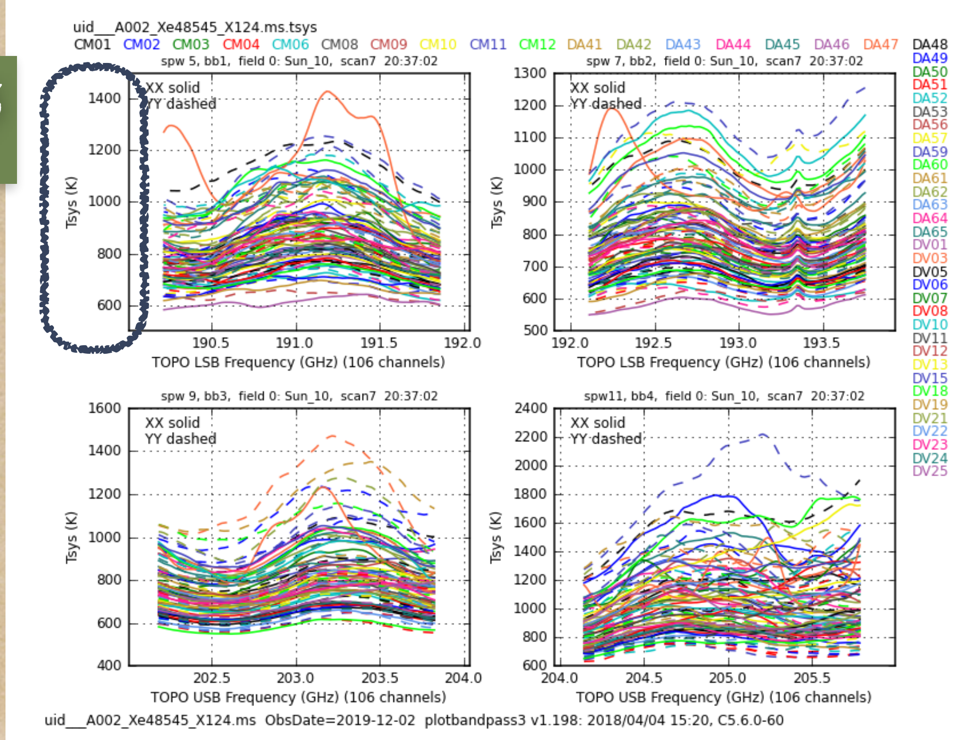


Flagged antennas

Band6



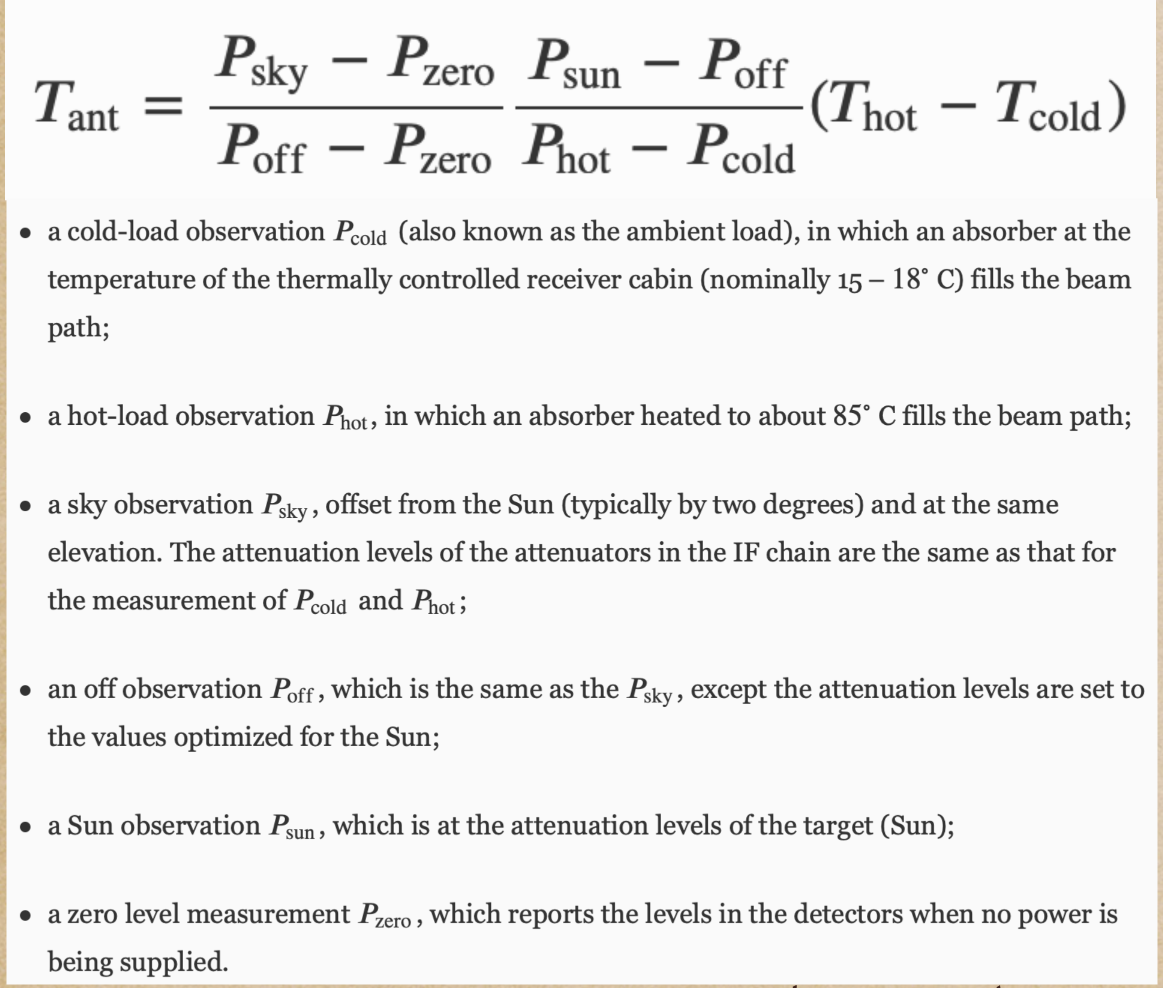
Band5



- The number of the flagged antennas by the anomalous Tsys in Band3 is always larger than that in the other bands (> 5 antennas in Band3).
- It might be caused by the unstable of the MD mode.
- The optimization of bias voltage and LO power for Band5 should be applied to Band3 too?

2. Large variation of T_{ant} in a sub-scan.

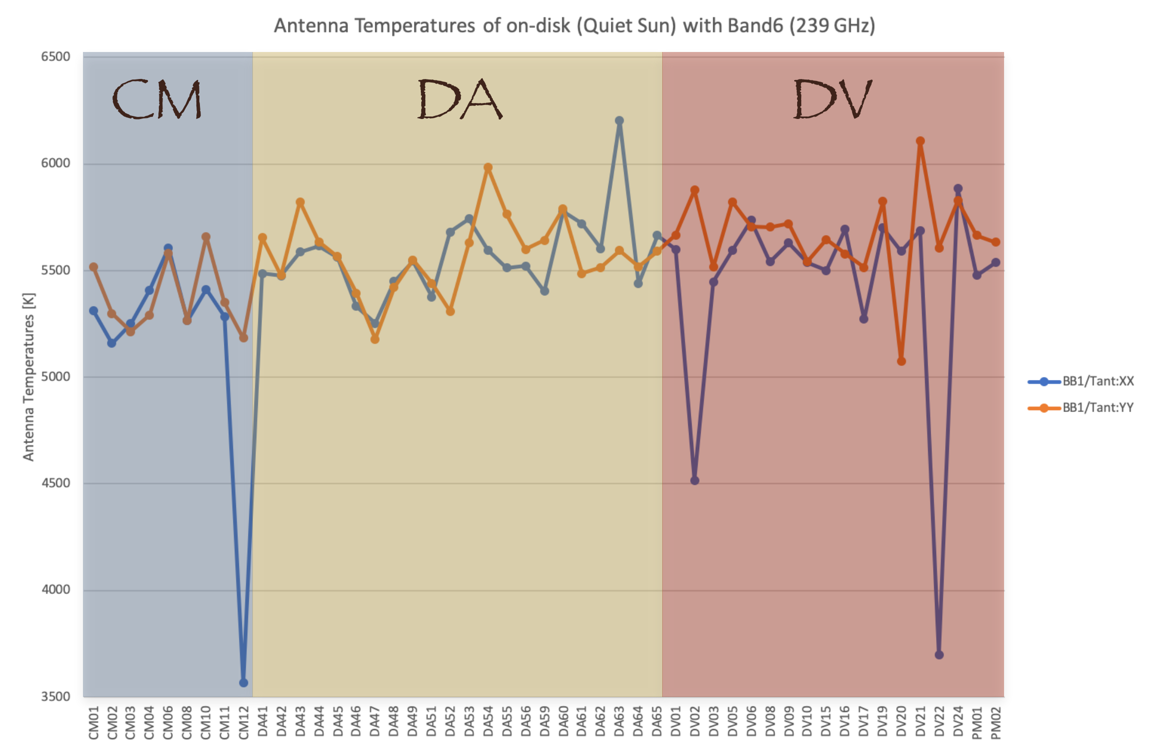
- T_{ant}: output power from the receiver caused by a target.
  - The value is derived using the data of the SQLD and the following formula, because the dynamic range of the corrleator is not enough for the calculation.



$$T_{\text{ant}} = \frac{P_{\text{sky}} - P_{\text{zero}}}{P_{\text{off}} - P_{\text{zero}}} \frac{P_{\text{sun}} - P_{\text{off}}}{P_{\text{hot}} - P_{\text{cold}}} (T_{\text{hot}} - T_{\text{cold}})$$

- a cold-load observation P_{cold} (also known as the ambient load), in which an absorber at the temperature of the thermally controlled receiver cabin (nominally 15 – 18° C) fills the beam path;
- a hot-load observation P_{hot}, in which an absorber heated to about 85° C fills the beam path;
- a sky observation P_{sky}, offset from the Sun (typically by two degrees) and at the same elevation. The attenuation levels of the attenuators in the IF chain are the same as that for the measurement of P_{cold} and P_{hot};
- an off observation P_{off}, which is the same as the P_{sky}, except the attenuation levels are set to the values optimized for the Sun;
- a Sun observation P_{sun}, which is at the attenuation levels of the target (Sun);
- a zero level measurement P_{zero}, which reports the levels in the detectors when no power is being supplied.

Shimojo et al. (2017)



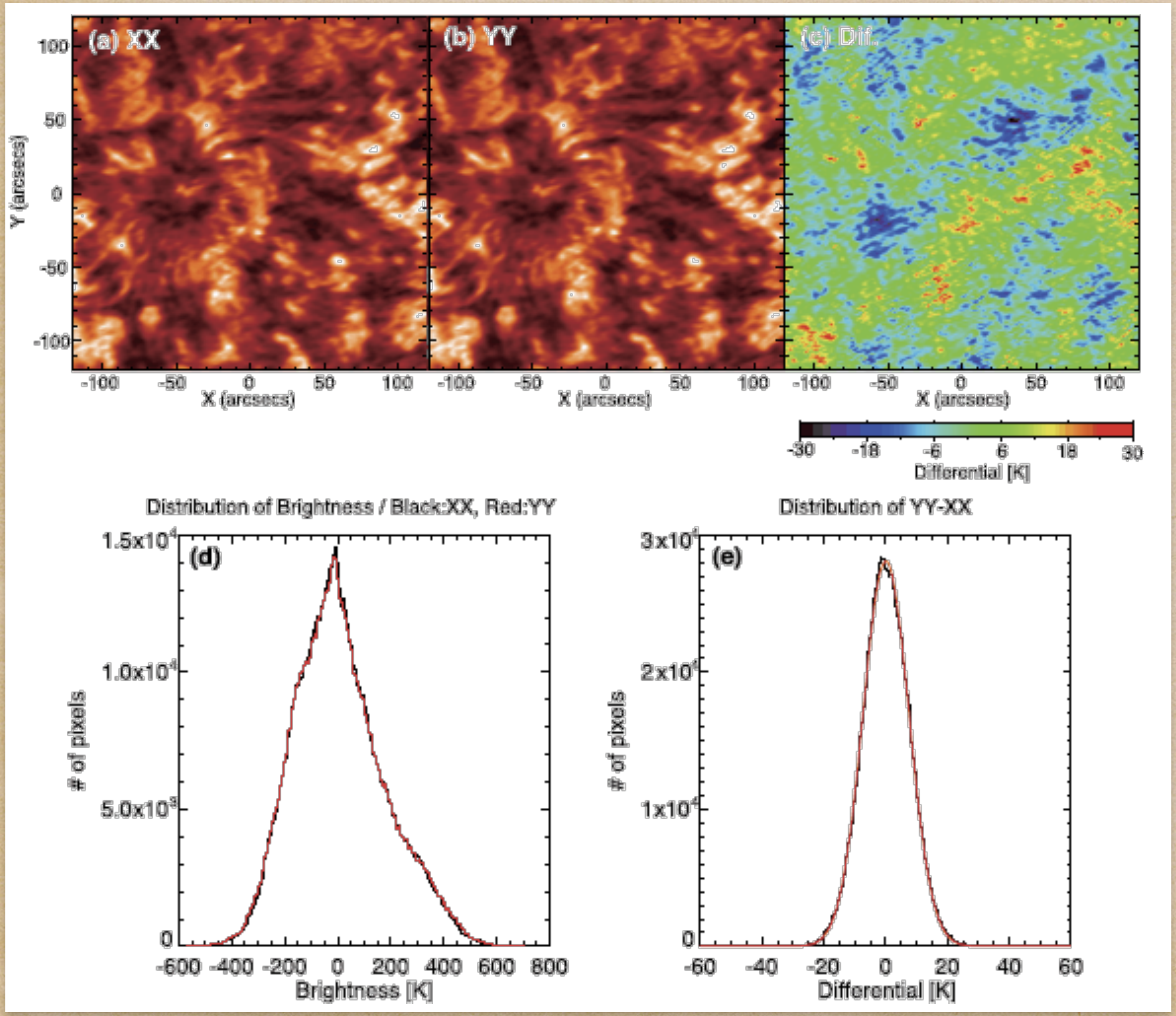
What is caused the large variation?

3. Asymmetry of the brightness difference between XX and YY.

[Background]

- Except for the limb observations, the whole FoV is covered by the Sun. So, we cannot use blank sky (an area included no radio sources) in an image for evaluating the noise level of an image.
- Instead of blank sky, we evaluate the noise level of a solar image from the difference between XX and YY images (orthogonal polarization data). For the evaluation, we assume that the polarization degree from the Sun is negligible small. (Shimojo et al. 2017)
- <ins>To estimate the noise level, the calibration of interferometric data is carried out for each polarization (XX, YY), independently.</ins>

Succeeded example of estimating noise level from the difference between XX and YY.

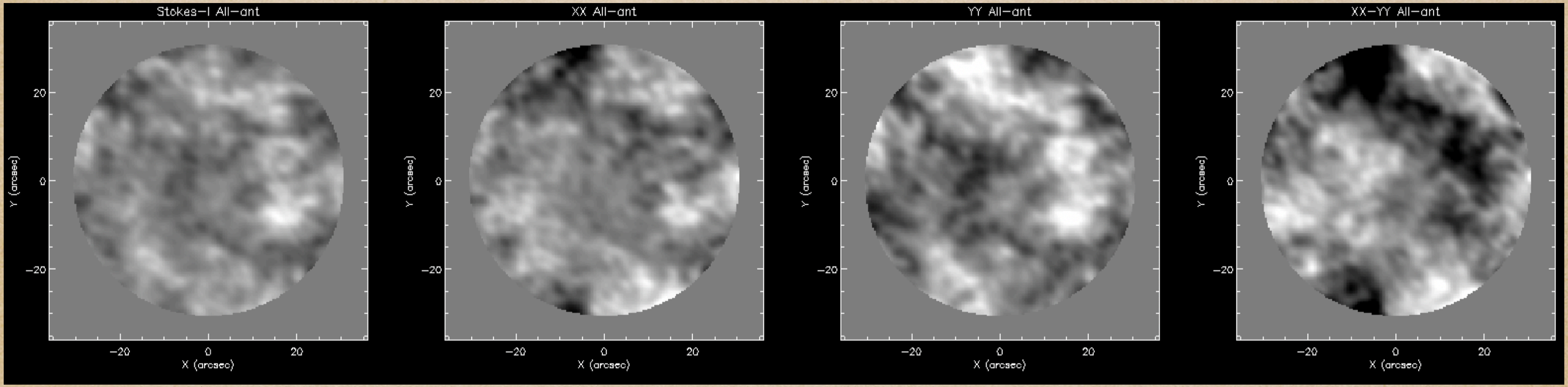


Band3 Sunspot from MOSAIC.

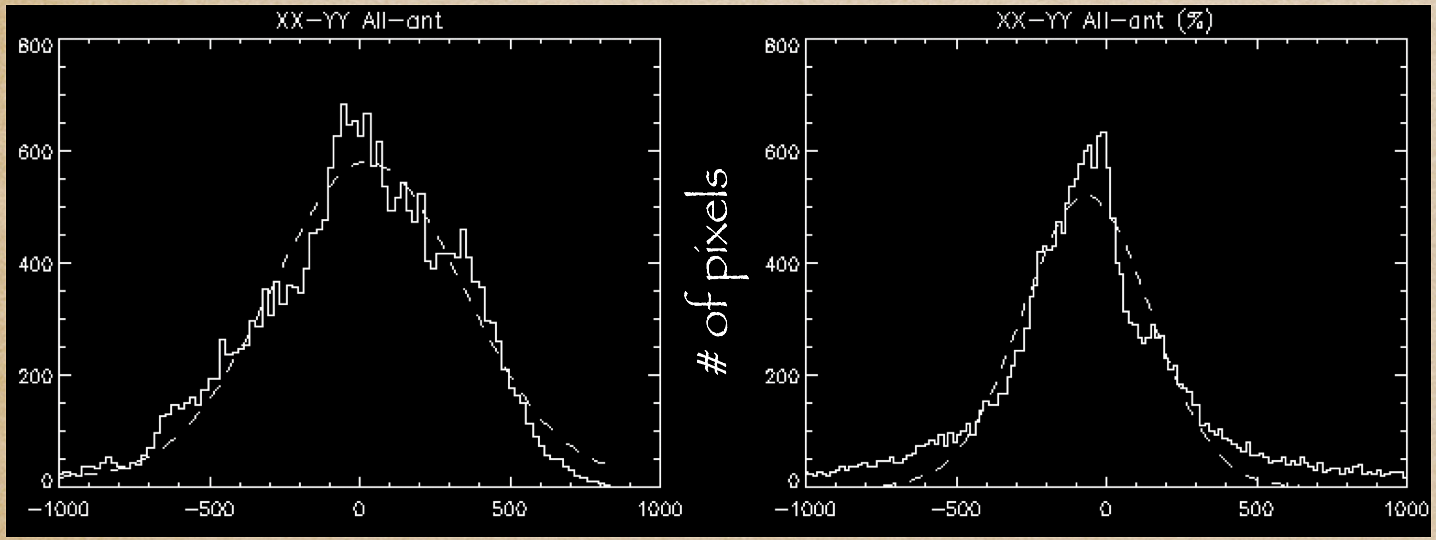
Shimojo et al. (2017)

Noise level: 3.7K

Unsucceeded example of estimating noise level from the difference between XX and YY.



Stokes-I XX YY XX-YY



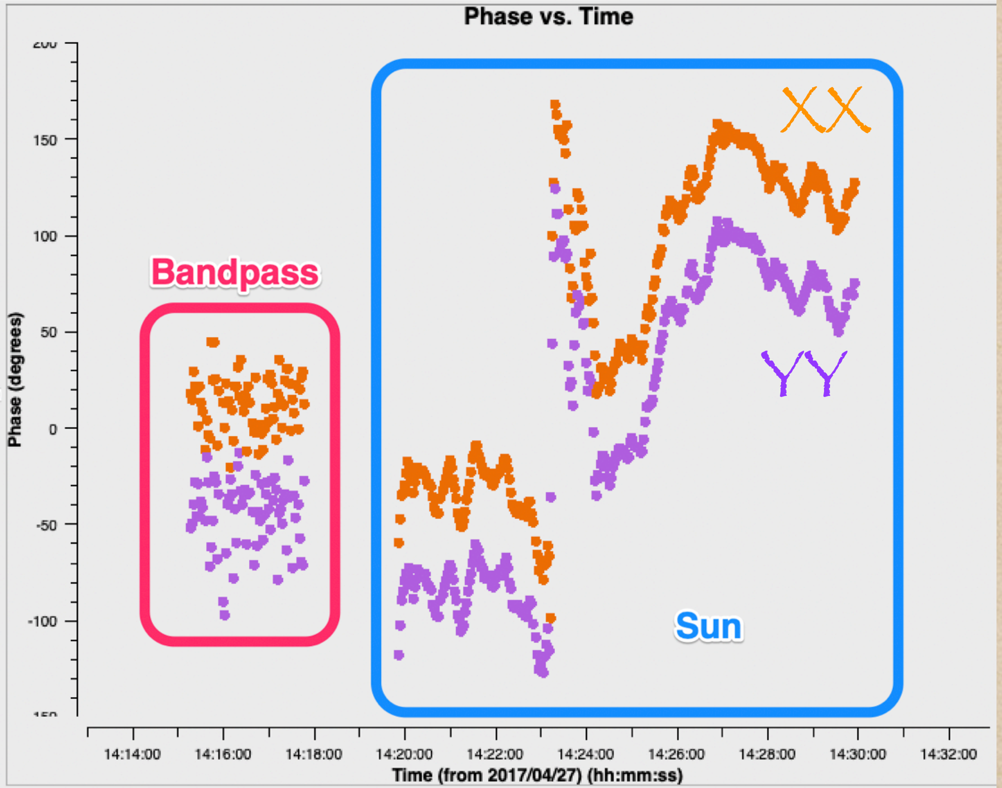
Difference XX-YY [K] (XX-YY)/Stokes-I [%]

Offset from “0”: 26.7 K / 65%
Width of the gaussian: <u>316 K / 210%</u>

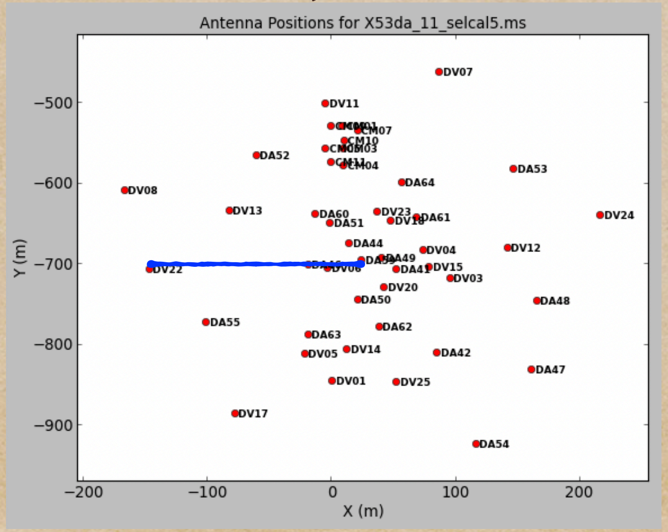
Project ID:2016.1.01532.S PI: Bin Chen
EB ID: uid://A002/Xbfb22d/X53da

- XX image differs from and YY images siginificantly😫.

What's happen?
"The phase calibration is partially failed!"

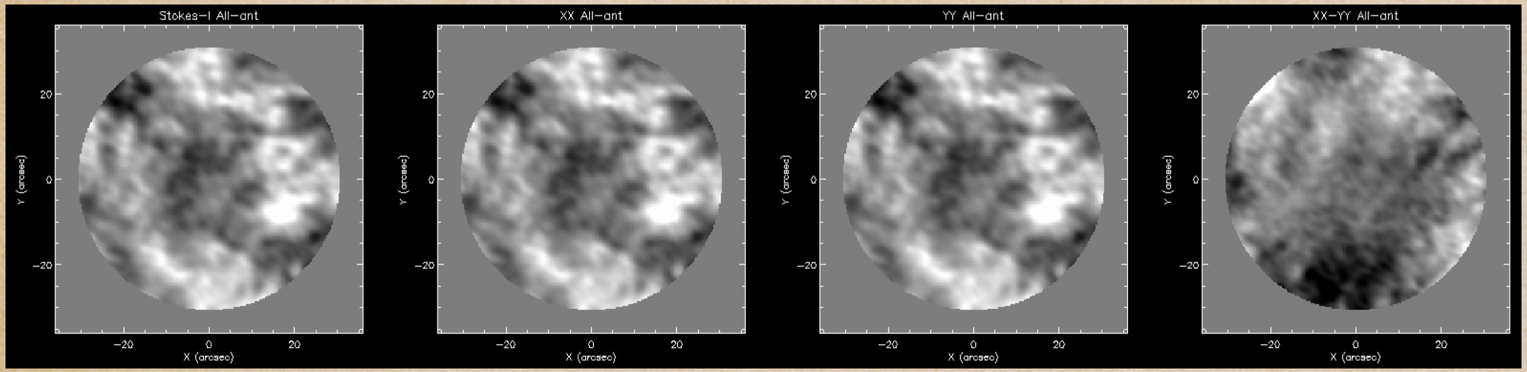


Time variation of the phase (DV59-DV22)



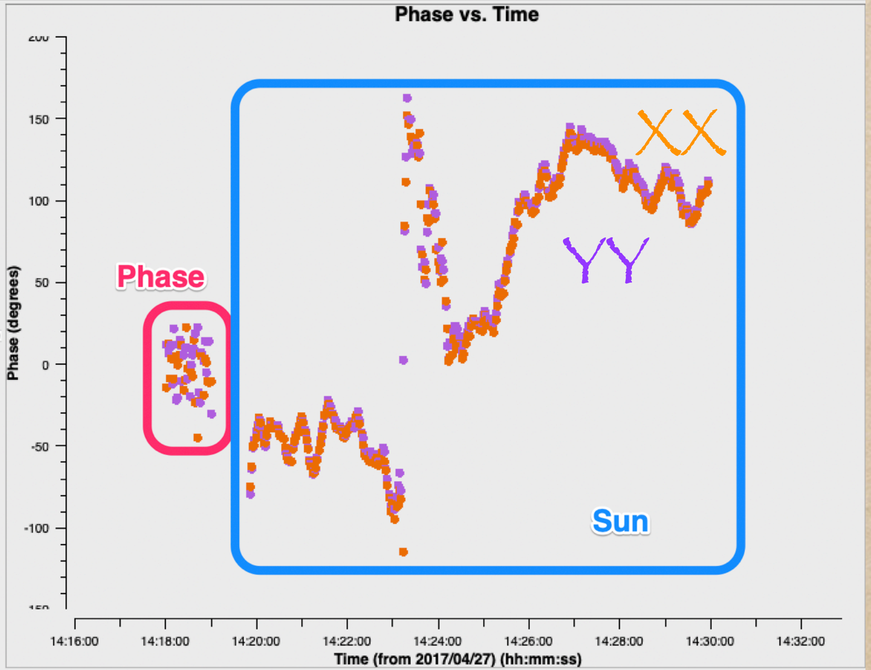
- The phase of the Sun is well measured, and the (relative) time variation of XX is the same as that of YY.
- But, there is a large offset (~50 deg.) between XX and YY.
- The offset is also shown at the bandpass calibration.

If the phase calibration is carried out using both XX and YY data,…

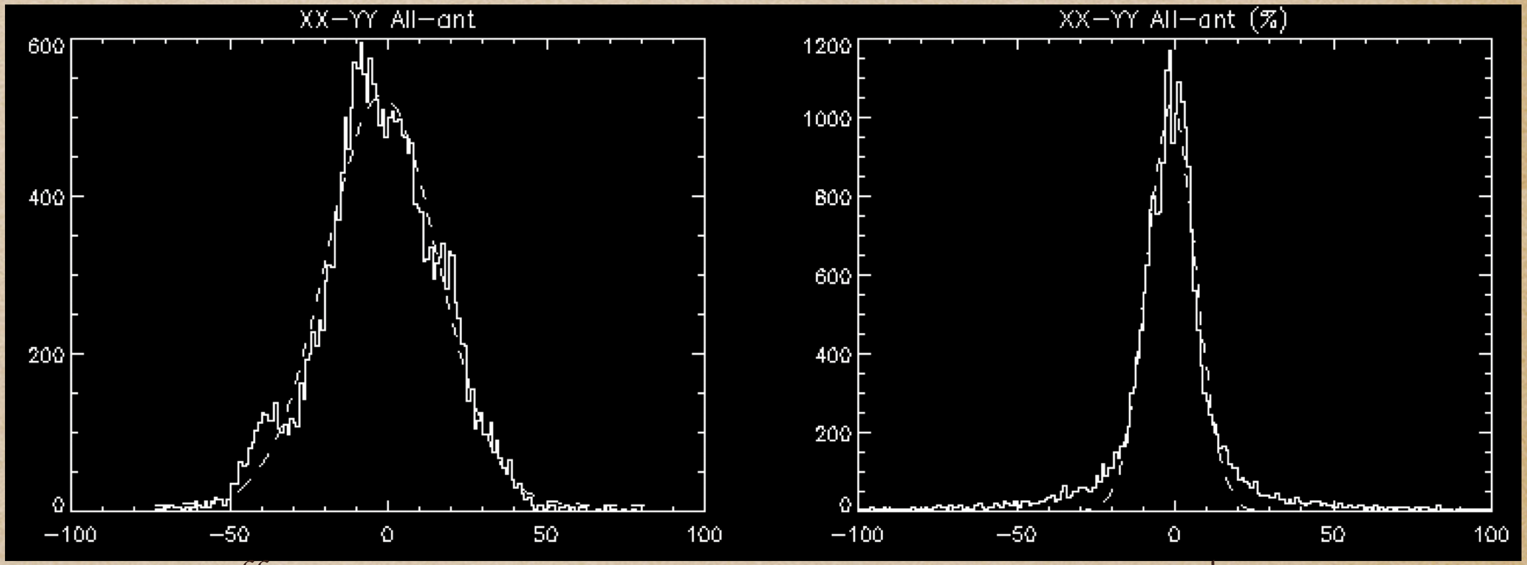


Stokes-I XX YY XX-YY

- Use "gaintype='T'" of the "gaincal" task, instead of "G".
  - "gaintype='T'" is the standard of ALMA QA2 calibration.



Time variation of the phase (DV59-DV22)



Difference XX-YY [K] (XX-YY)/Stokes-I [%]

Offset from "0": 1.8 K / 1.1%

Width of the gaussian: 17.5 K / 7.6%

Independency of XX and YY images for estimating noise level?

4. How to establish the flux calibration between spectrum windows?

- When we estimate the spectrum from only the images synthesized from each SPW data, the precision of them depends on only the precision of the calibration of the interferometric data. It is the same as most of the non-solar cases.

- To obtain the spectra of the structures on the solar disk, especially of the stable one, the combining of the synthesized images and the full-sun maps obtained with single-dish observations is essential.
    - In the case, the precision of spectra depends on mainly the precision of the calibration of single-dish data.

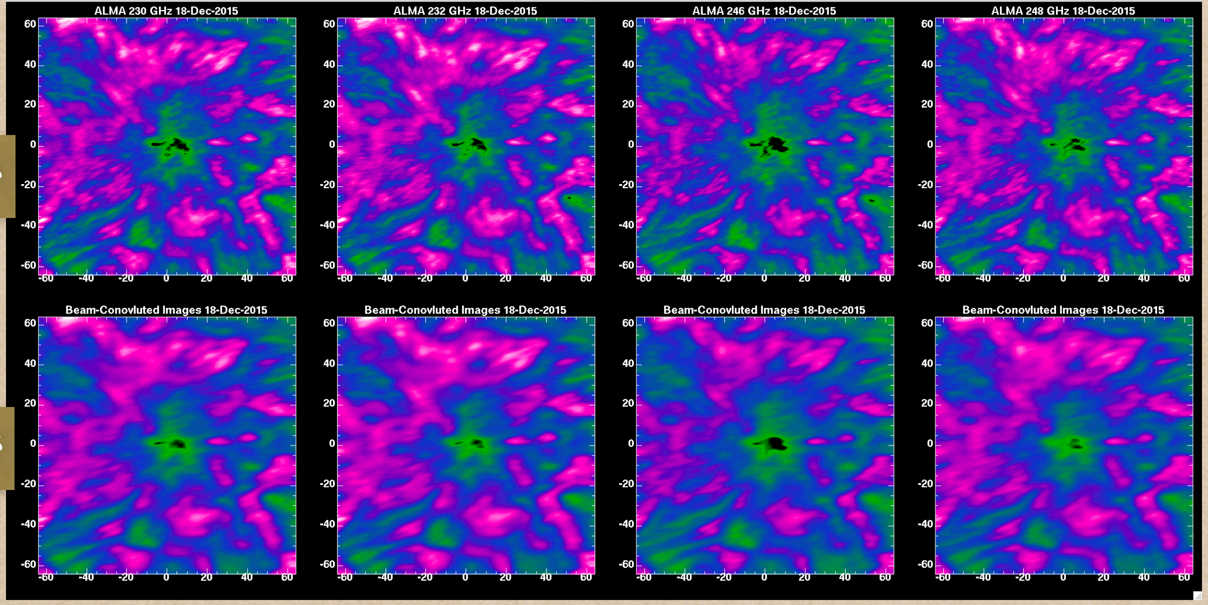
Example of deriving a spectrum map

- Data: SV data “Sunspot observed with MOSAIC/Band6 ”
- Before estimating the spectra of each pixel, we convolve all images using all synthesized beams of each SPW. The method is the same as that for NoRH data.
- [Issues] 1) Normalization using disk center value in the SD calibration. (In the case displayed in the page, I removed the normalization).

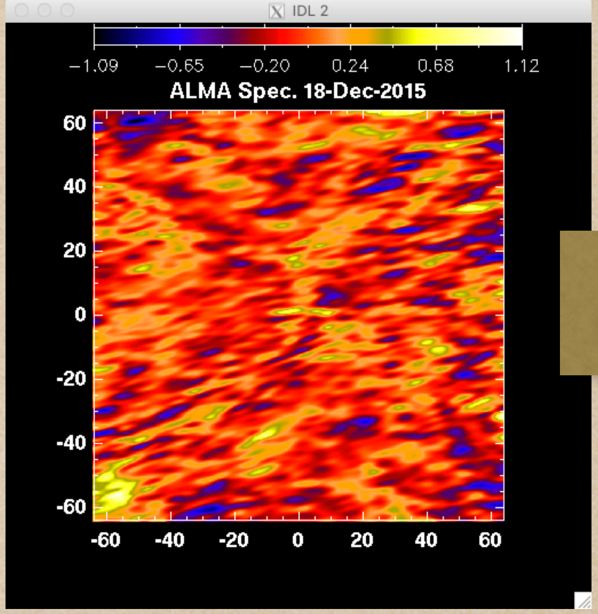
  2) one SPW of SD map shows large discord.

Original maps

Convolved maps

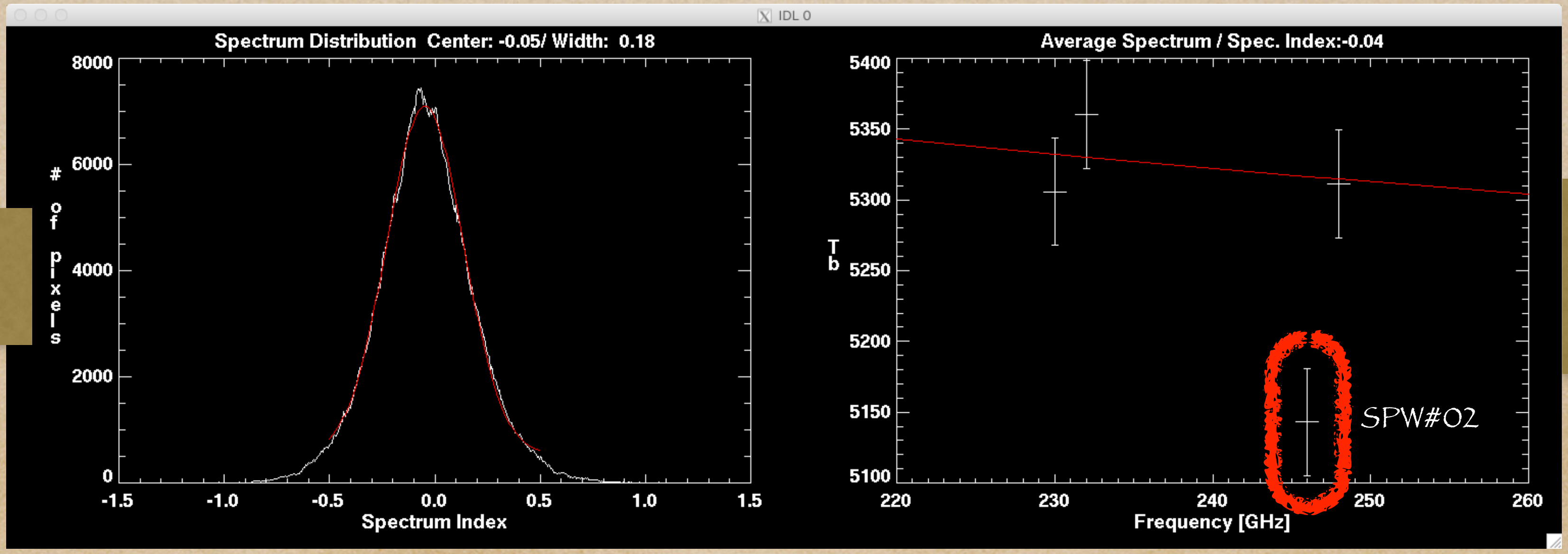


Spectral index map



Distribution of spectral indexes

Average spectrum without SPW#2 (Error bar: 10%)

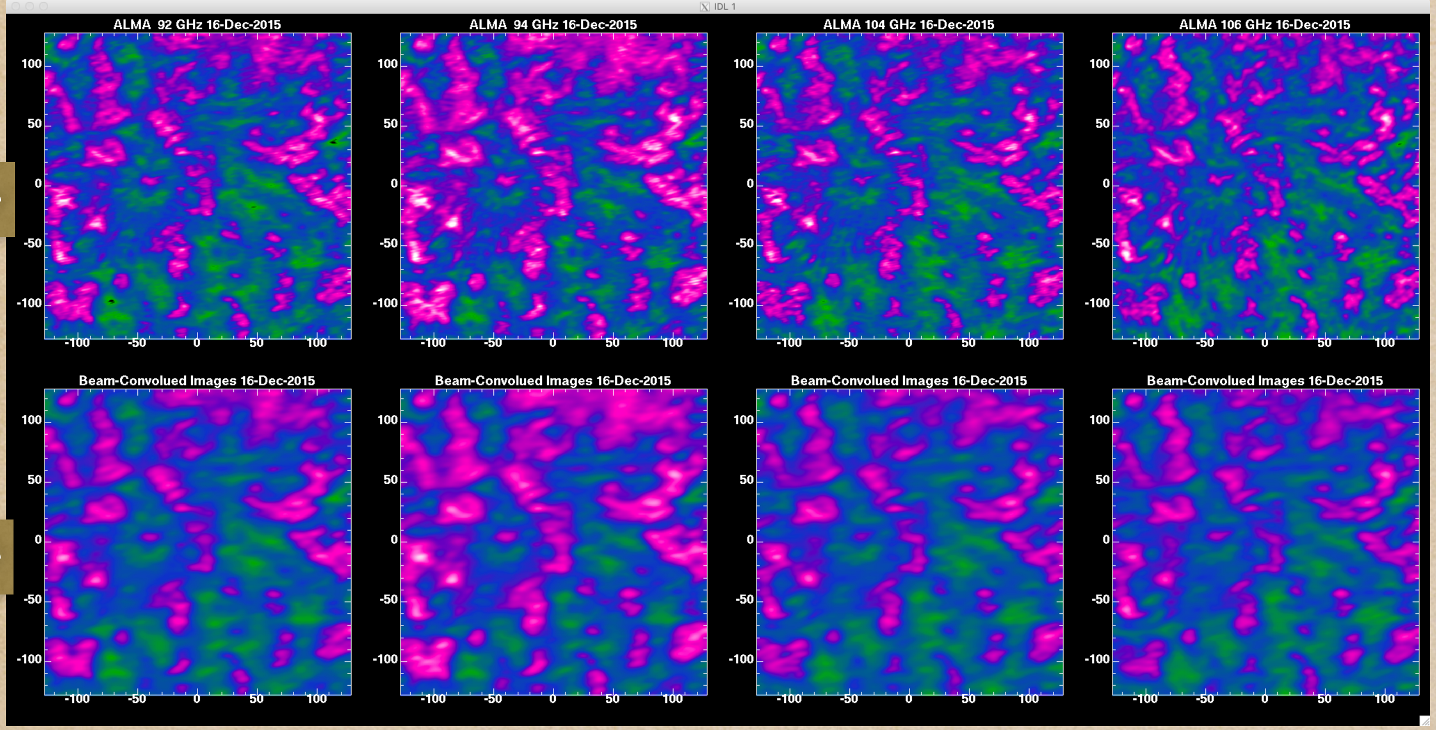


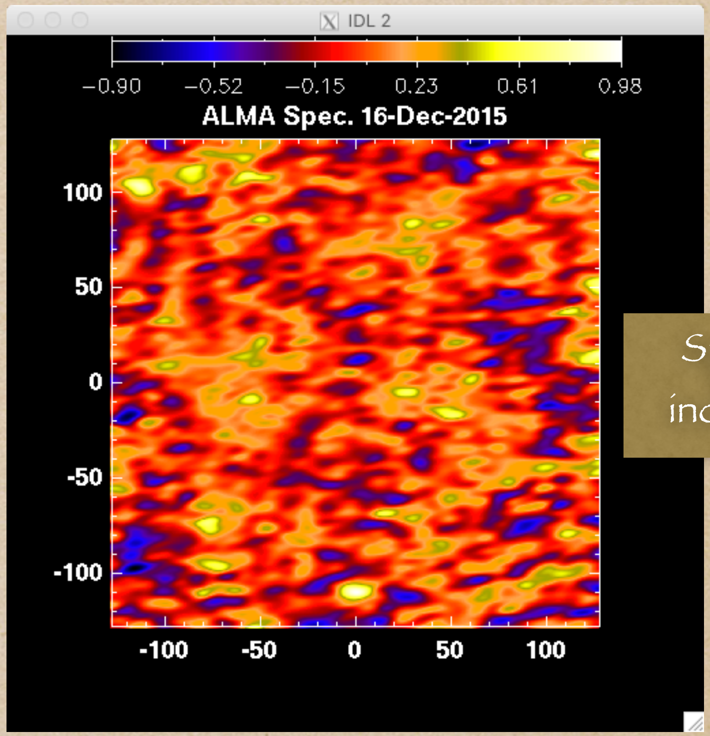
Example of deriving a spectrum map

- Data: SV data “Sunspot observed with MOSAIC/Band3 ”

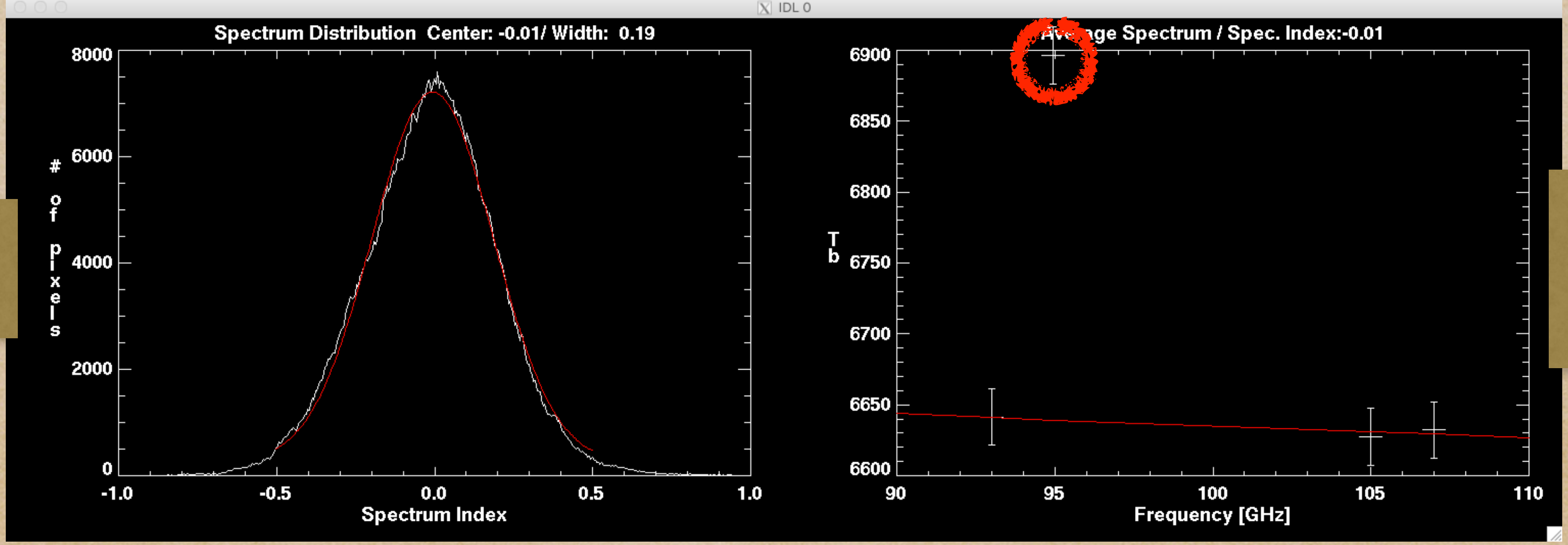
Original maps

Convolved maps





Spectral index map



Distribution of spectral indexes

Average spectrum without SPW#1 (Error bar: 10%)

5. The inconsistent of the flux calibration method between interferometric and single-dish observations.

- Interferometric data
    - Calibrate the sensitivity variation of the antennas using T_{sys} and $T_{ant.}$
    - Flux scaling is established by comparing the flux density recorded in the catalogue with the observed value.
- Single-dish data
    - Calibrated the flux using T_{sys}, T_{ant}, and the effective area of the antenna.
        - Flux calibrators cannot be observed with single-dish, because the sensitivity of the single-dish is not enough.

<u>The inconsistent of the methods influences to combined images or not?</u>

End

Thank you for your attention.