

ESO ALMA Development Study

HIGH-RESOLUTION SOLAR OBSERVATIONS WITH ALMA

Mid-term report



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1. Introduction – brief summary of the project goal

High spatial resolution for observations performed with ALMA has been one of the big promises for the community of astronomers and astrophysicist in general, and the experts in solar research represent no exception in this respect. While the colleagues studying the ‘standard’, cold ALMA targets can benefit from this supreme quality – unprecedented at the mm/sub-mm wavelengths and far better than provided by any instrument in the pre-ALMA era – the solar observations have remained quite constrained in this respect. Spatial resolution in the solar ALMA ObsMode has never exceeded ~ 0.6 arcsec, given the limits for available (as confirmed by the earlier CSV projects performed in 2014 – 2017) array configurations: C-4 for Band 3, C-3 for Bands 5 and 6, and C-2 for Band 7.

ALMA observations with higher spatial resolution have potential to answer many key and so far open questions in solar physics – among them, e.g., the issue of the heating of the upper layers of the solar atmosphere (the well known problem of *coronal heating*, which is important for stellar physics in general, not just for the Sun) – the dissipative shock waves that – according to conjectures based on the (R)MHD modelling – provide the key process for the heating, have definitely sub-arcsecond dimensions. Similarly, the expected filamentary (multi-thread) nature of solar prominences, could be revealed (or disproved) only by observations at higher resolution. ALMA is very specific in this respect as the brightness temperature at mm/sub-mm wavelengths can be much more directly converted into kinetic temperature of the solar plasma than it is possible at other wavelengths, where difficult and very uncertain non-LTE inversions have to be employed. Motivation in the solar ALMA community for higher spatial resolution, is therefore, indeed, very high.

The main goal of this project is to meet the wishes of the community and overcome the current limitations and, in this sense, ‘*long-baseline*’ or ‘*high-resolution*’ terms, used within this report, refer to anything significantly better than the so far posed constraints. **As it can be seen further, we are speaking about extending the array baselines to configurations, say, C-6/C-7** (the actual new limits are being subject of the main final deliverable of this study), which is not – in general ALMA terminology – really long-baseline, but for the solar observations it represents a significant leap ahead towards high spatial resolution. This is – as it has been already written – one of the very desired quality wished by the community. In addition to meeting this wish, there is an additional benefit in the increased flexibility in scheduling of solar observations: Frequently an interval of plausible array configurations is requested in the ALMA OT proposal and broadening the interval of configurations suitable for the solar observations would relax form necessity to schedule them into confined and rather narrow periods of year.

There are basically two main reasons, which limit the array extension for observations of the Sun:

- (1) Inability to correct short phase variations (between two phase-cal scans) by means of WVR signal. This is the standard calibration step for the cold targets, which is not working for the Sun, whose brightness temperature exceeds that of the atmospheric WV line more than by order of magnitude and leads to the WVR saturation. The fast phase variations related to the

tropospheric turbulence lead to the *de-coherence* of the signal, if its integration time exceeds the typical time-scale for phase variation and if the fast-varying phase errors cannot be corrected. For most of the science targets, one actually needs a reasonably long integration time in order to get a significant signal. On the other hand, for the Sun – thanks to its high brightness – just very short snapshots (actually their high-cadence sequence) are sufficient for reaching comfortably high SNR. With the short-integration (high-cadence) observations, the atmosphere can be considered as frozen-in. Consequently, the signal stays *coherent* (at least if we ignore the time-varying deformation of the wavefront at the scales smaller than the single antenna diameter), just the visibilities are loaded by a time-dependent phase errors. These could be, potentially, corrected by self-calibration procedure. This simple observation also makes a basis for the main methodological approach of this study: Self-calibration of the series of short-int snapshots of the solar target.

- (2) Second issue is related to the structure of the solar images, namely their broad span of spatial scales leading to the wide continuum in the Fourier space. Since the smallest expected scale in the solar atmosphere (the physically determined dissipation scale) is still many orders of magnitude smaller than what we can expect to resolve in our images, each extension of spatial resolution (i.e., extension of the array configuration) leads to further extension (widening) of the Fourier spatial spectrum. Consequently, its coverage by the actual visibilities in the uv domain gets diluted, in other words, the ratio of the ‘information contents’ present in our observed data (represented by the count of instantaneous visibilities) to the same quantity for the reconstructed image (number of grids in the uv -space with non-zero signal), drops down. One can, thus, expect a limit in extending the array configuration even for the idealized case of the observations without influence of the Earth’s atmosphere. The effect of sidelobes in the synthesised beam, becoming more pressing with the diluted uv space, has, moreover, an influence on the actual SNR at the smallest scales, as it increases uncertainty of the brightness temperature in the small pixels of the highly-resolved image. And, clearly, even more this issue may get significant in the real case of the visibilities loaded by the errors implying from the tropospheric turbulence.

To sum up, the so-far imposed quite strict limits for array configurations (see above) do not count with the possibility to correct a sequence of distorted images (each short-int frame being captured, however, with the ‘frozen’ Earth’s atmosphere) *posteriori*, by self-calibration, as described in the Item (1) above. The study aims at pushing the limits of the maximum baseline length as much as possible, nevertheless, with respect to the possible limitations described in the Item (2). Clearly, the new limiting baseline lengths will depend – in addition to the observing frequency – also on the tropospheric conditions. These are normally characterized by the phase variations of the band-pass calibrator, measured at its standard time-scale during the *Go/noGo* decision procedure (usually from the band-pass scan of the preceding EB observation). This is schematically illustrated in the Fig. 1, which is not yet in its final version (this is, basically, contents of the pre-final milestone M4) but the displayed lines are, to a large extent, resulting from the so far performed simulations (See Section 4.1).

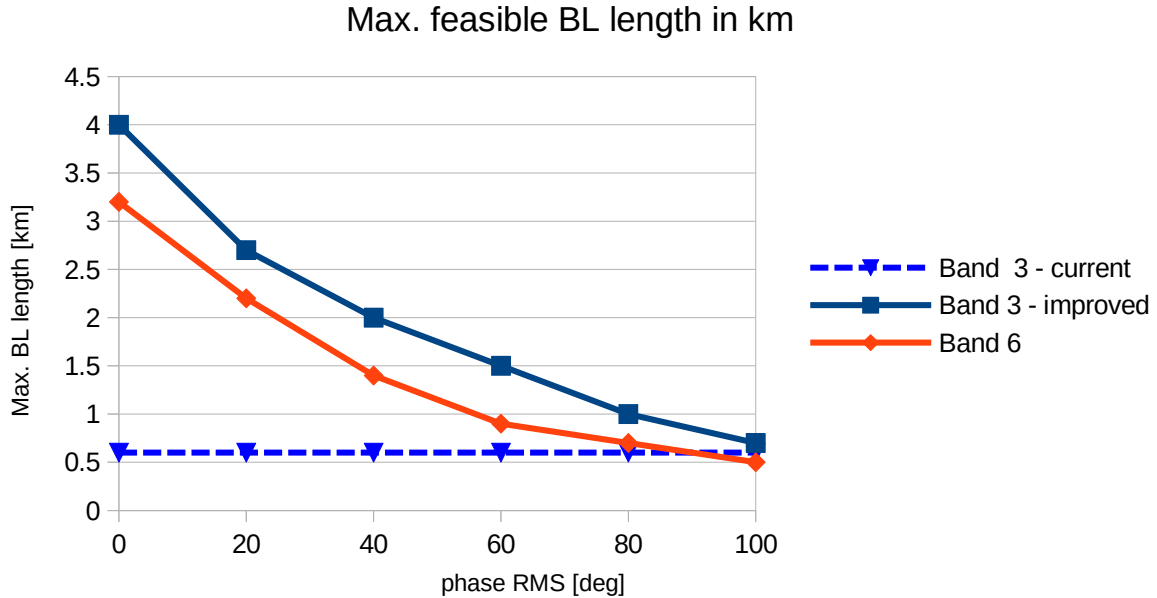


Figure 1: Schematic illustration of the main goal of this study: For each observing band and the phase RMS as measured by the **standard** Go/noGo procedure (at the BP scan of the previous execution) find the maximum extension of the ALMA configuration still usable for solar single-pointing interferometry. The figure represents an illustrative graphical expression for the **solar** Go/noGo - the points below the line are 'Go', the lines represent the marginal conditions.

In another turn, the Figure 1 represents (so far just an illustration of) the revised *Go/noGo* criterion specifically for the solar single-pointing interferometric observations – the lines being the marginal cases. Thus, exactly such a figure (when finished) represents the main ultimate goal of this study.

When mentioning the inability to use WVR for the correction of rapidly varying phase errors in solar observations, we should mention also the idea of Richard Hills, who suggested to use differential (i.e. per spectral channel in the TDM mode) absorption of the solar mm radiation in the wing of the WV line as replacement. This approach may be working in the Band 5 observations and it is thus less general. Nevertheless, it can further improve the situation in Band 5 data and this study pays attention to exploration of this possibility, too. In the SoW for this study and within this report this supplementary methodology is referred to as *Approach 2*, while the general-use method based on the posteriori self-cal correction of time series of the short-integration solar images is called *Approach 1*.

More details about motivation, basic ideas, and methodological approaches to this development study can be found in the *Scientific & technical description* of the original proposal to the study, which is attached as *Annex 2*.

2. Formal basis

The research is performed under the *Collaboration agreement no. 102502/19/114084/HNE* between ESO and the Astronomical Institute of the Czech Academy of Sciences, which is the hosting institution of the Czech node of the EU ARC.

2.1 Related documents

- Statement of Work for this study (SoW) – attached as *Annex 1*.
- Project proposal: Scientific & technical description (rev. 2020) – attached as *Annex 2*.
- Richard Hill’s calculations of sensitivity of the phase delays by the WV in the ray-path vs. differential spectral absorption – *Annex 3*.
- Listings of the simulation, calibration and imaging scripts – attached as *Annex 4*.
- Observation shift-log report, `listobs()` output, and the QA2 report – attached as *Annex 5*.
- Mid-term review plan containing the revised/clarified deliverables as agreed during the Kick-off meeting in September 2022 – sent as an invitation to the panelists and observers
- General parent JIRA ticket for the project: <https://jira.alma.cl/browse/CSV-3831>
- Child-thread for the CSV observations: <https://jira.alma.cl/browse/CSV-3832>

Further resources are available through the references/citations or as the hypertext links directly in the text.

2.2 List of abbreviations

The standard and notorious abbreviations used in the ALMA documents are exploited also in this report, without specific definition. Here we define just these less usual.

ASU	Astronomical Institute (of the Czech Academy of Sciences)
BP	Band-pass (calibrator, scan)
Cy <i>N</i>	(ALMA observing) Cycle no. <i>N</i>
EB	Execution block
INT	Interferometry/interferometric
FoV	Field of view
KOM	Kick-off Meeting
MTR	Mid-term report / Mid-term review
PB	Primary beam

PM/PR	Progress meeting / progress report
PWV	Precipitable water vapour (a measure of, in mm)
QA2	Quality Assurance Level 2
(R)MHD	(Radiative) Magneto-Hydro Dynamics
SOT	Solar Optical Telescope (onboard Hinode satellite)
SoW	Statement of Work
SP	Single-pointing
SSG	Solar Script Generator
WV/WVR	(Earth atmospheric) water vapour / Water-vapour radiometer.

3. So-far project timeline, coordination, and monitoring

The project has been officially started by the Kick-off meeting (KOM) on September 29, 2022. Its execution is regularly monitored and advised by the Project advisory board: Eric Villard, Carlos de Breuck, and Pavel Yagoubov.

3.1 Progress meetings/reports

After the KOM, we have held so far six Progress meetings (PM) connected with reporting and advising for the further activities. The PMs are held online and usually last around 2 hours in order to find enough time for discussion. The progress reports (PR) usually in two versions (pre- and post-meeting) are loaded in the ESO PDM system.

3.2 Informal consultations/workshops

In addition to the formal PMs we have held several further informal shorter consultations – offline (by e-mail), on-line and even face-to-face: With Eric Villard and Luke Maud we have had an opportunity to discuss specific issues of the project during the EU ARC All-hand meeting in Bologna in October 2023.

Moreover, in December 2023 we (the team at ASU and the Project advisory board) had a brief on-line workshop with the team at University of Oslo (UiO), which has been performing preceding solar ALMA Development Study [High cadence imaging of the Sun](#). The goal of the workshop was to avoid useless duplicate research (namely in simulations) and to compare the obtained results in the areas of overlap between both projects. The outcomes of the meeting are recorded in our PR no. 5.

4. Deliverables for the milestone M1

According to revised SoW (described in *Annex 3*), the milestone M1 in the mid-term of the project consists of four deliverables/activities: DS1.1.1, DS1.1.2, D.1.1.3 (related to the main *Approach 1* based on self-calibration of the sequences of short-integration snapshots), and DS1.2.1 (related to the specific treatment of the WV absorption signal in Band 5 – in the SoW referred as *Approach 2*). These are now presented in the following paragraphs 4.1 – 4.4.

4.1 Setup of the CASA simulations for larger baselines (DS1.1.1)

Simulations can be seen as to some extent as an initial task, whose purpose is to provide an apriori estimated map in the parameter space (maximum baseline length, phase RMS, observing frequency): To draw a border line between setups, for which the extended configuration still should be feasible, and those, where we cannot expect good results – basically making a apriori version of Fig. 1. Without this preliminary knowledge it would be difficult to request observing time with just a randomly picked array configuration.

Since this task in many respects represents an extension of the work done by the preceding ALMA Development Study [High cadence imaging of the Sun](#), we start with briefly summarizing the main differences in the approach/setup and the progress done beyond the previous study:

- **Extended configurations.** Clearly, contrary to the preceding Development study, we have focused on the so far unexplored configurations: C5 – C8 in Band 3, C4 – C7 in Band 5, and C3 – C7 in Band 6.
- **Heterogeneous arrays.** Because the instantaneous *uv* coverage is essential for successful imaging of the Sun with extended configurations (extremely broad range of spatial scales in the longer-baseline solar image in conjunction with the fast internal dynamics of the solar atmosphere demands it), we have used very consequently CASA **simulator tool**, avoiding the **simalma()** task entirely. This enables us to simulate mixed 12m + 7m (a.k.a. “kitchen-sink”) array, which is actually used for the solar observations, and whose heterogeneous baselines have been ignored in the previous simulations. The mixed array (ACA + 12m) has been used in all our simulated array configurations.
- **Atmospheric perturbation/corruption model.** Realistic model of the atmospheric turbulence, which influences namely the phase errors, is essential, too. In this study we do not use **sm.settrop()** and **sm.setnoise()** but rather a Python based **ATMOS.py** model (Ed Fomalont 2021, by courtesy of Eric Villard). This model produces mangled gain calibration table, with the phase delays corresponding to the atmospheric model controlled by a (low-dimensional) set of free parameters. Subsequent call to **applycal()** projects the perturbations into the simulated measurement set. Further enhancement is envisaged, using the improved atmospheric model by Yoshiharu Asaki & Luke Maud (2023) in the near future (see Section 7).

- **Input idealized model.** Unlike the previous study, which uses results of the numerical simulations as an input model image, we use real solar images in white light from the Hinode/SOT.

The individual parts of the setup will be discussed more in detail in the subsequent paragraphs.

4.1.1. Input (unbiased) model

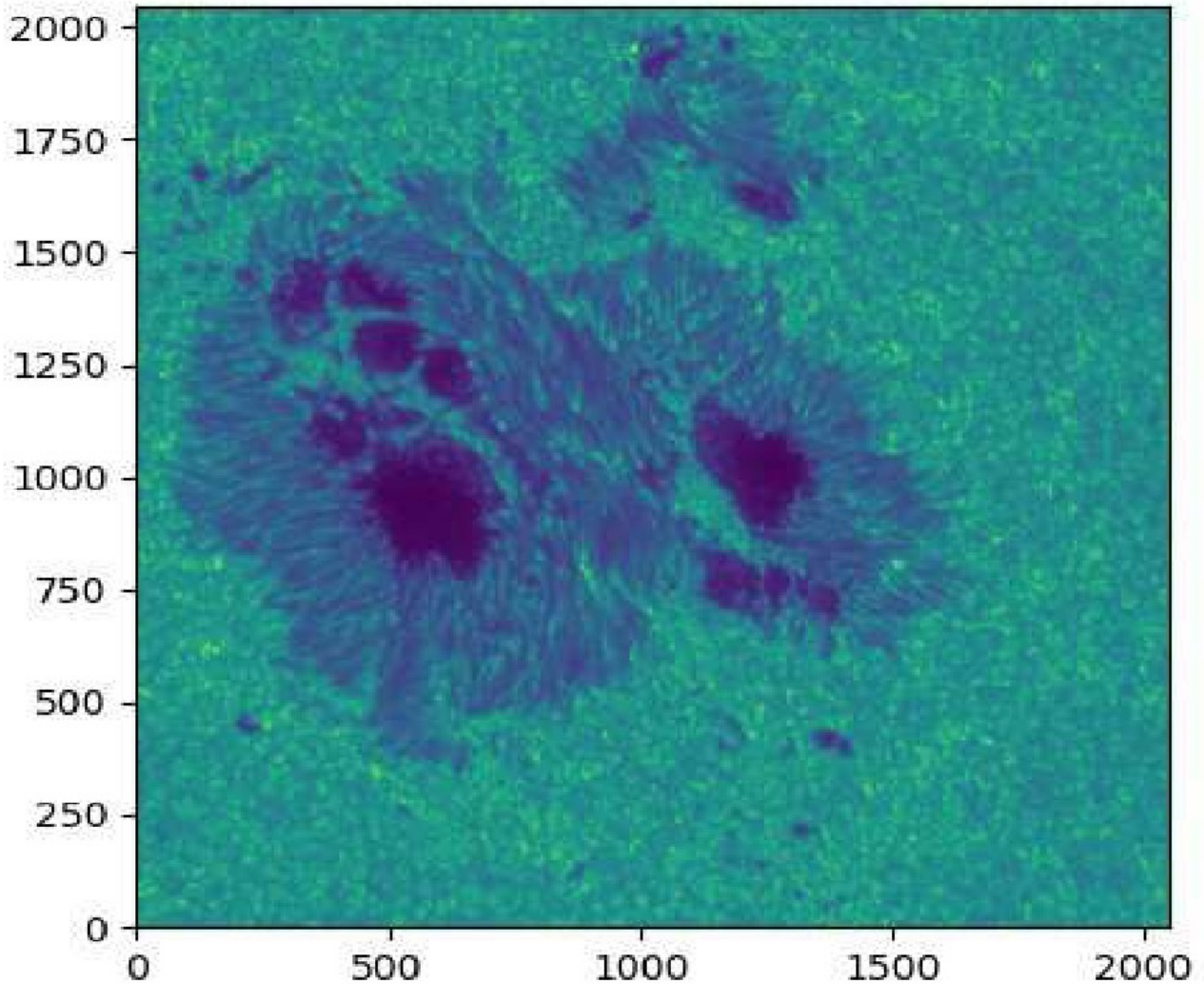


Figure 2: Sunspot image from the SOT/Broadband Filter Imager (a continuum centered around wavelength of 430 nm).

We are using real images of the Sun in white-light as an input model. The images has been taken by the Solar Optical Telescope (SOT) onboard the Hinode satellite. The main advantage to the inputs from the (R)MHD modeling (as used in the previous study) is the sufficiently broad range of scales covered by the image: The span between its resolution (about 0.05 arcsec) and FoV (109 arcsec) covers the expected

range of scales even for the pretty extended ALMA configuration (C7 in Band 3). For the yet longer baselines (C-8 and beyond) we had to artificially down-scale the image by a factor of ~ 2 in order to reach the resolution (ALMA synthesized beam size) and, consequently ‘extend’ the FoV of Hinode/SOT using mirroring/flipping the image along its boundaries so that it is larger than that of the ALMA 12m antenna primary beam. As a result, the natural range of scales present in the solar atmosphere (albeit shifted towards the higher spatial frequencies for the extra-long baselines) is preserved. Note that the span of the scales is independent on the observing frequency – with increasing frequency both its high-end (the resolution given by the synthesized beam size) and low-end (the FoV determined by the primary-beam of the 12m antenna) just shifts to higher spatial frequencies, but the span (the ratio between low and high ends) remains constant. To that end, we can use the same model image for various frequency bands, rescale its pixel size such a way that it fits the ALMA resolution and adapt the FoV accordingly. On the other hand, with increasing length of the longest baseline the ratio between the smallest and largest scale increases and the model image need some manipulation – for more compact configuration it can be cropped, for more extended such as C-8 and beyond, it has to be extended as described above.

In contrast, the MHD-based input model images do not have their size sufficient to cover entire ALMA FoV and have to be ‘tiled’ to a bigger image (which is possible thanks to the periodic boundary conditions/BC used in the underlying RMHD model). Such a technique increases the size of the image, on the other hand, the Fourier domain of such a tiled-up image is not broadened. Since one of the main issues/risks of the current project is connected with the question, whether we will be able to reconstruct the image from the diluted (as a consequence of extended configuration) visibilities in the uv space, we consider the natural span of the scales as present in our input model based on the high-resolution optical observation, to be a significant feature for confidence of the simulations.

Honestly, there are disadvantages of our approach, too: The structures in the photosphere (as observed by the SOT) need not to correspond to those in the higher layers of the solar atmosphere, which are visible namely in Band 3. Also, the brightness in the optical image is not so closely related to the brightness temperature at mm wavelengths. And last but not least – the initial setup uses a static image (albeit we are going to use high-cadence SOT movies in the next period – see Section 7) so for now we have ignored the quick *real* small-scale features (e.g., thin, moving shock-fronts) and focused on the *apparent* fast changes in the image introduced by the turbulence in the Earth’s atmosphere. Nevertheless, we still believe that the structure function of the *solar* atmosphere is represented quite truly by the input model image, and – above all – in its full span of scales that can be visible by ALMA.

Figure 2 shows the sunspot image captured by the *Broadband Filter Imager* of the SOT. The original image was cropped to 2048 px by 2048 px with the Sunspot at the center. The image size corresponds to the expected range of scales (cell-size – FoV) for a single-pointing INT image taken in the configuration C-7. As it has been written above, the image has been extended by its mirror/flipped copy for the yet longer-baselines configurations (C-8). The intensity map has been taken as is – i.e. in the arbitrary units, without any transformation into brightness temperature. Such a transformation would just introduce linear scaling of the values by some constant factor, which does not influence the results. We have used this high-resolution and rather broad FoV image in the visible light (centered around wavelength of 430 nm) namely for the above described nice property – that it provides a natural range of scales for the structures in the solar atmosphere. It may be objected, on the other hand, that it captures a bit different layer of the solar atmosphere – ALMA is sensitive rather to the chromosphere (Band 3) or the layers around the temperature minimum (Band 6; see, e.g., [14] or [20]). More relevant comparison is possible with, e.g., AIA image at 30.4 nm – what we are actually doing with the test

observation data (see Section 5.1.3) in Figure 22 – as the observation at this wavelength captures similar layer of the solar atmosphere as ALMA in Band 3. Nevertheless, while the SOT optical images are available in the high resolution and the wide field enough to provide sufficient span of scales for simulations, the rather low-resolution AIA images lack this property. However, the requirement for the scale coverage is, obviously, an essential one for the image that serves as the simulation input model, and thus it determined our selection.

4.1.2. Generating the simulated MS and its subsequent corruption by the atmospheric turbulence

In order to set up the simulation sequence, we tried the CASA default simulation tasks such as ‘*simobserve*’, ‘*simanalyze*’, and ‘*simalma*’ first. However, due to the complexity of solar observation, the standard tasks is not suitable for appropriate simulation procedure that as much as possible mimics the actual solar observations. Namely, the combined 12m+7m array cannot be reached with the standard *simalma()* setup.. Therefore, we turned to the CASA *simulator tool* in order to take the opportunity of more free parameters when creating a measurement set from scratch.

The workflow of the whole simulation sequence can be briefly described as follows:

- a) Preparing the image which will be the input model for the simulation.
- b) Using CASA simulator tools to simulate the ALMA solar observation with a combined array of both 12-m and 7-m antennas and generate the measurement set.
- c) Applying Phase error to the measurement set created in step b) to simulate the atmospheric disturbance during observation.
- d) Performing a self-calibration routine to the corrupted measurement set, and compare it with the original model image. In the self-cal loop the *solint* interval is consecutively diminished.

As mentioned in Introduction (Issue no. 2 related to the diluted *uv* coverage), one can expect an existence of the very upper limit for the longest baseline, beyond which the image synthesis (using the traditional deconvolution algorithms) is no more possible because in the solar images we have (i) broad range of scales that effectively continuously fill entire Fourier space and (ii) sparse instantaneous sampling at the same moment. The large fraction of non-sampled flux from the extended source like the Sun clearly represents a limiting factor for convergence of imaging, at least with the standard CLEAN algorithm including its sub-variants like *mtmfs-clean*. In order to find this very limit independent on the tropospheric conditions for each observing Band, we have started the preliminary analysis with simulations without the Step (c), i.e., with no phase errors due to the Earth atmospheric turbulence, letting just the issue of diluted *uv* space to act.

For the sake of stressing this issue yet a bit more, we have performed the simulations both with mixed 12m+7m array (what is the actual case in solar ALMA observations) and the 12m array only. This experiment has been chosen in order to decide, whether the advantage of more dense *uv* space in the combined array eventually prevails over the complications that are connected with heterogeneous-array imaging (e.g. mosaic gridding even for the single-pointing images or the uneasy primary-beam correction).

The results are displayed in Figure 3 and Figure 4. Because the simulated brightness temperature is in arbitrary units, we plot all images (T_B maps) as normalized into the same range 0.0 – 1.0 .For the C-8

configuration we had to expand the model image in line with diminishing its native pixel size in order to match the resolution and FoV for ALMA Band 3 in C-8. The C-7 configuration does not need this model-image manipulation (see the troposphere-perturbed case in Figure 5) but in this case we kept it for the sake of direct comparison of the two images. The parameters for *tlean0* are – except of the cell-size and image-size – the same as used through the entire study and can be read in the code listings in the *Annex 4: The scripts*.

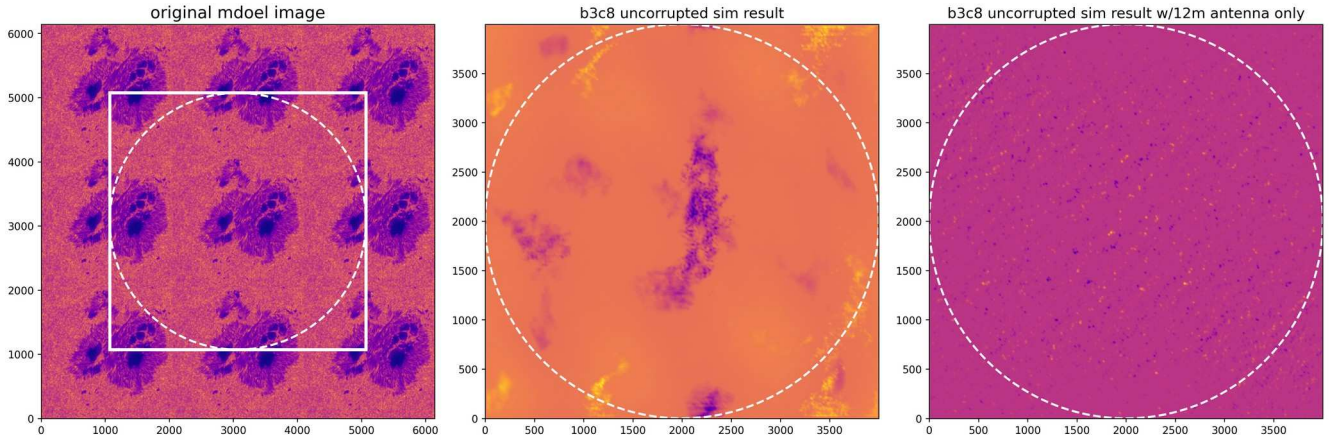


Figure 3: Idealised (no troposphere) simulation of Band 3 in configuration C-8. Left: The model image expanded in order to fit the ALMA FoV, middle: Deconvolved simulated ALMA image with combined 12m + 7m array, right: deconvolved simulated ALMA image with 12m array only. The circle in the box shows FoV of a 12m ALMA antenna for Band 3, which is ~ 1 arcmin. One pixel at the x and y axes thus corresponds ~ 0.016 arcsec (which is 6x oversampling the synthesized-beam size of 0.096 arcsec in configuration C-8). Maximum recoverable scale for the solely 12m array (right panel) is ~ 1.4 arcsec, corresponding to 85 pixels. The color scale is in units normalized to the interval 0.0 – 1.0 and the same for all panels – lighter color corresponding higher brightness temperature – see the color-scale bar in the Figure 8.

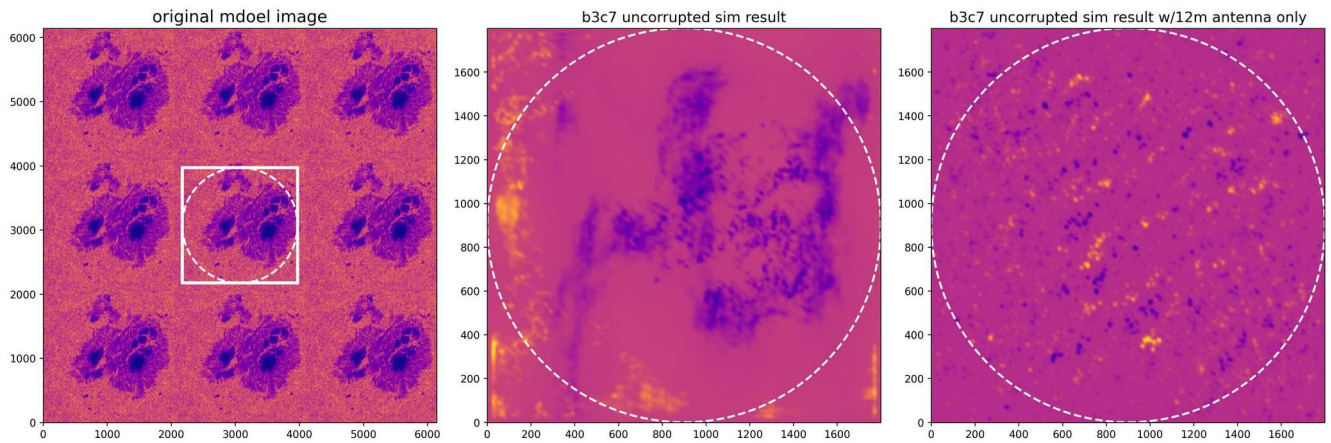


Figure 4: Like in Figure 3, now for the array configuration C-7. One pixel (unit at the axes) corresponds to 0.033 arcsec, the boxed circle (Band 3 PB for 12m antenna) is ~ 1 arcmin.

The results clearly show importance of the 7m array – without 7m antennas the synthesized image both in C-8 and C-7 even remotely does not resemble the original model. With the C-7 and combined 12m+7m baselines, the image qualitatively approaches to the original model: We did not have done fidelity-image analysis for this troposphere-less simulation but we did it for the same but perturbed case (see Figure 5 below) and indeed, after self-calibration the relative difference between the model and simulated deconvolved image is plausible.

On the other hand, in the configuration C-8, the proximity between the model and reconstructed images is not reached even at the qualitative level. It should be noted that the maximum recoverable scale (MRS) for solely 12m array in the C-8 configuration is just 1.4 arcsec. Clearly, presence of the 7m array is therefore crucial. We did not investigate the case where both arrays are present but the mixed 12m—7m baselines are missing. However, this case was tried by colleagues in Oslo with their simulation setup and they found even the C-6 configuration as the last plausible for the Band 3 observations (in our case C-7 is still OK), which demonstrates importance of the heterogeneous baselines for improvement of imaging. In the case of full mixed-baselines array, MRS – as given by the shortest baselines – is the same as the FoV and, moreover, the intermediate scales are covered well, as was proved by analysis of the observed test dataset (see Figure 21).

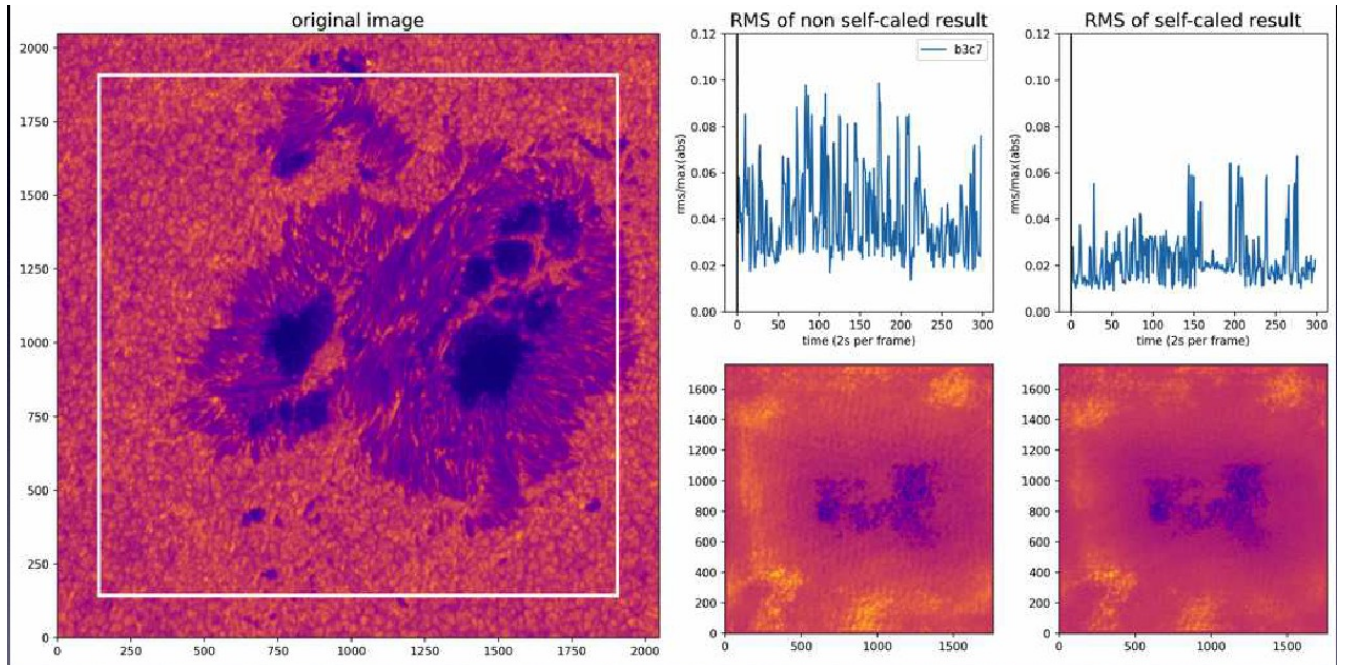


Figure 5: ALMA simulation of Band 3 in C-7 configuration corrupted by the tropospheric turbulence. Self-calibration still allows to reconstruct the image. Scaling at axes as in Figure 4.

In addition to failed convergence, the sparse antenna array in extended configuration has a yet one more potential risk for the image quality – increased uncertainty in determination of the brightness temperature due to the more pronounced side-lobes of the synthesized beam – this results into higher **noise in the image**, which can be – only to some extent – ‘cured’ by appropriate weighting scheme.

The higher spatial resolution is not itself a limiting factor that would prevent us from reaching a sufficient SNR, since the sensitivity of the array is independent of the lengths of the baselines. Also the brightness-temperature contrast can be expected at hundreds of Kelvins even at the smallest resolved scales, at least for the structures, which are of our utmost interest to be observed with the high resolution, like the chromospheric shock waves and discontinuities or the fine emission threads in prominences. Nevertheless, the synthesized side-lobes may add further noise to the clean image and deteriorate its quality. In the extreme case, we can expect the CLEAN algorithm even fail to deconvolve the image and in this sense both issues are related. Here we present the extreme situation, where it was clearly impossible to reproduce the original model image even in its rough features. The finer issue of increased noise at smallest scales in the images that were successfully reconstructed, has to be yet investigated by more detailed analysis of the fidelity images. We plan to perform wavelet analysis on the fidelity image in order to find out, whether the relative difference between the model and reconstructed images tends to grow under specific circumstances – either the small-scale limit of spatial frequencies or in the specific parts (e.g., with high or low signal) in the image.

Similar analysis has been done for Band 5 and it was found that the C-6 is the last array configuration, where we have reached at least qualitative agreement between the model and reconstructed simulated image. This preliminary analysis has shrunk the space of possible configurations for our further more detailed investigations, now with the inclusion of the tropospheric effects. The complete procedure can be illustrated on the case of ALMA simulated observation in Band 5 in the configuration C-6.

1. We calculated the synthesis beam using the wavelength and array configuration information, and determined the time and pointing direction of the ‘pseudo’ observation. Normally we put the model image exactly at the center of the Sun at a given time when ALMA can observe it.
2. We then converted the model image from fits file to CASA image file using *importfits*, during which the beam information and a 4D coordinate axes that contains directions and spectral values will be given to the image (e.g. ['06h06m56.98', '+23d25m45.5', '198GHz', 'T']).
3. Inspired by the examples presented in the webpage of CASA simulator (<https://casadocs.readthedocs.io/en/stable/api/tt/casatools.simulator.html>), we combined the ALMA 12-m and 7-m antenna array and simulate a solar observation with pre-set integration time of 2 second and duration of 10 min. An ideal measurement set was generated during the process and ready to be corrupted by the atmospheric turbulence.

We modified the script `ATMOS.py` (Fomalont, Villard 2023 – see the adapted code in *Annex 4*) in order to generate a series of Gaussian-like phase disturbance based on the baseline length from a given reference antenna, and applied them to the ideal measurement set using *gaincal* command in CASA. Figure 6 shows the scatter plot of the phase rms as well as the phase error vs. the baseline length measured as a distance from the given reference antenna. The left panel shows the underlying model of the atmospheric structure function: The phase rms increases rapidly (with the power index 0.8) until it reaches a given baseline length for which we specify the phase error (30 degs for this specific case) and saturates there (see the slower rise with the index 0.25) . The typical phase error can be tuned in

order to represent different observing conditions. As we are interested in correction of the fast phase variations in self-calibrated movies, we focus on characterization of the observing conditions by the phase rms error rather than PWV. However, these two quantities are somewhat related as reported by L. Maud et al. in ALMA Memo 624 [24] – see Fig. 13 and discussion at page 19 of this ALMA Memo. The median phase rms for the data without corrections to WVR is reported to be $\sim 0.2\text{mm}$ for 1 km baseline and 120s integration; this corresponds to ~ 30 degs for the Band 3 data. In this sense, the values of phase rms errors used in our simulations are rather typical: 30 degs, which is the value used for the most of our results shown in the report, being close to median, the higher modeled values corresponding to a bit worse weather conditions. Per the phase-rms/PWV scatter plot in Fig. 19 in [24] the phase errors used in our study should also fall into range of the typical values for the PWV.

Figure 7 shows the plot of phase gain cal table which was then applied to the ideal measurement set to form the ‘corrupted’ one that simulates the atmospheric disturbance in observations. After applying the phase error and generating the ‘corrupted’ measurement set, we then performed the self-calibration/imaging loop with the ‘corrupted’ measurement set. In view that the solar limb observations have many issues already in the current, compact configuration setup, we did not aim at them with the higher resolution. Sure, there is a lot of scientific motivation for having them, too (e.g. the structure and dynamics of solar spicules or the already mentioned fine threads in prominences) but the limb data require careful combination of the INT and regional TP observations and this task aims beyond the possibilities of the current study.

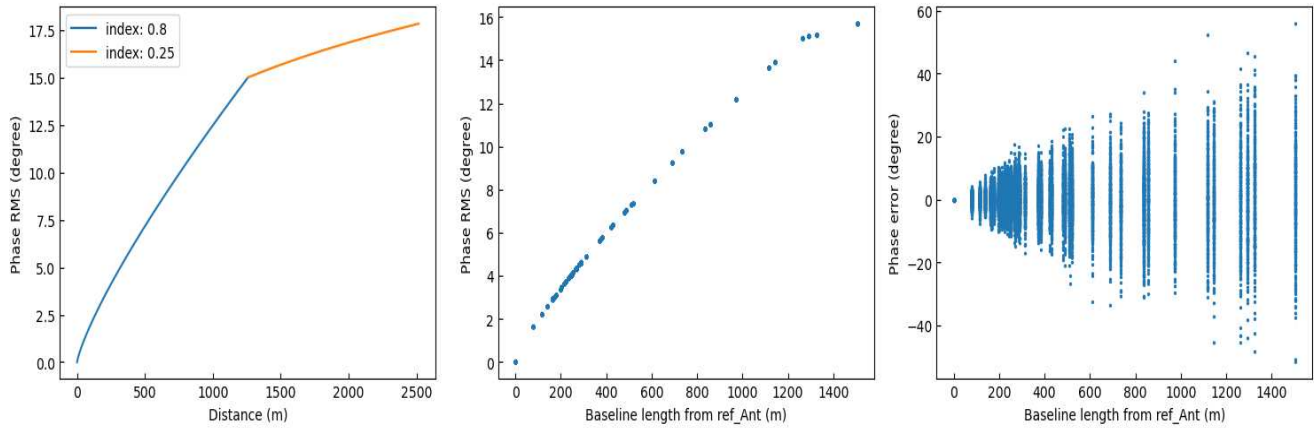


Figure 6: An example of the Gaussian phase error generated by the script. Left panel: Used model for the atmospheric structure function. Middle panel: Realization of that model for the array configuration C-6 (Note: The baselines lengths are measured from the ref. antenna, which is close to the array center; the longest distance is thus $\sim 1500\text{m}$). Right: Resulting randomized (Gaussian) phase errors for the tested configuration C-6.

4.1.3. Calibration, imaging, self-calibration

Simulated dataset contains just the phase errors introduced by the ATMOS code – these have no long-term trend to be removed by phase calibration (the phase calibrator is not contained in the MS either). The standard calibration step is thus skipped with the simulated data and we continue directly to self-calibration/imaging loop.

Based on the *ALMA memo 620* (see [23]), which discusses the general idea behind the self-calibration of radio interferometers as well as our previous experience in processing the ALMA solar observational data, we carried out a self-calibration scheme which uses a decreasing solution interval as the self-cal proceeds.

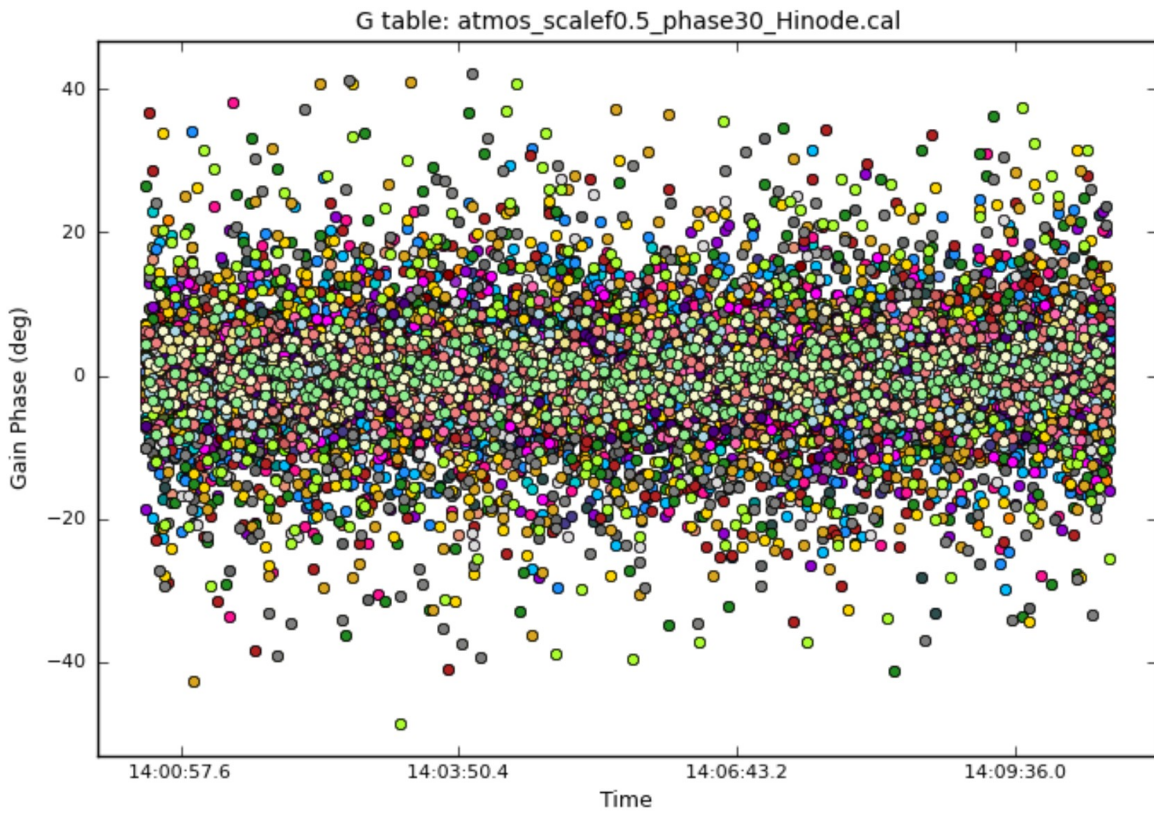


Figure 7: Phase gain cal table plot. Different color represent different antenna. The plot has been acquired for the phase RMS of 30 degrees. This is considered to be corresponding to a typical weather condition at AOS – see the text (Luke Maud, personal communication and [24]).

The general self-calibration scheme can be described as follows:

- A. Split out target data, so this now forms the DATA column of a new MS file.
- B. Make an image from the entire scan period using the ***tclean*** task in CASA, to use as a model for self-calibration. The model is stored in the dataset for later use.
- C. Determine phase corrections for each solution interval relative to the model given by step B using the ***gaincal*** task in CASA, and generate a self-calibration table.
- D. Apply the phase corrections to the DATA column using the ***applycal*** task in CASA and generate an intermediate CORRECTED data column.
- E. Split out the CORRECTED data column to a new MS file, then repeat from step B until the result is satisfactory.
- F. When this loop is finished, repeat the procedure for diminished solution interval. We change the `solint` parameter gradually down to the integration length.

The stopping threshold for self-calibration often depends on the residual as well as the self-calibration table, which will be demonstrated later in section 4.2.

4.1.4. Results

In order to compare the result under certain conditions, some general ***tclean*** parameters that come from previous self-calibration scripts for solar data are kept to the same value throughout the whole routine. The complete set of the parameters can be found in the code listings in the *Annex 4: The scripts*. For example, while doing the simulation of Band 5 observation under array configuration 4, 5 and 6, we modified the cell size as well as the *imsize* for each configuration while keeping the remaining ***tclean*** parameters unchanged. However due to the large image size in pixels at longer baseline configuration, the self-calibration results from Band 5 configuration 6 is not as good as the others, which can be seen from Figure 8 to Figure 10. The simulated brightness temperature (in arbitrary units), has been, again, normalized to the range 0.0 – 1.0. The color coding used in all subsequent simulated brightness maps is shown by the bar next to the left panel of Figure 8. The improvement between raw image and self-caled ones are minimal in this large configuration case. This issue is mainly caused by the model image was not cleaned enough during the self-calibration process. Further comparison and analysis will be given in section 4.2.

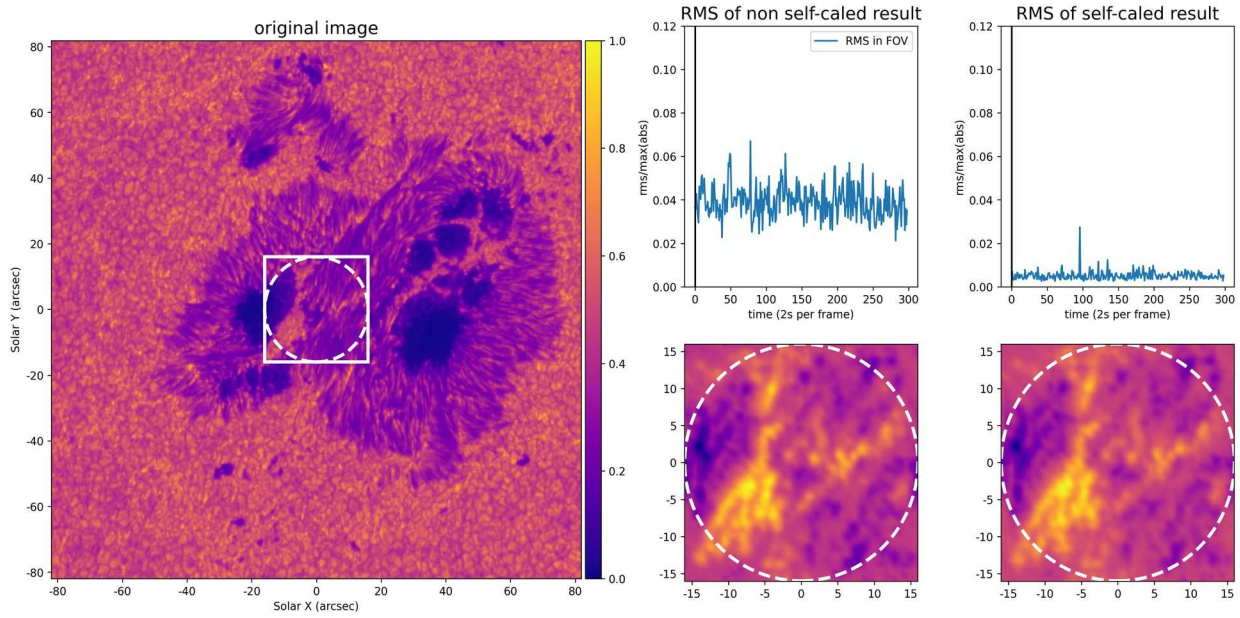


Figure 8: Simulation results of ALMA Band 5 configuration 4. Square in the center represents a bounding-box for the circular FoV – PB of 12m antenna in Band 5. Axes are in arcsecs, their origin (offset) has been arbitrarily set to the image center. The color-coding scheme for this and related figures is shown by the bar next to the left panel.

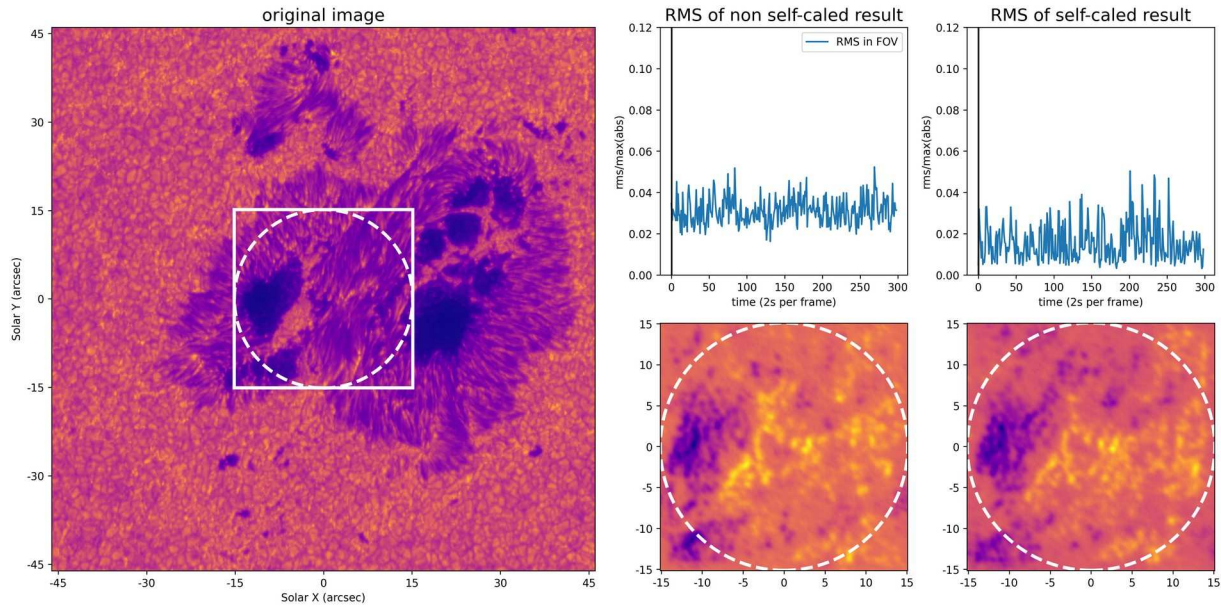


Figure 9: Simulation results of ALMA Band 5 configuration 5. .

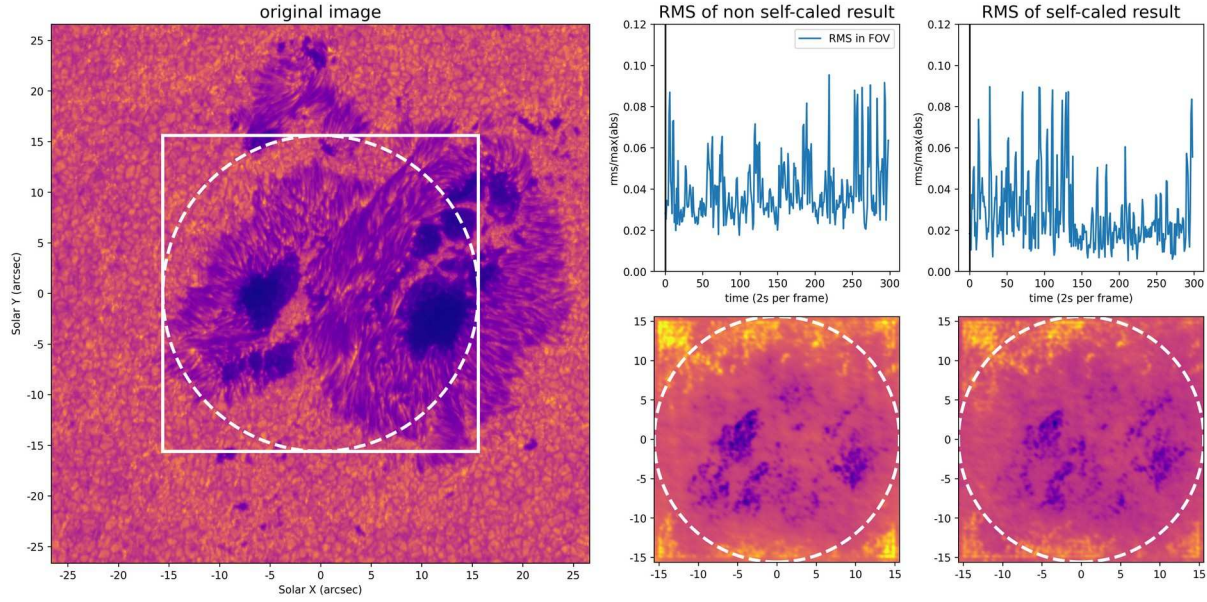


Figure 10: Simulation results of ALMA band 5 configuration 6.

4.2 Comparison of the selfCal-corrected results with the original unbiased model images – quality assessment (DS1.1.2)

In order to assess quality of the imaging and self-calibration procedure, we are using various metrics for reconstructed image features. Some – like standard image fidelity – rely on the knowledge of the ideal model (that has been used as a simulation input), the others are more general and try to assess the imaging/selfcal quality just from the resulting synthesized images. Such metrics are suitable for the observations (where we have no ideal model to be compared with the result), too. The goal is to study the correlations between the standard image fidelity and a model-independent metrics and pick one that correlates the best for future quality assessment of the images/movies obtained from actual observations.

4.2.1 Image fidelity

Standard quantity defined in CASA docs for `simanalyze()` – ratio between reconstructed image and its (absolute) difference to the ideal input model. Clearly, both the model and reconstructed images need to be known for calculation of this metric. In our results in, e.g., Figure 12 and following we are using “normalized difference”, which is just the inverted standard fidelity.

4.2.2 Self-cal-corrected vs. uncorrected phase RMS

Phase-based metric: Phase RMS time series for raw and self-calibrated image sequences. Does not measure the quality of the image itself but rather ‘convergence’ of the self-cal/imaging loop.

4.2.3 Scale analysis: Fourier (power) spectra of the input-model, simulated clean image, and its residual

Analysis of the image structure: Which scales present in the original ideal image have been truly transferred to the synthesized image and what remained yet in the residuals. Can be used also just for clean and residual image, without apriori knowledge of the ideal model.

4.2.4 Results

For comparison between self-calibrated images and non self-calibrated ones, we then use the model image to create the fidelity images and study the difference between these two results.

We show here ALMA simulation of Band 5 and array configuration C-6 as an example. We first generate the “normalised difference” images (which are just the inverted standard fidelity) by subtracting the normalized model image from the normalized results, which could be either the unself-cal or the self-cal image. Then calculate the standard deviation as well as the mean value of each fidelity image and plot these values as dependence on time.

We found that the mean value of this series of fidelity images from the self-cal procedure (Figure 12) has a less spiky feature compared with the unself-calibrated ones (Figure 11), which indicates that the self-calibration does help reduce the random noise which simulates the atmospheric disturbance.

However, since the model image is not changing according to time, if the random noise is fully cleaned, the standard deviation of the fidelity images will stay the same while the mean value shows almost no spiky features in the figure.

As we looked into our self-calibration procedure, we noticed that due to the long baseline we used in simulation, the image size in pixel (1200 px by 1200 px) is far larger than that of previous ALMA solar observations, which, in the case of ALMA band 3 configuration 4, is only ~ 400 px by 400 px.

Thus, the self-cal result shown in Figure 12 is not cleaned enough with current `niter` (= 40,000) setting, which also proved by Figure 13 showing the gain table plot of the last round of the self-cal procedure. Unlike the normal gain table plot we see from the last round of self-calibration, the phase correction is still too large, especially at the end part of the simulation.

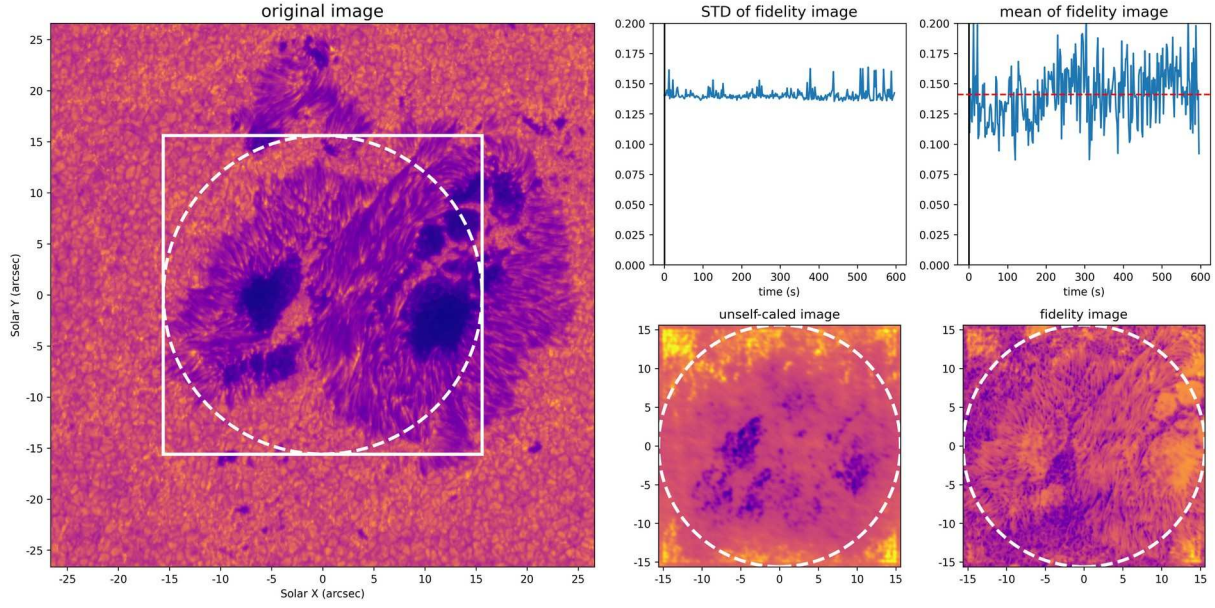


Figure 11: Comparison between model image and unself-caled results. Band 5 in the C-6 configuration.

With the new $niter=200k$ setting, we plotted Figure 15, which shows the comparison between model image and self-caled result as well as the corresponding fidelity image. The standard deviations of the fidelity images are almost constant, represented by the horizontal line in the upper middle panel of Figure 15. While there is a general pattern for the mean values of the fidelity images, the spiky features seen in Figure 11 and Figure 12 top right panel, are almost gone as compared to that in Figure 15, indicating that the random noise, which is caused by the atmospheric turbulence, is mostly cleaned from the dataset.

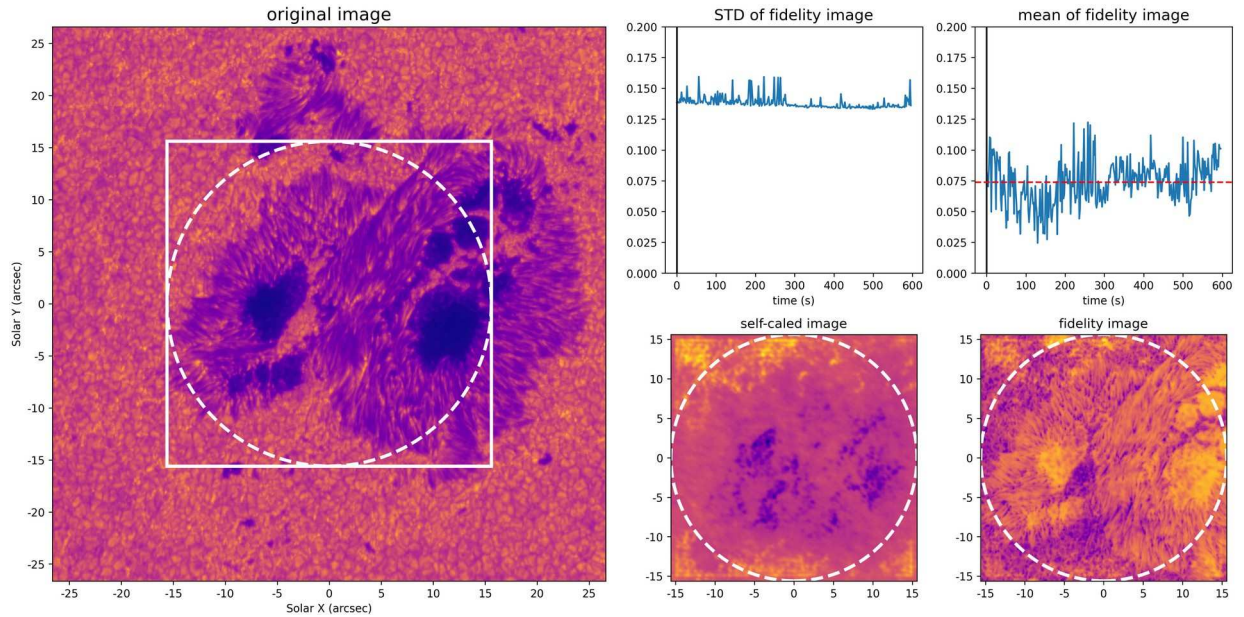


Figure 12: Comparison between model image and self-caled results. Cleaning iterated over 40k cycles.

To further analyze the simulation results, we made power spectrum for all the three cases we presented above: unself-caled raw image, self-caled image with small `niter` number (40,000), and self-caled image with large `niter` number (200,000). The power spectra were made from the first frame of the snap-shot movie from the whole 10 min simulated observation to serve as an example.

Unlike the raw image and less self-caled one, the power spectrum of the deeply self-caled image shows a strong signal near the small k number, which corresponds to large features in the map. This result proves that the large `niter` setting is useful in recovering the overall shape of the model image (Figure 15).

In order to measure the qualitative ‘spikiness’ of the frame-to-frame jumps as shown in Figure 11 and Figure 12 in more quantitative manner, we devised a possible metrics for measuring it. We do the differences between the adjacent snapshots (basically a time derivative) and plot the mean and standard deviation of the difference images as a next plot. Basically, a normalized (to the length of the series) integral of the difference curves provides a number that measures the frame-to-frame jumps. Again, we show two examples for self-calibrated series and its non-self-calibrated counterpart in Figure 16 and Figure 17.

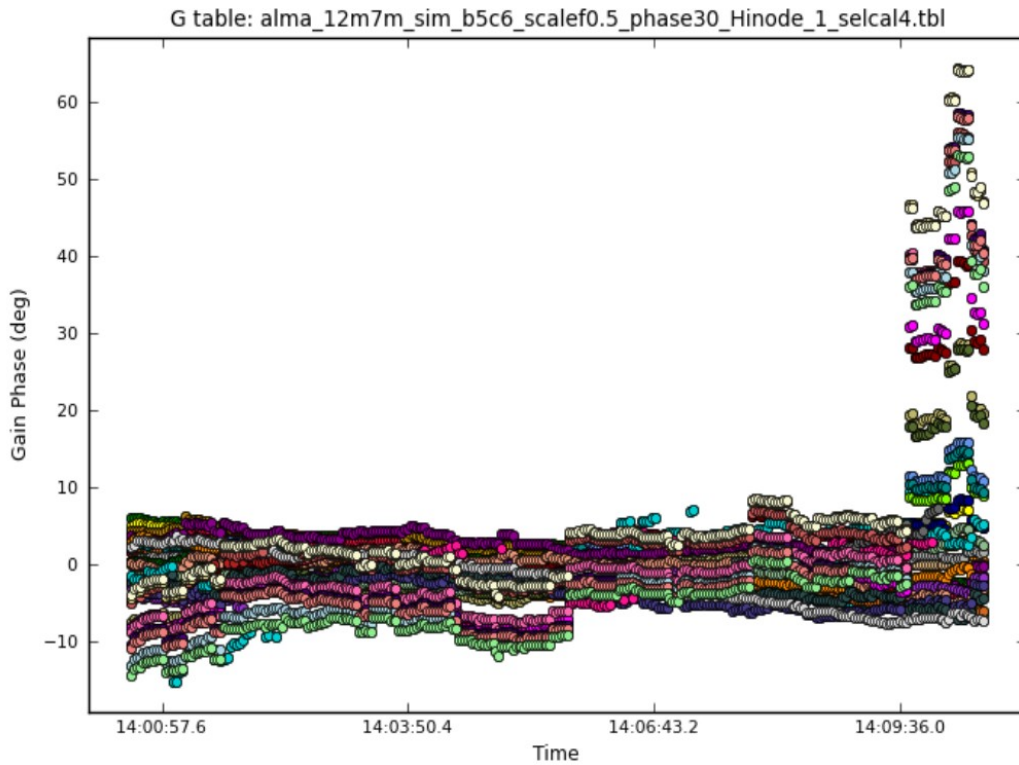


Figure 13: Gain table plot for the last round of self-calibration which uses `niter` = 40,000.

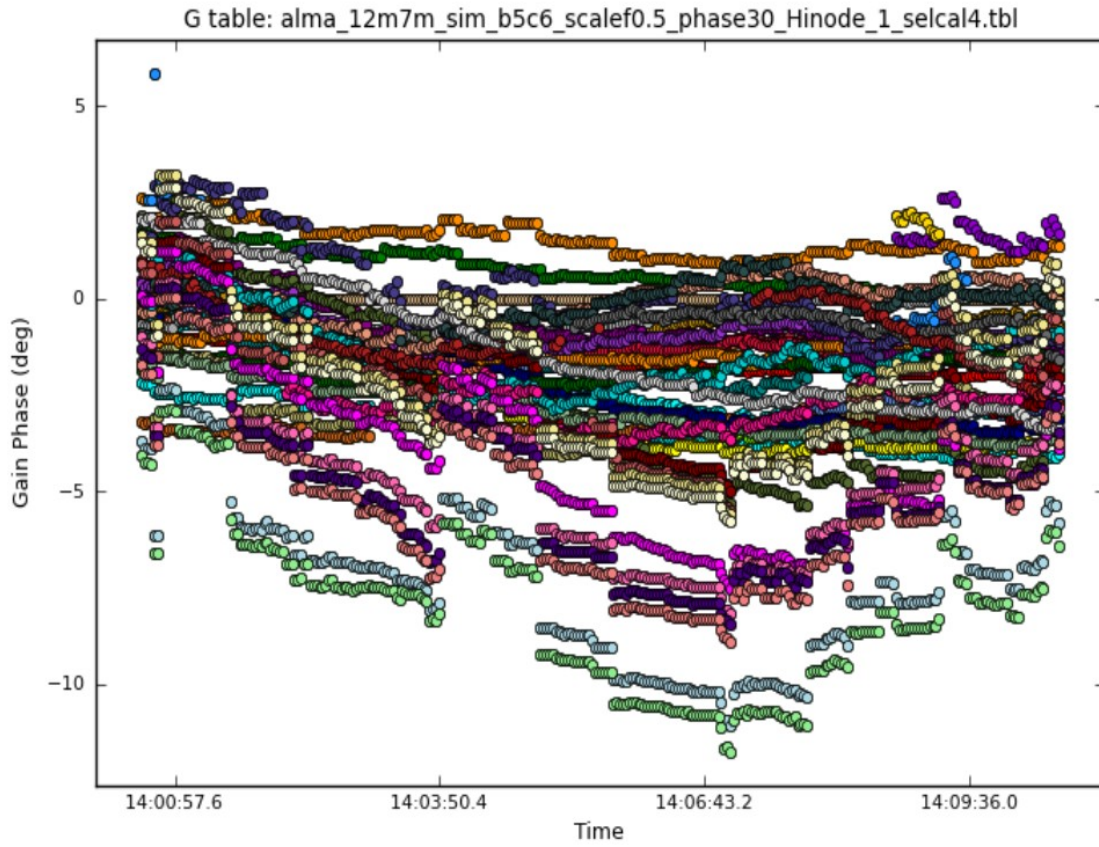


Figure 14: Gain table plot for last round of self-calibration which using $niter = 200,000$.

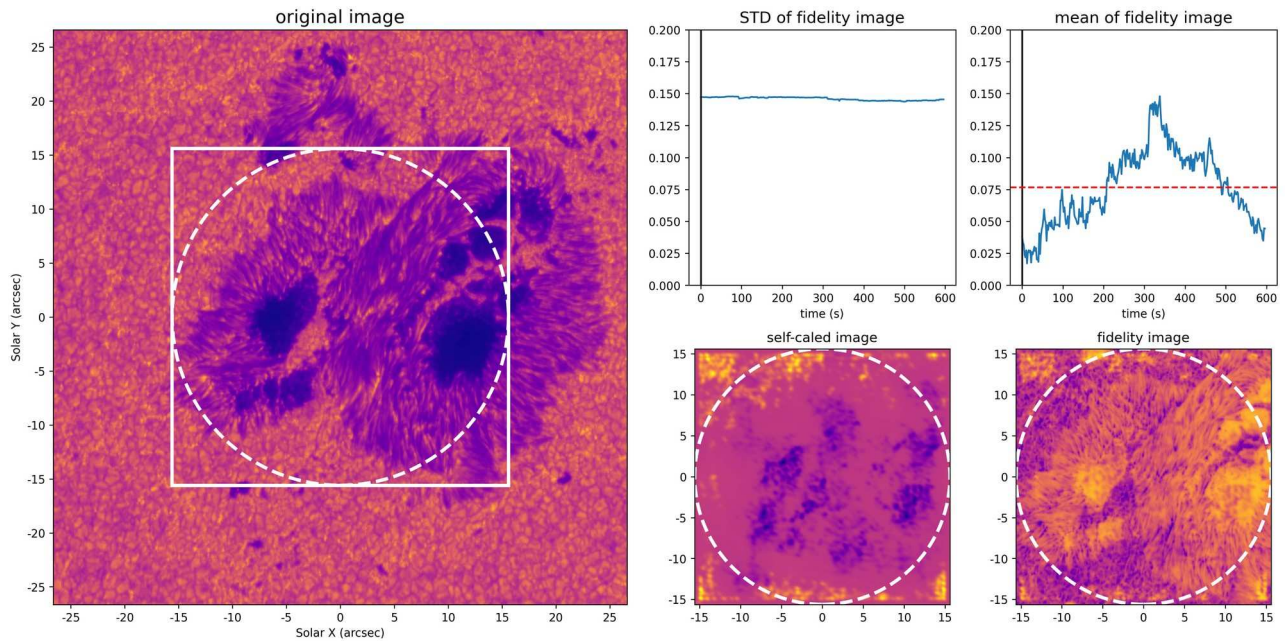


Figure 15: Comparison between model image and self-cal results with $niter$ set to 200,000.

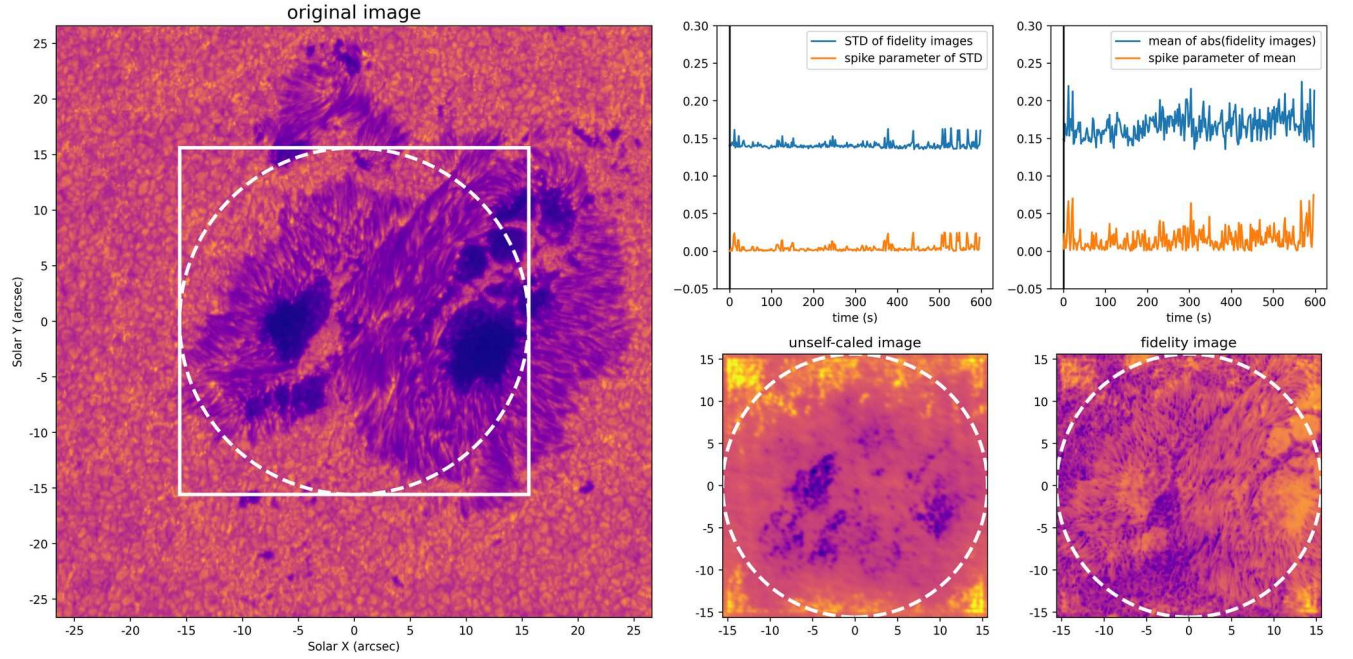


Figure 16: More quantitative measure of the spikiness as displayed in Figure 11 and Figure 15 obtained from running differences – the orange curve. Its normalized integral provides a metric for characterizing frame-to-frame jumps in the time series. Result for the time series without self-calibration correction.

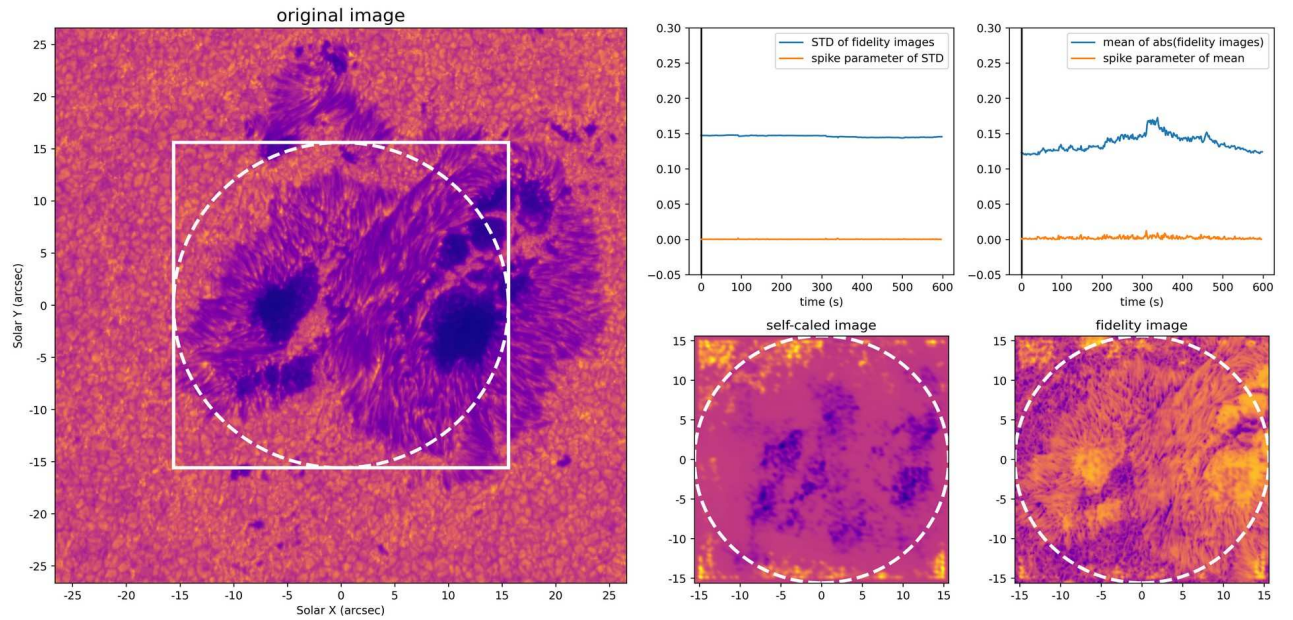


Figure 17: The same like in Figure 16 but now for the self-calibrated series (cleaned with 200k cycles).

4.3 Solar specific Go/noGo criterion (DS1.1.3)

As it has been written in Section 1, the main goal of this study is to find, whether solar observation with a given array configuration and in a given frequency band is possible for the given phase metrics (RMS), as established from the BP phase variations of the preceding execution. The boundary/marginal cases should be expressed by the lines as those, which are schematically shown in the illustration in Figure 1.

Using the simulations in the setup described above in paragraph 4.1 in conjunction with the measures that define the quality of the imaging and self-calibration procedures of time sequences of solar snapshots presented in paragraph 4.2, we have started to explore the parametric space [base-line length; BP phase RMS; observing frequency] in order to find the points of the boundary lines for solar Go/noGo. If one of the following (negative) criteria was met, the respective point in the parametric space was marked as “noGo”:

- The images in series has been poorly reconstructed – the low image fidelity. Most likely supercritical dilution of the uv coverage, imaging failed.
- The phase variations not well removed by the self-calibration procedure – self-calibration loop not converging.

Otherwise, the point was marked as “Go”.

Insofar we have been mapping the phase RMS to the solar Go/noGo from the ‘standard’ Go/noGo measurements, i.e. the RMS of the BP-calibrator scan from previous observation is measured on the timescale of minutes (typically 5 min.). Since for the solar observations the much shorter timescales (on the sub-second scale, that are, however, not directly reachable from the BP scan) are relevant, and at the same moment the modified Go/NoGo procedures are started being utilized by ALMA, measuring the RMS at much shorter (a few tens of seconds, typically 30s), the future variants of the Figure 1 shall include mapping between solar Go/noGo and phase RMS as measured at the shorter timescales, too.

First, it has been found that even with the unperturbed case of the phase RMS=0 – see Figure 3 – we cannot use more extended configurations than C-8 for Band 3: Already for this marginal configuration even qualitative agreement between the input model and the reconstructed image is not reached. The reason is in specifics of the solar observations – broad, continuous range of spatial scales in the image in connection with the sparse instantaneous uv sampling. It is possible that future deconvolution algorithms may overcome this limit but for the standard CLEAN-based procedures the uv-space dilution represents the very upper limit. Then different frequencies under different weather condition (as characterized by the phase variations) have been tried. The so-far reached results can be summarized as follows:

- **Band 3:** Marginal (already rather “noGo”) configuration for unperturbed case (0 deg phase variations) is **C-8**.
- **Band 3:** Limiting configuration is **C-7** with 30deg variations.

- **Band 5:** Limiting configuration is **C-6** with 120deg variations.
- **Band 6:** Limiting configuration is **C-5** with 120deg variations.

The results are displayed in Figure 27, which is a still developing but actual realization of the scheme in Figure 1. Further calculations (for further vector of parameters) are on their way, however, we would like to first change the model for atmospheric phase corruption. The main reason – in addition to higher fidelity of the new model (Python code by Asaki & Maud, 2023) – is the inclusion of the integration-time dependence in the model. It has been found (e.g., [15]) that the phase correlations for a given band and baseline decrease with shortened integration time. Since the Sun is going to be observed with higher cadence (typically 0.1 – 0.2 sec) than the BP calibrator (2 – 6 sec), whose phase variations are at the x-axis in Figure 27, the model should include this difference.

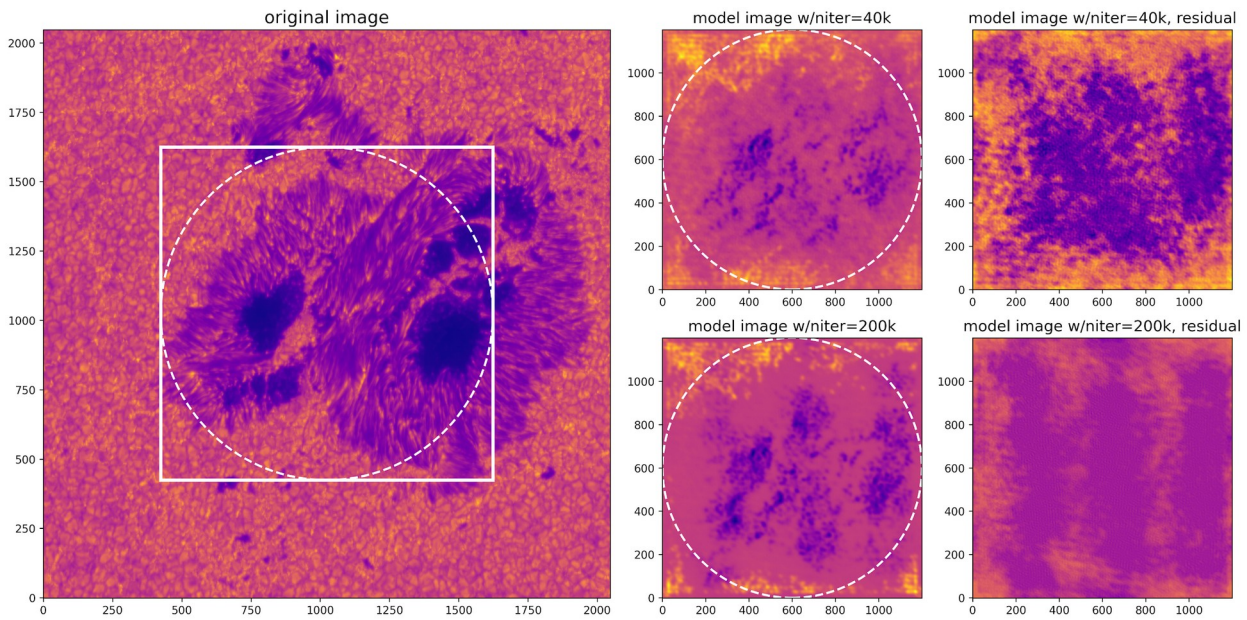


Figure 18: Comparison of model and residual between two different niter cases. Both residual images are plotted under same scale.

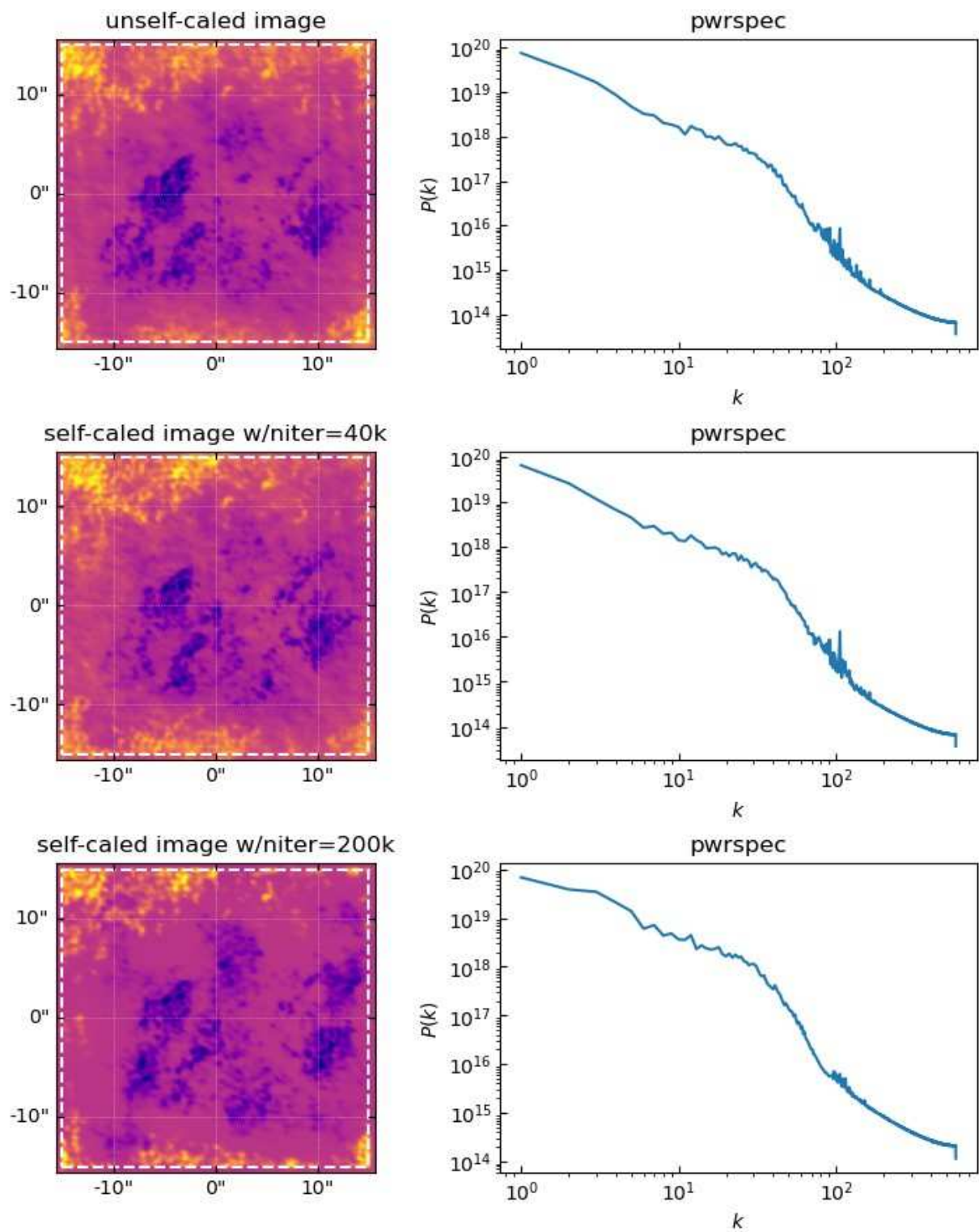


Figure 19: Power spectrum comparison between unself-caled and two self-caled images.

4.4 Analytical relation between *absorption* in the water vapour and the phase delay in Band 5 (DS1.2.1)

This part represent legacy of Richard Hills, a member of the development project team, who, sadly, passed away before the project has started.

Absorption of the solar radiation transmitting through the atmosphere column above each antenna in the contained WV cannot be measured absolutely: We need to record the absorption with the cadence of integration, and because we do not have any amplitude calibration at this short time-scale, its decrease with time hardly could be attributed just to increased absorption. On the other hand, the differential measure (a spectral slope), which includes relative increase/decrease in the amplitude as compared through all frequency channels or their representative sample, is in principle feasible. Alternatively, one can compare the signal as integrated per SPWs, as it is indicated in Figure 27 from the real CSV data (see Section 5.2).

Following the Richard's derivation, whose full text is attached as *Annex 3: Differential absorption in WVR line & the phase delays*, the phase difference introduced by the WV column is related to its fractional absorption by relation

$$d\phi = 2\pi/\lambda \cdot r_{\text{eff}} \cdot (-1/\tau_1) \cdot dT_{\text{sig}} / T_{\text{sig}}$$

where r_{eff} is the effective refractivity, to be approximated by a value of 6.3 for reasonably broad range of parameters and τ_1 is the opacity for 1mm PWV.

The detailed tables with calculation of the sensitivity of $d\phi$ to the change of differential absorption done by Richard are to be found here: <http://wave.asu.cas.cz/barta/ALMA/DS2022/wv-cal/>.

Having now the Band 5 data, we are aiming at verifying these calculations by scatter plot of phase-error per antenna and integration as found by self-calibration vs. the differential absorption, also per antenna and integration, as found from the auto-correlation spectra for each antenna.

Let us note that albeit this procedure is devised and being tested (see Section 5.2) in the ALMA Band 5, it is of more general use and can be – if conceptually proven in Band 5 – also, for example, in Band 7 for the WV line at 324 GHz.

5. Verification of the project approaches at the CSV data

To our greatest pleasure, JAO/ALMA accepted our proposal for the CSV observations and with the kind help of our Project advisory board and Hugo Messias at ALMA the observing plan has been negotiated by means of JIRA CSV-3832. The project got code 2022.1.00031.CSV and has been executed at the end of November (Band 3 data in a transitional configuration close to C-7) and mid December (Band 5 data in C-6). The basic data processing started at the end of the year and advanced analysis is still ongoing. However, already now we can present practical verification (or at least indication of feasibility) of the approaches/activities that are described above in *Deliverables* (Section 4).

5.1 Verification of self-cal corrections for short-integration observations

5.1.1. Observation description

We present detailed results for Band 3 observations here. The Band 5 data are still under processing (self-calibration).

Observation in **Band 3** has been performed on November 29, 2023, on 13:34:39 – 14:01:57 UT. The data have been taken in the (almost) C-7 configuration, under “marginal weather condition” as reported at JIRA ticket. The time on-source includes just a single scan of 10 minutes, with integration of 192 ms. More than 50 antennas have been used for analysis, just one (of 53 available) has been fully flagged during the processing. The observing sequence is shown in Figure 20 (output of `listobs3()`). Full MS info is attached in *listobs.txt* in *Annex 5: Observation reports*. In addition to the `listobs()` output, *Annex 5* contains shift-log report for the entire project, and the QA2 report from the data calibration.

Band 5 execution (the successful one) took place on December 16, 2023, on 13:12:26 – 13:37:25 UT (one scan of 7 minutes on source) in configuration C-6. There were 52 antennas in combined 7m+12m array, 2 of them (one 7m and one 12m) had to be flagged. The PWV was 4.5mm, Array configuration and the *uv*-space coverage are shown in Figure 21. Importance of the combined (heterogeneous) array mentioned in Section 4.1 and summarized in Section 7 is clearly visible: The 7m-12m baselines create “nests” of point in the *uv* space leading to its denser coverage. Again, the detailed info is in *Annex 5*.

5.1.2. Calibration, basic imaging

Calibration has been assisted by the Solar Script Generator (SSG – see Section 6) – a tool whose development has been eventually finished in connection with processing of the CSV data of this study (the observed datasets brought a new motivation).

The procedure of solar ALMA data calibration is described at the Confluence page:

<https://confluence.alma.cl/display/DMG/Solar>

With respect to the standard calibration, it includes few more steps, above all a call to the `sol_ampcal2()` routine from the collection *sun_reduction_utils.py*. This assures the proper amplitude calibration taking into account both T_{sys} and T_{ant} for the Sun (see Shimojo, 2017). The last calibration step includes, moreover, attributing the correct reference sky coordinates (RA, Dec) to the solar-target fields at the reference time. This is not really solar specific feature and it is present in any ephemeris (solar-system) object.

One antenna has been flagged because extremely high T_{sys} values. At the very end of calibration procedure, `au.generateQA2Report()` has been called and its results checked. Generated QA2 report is attached in the *Annex 5*. The calibration result has been *QA2 passed* and basic imaging

(integrated over the science scan) was all right, too. Hence, we continued with separation to the integration-based time sequence, and self-calibration loop.

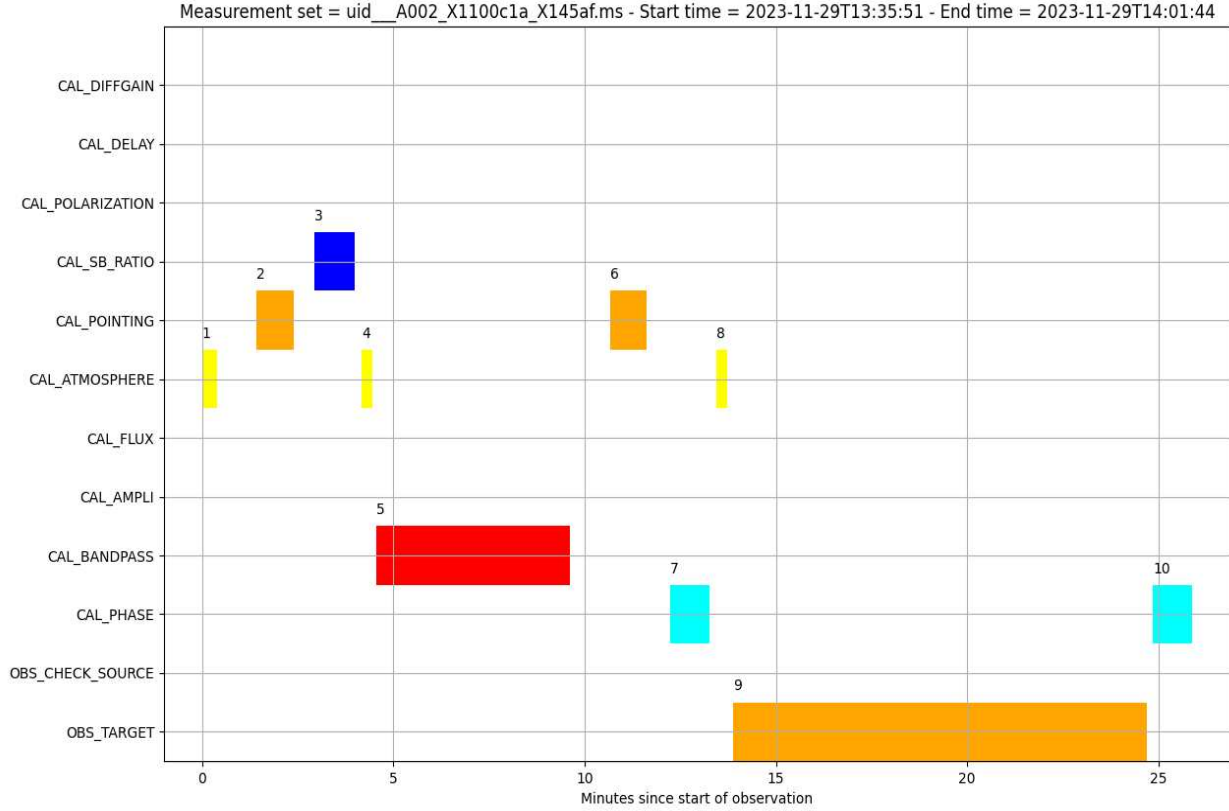


Figure 20: ALMA Band 3 test observation with colored blocks showing different target.

5.1.3. Self-calibration / imaging loop

The scheme of a general self-calibration for solar observation that contains multiple scientific scans can be described as follows:

- split the data that have been corrected using standard calibration into sub-datasets according to the scan index.
- For each sub-dataset, make an image from the entire scan period using the ***tclean*** task in CASA, to use as a model for self-calibration. The model is stored in the dataset for later use.
- Determine phase corrections for each solution interval relative to the model given by step b using the ***gaincal*** task in CASA, and generate a self-calibration table.

- d) Apply the phase corrections to each image in the sub-dataset using the **applycal** task in CASA and generate an intermediately corrected sub-dataset.
- e) Iteratively repeat steps b-d, substituting in each intermediate sub-dataset, until no further correction is needed, as determined by checking the calibration table for reduction of the residuals.

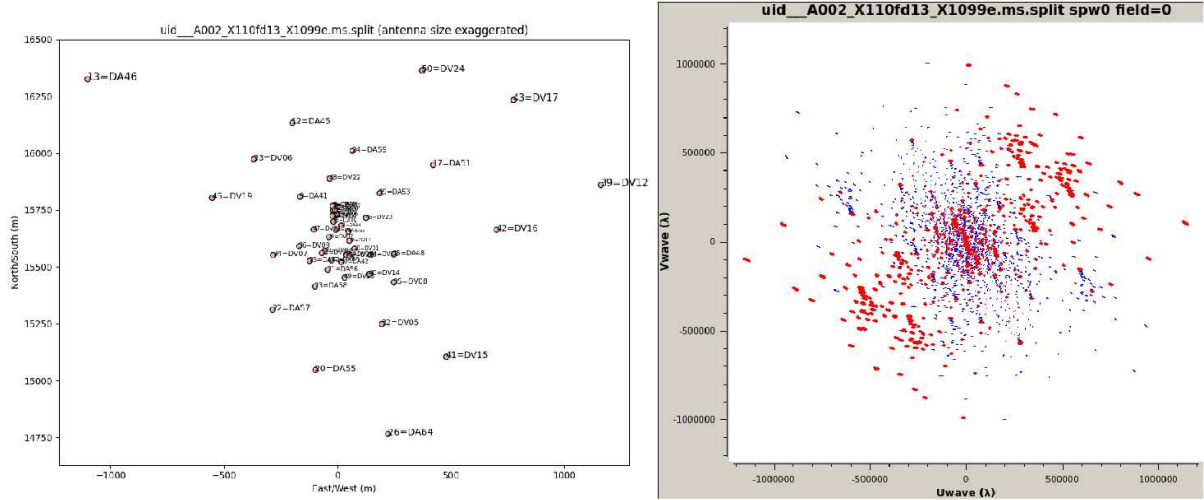


Figure 21: Antenna array configuration and the uv-coverage for the solar target for the Band 5 observation.

For the test solar observation, since we only have one on target scan, we will neglect step (a) and focus on the rest. We will also repeat step (b) to (d) for a fixed 5 times and compare the self-calibration results between different setups, just like what we did for the simulations.

Illustration of the successfully reconstructed image (a single snapshot – the entire-scan spanned self-calibrated movie is still in production) is displayed in Figure 22. The four panels show the ALMA clean brightness map, its corresponding residuum, and – for the sake of comparison – also simultaneously observed data of the same region at the Sun from two other instruments – *Atmospheric Imaging Assembly* (AIA), and the *Helioseismic and Magnetic Imager* (HMI), both onboard The Solar Dynamics Observatory (SDO). The cleaning has been stopped after 200k iterations and the image quality has been subsequently checked. Namely, the residual RMS is less than 10% of the RMS value in the clean image, which is the primary cleaning threshold for us. As the secondary criteria of the image-reconstruction quality we use (similarly as with the simulated data, see – section 4.2.3 and Figure 19) the power spectra in the clean and residual images – see Figure 24 below. This auxiliary measure indicates the successful reconstruction, too. Moreover, from the intensity contours overlaid on the top right panel of Figure 22, we can see that there are some overlaps between the features seen in ALMA Band 3 map and AIA 304Å image. Since AIA 304Å is also sensitive to the solar chromosphere, these similarity in features represent another indication of the quality of the self-calibration results.

During the self-calibration procedure, the image size and cell size are set according to the suggestion given by qa2 report, which is [2048 px, 2048 px] and 0.04 arcsec for the Band 3 configuration C-7 case. As it has been revealed already in the simulated datasets (Sections 4.1.3 and 4.1.4) **tclean** for large images (2kpx x 2kpx and larger), whose size implies from the higher resolution, needs

significantly more iterations (typically 200k cycles are required to reach the above stopping criterion) comparing to the ‘standard’ so-far performed solar imaging of the data taken solely in the compact configurations. Consequently, the whole routine is time consuming has to be conducted with CASA parallel processing.

While we performed the self-calibration procedure, a “mistake” has been made in the sense that the “standard” number of *tclean()* iteration, as typically performed in the QA2 solar imaging script, has been used (40k cycles). This eventually led to early termination of each round of the self-calibration. Though we found out and corrected the issue in the script, we present the deficient result here, too, as it could serve as a good example of how *niter* setting really affects the self-cal result of actual observational data. The issue is illustrated in Figure 23, which shows the ALMA map generated during the first round of the erroneous self-calibration routine. Along with the clean image, the corresponding residual is displayed, as well as the power spectrum for both clean and residuum images. As it can be seen, the residual level is comparable to the clean map itself (and far from our stopping criterion for residual to be less than 10% of the clean image), indicating the failure of this self-calibration. The secondary quality metric – the power spectrum – also doesn't show any sudden drop at the tail part, like we can see in the well self-caled ones – see Figure 24 below for comparison.

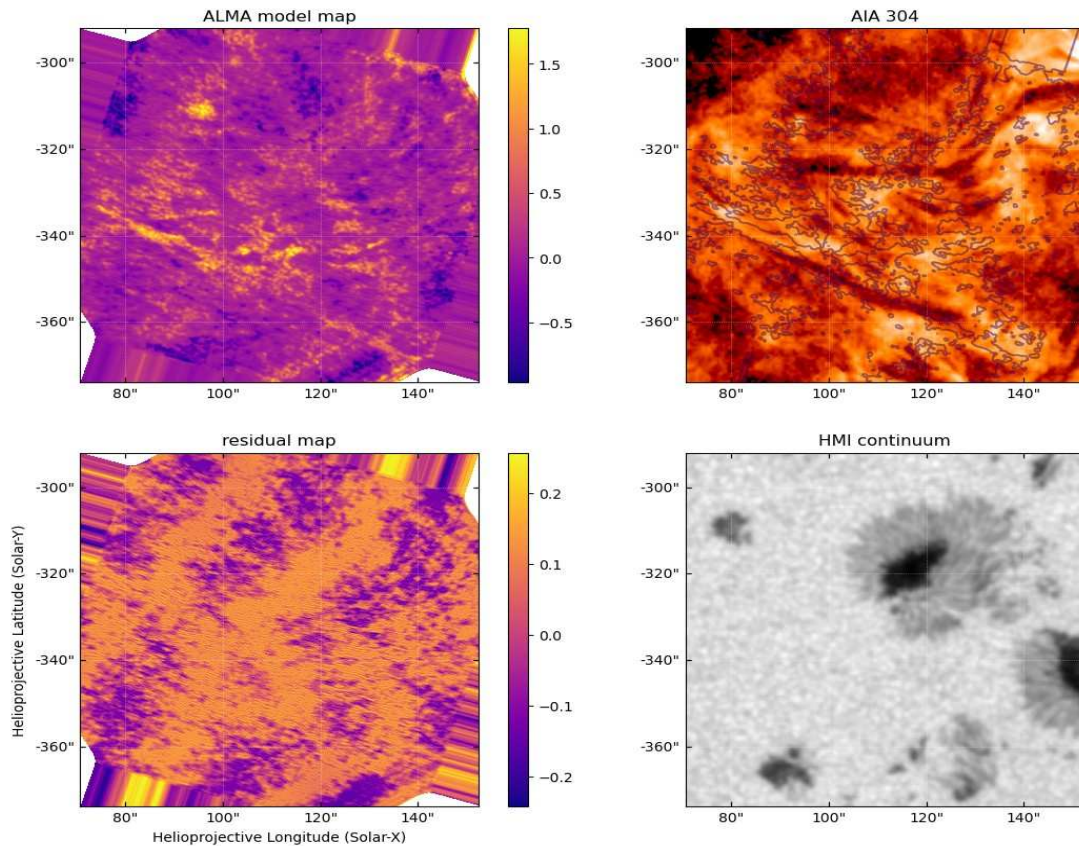


Figure 22: ALMA map and its residual in comparison with AIA 304Å image and HMI continuum image. The AIA wavelength is sensitive to the solar chromosphere, basically we can expect to see similar structures as visible in the ALMA Band 3. The HMI optical continuum shows the underlying photospheric structure – the small sunspot and serves as the context image.

As a direct comparison to Figure 23, which displays the self-cal results with the `niter` settings used in the QA2 imaging of the so-far compact-configuration observations, Figure 24 shows the ALMA map and its residual from the first round of self-cal procedure when the cleaning process is finalized with the `niter` parameter suitable for the large, high-resolution images. The residual is much lower and much less structured compared to the one in Figure 23. The power spectrum also include a break (the slope change) followed by a sudden drop at roughly $k = 100$, which indicate the scale of the smallest feature is about 15 pixels. Yet better is the insignificance of the residuum for proper `tclean()` settings (i.e., the correspondingly higher number of iterations) seen in Figure 25, where the clean image and its residuum are displayed in the same range of values (note the same color-scale bar aside).

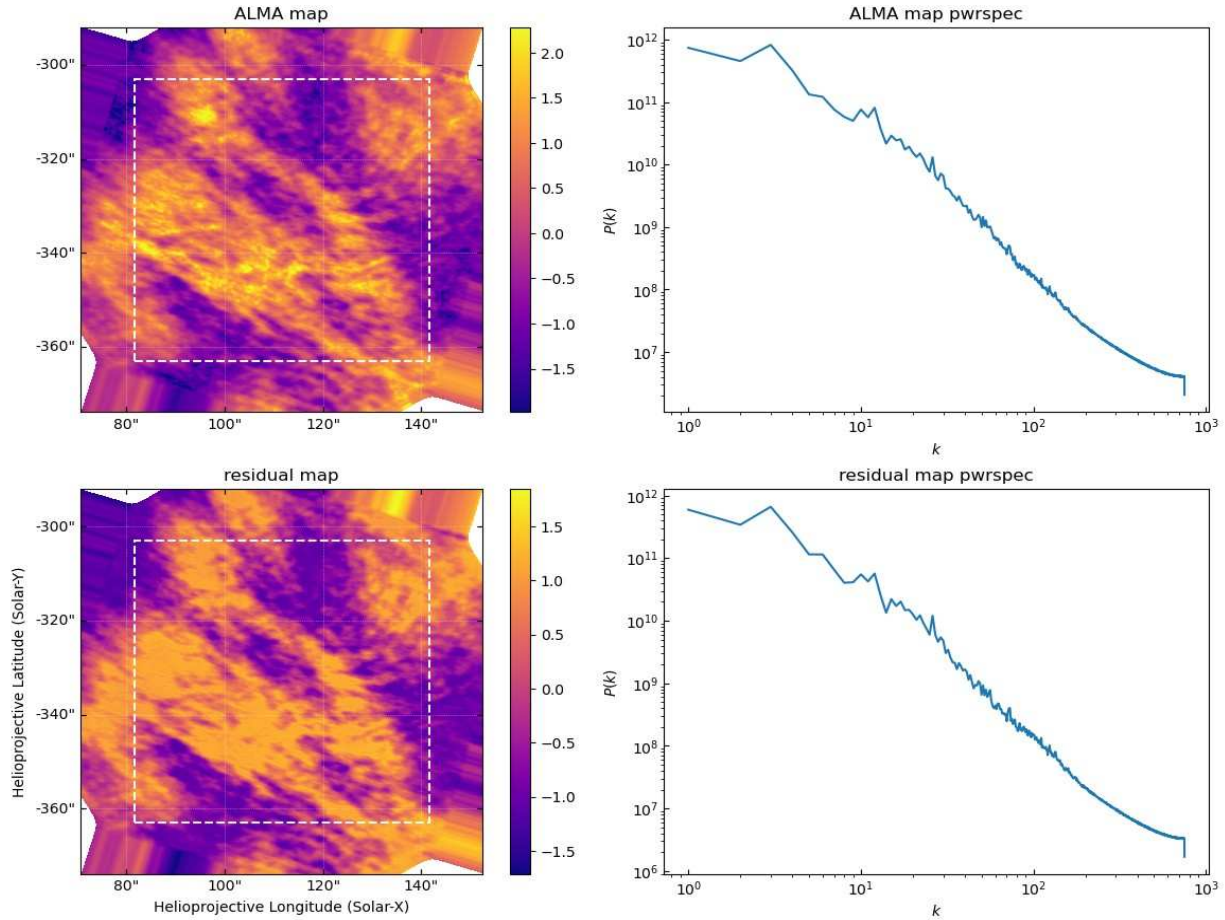


Figure 23: ALMA map generated in the first round of self-cal routine and the corresponding residual image. The `tclean` process in the self-cal loop has been interrupted prematurely by mistake. The residuum still contains a lot of structures because of that error what is also demonstrated at its Fourier power spectrum.

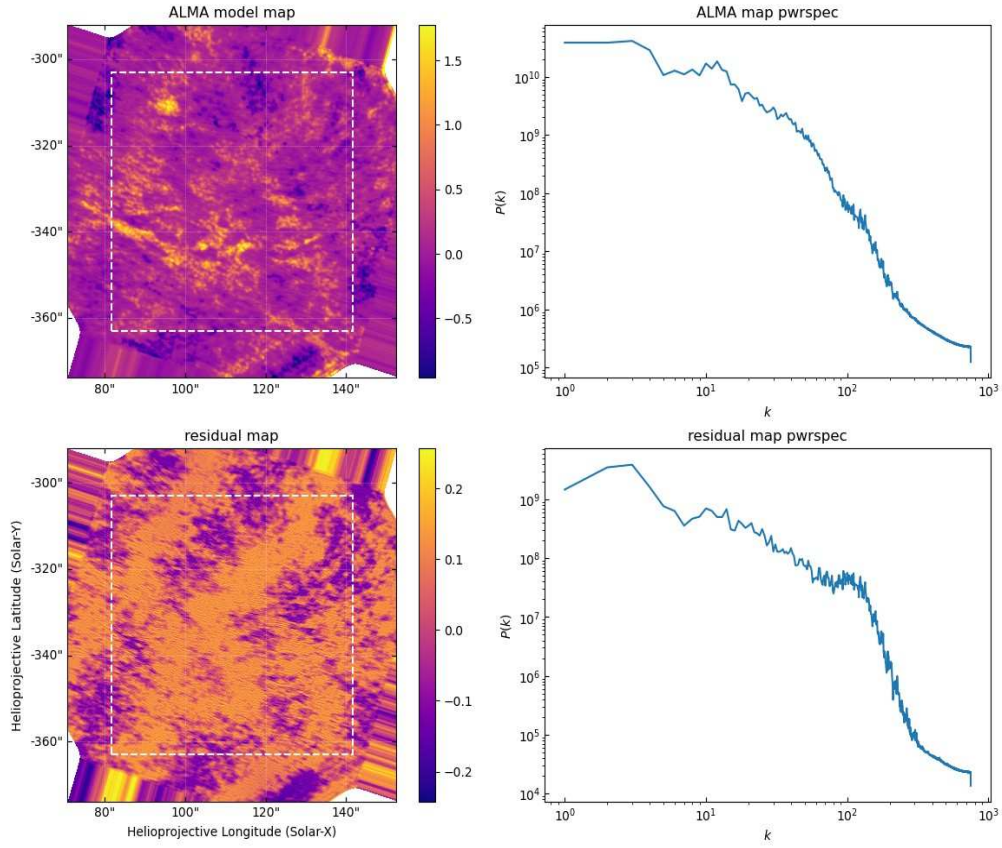


Figure 24: Fully-cleaned ALMA map and its residual, together with corresponding power spectrum.

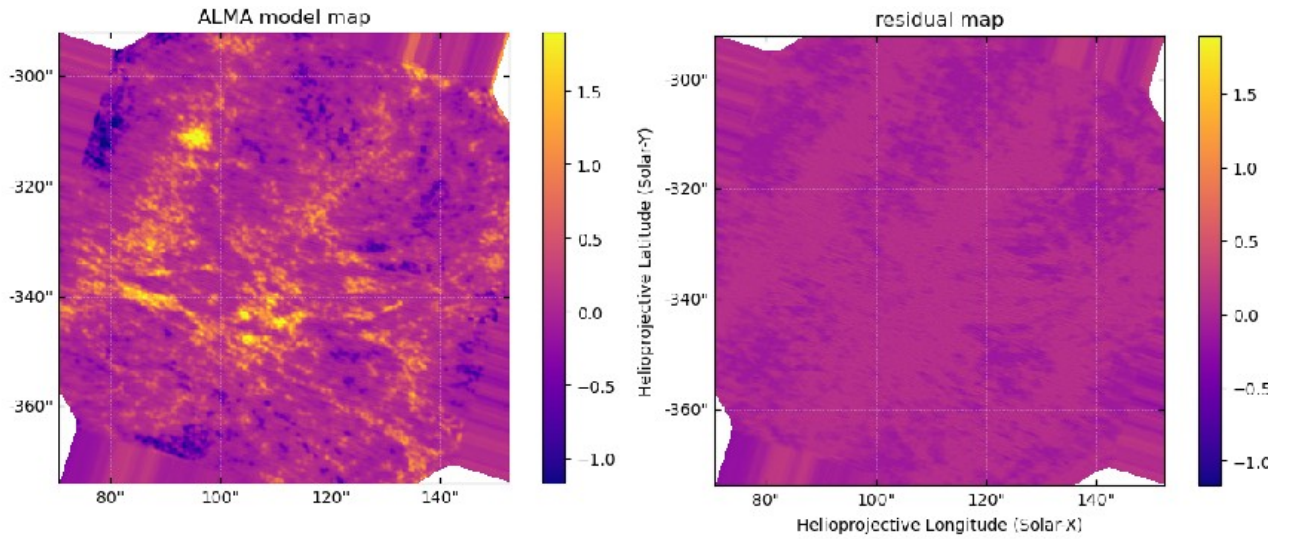


Figure 25: Clean (left) and residuum (right) maps for the Band 3 data with appropriate number of iterations in `tclean()`. Essentially the left panels of Figure 24, now displayed in the same range of values (and corresponding color scale).

5.2 Replacement of the WVR signal by differential absorption of the solar mm radiation in Band 5: Indication of feasibility

Richard Hills estimations for relation between WV differential absorption and phase delay, as presented in Section 4.4, rely on the significant slope of the solar spectrum in the wing of the WV line at 183 GHz. As we are still in the middle of processing of the quite recent Band 5 data, just the preliminary results are presented here.

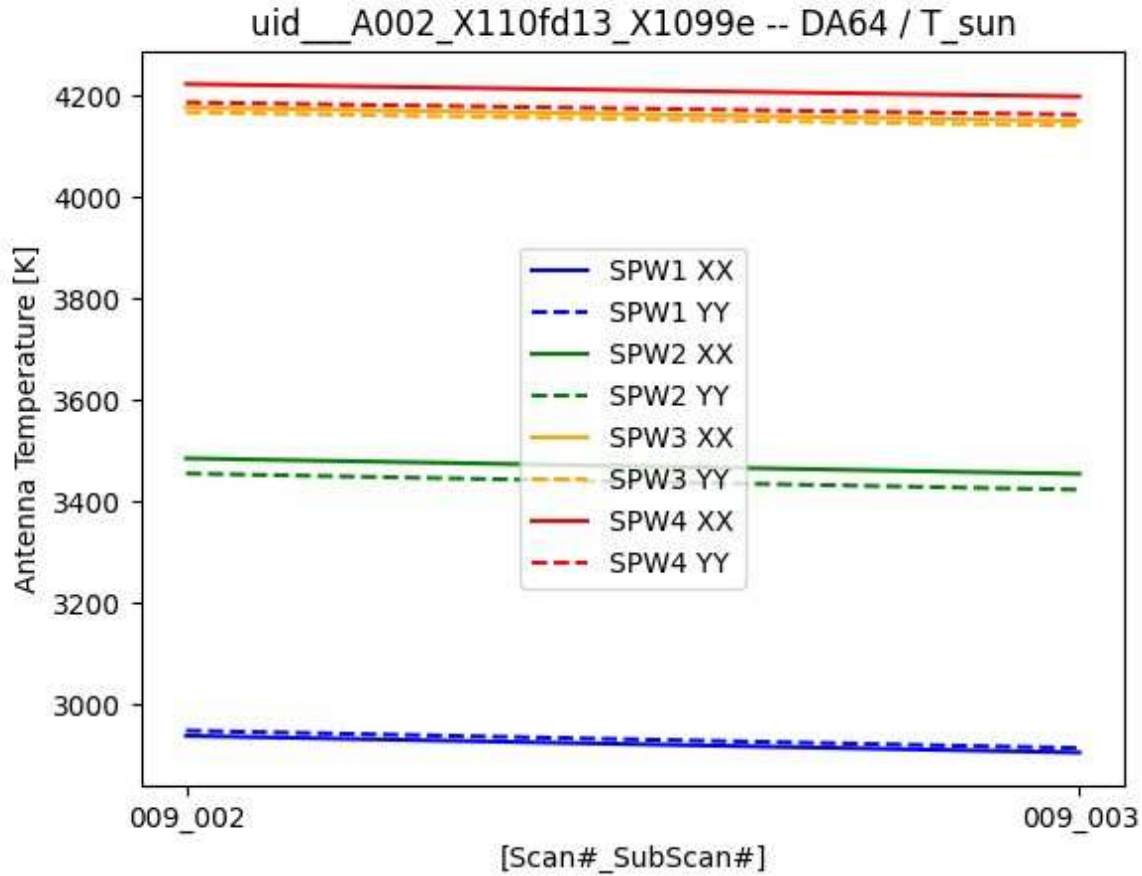


Figure 26: Spectral dependence of T_{ant} – differential influence of the WV line in spw0 and spw1 (in the legend of the figure as SWP1 And SPW2, respectively) is visible. The frequencies of the SPWs increases from SPW1 to SPW4, meaning that we are going apart of the WV line with increasing SPW id. The WV line is most pronounced in the SPW1, its wing partly covers SPW2, too.

An intermediate step in solar calibrations requires calculation of the antenna temperature T_{ant} (Shimojo et al., 2017). This is basically the brightness temperature of the target field averaged of the FoV, but – at this stage – before applied band-pass correction. Hence, it contains the influence of the atmospheric WV line on the spectrum formation. The following Figure 26 shows clear decrease of the T_{ant} in SPWs 0 and 1, as approaching towards the WV line core. This is preliminary indication of the spectral slope. As a next step, we shall resume the (now flagged) auto-correlations and try to recover the

spectral slope in its time dependence for each antenna. Its value is going to be correlated with the phase error as found from the self-calibration loop in Band 5 data (so far running).

6. Development side product: Solar Script Generator

Insofar, the solar ALMA observations are processed (in frame of the QA2) fully manually. It means that the calibration and imaging scripts are copied from one processed EB to another and used as template that has to be manually edited with each new analysis. Since Cy6 the Czech node of the EU ARC has introduced significant amount of automation directly into the scripts (finding observing band, specific calibrators fields and scans, automatic estimation of the image- and cell-sizes, etc.). However, still many parts requested attention of the data analyst, the script execution had to be interrupted at many break-points in order that the analyst manually finds and fills requested values (e.g., the flux density in `setjy()`). Moreover, the script itself got extended (almost twice) by this repeating ‘service’ lines of the code and became complicated and cumbersome.

Clearly, the way out has been found in taking these parts of the code that basically takes care of automated generation of those parts of the script, which depend on the specific processed EB, out of the script itself and create the *reduction script generator for the solar observations*, exactly as it has been defined in the collection of *Analysis Utils* (`es.generateReducScript()` by Eric Villard). This can be – in line with the historical development of the ‘standard’ data processing – considered as the first step towards the standard ALMA pipeline processing for the solar data.

Although this task does not belong to the goals of this development study, the new CSV datasets obtained as a part of the project, have helped us to finalize the development of the *Solar Script Generator* (SSG), which started already in 2020 but has been interrupted because of other, more pressing business and also lack of motivation (there were no EU solar observation to be processed between 2020 and 2023).

In spite of the clear inspiration by Eric’s Villard script generator in the *aU* library, we have selected a bit more relaxed (or lazy) approach and used implementation based on the *static template* of the calibration script, which contains all the repeating code, not specific to any processed EB. This general lines of the codes are interleaved with the *keys* – firmly defined placeholder strings, put into the points, where the EB-specific part of the code should appear. The *script generator* itself then reads this static template and – based on the analysis of MS (meta)data – it generates a Python dictionary, which map the placeholder keys to the actual lines of the code. At the final stage it replaces the keys with the values and prints the final script into a file.

The code is available here: <http://wave.asu.cas.cz/barta/sw/ALMA/ssg/> and it is self-documented by heavy commenting inside both the script and the template. Its usage (after properly setting the paths in the CASA init file) is similar to that of the reduction script generator in the *aU* module:

<in CASA>

```
import SolSG as ssg  
  
sso = ssg.stuffForSolarDataReduction()  
  
sso.generateSolCalScript(asdmName,doQA2=True)
```

Our motivation to finish this not fully related task as an auxiliary/preparatory activity within this study has been primarily given by increasing divergence between calibration and imaging scripts in the community of ALMA data (QA2) analysts: There existed multiple versions differing by the ARC and the last cycle that the script has been in usage. The reduction of the CSV data has been thus preceded by comparative research in the existing scripts. This unsatisfactory situation is clearly caused by low number of the solar projects observed – typically one per cycle world-wide (so only one ARC is performing solar QA2 per cycle). Hopefully, introduction of the SSG will not only boost the solar QA2 towards ALMA pipeline processing in the future, but it shall also help to keep coherence in the solar data reduction procedures across the ARCs and the consecutive ALMA cycles.

The SSG generator has been successfully used for preparation of the final version of calibration scripts for the CSV data reduction in this study and moreover tested on the older (2018) solar-prominence mosaic.

7. Conclusions and plans for the next period

The study is a bit behind half of its nominal duration, so the final results should yet come. But already now there are interesting preliminary outcomes:

- The simulations shows that **solar observations in Band 3 should be possible up to configuration C-7 and in Band 6 up to C-6**. More extended arrays (C-8 and beyond in Band 3) give poor results in reconstructed images even for the idealized limit of the zero atmospheric turbulence. Most likely, the dilution of the *uv* coverage mentioned in the Section 1, is already critical for more extended configurations and it is hard to invert the visibilities into synthesized image. Interestingly enough, the group at Uni Oslo (UiO) just tried to run their simulations for the preceding study oriented at high-cadence observations with the extended ALMA configurations, too and they found similar limits, just one ‘size’ smaller: C-6 for Band 3 and C-5 for Band 6. In our opinion, this small difference may be attributed to the different simulation setup; namely our simulations include **heterogeneous array** (12m + 7m, including mixed baselines), while the simulations at UiO included just 12m array (or perhaps, also 7m antennas, but separately). The higher number of baselines at the middle range in our mixed array might led to better performance in **tclean()** and, consequently, push the limit to the more extended configuration (see Figure 21). Nevertheless, it is more or less clear that longer baselines than those in C-7 are out of capability of the Solar ALMA ObsMode, at least with the so far used traditional CLEAN algorithm, including its sub-variants. We summarize the so-far obtained results in this direction in Figure 27
- The so far obtained **CSV observations** in Bands 3 (performed in the transitional configuration close to C-7) and 5 (done in C-6) **confirm the simulation results**, at least in the sense of the lower limit: It was possible to perform interferometric synthesis with those baselines and results of the self-calibration procedure in Band 3 revealed really great amount of details. Interestingly, the weather during the Band 3 observation, has been reported as just marginal. In spite of that, the self-calibrated series obtained from that observation are still scientifically valuable (we plan to publish the dataset as the CSV data, upon finished time-domain imaging and self-calibration) – this **opens the possibility to use the standard ‘noGo’ time for the simple solar observations** and boost the observatory science time, provided that self-calibration is included into the solar QA2 procedure.
- The results are also the **first observational proof that ALMA is capable of high-cadence observing**: The CSV data in both Bands 3 and 5 have been taken with an integration time of 192 milliseconds and yet calibrate and image well. The older CSV data taken for the preceding “High cadence” study did not pass QA2 (because of a bug with drifting/jumping phase-center with 30s period, related to the general-relativity correction), so these are the first high-cadence data ever.
- Albeit the **differential decrease of the antenna temperature** (basically the brightness temperature of the Sun as integrated over the PB *before* the BP calibration) **towards the line**

core of the WV is detected, we are still not able to correlate its time variations with the time-varying phase error for each antenna. For that we have to finish the self-calibration of the Band 5 series, which is – up to the report delivery – still running (and CPU-time demanding) process.

Clearly, many activities are yet in their run and we hope to present their results at the MT Review presentation and update the MT Report in response to the reviewers comments accordingly. This immediate task defines our work (that is actually already running) for the nearest future.

On the longer horizon of next two months we would like to concentrate on

- Replacement of the so far used ATMOS code for corruption of the simulated MS with the phase errors, by the new model of the phase errors introduced through the atmospheric-turbulence, kindly provided by Yoshi Asaki & Luke Maud. We received the code with documentation and training MS in December, basically at the same moment, when we got also the CSV data. For obvious reasons we have focused on the data processing first, postponing the simulation activity to the next period.
- Correlation between image fidelity (direct comparison between reconstructed image and its original unbiased model) and those metrics of the imaging quality (like power spectra of clean/residual), which are not dependent on apriori knowledge of the idealized input model. In the simulations we can always use both types of metrics for estimating the image quality, however, in the observations we will have just those, which cannot rely on comparison to the model. For this sake, the metric that gives the best coincidence to the direct comparison in the simulation case, shall be selected for the observed data, too.
- Improved performance in cleaning of the large solar images. As it has been described above, the large images (actually, the issue seems to be related rather to the broad spatial Fourier spectrum – presence of the flux at many spatial scales than to the size itself) makes the procedure of per-frame (per integration) imaging and self-calibration very (CPU-) time demanding. We shall explore broader range of parameters for the multi-scale and MTMFS cleaning than which has been so far used for in the ‘standard’ solar imaging. Another possibility we see in using manually-controlled multi-scale cleaning: First do the larger scales with a bigger cell-size and using *uvtaper*. Such low-resolution images shall also remain stable over multiple integrations/frames. This is achieved by time-scale separation between actual dynamical processes in the solar atmosphere and the (much faster) phase distortions caused by the Earth’s troposphere turbulence. The spatial and temporal dynamic scales in the solar atmosphere are roughly related by the sound speed: 1 arcsec in the image corresponds to ~ 700 km at the Sun and this spatial scale is changing at the timescale of ~ 20 seconds, if we take into account a typical chromospheric sound speed of 10 km/s and the rather safe Mach number in the shocks $M=3$. The pair-wise phase differences between antennas are contained even in the tapered image since no antenna is so far from the rest of the array that it has no baseline point in the tapered *uv* space. Hence, its phase delay is still corrected by the self-calibration procedure. This

low-resolution and low-cadence series, which should be much less CPU-demanding to obtain, will be subsequently used as an input model for the full-resolution (both space and time) deep cleaning. Since the flux at larger scales will be already removed, the small-scale cleaning should run also much faster.

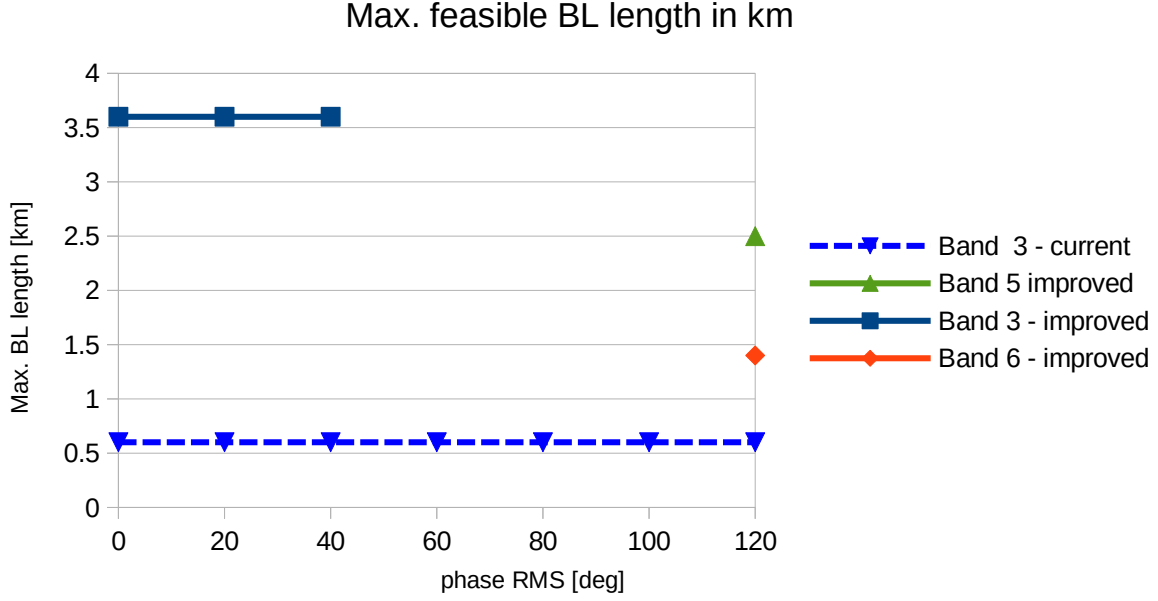


Figure 27: The so far obtained upper limits for solar observations if the fast-cadence sampling followed by post-processing that involves self-calibration loop is employed. Most of the points are base on the simulation results, the point for Band 3 at configuration C-7 (BL length of 3500m) at phase RMS 40 deg has been confirmed by the test observation data. For the idealized no-troposphere case ($RMS = 0$ deg) the simulation found that configuration C-8 in Band 3 is already beyond the plausible limit, therefore the nearest lower configuration C-7 with the longest baseline of 3600 m is displayed. However, it is possible that some hybrid configuration between C-7 and C-8 would still be manageable. The maximum baseline length for Band 5 and 6 corresponds to configurations C-6 and C-5, respectively.

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Annex 1: Statement of work



**Atacama
Large
Millimeter /
submillimeter
Array**

ESO ALMA Support Centre

Towards High-resolution Solar ALMA Images Overcoming current ObsMode limitations

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Change Record

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1. Introduction

The Atacama Large Millimeter/submillimeter Array (ALMA), an international astronomy facility, is a partnership of Europe, North America and East Asia in cooperation with the Republic of Chile. ALMA is funded in Europe by the European Organization for Astronomical Research in the Southern Hemisphere (ESO), in North America by the U.S. National Science Foundation (NSF) in cooperation with the National Research Council of Canada (NRC) and the National Science Council of Taiwan (NSC) and in East Asia by the National Institutes of Natural Sciences (NINS) of Japan in cooperation with the Academia Sinica (AS) in Taiwan. ALMA operations are led on behalf of Europe by ESO, on behalf of North America by the National Radio Astronomy Observatory (NRAO), which is managed by Associated Universities, Inc. (AUI) and on behalf of East Asia by the National Astronomical Observatory of Japan (NAOJ).

ALMA's primary function is to observe and image with unprecedented sensitivity and angular resolution the Universe at millimetre and sub-millimetre wavelengths.

This document outlines a work plan for the development of new Solar ALMA observing modes that would allow to overcome some of the current system limitations.

2. Scope

In the framework of the ESO “Advanced Study for Upgrades of the Atacama Large Millimeter/submillimeter Array (ALMA)” (CFP/ESO/19/25417/HNE), the present Statement of Work (SOW) is applicable to the:

Towards High-resolution Solar ALMA Images Overcoming current ObsMode limitations

This activity consists of the following elements:

1. Change of the Go/noGo procedure followed by the selfCal-based posterior phase corrections for times series of the high-cadence solar interferometric images. This shall be the main and universal approach. This approach will include the following activities:
 - Set up CASA-based simulations including atmospheric turbulence and add selfCal-based corrections of the fast phase variations. The simulations should be compared with the primary (model) images used as input.
 - Expand these simulations for longer baselines.
 - Verify the ability to separate the real and apparent dynamics of the Sun when using larger baselines.
 - Analyse the impact of sparser uv coverage in the larger configurations using these simulations.



- Determine the maximum yet acceptable configuration for each ALMA band depending on the phase metrics measured during the solar-specific Go/NoGo test, integration/sub-scan duration (cadence), and spatial setup (single pointings, size of small mosaics).
 - Request, and if obtained, analyse short real test data (e.g. actual Go/NoGo test and science observation of the Sun) and verify/analyse if the altered go/no-go test is appropriate.
2. Utilization of the atmospheric WV line seen in absorption on the edge of the science SPW of Band 5. This is considered as a supplemental approach, which can provide further improvement, but it is usable just for the Band 5 data. This approach will include the following activities:
- Identify an appropriate archival Band 5 dataset in configuration 2 to test the proposed procedure.
 - Adapt the mathematical model in `wvrgcal()` to relate the absorption of the solar continuum radiation to the water vapour column density and consequently to the atmospheric phase delay.
 - Apply the previous method to the analysis of existing Band 5 solar test observations in configuration C-2 or alternatively, new observation in configuration up to C-4.
 - Use archival non-solar Band 5 observations with strong bandpass calibrators to verify the water vapour column derived from absorption with those from the radiometer and compare both with the observed phase variations.
 - Optionally, verify if this technique can be used in other bands with strong water vapour lines such as the 324 GHz line in Band 7.
 - Based on the new Go/NoGo criteria for solar observations, determine the limitations of the present method, and specify the conditions in which it can be used.

The technical characteristics of the study are provided in the proposal [AD1].

3. Related Documents

3.1 Applicable Documents

The following documents of the exact issue shown form part of this SOW to the extent specified herein. In the event of conflict between the documents referenced herein and the present document, the terms of the Statement of Work shall be considered as superseding requirements.

AD1 CFP/ESO/19/25417/HNE “Towards High-resolution Solar ALMA Images Overcoming current ObsMode limitations”, Advanced Study for Upgrades of the Atacama Large Millimeter/Submillimeter Array (ALMA), Author: M. Bárta;

AD2 ALMA Documentation Standards
ALMA-80.02.00.00-003-G-STD



3.2 Reference Documents

The following documents, of the exact version shown herein, are listed as background references only. They are not to be construed as a binding complement to the present document.

RD1 Alma Documentation Control Plan
ALMA-80.02.00.00-011-F-PLA

4. Requirements

4.1 Project definition

ESO

The term “ESO” (European Organisation for Astronomical Research in the Southern Hemisphere) is the Executive Organization that has concluded with the Contractor for the Work.

Contractor

For all purposes related to this SOW and associated documentation, the term Contractor shall mean the Contractor’s firm, its employees, its paid and/or unpaid associates, its subcontractors and sub-subcontractors, consultants, suppliers, service providers and all other contracting and otherwise associated parties.

Technical Proposal

For the purpose of this SOW Technical Proposal means the Proposal [AD1].

4.1.1 Project Milestones

The work shall be organized according to the schedule milestones in Table 1. The milestone definitions being:

M0 Kick off. Starting of the activity

M1 Delivery of the Mid-Project review data package: in preparation for milestone M2 the data package as specified under deliverable DS1 shall be delivered to ESO

M2 Mid-Project review: based on the data package delivered under milestone M1, a review under the guidance of ESO will be held

M3 Delivery of the Final study review data package: in preparation for milestone M4 the data package as specified under deliverable DS2 shall be delivered to ESO

M4 Final Review: based on the data package delivered under milestone M6 a review under the guidance of ESO will be held

M5 Provisional Acceptance of the Documentation Package: provisional acceptance of the documentation package is granted once all actions from the Final Review, milestone



M4, have been resolved and Final data package delivered to ESO as specified under deliverable DS3.

Table 1 - Milestones

Milestones	Date
M0 - Kick off	T_0
M1 - Delivery of the Mid-Project review data package	$T_0 + 11$ months
M2 - Mid-Project review	$T_0 + 12$ months
M3 - Delivery of the Final study report review data package	$T_0 + 23$ months
M4 - Final Review	$T_0 + 24$ months
M5 - Provisional Acceptance of the Documentation Package	$T_0 + 25$ months

4.1.2 Deliverables of the Study

As part of the project, the contractor will deliver documents and support reviews as shown in Table 2. Final versions of all documentation shall be delivered at milestone M5 latest.

All the documents to be delivered within the scope of ESO contracts are under the managerial responsibility of ESO and shall be reviewed and/or approved by ESO.



Table 2 - Deliverables

ID	Deliverable description	Delivery for Milestone
DS1	Delivery of the Mid-Project review data package: Preliminary report containing results from both approaches: • Approach 1 ○ Setup of the simulation sequence in CASA for larger baselines; ○ Comparison of the “blind-shot” selfCal-based correction results with the original unbiased model images; ○ Measurement of the phase metrics from a changed go/no-go test on a short timescale; • Approach 2 ○ For Band 5, present analytical calculations/model that binds the absorption signal to the water vapour column density to the phase delay.	M1
DS2	Delivery of the Final study review data package: Analytical study/report that will devise feasible (alternative) ways, which would enable solar ALMA observations with more extended configurations. For each of the alternatives the following shall be documented and compared to test observations where available: • Benefits/constraints: Maximum resolution (max. baseline length) reached vs. sci/tech (side-effect) constraints introduced by the implementation. The ultimate goal: Finding the maximum yet acceptable baseline length in dependence on (i) the observing frequency, (ii) the phase metrics as measured by Go/NoGo test prior to the observation, (iii) observing cadence, and (iv) spatial setup (single-pointing or a small mosaic); • Implementation requirements and suggested implementation procedure; • Estimation of implementation costs (albeit it may be only in the form of test time and manpower).	M3
DS3	Final data package: The Final data package shall consist of the documentation delivered under DS1 and DS2 but updated for the issues and actions agreed at Mid-Project review (M2) and Final Review (M4) respectively.	M5



4.2 Tasks Applicable to all Project Phases

This Chapter defines the basic tasks that are common to all project phases.

4.2.1 Project Management & Control

4.2.1.1 Project Management

The Contractor shall establish and maintain an effective project management structure to achieve the objectives of the Agreement.

The Project Office shall coordinate and control all technical, and contractual activities, the project resources, and manage all disciplines required for the successful completion of the Study. To be able to do so, the Project Office shall have effective control and support from appropriate senior management of the Contractor's organization.

The **Key Personnel** of the project shall consist of people with experience in the specific technologies and/or domains required by the scope of work. Appointment and exchange of key personnel, in particular Project Manager, during the execution of the Study shall be agreed with ESO in due time.

The Contractor shall assign a **Project Manager** with authority over the involved personnel and resources. The project manager shall be given full authority to negotiate with ESO and their Sub-Contractors and/or suppliers all issues related to the Agreement and shall be the **Single Point of Contact (SPC)** for all formal matters.

If events occur which could impact on the project milestones, e.g. technical problems or changes requests initiated by ESO or by itself, the Contractor shall evaluate every possible solution to avoid or limit the impact on the schedule.

4.2.1.2 Project Reporting

a) Progress Report

The Contractor shall provide ESO with Progress Reports, duly approved and signed by the Project Manager:

- 1) before the 5th of every second month following the project Kick-off.

The Progress Report shall clearly summarize the current status of the work in progress. It shall briefly describe the results achieved in this period and planned for the next period. It shall also give an account on every problem detected at any level (i.e. technical, programmatic, finance) of the project during the reporting period(s) and identify the corrective actions.

The Progress Report shall also contain the Action Item List (AIL) and the status of all Action Items which shall also be reviewed at each progress meeting. The Progress Reports shall be sent by email to the ESO Technical Representative no later than three working days after the end of the reporting period. In the course of critical phases, ESO reserves the right to ask the Contractor additional reports.

b) Red Flag Report

Independently and in addition of to the regular Progress Reports, the Contractor shall report any event with significant implications on schedule, design or cost. A Red Flag Report shall be issued by the Contractor within 24 hours after occurrence of a major problem jeopardizing delivery, the achievement of the milestones defined in this Agreement, or the



achievement of technical performance and requiring the immediate attention of ESO. This reporting shall apply to problems at all project levels.

4.2.1.3 Progress Meetings and Reviews

Progress Meeting shall be held either at Contractor premises, at ALMA European premises, or by tele or video conference (to be agreed case-by-case) on a bi-monthly basis, in any case the week following the receipt of a monthly Progress Report by the assigned ESO Technical Representative. The **Agenda** and the **List of Participants** shall be communicated to ESO at least three days before the meeting. ESO reserves the right to call extraordinary Progress Meeting, one week in advance.

The purpose of the PM is to review the progress of the work, to highlight and discuss detected and reported problems or concerns, and to determine corrective measures to be taken.

Unless specifically requested otherwise by ESO, the Contractor shall write the **Minutes of Meeting (MOM)**. The Minutes shall be signed by all the parties at the end of the Meeting. The signature of such minutes indicates solely that the wording is correct and properly reflects the outcomes. The signature shall however not be construed as a formal, contractual agreement. Any matter having contractual implications shall be handled in accordance with the regulations of the Agreement. The Minutes shall include a **List of Action Items (AI)** with appropriate deadlines and responsible, and shall be under configuration control.

The Contractor shall plan and prepare project reviews in consultation with ESO, particularly the location, agenda, and participants of the reviews will have to be agreed.

The following reviews shall be held:

- The Mid-Project review (M2) is a review to assess the work performed in the first phase of the study;
- The Final review (M4) is a review to assess the work performed in the second phase of the study.

A review is closed when all issues and comments raised by the review board and accepted by ESO have been taken into account.

4.2.2 Configuration Control & Data Management

4.2.2.1 Configuration Control

The plan for the management of the ALMA documentation is provided for information in [AD2]. The Contractor is invited to adhere to this plan. As part of it, the Contractor shall maintain the Configured Items Data List. The CIDL identifies all the official and valid documentation ("configured items") of the Project. It is a key element of the Configuration Control process and for the particular project shall include the list of project reports (e.g. included in Review Data Packages).

4.2.2.2 Change Request Procedure

Both parties, the ESO and the Contractor, may at any time request a change, which may affect the Contractual Conditions:

- Agreement



ESO ALMA Support Centre

Towards High-resolution Solar ALMA Images
Overcoming current ObsMode limitations

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- Statement of work
- Documentation
- Schedule

In response to a Change Request initiated by ESO, the Contractor shall return a reasonable and justified Change Proposal within 4 weeks (subject to negotiations between parties), and, if agreed by ESO, implement the change defined in the requested change. In the case of a Change Request initiated by the Contractor, ESO have no obligation to accept the proposed change and will, in any case, provide a reply to such requests within 4 weeks. In any case, the implementation of a Change Request shall not start prior to the written authorization or approval by ESO in accordance with the contractual requirements.

When preparing a Change Request, the Contractor shall investigate the proposed change and provide ESO with all information for a decision, including, but not limited to:

1. The reason for the change.
2. An assessment of the technical feasibility, including an analysis of all the impacts on the products and on the total system (i.e. performance, specifications, interfaces, etc.).
3. The necessary modifications of the contractual documents (Statement of Work,) shall be clearly indicated by quoting the OLD and NEW versions of the text and/or the drawing.
4. The total schedule impact, i.e. on any contractual milestones.
5. The total cost impact, giving differential costs changes on labor, operations and capital, for each affected Work Elements/Work Packages.
6. Other related factors such as reliability, safety, integrity, maintenance, etc.
7. Any additional documents deemed necessary.

A template of ALMA Change Request is provided on the ALMA document server (EDM or its replacement). The procedure for the submittal and processing of Change Request is given for information in [RD1]. Each proposed change must be identified by an individual and unique number, which shall be used by all subsequent correspondence as reference. The Contractor shall keep a record with all initiated changes with their status (approved, rejected, pending, closed) and provide an updated status together with the Progress Reports.

4.2.2.3 Document Format and Identification

All written documentation and information issued by ESO will be forwarded to the Contractor Project Office for further distribution within the Contractor organization as necessary.

The project documentation shall comply with the document standards described in [AD2].

--- End of document ---

Annex 2: Proposal

- Scientific & technical description

Call for Proposals CFP/ESO/19/25417/HNE

ALMA DEVELOPMENT STUDIES 2019

TOWARDS HIGH-RESOLUTION SOLAR ALMA IMAGES
Overcoming current ObsMode limitations

Revised version

as a follow-up of the *1st International Solar ALMA Imaging Workshop* held
in Oslo, March 2nd – 6th, 2020

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TOWARDS HIGH-RESOLUTION SOLAR ALMA IMAGES

Overcoming current ObsMode limitations

Preamble to the revised version

This proposal for *ALMA Development Study* is a revised version of the project submitted in September 2019. The revision has been motivated by an ESO clarification request with the purpose to:

- (i) Identify the best up-to-date practices and methods for accomplishing the project objectives, based on outcome of the discussion held during the *1st International Solar ALMA Imaging Workshop in Oslo* in March 2020.
- (ii) Down-select the number of alternative approaches suggested in the original proposal, in order to focus right on the few most promising ways as identified in (i).
- (iii) Describe the methods used for the project solution and resources requested for it (namely in terms of the EoC test time and manpower at ALMA Observatory) in more detailed and specific way.

As a result of the Workshop summary and subsequent project team discussion, we decided to concentrate only on two approaches:

1. Change of the *Go/noGo* procedure followed by the selfCal-based posterior phase corrections for times series of the high-cadence solar interferometric images. This shall be the main and universal approach.
2. Utilization of the atmospheric WV line seen in absorption on the edge of the science SPW of Band 5. This is considered as a supplemental approach, which can provide further improvement, but it is usable just for the Band 5 data.

Alternative approaches (Items 2,3,5, and 6 in the original proposal) are abandoned in favor of detailed investigation of the two above selected (Items 1 and 4 in the original proposal). Relevant parts of this revised proposal have been upgraded accordingly to this decision and are described in detail below. A new section “*Other requested resources*” have been appended at the end of this document. Requested EoC time and help of ALMA/ESO staff is specified and summarized there. Because of increased focus on *Approach 1*, the core team has been strengthened by relevant expertise of L. Maud (ESO) and S. Wedemeyer (Uni Oslo).

Summary

Goal of the project

Solar ALMA ObsMode is currently severely limited to compact array configurations only, allowing observations with max. baselines corresponding to C43-3 (C43-4 in Band 3). This fact limits the resolution to $\sim 1''$, preventing a lot of key solar research with ALMA. The project aims at breaking the limitations – we plan to design and in-detail investigate possible ways for an upgrade of the *Solar ALMA Observing Mode* that would overcome its current unsatisfactory status. As a result, we shall get the new range of possible configurations depending parametrically on the observing ALMA Band and atmospheric conditions measured as phase-error metrics.

Timeline

Total duration: Two years from the kick-off of the project. Mid-term review after one year.

Requested resources (from ESO/ALMA)

- Personal costs for one 100% FTE dedicated researcher (postdoc) for entire duration of the project (2 years) + 0.4 FTE to support the effort in the involved institutions.
- Mobility/cooperation travel support (between involved institutions; visiting ESO).
- Allocated testing/EoC time ($\sim 2 - 3$ hours) at ALMA.

Deliverable

Analytical study/report that will devise feasible (alternative) ways, which would enable solar ALMA observations with more extended configurations. For each of the alternatives we plan having documented its

- Benefits/constraints: Maximum resolution (max. baseline length) reached vs. sci/tech (side-effect) constraints introduced by the implementation. The ultimate goal: **Finding the maximum yet acceptable baseline length in dependence on (i) the observing frequency, and, (ii) the phase metrics as measured by Go/NoGo test prior to the observation.**
- Implementation requirements and suggested implementation procedure.
- Estimation of implementation costs (albeit it may be only in the form of test time and manpower).

The study is intended as a guide and starting point for the later actual implementation of the *Solar ALMA Observing Mode* upgrade.

Motivation – Overcoming the current-state limitations

High angular resolution is undoubtedly one of the key and prominent qualities that ALMA provides for scientific observations. Indeed, already since the successful *Long-baseline CSV campaign* (ALMA Partnership – Fomalont et al., 2015) many branches of astrophysics are greatly profiting from break-through discoveries allowed by ALMA observations at extended configurations – let us name, among others, at least the example of unique collection of observations of protoplanetary discs, which got broadly known even in the general public.

The solar scientific observations have been planned already from the very beginning of the ALMA project preparation and already the early-stage relevant documents (e.g., Bastian, 2002; *ALMA DRSP* – Benz, 2006; Loukitcheva et al., 2008, Karlický et al., 2011; Heinzel et al. 2015; Wedemeyer et al., 2016) mention many key science cases, for which the high angular resolution is essential. Again, let us name just one example – the long-standing mystery of the mechanism for heating of upper layers of the solar atmosphere: Since actual dissipation of energy takes place at small scales, high-resolution is essential for this (and many others) key research problem.

The *Solar ALMA ObsMode* has been officially approved in December 2016 (also thanks to the EU ARC contribution by the project “Solar Research with ALMA” carried out in frame of the previous ESO *ALMA Development Study* programme) and the Cycle 4 thus allowed the first solar science with ALMA (ESO, 2017; Brajša et al., 2017; Shimojo et al., 2017; White et al. 2018; Bastian et al., 2018). In order to enable the promised solar science with ALMA to the community soon, the *ObsMode* has been offered as a “non-standard”, with many limitations (compact arrays, Bands 3 and 6 only, TDM, no polarization, etc.).

One of the most severe constraints is the maximum baseline length $\sim 500\text{m}$ – the array configurations allowed for the mode are up to C43-3 (exceptionally C43-4 in Band 3 since Cy7), what prevents solar physicists of profiting from the high-resolution ALMA capability, which brought so much new results in other astrophysical research. Where this limitation for solar observations comes from? First, already the fact that we use the day-light observing time naturally brings higher values of PWV and, consequently, the higher phase RMSs. For the non-solar targets (even those observed at day time) there is, nevertheless, a possibility – used in the standard calibration procedure – to correct the fast phase variations between the phase-calibrator scans via water-vapour radiometers (WVRs) measurements and posterior *wvrgcal()* procedure. For the Sun this is, however, impossible as the brightness temperature of the Sun is much higher than contribution of the atmospheric water vapour, the WVRs get even saturated. Since we are lacking possible correction mechanism for fast phase variations in the solar *ObsMode*, the standard-interferometry *Go/noGo* tests based on phase RMS measurements (on a long time scale) preclude solar observations with longer baselines.

Many solar science cases, for which the resolution is not so critical, has been already successfully observed – repeating it with merely different (but by nature the same) target will likely bring no new information. Since new capabilities including the high-resolution observations are not being offered, some frustration and loss of interest in solar ALMA observations is visible inside the solar physics community; this can be seen in a significant drop of solar-oriented proposals during the last Cycles. On the other hand, there is a strong call for the high-resolution solar ALMA observations among researchers. Addressed by this challenge we propose the corresponding upgrade of the *Solar ObsMode*. The project aims at finding the possible ways out of the above mentioned limitation and the deep investigation of their feasibility, implementation requirements, limits of their applicability, and estimated implementation and running costs (in broader sense, e.g., loss of another quality). There are already a few ideas on the table that have emerged within the *Solar ALMA Development Team*. These have been recently discussed during the Oslo Workshop in March 2020, namely in frame of the short topical session devoted to this project. From around six possible approaches (partly overlapping), the two described in the next section were identified as the most promising and selected for further detailed elaboration. Nevertheless, we expect improvements and new ideas to appear, when the topic will be really focused and systematically investigated in frame of the project.

Upgrading the *Solar ObsMode*: Most promising approaches

The goal of this study is to present detailed analysis of two realizations (one “main” and one “supplemental”) for the *Solar ObsMode* upgrade in the sense of higher angular resolution with all their strong and weak aspects, implementation requirements and procedure, and estimation of the implementation costs. It shall be the responsibility of ALMA and its regulating bodies which, and if any, of those suggested ways will be eventually implemented. Here we present the ideas that already emerged and have been discussed within the project team, but definitely need to be

investigated in detail in frame of the proposed project. We cannot, however, preclude that another smart solution to this problem emerges during the project execution.

1. Alternation of the *Go/noGo* procedure for solar observations and posterior selfCal-based phase corrections in high-cadence interferometric images

Specifics of the solar observations (namely the high brightness of the Sun) bring many difficulties, including lack of the standard WVR corrections for the fast phase variations, what is essential with respect to the goal of high-resolution solar images. On the other hand, they can also yield opportunities that are impossible in the standard interferometry of relatively weak targets. Namely, the high brightness temperature of the Sun breaks – sometimes unconscious – “paradigm” of interferometric observations, which claims that we need rather long observing (total signal integration) times for reaching sufficiently high S/N ratio. Since the image integration in the “standard” interferometry is being performed over period largely exceeding the time-scale of the phase variations, the resulting image is *blurred* and the resolution (long-duration coherence) is lost. On the other hand, with the Sun, which provides enough signal even for the shortest so-far possible integration times (0.16 s as per current correlator limit), we can get *series* of relatively sharp (see below) but *distorted* images instead of a single blurry image (Bárta 2019). Of course, the distortion is also varying on the time-scale of the (Earth) atmospheric turbulence, but the apparent motion (and the brightness variations) can be to some extent distinguished and separated from the real dynamics of the Sun: The large-scale solar structures change at much longer timescale (minutes) than the integration time (a fraction of seconds). For this sake, there is already well established and tested method of *Self-calibration with cascading time-scale separation*: Self-cal is first done for the solution intervals covering entire scan, then its halves, quarters, and so on, till the (atomic) integration time scale. Its results in the form of impressive solar ALMA movies, made from the series of self-calibrated per-integration images, have been presented at the Oslo workshop in March

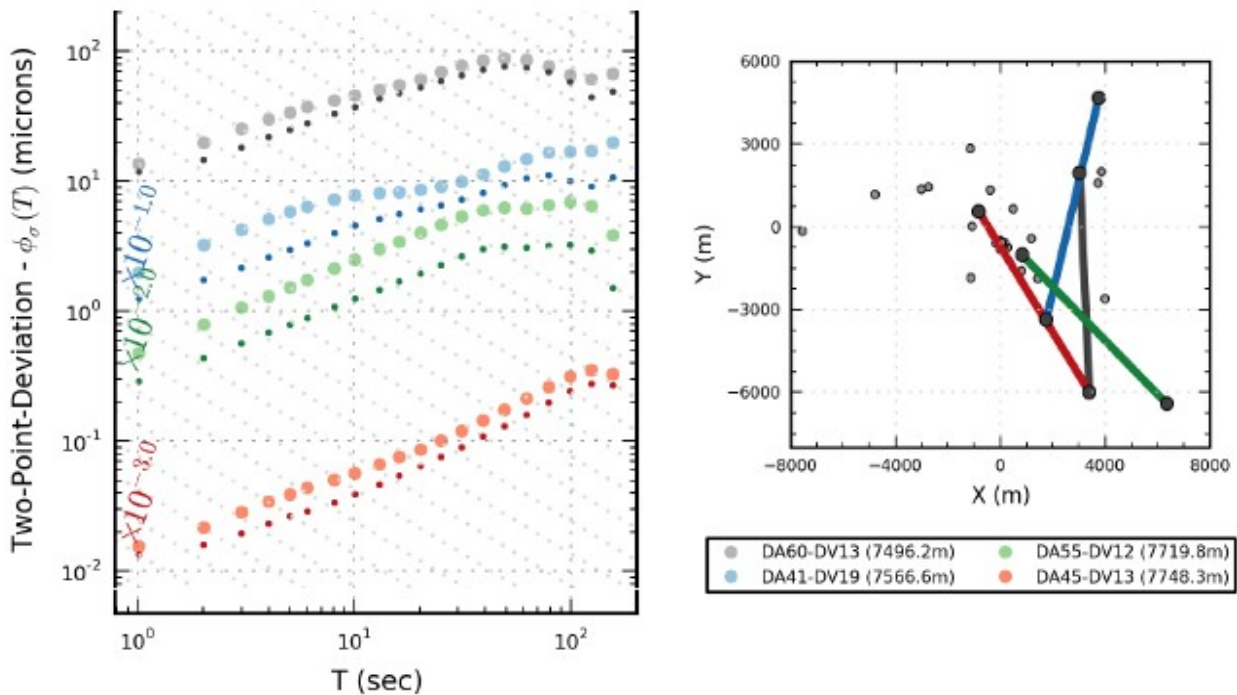


Fig. 1: The fast phase variations measured by means of two-point deviations (TPD) for four selected baselines vs. the timescale. Adopted from Maud et. al. (2017b). Raw (big bullets) and WVR-corrected (small ones) data have been used as an input.

2020 (e.g., Wedemeyer+Szydlarski, Shimojo, Bastian – Workshop summary is planned to be published as an ALMA Memo).

There is also a couple of studies of the fast phase variation, their influence to the coherence and image quality and counter-acting measures – e.g. Maud et al. (2017a, 2017b). The authors found – among other results – that the phase variations measured via the metrics of the *two-point deviations* (TPD) decrease strongly with the time lag between the two points of phase-error measurements – see Fig. 1. Putting it another way: The fast variations are not so harmful for the short integration times (i.e., the *sub-scan* duration in the solar mode). The authors of the ALMA Memo no. 606 (Maud et al., 2017a) even literally recommend to use *short Go/noGo* test, with the time-scale corresponding to the sub-scan time. The Sun is pretty bright, so the sufficient duration for collecting the enough signal is on the sub-second timescale. The *Go/noGo* test, which uses band-pass calibrator, likely will need a bit longer duration to reach sufficient S/N ratio in order to provide trustworthy results of the test, however, we should tend to as short time-scale as possible for the test, in order to approach the real timing in the subsequent solar science observations.

To sum up: It is well possible that we have made the (basically non-existent) problem of “impossibility” of solar observations on the longer baselines ourselves, just because applying the standard (long time-scale) *Go/noGo* phase-variation test in an inappropriate situation. Should the proposed study show that the above is correct, merely relaxation from the too strict *Go/noGo* test for solar observations and postponing the problem of distorted images to the post-processing (solar-specific *self-cal* loop) would be the simplest solution of the entire problem. However, detailed investigation via simulations and real testing is required. The details are described below in “*Methods*”. We plan to focus namely at this approach because it could work universally, for all ALMA observing bands.

2. Using absorption water lines in science SPWs of Band 5

Because of low additional “costs” (the Band 5 solar data are already there, we can just analyze them within the team with no demand on the EoC time nor help of the ALMA staff), we suggest a supplemental approach for the Band 5 solar data, which could, to some extent, further improve the fast phase-error corrections similarly like WVRs do so for the non-solar data.

Atmospheric water line centered at 183 GHz partly (by its wing) reaches to the science SPWs of the Band 5. This fact, on one hand, degrades some frequency channels in those SPWs (BB1 in the currently used setup with the LO frequency set to 198 GHz), on the other hand, it brings the possibility to use those channels for measuring of the absorption of solar continuum in the water vapour directly (Hills 2019). This could be used for estimation of the WV contents without using the WVRs. The signal is not saturated in this case – the science SPWs are attenuated electronically via the MD technique. Instead of that we face another problem: Adaptation/generalization of the mathematical model, which in the standard *wvrgcal()* ties the water-vapour *emission* with the phase delay, in the way that *absorption* of the solar continuum radiation in the atmospheric water vapour is related to the water-vapour column density and consequently to the atmospheric phase delay.

There have been several methods suggested for recalculation of measured signal variations to the phase delay in Hills (2019), e.g., total power at a single freq. channel, in the entire SPW, or in an entire sideband, or detailed analysis of (the slope of) the auto-correlation spectra. Hills (2019) also estimated sensitivity of the TP variations measurements to phase delay vs. frequency for various set of other parameters (receiver gain stability, PWV, etc.) – one such example is shown in Fig. 2. This

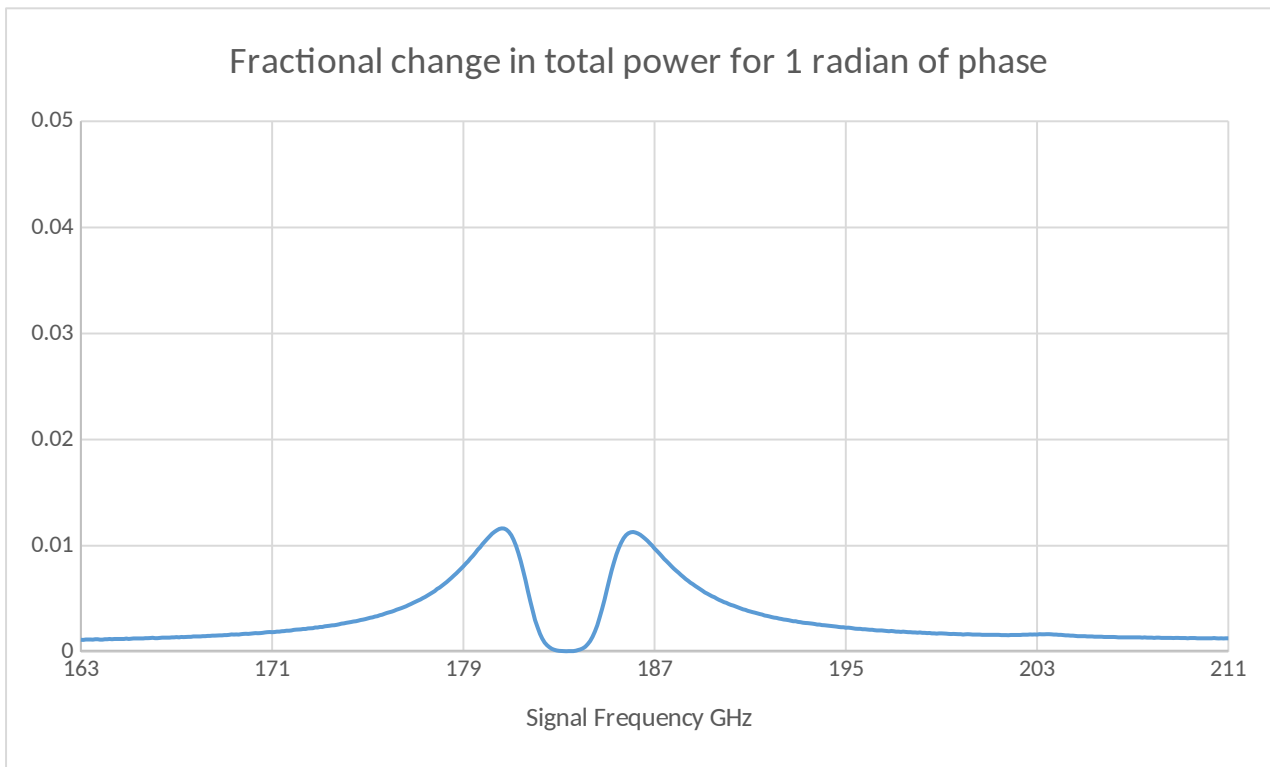


Fig. 2: Response of total power in Band 5 to the increase of PWV causing the phase delay of 1 rad. From Hills (2019).

method needs further elaboration and testing, but has no demands on hardware change, EoC time nor ALMA staff help.

Methodology

The *Approach 1* will be investigated dominantly by means of the CASA-based simulations, which shall include atmospheric turbulence mixed with the (simulated) proper solar dynamics, followed by the *selfCal*-based corrections of the fast phase variations. The solar-specific self-calibration loop, which is essential for correction of the series of the distorted images, is already now quite well developed for the single-pointing data (and work is underway for small mosaics), the most intensive effort being done at Uni Oslo in frame of the currently performed ALMA Development Study “High-cadence solar ALMA imaging” (PI S. Wedemeyer). In this respect, the currently proposed project will follow up the results of this on-going study. CASA-simulated solar ALMA visibilities will be created for longer-baseline arrays and realistic atmospheric conditions. Time series of self-calibrated maps will be then compared with the primary (model) images used as an input to CASA simulations. We shall concentrate not only at our ability to separate the real and apparent dynamics of the Sun when using longer baselines, but also resolve the issue of yet more sparse *uv*-space coverage, which becomes more critical for extended configurations. This can make a problem for the solar images as they naturally contain emission structures at all possible scales from the pixel size to the size of FOV. Using the simulations we shall **find the maximum yet acceptable configuration depending parametrically on the observing ALMA Band and phase metrics measured during the solar-specific Go/noGo test**. After the optimum procedure for self-cal loop shall be identified in the simulated data, which would enable the maximum possible baseline lengths, we would like to try it also on the real test data – very short sequence (~10 minutes of on-

source time per Band) of solar observation would be sufficient. Of course, the altered *Go/noGo* test have to be tried, too. We discussed this possibility during the Oslo workshop – the outcome is that such a test can be done during any ALMA technical break (e.g. because of array configuration change – A. Hales, workshop discussion).

The supplemental *Approach 2* needs substantial modification of the *wvrgcal()* underlying model and procedure – this will be done in collaboration with its authors/developers. Tests, to what extent the procedure helps, can be done on already existing solar Band 5 data in C-2 configuration. Having another set of solar Band 5 data taken at the longer baselines ($> C-4$) would be helpful, but not vital. Instead of that, we shall search for appropriate archive Band 5 data of non-solar observations and compare the WV-radiation (from the WVRs) and WV-absorption seen in the data for the band-pass calibrator, with the phase variations of the same body.

The team and its resources

The project team is formed by its core, represented by researchers working more intensively on the topic, and external collaborators, whose particular expertise will the core-workers occasionally request for consultations.

The core:

- Miroslav Bárta (PI), Astronomical Institute, EU ARC.CZ, Ondřejov, Czechia
- **Full-time dedicated researcher**, Astronomical Institute, EU ARC.CZ, Czechia
- Tim Bastian, National Radio Astronomy Observatory, USA
- Roman Brajša, Hvar Observatory, Faculty of Geodesy, University of Zagreb, Croatia
- Dale Gary, New Jersey Institute of Technology, USA
- Antonio Hales, Joint ALMA Observatory, Chile
- Richard Hills, Cavendish Laboratory, Cambridge, UK
- Hugh Hudson, School of Physics and Astronomy, University of Glasgow, UK
- Luke Maud, ESO, Garching, Germany (phase variations, phase metrics)
- Masumi Shimojo, NAOJ, Tokyo, Japan
- Ivica Skokič, Hvar Observatory, Faculty of Geodesy, University of Zagreb, Croatia
- Sven Wedemeyer, Institute of Theoretical Astrophysics, University of Oslo, Norway

The *Full-time dedicated project researcher* has to be appointed first, we plan to publish an open call for the position in case of this proposal gets approved. This new position is essential for the project success as the other core members – though having good expertise in the topic (but at the same moment frequently busy with other duties) – cannot devote their time entirely to the detailed, particular or routinely project tasks.

External collaborators:

- Shin'ichiro Asayama, East Asia ALMA Support Center, Tokyo, Japan
- Bin Chen, New Jersey Institute of Technology, USA
- Bart De Pontieu, LMSAL, USA;
- Gregory Fleishman, New Jersey Institute of Technology, USA
- Akihiko Hirota, Joint ALMA Observatory, Chile
- Kazumasa Iwai, National Institute of Information and Communications Technology, Japan
- Sujin Kim, Korea Astronomy and Space Science Institute, Daejeon, Republic of Korea
- Neil Philips, ESO, Garching, Germany

- Tsuyoshi Sawada, Joint ALMA Observatory, Chile
- Giorgio Siringo, Joint ALMA Observatory, Chile
- Stephen White, AFRL, USA
- Pavel Yagoubov, ESO, Garching, Germany
- Yihua Yan, NAO, Chinese Academy of Sciences, Beijing, China.

The entire Team (core + external experts) is formed from the members of the *Solar ALMA Development Team* (e.g., ESO, 2017) – the researchers, who actively took part in the basic development of the *Solar ALMA ObsMode*. Moreover, we have asked also Dr. Luke Maud (ESO) for kind sharing of his expertise on phase-variation metrics. The *Solar Team* is still active, having regular bi-weekly telecons (led by Tim Bastian) and sharing the documents (see in *References*). Moreover, in addition to the development tasks, the *Solar Team* members are involved in organization of ALMA solar scientific observations and regularly work on the solar data processing/QA2 (entirely manual data reduction). To sum up, there is a good amount of required expertise in the current-project Team: For example, the PI (M.B.) worked as the project manager of the previous ALMA Development Study “Solar Research with ALMA” (and overtook the role of the bidder-representative, after Prof. M. Karlický had retired), R. Brajša was the PI of that project, I. Skokič the dedicated full-time researcher. T. Bastian and M. Shimojo have been leading the NA ARC and EA ARC participation, respectively, R. Hills is one of the leading experts on ALMA hardware and technology, S. Wedemeyer is leading related project, whose results will be very useful for accomplishing the goals of this one, etc. The bidding institution will also take advantage of being involved into EU ARC and ESO for direct cooperation with the ESO-based researchers, also with those not explicitly listed above.

The collaborating institutes are well equipped with resources required for carrying out the project, namely a hardware for the test-data processing and CASA simulations – e.g., the Czech node of the EU ARC in Ondřejov (EU ARC.CZ) has dedicated high-performance cluster for ALMA data processing (used for the QA2 services) and 10 years lasting experience with CASA.

Expected timeline

If approved, the project would come into its preparation phase. In this period the core team will search for a suitable candidate for the open postdoc position. After filling the position the project is expected to start by the *Kick-off Meeting* at ESO, where the details could be yet negotiated. The mid-term review is planned one year after the project kick-off. Till then we plan to have finished procedures for generating CASA-simulated series of high-cadence images with longer ($\sim 3 - 5$ km) baselines for *Approach 1* and comparison of their “blind-shot” selfCal-based correction results with the original unbiased model images. We shall also have measured the phase metrics from changed *Go/noGo* test on a short timescale. In parallel we shall work on the analytical calculations/model that binds absorption signal of the WV line to the phase delays (*Approach 2*).

The 2nd half of the project is planned to be devoted to more systematic parametric study of *Approach 1* with the aim to find *optimized procedure* and maximum possible extent of the array configuration for a given observing frequency and phase RMS as measured by the specific solar *short time-scale Go/noGo* test. In parallel we shall apply *Approach 2* to the existing Band 5 solar data and study its effect. Also the non-solar archive Band 5 data for strong band pass calibrators (if some suitable are found) shall be used for comparison among (i) WVR data, (ii) Absorption in science SPW in the WV-line wing, and (iii) actual phase variations found for the band-pass calibrator. Finally, the *Approach 1* shall be tested on the real EoC data – we shall verify at least

a few points of limiting line for the allowed baseline length in the parametric space that spans over the observing frequency and (short-timescale) phase RMS.

At the final review (2 years after kick-off) the study serving as a background for further decision on upgrade of the *Solar ObsMode*, shall be delivered. Last but not least: Focusing at the topic for the first time more systematically in frame of a dedicated project, new, unexpected, ideas on how to overcome the current limitations of the solar mode, may emerge.

Project costs

Requested financial support from ESO for the project are planned to cover namely: (1) The dedicated postdoc researcher, working at 100% for the project tasks, and, (2) Collaboration (team meetings, f2f visits, travelings to ESO) among the team members. Obviously, a lot of effort is going to be “voluntary”, actually done in frame of the research supported by involved institutions.

Calculations for the requested support from ESO are as follows: Personal costs for postdoc based at the Astronomical Institute in Ondřejov – table-based monthly salary + bonuses for researcher of the category V3B: 1900 EUR (gross); +36% deductions for the health-care and social insurance, times 24 month of the project duration gives approx. 62 kEUR. We take this amount as a base for other FTE-related costs calculations: There will be next 0.4 FTE allocated for the work at the project paid from the ESO project resources (plus further 1.4 FTE supported by the involved institutions) giving $0.4 \times 62 = 24.8$ kEUR. The total personal costs for the project execution are thus approx. 87 kEUR. The collaborating institutions (Zagreb, Cambridge, Glasgow) will use 2 kEUR each for travel to the project-team meetings, the bidding institution (EU ARC – Czech node) would need yet some extra money for (i) traveling more frequently to ESO, (ii) because of hosting the PI and dedicated postdoc, in total 6 kEUR. The total project costs requested from ESO are thus $87 + 3 \times 2 + 6 = 99$ kEUR.

The spread of the costs (in kEUR) among involved institutions (ESO share + involved-inst. contributions) is summarized in the following table:

Institution	Total FTE for the project	FTE requested from ESO	Total FTE costs	FTE costs req. from ESO	Travel costs (all req. from ESO)
Ondřejov	1.2	1.1	74.4	68.4	6
Zagreb	0.4	0.1	24.8	6.2	2
Cambridge	0.2	0.1	12.4	6.2	2
Glasgow	0.2	0.1	12.4	6.2	2
NRAO	0.2	0	12.4	0	0
NAOJ	0.2	0	12.4	0	0
NJIT	0.2	0	12.4	0	0
ALMA	0.2	0	12.4	0	0
Total	2.8	1.4	173.6	87	12

Other requested resources

In addition to the financial support for being able to carry out the study, our team will need support in the following immaterial resources:

- EoC test time at ALMA. We shall need a really short test of the procedure described in *Approach 1*: **One science scan = ~10 min on-source observation for each allowed Band** (3, 5, 6, and 7) of the Sun with as much complete 12m+7m array, in the (limiting) configuration specified later as a result of our simulations and their analyses. In addition to that, **a short test of modified Go/noGo procedure** – measuring the phase RMS at as much short as possible time scale. This can be done during technical break (A. Hales – discussion during the Oslo workshop) **with quite incomplete array**. For supplemental *Approach 2* (WV line in absorption): The existing Band 5 CSV data (2019.1.0005+13.CSV; array configuration: C43-2, LO freq. 198 GHz) are useful for rough estimation of the efficiency of phase error corrections based on the atmospheric WV line absorption. However, it would be fine (but not vital) to have another EoC observation with longer baselines and a bit lower LO in order to be closer to the WV line center in BB1. Alternatively, observation of a strong bandpass calibrator with an **incomplete array** (e.g., during the technical break) containing mid-size baseline at the same spectral setup (TDM continuum centered around LO frequency ~196 GHz) would be helpful for testing the procedure. In total: We request (as a minimum) **2 hours of total time with complete array** + some “cheap” time during the technical breaks, in amount given by opportunity.
- Expert consultations. It may happen that the team would need expert advice from ALMA or ESO staff beyond involvement of the experts working in the team (A. Hales, P. Yagoubov, L. Maud). Except of the tests described above and (seldom) request for external expertise sharing our project should not take any other manpower of ALMA/ESO staff.

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Annex 3: WV line sensitivity – Calculations by Richard Hills

Sensitivity of Phase Correction based on Absorption Fluctuations

We assume that we are pointing at a fixed position on the Sun and making an aperture synthesis image. To calculate the phase correction, we assume that the observed fluctuations in the total power are due to variations in the atmospheric transmission caused by fluctuations in the amount of water along the line of sight from each antenna to the Sun. We want to find out how much error we will make in the correction if, instead, the variations are due to something else such as receiver gain fluctuations or variations in the solar emission. (Note that the latter will not be important if all the antennas have the same beam pattern and are pointing at the same region of the Sun.)

We write the total power received as:

$$T_{sig} = \eta \cdot T_{sun} \cdot Trans + T_{atm} \cdot (1 - Trans) + T_{rx} \quad (1)$$

where T_{sun} is the Sun's brightness temperature, η is the appropriate beam efficiency, T_{atm} is the physical temperature of the water in the atmosphere, and T_{rx} is the effective receiver temperature (which would include things like the losses in the antenna).

$Trans$ is the transmission of the atmosphere, which is:

$$Trans = \exp[- (w \cdot \tau_1 + \tau_{dry})] \quad (2)$$

where w is the amount of water in the line of sight to the Sun in mm, τ_1 is the opacity for 1mm of water, and τ_{dry} is the opacity due to the "dry" components – mainly oxygen and ozone. These opacities are of course strong functions of frequency but relatively weak functions of temperature, pressure, etc. I have used some numbers I had from the atm model which should be good for ALMA conditions but I have not checked the details.

By substituting for $Trans$ in (1) and differentiating one finds that the variation in total power due to a small change in w is

$$dT_{sig} = -\tau_1 \cdot (\eta \cdot T_{sun} - T_{atm}) \cdot Trans \cdot dw$$

This means that, so long as the first term in equation (1) dominates, i.e. $(\eta \cdot T_{sun} - T_{atm}) \cdot Trans \gg T_{atm} + T_{rx}$, the fractional change in the total power is

$$dT_{sig} / T_{sig} = -\tau_1 \cdot dw$$

The change in the path to the antenna (in mm) due to the extra water is just given by $dp = r_{eff} dw$ where r_{eff} is the effective refractivity. To a good approximation this is equal to 6.3: there is a weak temperature dependence and a small frequency variation (dispersion) which we will neglect. The phase change is therefore

$$d\phi = 2\pi/\lambda \cdot r_{eff} \cdot dw = 2\pi/\lambda \cdot r_{eff} \cdot (-1/\tau_1) \cdot dT_{sig} / T_{sig} \quad \text{where } \lambda \text{ is the observing frequency.}$$

So the conversion from fractional change in power to phase depends only on τ_1 and not on all the other quantities in equations (1) and (2).

The assumption that the first term in equation (1) is dominant will be true so long as we have a reasonably good receiver temperature and the opacity is not very large. At the center of the 183GHz line, however, the opacity can get quite large. I have therefore done the sums numerically in the spreadsheet assuming a small change (1 micron) in the amount of water. The other parameters are listed and can be changed but, apart from the amount of water, these have very little effect on the results. Separate sheets are given for the cases $w = 1, 2$ and 4 .

I considered four possible ways of making the correction. In each case I assumed (guessed) a possible value for what the instrumental errors, e.g. gain fluctuations, might be and calculated what the corresponding

phase error would be. Remember that these measurements have to be made separately on each antenna and the correction is made to the phase of the signal from that antenna. The loss of coherence is therefore $\cos(\sqrt{2} \cdot d\phi)$, i.e. if $d\phi$ has an rms variation of 0.3 radians we lose about 10% coherence. This is probably a reasonable goal.

Exactly how one does the full observing sequence which includes moving to a phase calibrator from time to time (and perhaps making measurements with the conventional water-vapour radiometers at those points) is not clear to me, but presumably we need to follow the variation in power over the time between observations of the phase calibrator. The assumed values for the gain variations, etc., should therefore correspond to that period.

The cases are:

- 1) Total power. One simply chooses some suitable frequency in the observing band and measures the total power fluctuations. I took 10^{-3} for the stability in this case. The plot shows that if the stability is as poor as this, one would have to put one of the observing bands quite close to the water line, where the opacity is probably too large to use it for astronomy.
- 2) Fluctuations in the slope across a spectral window. This could be measured using the auto-correlation spectrum and the stability should be pretty good. I assumed that the slope is measured in units of change per GHz and took a value of 10^{-4} for the stability. One sees that, for the larger values of w , there are places in the plot of the fluctuation, $dT_{\text{sig}}/T_{\text{sig}}$, against frequency has turning points, so measurements that rely on the slope will not work there. So long as $w < 4\text{mm}$, however, LO frequencies in the range ~ 195 to 200 GHz look OK.
- 3) Difference between two neighbouring spectral windows. Here one would use the total power counters associated with the pair of windows in a sideband. One sees that with a stability of $2 \cdot 10^{-4}$ (in the difference) this looks OK with LO between about 194 and 199 GHz .
- 4) Finally, one can take the fluctuations in the difference between the total power in the upper and lower sidebands. This gives a bigger change in signal but the errors are likely to be larger because less of the hardware is in common. For $5 \cdot 10^{-4}$ this looks OK from about 193 to 198 GHz .

I must emphasize that these stability estimates are complete guesses. Obviously we need experiments to find out what the reality is and which is the most promising method. In all cases, however, these values are much larger than the errors due just to radiometric noise: remember that for 1 second integration the radiometric fluctuations are down to 10^{-4} for a bandwidth of just 100 MHz . The errors that I expect to dominate will be due to things like temperature variations, LO level changes, etc.

One could perhaps use a combination of 2) to 4) above to get a better results and estimate the errors. We also have two polarization channels so we get two values for each measurement. These will have independent noise but partially correlated other errors, so this will probably not help much.

Conclusion

The tension here is between having the LO frequency low enough to be able to measure the changes in absorption and being far enough from the line to avoid having excessive absorption and slope across the lowest spectral window. With the LO at 198 GHz , the transmission in spw0 is about 89% for $w = 1\text{ mm}$ and the slope is less than 2% per GHz. I think this would be no problem. For $w = 4\text{ mm}$ the transmission is down to $\sim 63\%$ and the slope is about 5% per GHz, which is getting pretty high but my guess is that the standard calibration procedures would still cope reasonably well. It may be that the stability is hopeless in the daytime when the water is that high anyway.

Annex 4: Code listings

```
#!/usr/bin/env python3
# -*- coding: utf-8 -*-
"""
```

```
=====
MAKE UNCORRUPTED VISIBILITIES FROM THE IMPORTED OPTICAL SOLAR IMAGE
=====
```

```
Created on Thu Apr 13 12:42:12 2023
```

```
@author: yichai
```

```
"""
# import os
# import glob
# import numpy as np
# from simutil import simutil
# u=simutil()

#casa6
import os
import glob
import numpy as np
from casatools import simulator, image, table, coordsys, measures, componentlist, quanta, ctsys
from casatasks.private import simutil
sm = simulator()
u = simutil.simutil()

#working directory
#os.chdir('/Users/yichai/Documents/ALMA_simulation/CRISP_8542_20210819_b3c4_image/')
os.chdir('/Users/yichai/Documents/ALMA_simulation/alma_cycle9_configuration_files/sim_b5c6_Hinode_p30/')

#parameters
#keywords = 'CRISP_8542_20210819_b3c4'
keywords = 'Hinode_SOT_20150623T102846_b5c6'
#reftime = '2021/08/19/17:28:00' #CRISP
#reftime = '2015/06/23/10:28:00' #Hinode
reftime = '2015/06/23/14:00:00' #Hinode modified time
#tstep = 10 #second
overwrite = True
defaultaxes = True
#phasecenter = 'J2000 09h55m30.91 12d37m47.9'
#phasecenter = 'J2000 06h06m20.46 23d25m48.8'
phasecenter = 'J2000 06h06m56.98 23d25m45.5' #Hinode modified coordinate
#array configuration file location
ALMA_main = '../alma.cycle9.6.cfg'
ALMA_ACA = '../aca.cycle9.cfg'

#import fits file
#band3 100GHz; band5 198GHz; band6 239GHz;
#fitsimage = '../Hinode_SOT_20150623T102846_single_mod_9.fits'
fitsimage = '../Hinode_SOT_20150623T102846_single_mod.fits'
#imagenname = 'Hinode_SOT_20150623T102846_single.image'
imagenname = 'Hinode_SOT_20150623T102846_single_mod_b5c6.image'
bandname = 'band5' #ALMA band name
ref_freq = '198GHz' #center frequency
delta_freq = "1GHz"
freq_resolution = "1GHz"
int_time = '2s' #integration time
etime = qa.quantity(60,'s') #duration of observation
out_put_ms = 'alma_12m7m_sim_b5c6_test_Hinode_mod.ms'
#defaultaxesvalues = ['09h55m30.91', '+12d37m47.9', '100GHz', 'I']
#defaultaxesvalues = ['06h06m20.46', '+23d25m48.8', '100GHz', 'I']
defaultaxesvalues = ['06h06m56.98', '+23d25m45.5', '198GHz', 'I'] #band3 100Ghz band5 198GHz
band6 239GHz band7 346.6GHz
beam = ['0.16arcsec', '0.16arcsec', '0deg'] #modify beam according to configuration and
wavelength
os.system('rm -rf '+ imagenname)
importfits(fitsimage = fitsimage,
           imagenname = imagenname,
```

```

        overwrite = True,
        defaultaxes = True,
        whichhdu = 1,
        defaultaxesvalues = defaultaxesvalues,
        beam = beam)

```

```

#changing image parameters so it suit the simulated ALMA configuration
#for single fits file

```

```

imagenname = imagenname

```

```

t = qa.time(qa.quantity(qa.convert(reftime, 's')['value'], 's'), form='ymd')
imhead(imagenname = imagenname, mode='put', hdkey='object', hdvalue='sun')
imhead(imagenname = imagenname, mode='put', hdkey='bunit', hdvalue='Jy/pixel')
imhead(imagenname = imagenname, mode='put', hdkey='date-obs', hdvalue=t[0])

```

```

# #center coordinate from CRISP image
# xc = imhead(imagenname = 'CRISP_8542_20210819_band3_config4.image', mode='get', hdkey='crval1')
# yc = imhead(imagenname = 'CRISP_8542_20210819_band3_config4.image', mode='get', hdkey='crval2')
# #change Hinode image coordinate to CRISP image
# imhead(imagenname = imagenname, mode='put', hdkey='crval1', hdvalue=xc)
# imhead(imagenname = imagenname, mode='put', hdkey='crval2', hdvalue=yc)

```

```

bmaj = imhead(imagenname=imagenname, mode='get', hdkey='beammajor')
cell = str(qa.div(bmaj, 6)['value']) + 'arcsec'
imhead(imagenname=imagenname, mode='put', hdkey='cdelt1', hdvalue=cell)
imhead(imagenname=imagenname, mode='put', hdkey='cdelt2', hdvalue=cell)

```

```

#read antenna config files, the antenna cfg file has one addition column of padnames

```

```

x,y,z,d,padnames,trash1,telescope,posobs = u.readantenna(ALMA_main)
x2,y2,z2,d2,padnames2,trash2,telescope2,posobs2 = u.readantenna(ALMA_ACA)

```

```

out_put_ms = out_put_ms
os.system('rm -rf '+out_put_ms)
print('now processing: ' + str(out_put_ms))

```

```

sm.open(out_put_ms)
sm.setconfig(telescopename="ALMA", x=np.append(x, x2), y=np.append(y, y2), z=np.append(z, z2), dishdiameter=np.append(d, d2), mount=['alt-az'],
padname=np.append(padnames, padnames2).tolist(), coordsystem='global', referencelocation=posobs)
sm.setspwindow(spwname=bandname,
freq=ref_freq, deltafreq=delta_freq, freqresolution=freq_resolution, nchannels=1, stokes='XX YY')
sm.setfeed(mode='perfect X Y', pol=[''])
sm.setlimits(shadowlimit=0.01, elevationlimit='10deg')
sm.setauto(0.0)

```

```

#sm.setfield(sourcename='sun', sourcedirection='J2000 09h55m30.91
+12d37m47.9', calcode='OBJ', distance='0m')
#sm.setfield(sourcename='sun', sourcedirection='J2000 06h06m20.46
+23d25m48.8', calcode='OBJ', distance='0m')
sm.setfield(sourcename='sun', sourcedirection=phasecenter, calcode='OBJ', distance='0m')
sm.settimes(integrationtime=int_time, usehourangle=False, referencetime=me.epoch('UTC', t[0]))
etime = etime
sm.observe(sourcename="sun", spwname=bandname, starttime=qa.quantity(0, "s"), stoptime=etime)
sm.setoptions(ftmachine="mosaic")

```

```

sm.predict(imagenname=imagenname)
sm.close()

```

```
#!/usr/bin/env python3
# -*- coding: utf-8 -*-
"""
```

=====

MANGLE THE GAIN CALIBRATION TABLE BY SIMULATED ATMOS. PHASE DELAYS

=====

Created on Mon Mar 27 12:52:13 2023

Based on the ATMOS code provided by Eric

@author: yichai

"""

```
import os
import glob
import math
from math import pi, cos, sin, tan, atan
import sys
import random
#import commands
import numpy as np
import datetime
import scipy as sp
from scipy import optimize
import cmath
import string
# from simutil import simutil
# u = simutil()

#casa6
from casatools import simulator, image, table, coordsys, measures, componentlist, quanta, ctsys
from casatasks.private import simutil
u = simutil.simutil()
sm = simulator()

#working directory
#os.chdir('/Users/yichai/Documents/ALMA_simulation/alma_cycle9_configuration_files/sim_b3c4_10min/')
#os.chdir('/Users/yichai/Documents/ALMA_simulation/alma_cycle9_configuration_files/sim_b3c4_combined/')
os.chdir('/Users/yichai/Documents/ALMA_simulation/alma_cycle9_configuration_files/sim_b5c6_Hinode_p30/')

scaleF = 0.5 # multiplication factor for tropospheric phases
#key_words = 'alma_12m7m_sim_b3c4_scalef0.5_phase30_test_combined'
key_words = 'alma_12m7m_sim_b5c6_scalef0.5_phase30_Hinode_test'
orig_data = 'alma_12m7m_sim_b5c6_test_Hinode_mod.ms' # INPUT ms
out_data = 'alma_12m7m_sim_b5c6_scalef0.5_phase30_Hinode_test.ms'
cal_table = 'atmos_scalef0.5_phase30_Hinode_test.cal'

#orig_data = 'alma_12m7m_sim_b3c4_test_combined.ms'
#out_data = 'alma_12m7m_sim_b3c4_scalef0.5_phase30_test_combined.ms'

# key_words2 = 'alma_12m7m_sim_b3c7_pwv1_Hinode_smooth'
# out_data2 = 'alma_12m7m_sim_b3c7_pwv1_Hinode_smooth.ms'
# cal_table2 = 'atmos_pwv1_Hinode.cal'

#frefant = '13' # reference antenna
frefant = '8'
fconf = '../alma.cycle9.6.cfg' # Configuration file
fconf2 = '../aca.cycle9.cfg'

#use half maximum baseline as threshold?
maxbl = np.max(u.baselineLengths(fconf))
#calculate other factor
degree = 30 #phase error
k1 = degree/((maxbl/2.)**0.8)
k2 = degree/((maxbl/2.)**0.25)
```

```

# prms = PRMS(antbl,scaleF):
#     antbl is antenna separation from reference antenna
#     prms is the rms phase for that antenna separation
def PRMS(antbl,scaleF):
    # The structure function here gives 30 deg phase rms at 10000m = 10km
    #
    #Lrms = 1.0/52.83 * antbl**0.8    # phase rms ~0.8 power to 10 km, 1/52.83*10000^0.8 ~ 30
    Lrms = k1 * antbl**0.8
    #Hrms = 3.0 * antbl**0.25        # phase rms ~0.25 power beyond 10 km
    Hrms = k2 * antbl**0.25
    # if antbl < 10000.0:
    #     prms = scaleF*Lrms
    # if antbl > 10000.0:
    #     prms = scaleF*Hrms
    if antbl < maxbl/2.0:
        prms = scaleF*Lrms
    if antbl >= maxbl/2.0:
        prms = scaleF*Hrms
    return prms

os.system('rm -rf '+out_data)
os.system('cp -r '+ orig_data+' '+out_data)

zant = []
zx = []
zy = []
zz = []
zpad = []

#read main array antenna info
f = open(fconf)
lines = f.readlines()
nlines = len(lines)
f.close()
for i in range(3,nlines):
    stuff = lines[i].split()
    zx.append(float(stuff[0]))
    zy.append(float(stuff[1]))
    zz.append(float(stuff[2]))
    zpad.append(stuff[4][0:4])

#read ACA info
f2 = open(fconf2)
lines2 = f2.readlines()
nlines2 = len(lines2)
f2.close()
for j in range(3,nlines2):
    stuff2 = lines2[j].split()
    zx.append(float(stuff2[0]))
    zy.append(float(stuff2[1]))
    zz.append(float(stuff2[2]))
    zpad.append(stuff2[4][0:4])

nant = len(zx)
zxref = []
zyref = []
zzref = []
zztot = []
nref = int(frefant)
for i in range(0,nant):
    zxref.append(zx[i]-zx[nref])
    zyref.append(zy[i]-zy[nref])
    zzref.append(zz[i]-zz[nref])
for i in range(0,nant):
    # The distance antenna is from reference
    # Used for getting antenna structure function

```

```

zztot.append(np.sqrt(zxref[i]**2+zyref[i]**2+zzref[i]**2))

# make gaintable 'atmos.cal' to be filled with atmospheric phase
tb.close()
os.system('rm -rf '+ cal_table)
gaincal(vis = out_data,
        caltable = cal_table,
        refant = frefant,
        minsnr = 0.001,
        solint = '40s', # should be time-scale of troposphere change?
        solint = 'int',
        calmode = 'p')

# Obtain certain 'atmos.cal' columns
# ans fill in antenna-based antmospheric phases with
#
tb.open(cal_table,nomodify=False)
yant = tb.getcol('ANTENNA1')
ytime = tb.getcol('TIME')
ycparam = tb.getcol('CPARAM')
Nycparam = ycparam
nant = len(yant)

print('      ant      time      antsep      rmsphase')

antbl_arr = []
prms_arr = []
perror_arr = []
for i in range(0,nant):
    antbl = zztot[yant[i]]
    # get rms phase for each antenna
    prms = PRMS(antbl,scaleF)
    # determine random GAUSSIAN phase error from rms phase
    perror = random.gauss(0,prms)
    # PRINT OUT ANT PHASE ERRORS
    #print('%3d %3d %7.1f %7.1f %7.1f %7.1f ' %(i, yant[i],ytime[i]-ytime[0],antbl,prms,perror))
    print('%3d %3d %7.1f %7.1f %7.1f %7.1f ' % (i, yant[i],ytime[i]-ytime[0],antbl,prms,perror))
    # put random phase in gaintable column CPARAM
    rperror = np.cos(perror*pi/180.0)
    iperror = np.sin(perror*pi/180.0)
    Nycparam[0][0][i] = 1.0*np.complex(rperror,iperror) #X POL
    Nycparam[1][0][i] = 1.0*np.complex(rperror,iperror) #Y POL ASSUMED SAME
    #save parameters
    antbl_arr.append(antbl)
    prms_arr.append(prms)
    perror_arr.append(perror)

np.save('antbl.npy',np.array(antbl_arr))
np.save('prms.npy',np.array(prms_arr))
np.save('perror.npy',np.array(perror_arr))

tb.putcol('CPARAM',Nycparam)
tb.flush()
tb.close()

#apply the atmospheric phases to uvdata
applycal(vis = out_data, gaintable = cal_table)
print('done')

fig_file = key_words+'_cal.png'
os.system('rm -rf '+ fig_file)
# plotcal(caltable = cal_table,
#         xaxis = 'time',
#         yaxis = 'phase',
#         showgui = False,
#         figfile = fig_file)

```

```
# plotms(vis = cal_table,  
#        xaxis = 'time',  
#        yaxis = 'phase',  
#        showgui = False,  
#        overwrite = True,  
#        plotfile = fig_file)
```

```

#!/usr/bin/env python3
# -*- coding: utf-8 -*-
"""
=====
IMAGING & SELF-CAL LOOP FOR A SINGLE IMAGE
=====
Created on Thu Mar 30 10:42:53 2023
@author: yichai
"""

#general parameters
#msco = 'alma_12m7m_sim_b3c4_scalef0.5_phase30_test.ms'
msco = 'alma_12m7m_sim_b5c6_scalef0.5_phase30_Hinode_test.ms'
keywords = 'alma_12m7m_sim_b5c6_scalef0.5_phase30_Hinode_test'

#msoc = 'alma_12m7m_sim_b7c4_pwv1_Hinode.ms'
#keywords = 'alma_12m7m_sim_b7c4_pwv1_Hinode'

#clean parameters
cell_size = '0.026arcsec' #b5c6
imsize = [1200,1200]
robust = 1.0
#threshold = '2.0Jy'
#niter = 40000
niter = 200000 #more niter for large images
#niter2 = 40000
pbmask = 0.2
gain = 0.025
#spw = '0,1,2,3'
#stokes = 'I'
field = '0'
#phasecenter = 0
#phasecenter = 'J2000 09h55m30.91 12d37m47.9'
phasecenter = 'J2000 06h06m56.98 23d25m45.5' #modified for Hinode data
#deconvolver = 'clark'
deconvolver = 'multiscale'
scales = [0,6,18]

#snr setup
minsnr=3.0

#refant = 'DA44'
refant = '8'
#reftime = '2021/08/19/17:28:00'
reftime = '2015/06/23/14:00:00' #modified time for Hinode data

#selcal_div = [1,4,15,60,240]
t_interval = ['inf','60','int','int','int']
#t_interval = ['int','int','int','int','int']
#t_interval = ['inf'] #for comparison between un-selfcaled data
#-----
# selcal_div: the duration for selcal:
# 1 : 1/1 scan (~8mins@Band6)
# 4 : 1/4 scan (~2mins@Band6)
# 15 : 1/15 scan (~32secs@Band6)
# 60 : 1/60 scan (~8secs@Band6)
# 240 : 1/240 scan (~2secs@BAnd6)
#-----

import analysisUtils as aU
es = aU.stuffForScienceDataReduction()

import os

#obtain scan numbers
myms = aU.createCasaTool(mstool)
myms.open(msco)
mymsmd = aU.createCasaTool(msmdtool)
mymsmd.open(msco)

```

```

tgt_scans = mymsmd.scansforintent('*OBSERVE_TARGET*')
mymsmd.close()
mym.s.close()

os.system('rm -rf '+keywords+'_?')
os.system('rm -rf '+keywords+'*_selcal?.ms')
os.system('rm -rf '+keywords+'*_selcal?.ms*')
os.system('rm -rf '+keywords+'*_selcal?.tbl*')

sc = tgt_scans[0]
msc = keywords+'_'+str(sc)+'_selcal0.ms'

#----- Preparing the initial MS

sc = tgt_scans[0]
msc = keywords+'_'+str(sc)+'_selcal0.ms'

# split(vis = msc,
#       outputvis = msc,
#       datacolumn = 'data',
#       scan = sc,
#       keepflags = True)

split(vis = msc,
      outputvis = msc,
      datacolumn = 'corrected',
      scan = sc,
      keepflags = True)

#fixplanets(msc, field = '0', fixuvw = True, refant=refant, reftime = reftime)
#tb.open(msc+'/POINTING', nomodify = False)
#a = tb.rownumbers()
#tb.removeverrows(a)
#tb.close()

tb.open(msc)
raw_data = tb.query('SCAN_NUMBER == %d && ANTENNA1 == 0 && ANTENNA2 == 2 && DATA_DESC_ID == 0' %
sc)
tt_data = raw_data.getcol('TIME')
tb.close()
tt_st = qa.time(qa.quantity(tt_data[0]-1, 's'), form="ymd",prec=8)[0]
tt_ed = qa.time(qa.quantity(tt_data[-1]+1, 's'), form="ymd",prec=8)[0]
tt_timerange = '%s~%s' % (tt_st, tt_ed)

for i in range(0,len(t_interval)):
    msc = keywords+'_'+str(sc)+'_selcal'+str(i)+'.ms'
    imgname_base = keywords+'_'+str(i)+'/'+keywords+'_'+str(sc)+'_selcal'+str(i)
    if os.path.exists(keywords+'_'+str(i)) == False:
        os.system('mkdir '+keywords+'_'+str(i))

    imagename = imgname_base
    print('Now synthsizing : '+imagename)

tclean(vis = msc,
      #spw = spw,
      #stokes = stokes,
      field = field,
      timerange = tt_timerange,
      phasecenter = phasecenter,
      imagename = imagename,
      cell = cell_size,
      imsize = imsize,
      interactive = False,
      usemask = 'pb',
      pbmask = pbmask,
      pblimit = pbmask,
      specmode = 'mfs',
      gridder = 'mosaicft',

```

```

weighting = 'briggs',
robust = robust,
niter = niter,
deconvolver = deconvolver,
scales = scales,
#threshold = threshold,
cycleniter = 1000,
parallel = True,
gain = gain)

tclean(vis = msc,
#spw = spw,
#stokes = stokes,
field = field,
timerange = tt_timerange,
phasecenter = phasecenter,
imagename = imagename,
cell = cell_size,
imsize = imsize,
interactive = False,
usemask = 'pb',
pbmask = pbmask,
pblimit = pbmask,
specmode = 'mfs',
gridder = 'mosaicft',
weighting = 'briggs',
robust = robust,
niter = 0,
deconvolver = deconvolver,
scales = scales,
#threshold = threshold,
calcres = False,
calcpsf = False,
savemodel = 'modelcolumn',
gain = gain)

impbcor(imagename=imagename + '.image',
pbimage=imagename+'.pb',
outfile=imagename+'.pbcpr', mode='divide')

exportfits(imagename = imagename + '.image',fitsimage = imagename + '.fits')

#----- create and apply calibration table
t_int = t_interval[i]
gaincal(vis = msc, caltable = keywords+'_'+str(sc)+'_selcal'+str(i)+'.tbl',gaintype =
'G',calmode = 'p',refant = refant,
solint = t_int, minsnr = minsnr)
#es.checkCalTable(keywords+'_'+str(sc)+'_selcal'+str(i)+'.tbl', msName = msc, interactive =
False)
applycal(vis = msc, gaintable = keywords+'_'+str(sc)+'_selcal'+str(i)+'.tbl',interp =
'nearest', applymode = 'calonly', calwt = False)

#----- create MS for next step of self calibration
nextmsc = keywords+'_'+str(sc)+'_selcal'+str(i+1)+'.ms'
split(vis = msc, outputvis = nextmsc, datacolumn = 'corrected', keepflags = True)

#remove older measurement set
os.system('rm -rf '+msc)

#generate snap-shot images
domovie = 0
if domovie == 1:

#----- Loop of synthesizing final images
if os.path.exists(keywords+'_F') == False:
os.system('mkdir '+keywords+'_F')

```

```

msc = nextmsc
imgname_base = keywords+'_F/'+keywords+'_'+str(sc)+'_selcalF'

img_step = 1
t_step = 2 #normal 10min scan: 2s, short-int scan:0.2s
for synth_num in range(0, tt_data.size):
    st_tim = qa.time(qa.quantity(tt_data[synth_num*img_step]-t_step/2., 's'), form="ymd",
prec=8)[0]
    ed_tim = qa.time(qa.quantity(tt_data[(synth_num+1)*img_step-1]+t_step/2., 's'),
form="ymd", prec=8)[0]
    timerange = '%s~%s' % (st_tim, ed_tim)
    imagename = imgname_base + '_%03d' % synth_num
    print('Now synthsizing ('+str(synth_num+1)+'): '+imagename)

tclean(vis = msc,
        #spw = spw,
        #stokes = stokes,
        field = field,
        timerange = timerange,
        phasecenter = phasecenter,
        imagename = imagename,
        cell = cell_size,
        imsize = imsize,
        interactive = False,
        usemask = 'pb',
        pbmask = pbmask,
        pblimit = pbmask,
        specmode = 'mfs',
        gridder = 'mosaicft',
        weighting = 'briggs',
        robust = robust,
        niter = niter,
        deconvolver = deconvolver,
        scales = scales,
        #threshold = threshold,
        cycleniter = 1000,
        parallel = True,
        gain = gain)

impbcor(imagename=imagename + '.image',
        pbimage=imagename+'.pb',
        outfile=imagename+'.pbcor', mode='divide')

exportfits(imagename= imagename + '.image',
        fitsimage= imagename + '.fits')

```

```

#!/usr/bin/env python3
# -*- coding: utf-8 -*-
"""
=====
IMAGING & SELF-CAL LOOP FOR A MOVIE
=====

Created on Tue Oct 17 10:51:22 2023
@author: yichai
"""

#general parameters
msco = 'alma_12m7m_sim_b5c6_scalef0.5_phase30_Hinode_test.ms'
keywords = 'alma_12m7m_sim_b5c6_scalef0.5_phase30_Hinode_test'

#clean parameters
cell_size = '0.026arcsec' #b5c6
imsize = [1200,1200]
robust = 1.0
#threshold = '2.0Jy'
#niter = 40000
niter = 200000 #more niter for large images?
#niter2 = 40000
pbmask = 0.2
gain = 0.025
#spw = '0,1,2,3'
#stokes = 'I'
field = '0'
#phasecenter = 0
#phasecenter = 'J2000 09h55m30.91 12d37m47.9'
phasecenter = 'J2000 06h06m56.98 23d25m45.5' #modified for Hinode data
#deconvolver = 'clark'
deconvolver = 'multiscale'
scales = [0,6,18]

#snr setup
minsnr=3.0

#refant = 'DA44'
refant = '8'
#reftime = '2021/08/19/17:28:00'
reftime = '2015/06/23/14:00:00' #modified time for Hinode data

#selcal_div = [1,4,15,60,240]
t_interval = ['inf','60','int','int','int']
#t_interval = ['int','int','int','int','int']
#t_interval = ['inf'] #for comparison between un-selfcaled data
#-----
# selcal_div: the duration for selcal:
# 1 : 1/1 scan (~8mins@Band6)
# 4 : 1/4 scan (~2mins@Band6)
# 15 : 1/15 scan (~32secs@Band6)
# 60 : 1/60 scan (~8secs@Band6)
# 240 : 1/240 scan (~2secs@BAnd6)
#-----

import analysisUtils as aU
es = aU.stuffForScienceDataReduction()
import os

#obtain scan numbers
myms = aU.createCasaTool(mstool)
myms.open(msco)
mymsmd = aU.createCasaTool(msmdtool)
mymsmd.open(msco)
tgt_scans = mymsmd.scansforintent('*OBSERVE_TARGET*')
mymsmd.close()
myms.close()

```

```

#----- Loop of synthesizing final images
if os.path.exists(keywords+'_F') == False:
    os.system('mkdir '+keywords+'_F')

sc = tgt_scans[0]
i = len(t_interval)-1
nextmsc = keywords+'_'+str(sc)+'_selcal'+str(i+1)+'.ms'
print(nextmsc)
msc = nextmsc
imgname_base = keywords+'_F/'+keywords+'_'+str(sc)+'_selcalF'

tb.open(msco)
raw_data = tb.query('SCAN_NUMBER == %d && ANTENNA1 == 0 && ANTENNA2 == 2 && DATA_DESC_ID == 0' %
sc)
tt_data = raw_data.getcol('TIME')
tb.close

#generate snap-shot images
domovie = 1
if domovie == 1:
    img_step = 1
    t_step = 2 #normal 10min scan: 2s, short-int scan:0.2s
    for synth_num in range(0, tt_data.size, img_step):
        st_tim = qa.time(qa.quantity(tt_data[synth_num]-t_step/2., 's'), form="ymd", prec=8)[0]
        ed_tim = qa.time(qa.quantity(tt_data[synth_num]+t_step/2., 's'), form="ymd", prec=8)[0]
        timerange = '%s~%s' % (st_tim, ed_tim)
        imagename = imgname_base + '_%03d' % synth_num
        print('Now synthsizing ('+str(synth_num+1)+'): '+imagename)

    tclean(vis = msc,
           #spw = spw,
           #stokes = stokes,
           field = field,
           timerange = timerange,
           phasecenter = phasecenter,
           imagename = imagename,
           cell = cell_size,
           imsize = imsize,
           interactive = False,
           usemask = 'pb',
           pbmask = pbmask,
           pblimit = pbmask,
           specmode = 'mfs',
           gridder = 'mosaicft',
           weighting = 'briggs',
           robust = robust,
           niter = niter,
           deconvolver = deconvolver,
           scales = scales,
           #threshold = threshold,
           cycleniter = 1000,
           parallel = True,
           gain = gain)

    impbcor(imagename=imagename + '.image',
            pbimage=imagename+'.pb',
            outfile=imagename+'.pbcpr', mode='divide')

    exportfits(imagename= imagename + '.image',
               fitsimage= imagename + '.fits')

```

Annex 5: Observation reports



Project state changes

Role	UTC	State
hmessias	2023-11-27T19:24:22	CSVReady

Timeline

Wednesday, 29 Nov 2023

UTC	Author	Details
SBEX 14:01		<i>Towards High-resolution Solar ALMA Images Overcoming current ObsMode limitations (CSV-3832) (Version 1.2)</i> --SUCCESS--
		Start/End 13:34:39 - 14:01:57 Project Code 2022.1.00031.CSV SchedBlock Sun_a_03_INT SB UID uid://A001/X362b/Xee0 Band ALMA_RB_03 ALMA Build ONLINE-CYCLE10-B-28-2023-11-04-05-00-00 Array Name Array90-BLC PI mbarta ExecBlock uid://A002/X1100c1a/X145af QA0 Status Array/Corr 12 [m]/64-antenna

Saturday, 16 Dec 2023

UTC	Author	Details
SBEX 12:59		<i>Towards High-resolution Solar ALMA Images Overcoming current ObsMode limitations (CSV-3832) (Version 2.5)</i> --FAIL--
		Start/End 12:58:05 - 12:59:12 Project Code 2022.1.00031.CSV SchedBlock Sun_a_05_INT SB UID uid://A001/X362b/Xee1 Band ALMA_RB_05 ALMA Build ONLINE-CYCLE10-B-28-2023-11-04-05-00-00 Array Name Array82-BLC PI mbarta ExecBlock uid://A002/X110fd13/X108e3 QA0 Status Array/Corr 12 [m]/64-antenna JIRA PRTSPR-70876
SBEX 13:04		<i>Towards High-resolution Solar ALMA Images Overcoming current ObsMode limitations (CSV-3832) (Version 2.5)</i> --FAIL--
		Start/End 13:03:20 - 13:04:05 Project Code 2022.1.00031.CSV SchedBlock Sun_a_05_INT SB UID uid://A001/X362b/Xee1 Band ALMA_RB_05 ALMA Build ONLINE-CYCLE10-B-28-2023-11-04-05-00-00 Array Name Array82-BLC PI mbarta ExecBlock uid://A002/X110fd13/X1099c QA0 Status Array/Corr 12 [m]/64-antenna JIRA PRTSPR-70876
SBEX 13:37		<i>Towards High-resolution Solar ALMA Images Overcoming current ObsMode limitations (CSV-3832) (Version 2.5)</i> --SUCCESS--
		Start/End 13:12:26 - 13:37:25 Project Code 2022.1.00031.CSV SchedBlock Sun_a_05_INT SB UID uid://A001/X362b/Xee1 Band ALMA_RB_05 ALMA Build ONLINE-CYCLE10-B-28-2023-11-04-05-00-00 Array Name Array84-BLC PI mbarta ExecBlock uid://A002/X110fd13/X1099e QA0 Status Array/Corr 12 [m]/64-antenna

MeasurementSet Name:
/scratch/barta/LB_Solar/Project_2022.1.00031.CSV/Sun_10_a_05_INT/X1099e/uid____A002_X110fd13_X1099
e.ms MS Version 2

Observer: mbarta Project: uid://A001/X362b/Xede
Observation: ALMA
Data records: 71494020 Total elapsed time = 1431.65 seconds
Observed from 16-Dec-2023/13:13:21.8 to 16-Dec-2023/13:37:13.4 (UTC)

ObservationID = 0 ArrayID = 0

Date	Timerange (UTC)	Scan	FldId	FieldName	nRows	SpwIds
Average Interval(s) ScanIntent						
16-Dec-2023/13:13:21.8 - 13:13:45.3	1	0	Sun		1082224	
[0,1,2,3,4,5,6,7,8,9,10,11,12,13,14,15,16,17,18,19,20,21,22,23,24] [0.016, 0.016, 0.016, 0.016, 1.15, 0.192, 0.192, 0.192, 0.192, 0.192, 0.192, 0.192, 0.192, 0.192, 0.016, 0.016, 0.016, 0.016, 0.192, 0.192, 0.192, 0.192, 0.192, 0.192, 0.192]						
[CALIBRATE_ATMOSPHERE#AMBIENT,CALIBRATE_ATMOSPHERE#HOT,CALIBRATE_ATMOSPHERE#OFF_SOURCE,CALIBRATE_ATMOSPHERE#REFERENCE,CALIBRATE_WVR#AMBIENT,CALIBRATE_WVR#HOT,CALIBRATE_WVR#OFF_SOURCE,CALIBRATE_WVR#REFERENCE]						
13:14:51.6 - 13:15:49.3	2	1	J1256-0547		856700	
[4,25,26,27,28,29,30,31,32,33,34,35,36] [1.15, 0.016, 0.016, 0.016, 0.016, 2.02, 1.01, 2.02, 1.01, 2.02, 1.01, 2.02, 1.01] [CALIBRATE_POINTING#ON_SOURCE,CALIBRATE_WVR#ON_SOURCE]						
13:16:21.5 - 13:17:24.7	3	1	J1256-0547		4247984	
[0,1,2,3,4,5,6,7,8,9,10,11,12] [0.016, 0.016, 0.016, 0.016, 1.15, 0.192, 0.192, 0.192, 0.192, 0.192, 0.192, 0.192, 0.192]						
[CALIBRATE_SIDE BAND_RATIO#IMAGE,CALIBRATE_SIDE BAND_RATIO#SIGNAL,CALIBRATE_WVR#IMAGE,CALIBRATE_WVR#SIGNAL]						
13:17:35.2 - 13:17:52.8	4	1	J1256-0547		811772	
[0,1,2,3,4,5,6,7,8,9,10,11,12] [0.016, 0.016, 0.016, 0.016, 1.15, 0.192, 0.192, 0.192, 0.192, 0.192, 0.192, 0.192, 0.192]						
[CALIBRATE_ATMOSPHERE#AMBIENT,CALIBRATE_ATMOSPHERE#HOT,CALIBRATE_ATMOSPHERE#OFF_SOURCE,CALIBRATE_WVR#AMBIENT,CALIBRATE_WVR#HOT,CALIBRATE_WVR#OFF_SOURCE]						
13:17:58.3 - 13:23:00.9	5	1	J1256-0547		21307624	
[0,1,2,3,4,5,6,7,8,9,10,11,12] [0.016, 0.016, 0.016, 0.016, 1.15, 0.192, 0.192, 0.192, 0.192, 0.192, 0.192, 0.192, 0.192] [CALIBRATE_BANDPASS#ON_SOURCE,CALIBRATE_WVR#ON_SOURCE]						
13:24:08.1 - 13:26:06.0	6	2	J1624-3213		2141776	
[4,25,26,27,28,29,30,31,32,33,34,35,36] [1.15, 0.016, 0.016, 0.016, 0.016, 2.02, 1.01, 2.02, 1.01, 2.02, 1.01, 2.02, 1.01] [CALIBRATE_POINTING#ON_SOURCE,CALIBRATE_WVR#ON_SOURCE]						
13:26:44.7 - 13:27:45.8	7	3	J1700-2610		4261556	
[0,1,2,3,4,5,6,7,8,9,10,11,12] [0.016, 0.016, 0.016, 0.016, 1.15, 0.192, 0.192, 0.192, 0.192, 0.192, 0.192, 0.192, 0.192] [CALIBRATE_PHASE#ON_SOURCE,CALIBRATE_WVR#ON_SOURCE]						
13:27:57.3 - 13:28:14.3	8	0	Sun		811720	
[0,1,2,3,4,5,6,7,8,9,10,11,12] [0.016, 0.016, 0.016, 0.016, 1.15, 0.192, 0.192, 0.192, 0.192, 0.192, 0.192, 0.192, 0.192]						
[CALIBRATE_ATMOSPHERE#AMBIENT,CALIBRATE_ATMOSPHERE#HOT,CALIBRATE_ATMOSPHERE#OFF_SOURCE,CALIBRATE_WVR#AMBIENT,CALIBRATE_WVR#HOT,CALIBRATE_WVR#OFF_SOURCE]						
13:28:23.8 - 13:36:03.2	9	0	Sun		31711160	
[0,1,2,3,4,5,6,7,8,9,10,11,12] [0.016, 0.016, 0.016, 0.016, 1.15, 0.192, 0.192, 0.192, 0.192, 0.192, 0.192, 0.192, 0.192] [OBSERVE_TARGET#OFF_SOURCE,OBSERVE_TARGET#ON_SOURCE]						
13:36:12.7 - 13:37:13.4	10	3	J1700-2610		4261504	
[0,1,2,3,4,5,6,7,8,9,10,11,12] [0.016, 0.016, 0.016, 0.016, 1.15, 0.192, 0.192, 0.192, 0.192, 0.192, 0.192, 0.192, 0.192] [CALIBRATE_PHASE#ON_SOURCE,CALIBRATE_WVR#ON_SOURCE]						

(nRows = Total number of rows per scan)

Fields: 4

ID	Code Name	RA	Decl	Epoch	SrcId	nRows
0	none Sun	17:32:41.451514	-23.13.55.18836	ICRS	0	33605104
1	none J1256-0547	12:56:11.166570	-05.47.21.52520	ICRS	1	27224080
2	none J1624-3213	16:24:59.619634	-32.13.24.43829	ICRS	2	2141776
3	none J1700-2610	17:00:53.154063	-26.10.51.72542	ICRS	3	8523060

Spectral Windows: (37 unique spectral windows and 2 unique polarization setups)

SpwID	Name	#Chans	Frame	Ch0 (MHz)	ChanWid (kHz)
0	X498997425#ALMA_RB_05#BB_1#SQLD	1	TOPO	191021.000	2000000.000
2000000.0	191021.0000	1	XX	YY	
1	X498997425#ALMA_RB_05#BB_2#SQLD	1	TOPO	192979.000	2000000.000
2000000.0	192979.0000	2	XX	YY	
2	X498997425#ALMA_RB_05#BB_3#SQLD	1	TOPO	203021.000	2000000.000

2000000.0	203021.0000	3	XX	YY				
3	X498997425#ALMA_RB_05#BB_4#SQLD	1	TOPO	204979.000	2000000.000			
2000000.0	204979.0000	4	XX	YY				
4	WVR#NOMINAL	4	TOPO	184550.000	1500000.000			
7500000.0	187550.0000	0	XX					
5	X498997425#ALMA_RB_05#BB_1#SW-01#FULL_RES	128	TOPO	192013.188	-15625.000			
2000000.0	191021.0000	1	XX	YY				
6	X498997425#ALMA_RB_05#BB_1#SW-01#CH_AVG	1	TOPO	191005.375	1796875.000			
1796875.0	191005.3750	1	XX	YY				
7	X498997425#ALMA_RB_05#BB_2#SW-01#FULL_RES	128	TOPO	193971.188	-15625.000			
2000000.0	192979.0000	2	XX	YY				
8	X498997425#ALMA_RB_05#BB_2#SW-01#CH_AVG	1	TOPO	192963.375	1796875.000			
1796875.0	192963.3750	2	XX	YY				
9	X498997425#ALMA_RB_05#BB_3#SW-01#FULL_RES	128	TOPO	202028.812	15625.000			
2000000.0	203021.0000	3	XX	YY				
10	X498997425#ALMA_RB_05#BB_3#SW-01#CH_AVG	1	TOPO	203005.375	1796875.000			
1796875.0	203005.3750	3	XX	YY				
11	X498997425#ALMA_RB_05#BB_4#SW-01#FULL_RES	128	TOPO	203986.812	15625.000			
2000000.0	204979.0000	4	XX	YY				
12	X498997425#ALMA_RB_05#BB_4#SW-01#CH_AVG	1	TOPO	204963.375	1796875.000			
1796875.0	204963.3750	4	XX	YY				
13	X498997425#ALMA_RB_05#BB_1#SQLD	1	TOPO	187021.000	2000000.000			
2000000.0	187021.0000	1	XX	YY				
14	X498997425#ALMA_RB_05#BB_2#SQLD	1	TOPO	187021.000	2000000.000			
2000000.0	187021.0000	2	XX	YY				
15	X498997425#ALMA_RB_05#BB_3#SQLD	1	TOPO	187021.000	2000000.000			
2000000.0	187021.0000	3	XX	YY				
16	X498997425#ALMA_RB_05#BB_4#SQLD	1	TOPO	187021.000	2000000.000			
2000000.0	187021.0000	4	XX	YY				
17	X498997425#ALMA_RB_05#BB_1#SW-01#FULL_RES	128	TOPO	188013.188	-15625.000			
2000000.0	187021.0000	1	XX	YY				
18	X498997425#ALMA_RB_05#BB_1#SW-01#CH_AVG	1	TOPO	187005.375	1796875.000			
1796875.0	187005.3750	1	XX	YY				
19	X498997425#ALMA_RB_05#BB_2#SW-01#FULL_RES	128	TOPO	188013.188	-15625.000			
2000000.0	187021.0000	2	XX	YY				
20	X498997425#ALMA_RB_05#BB_2#SW-01#CH_AVG	1	TOPO	187005.375	1796875.000			
1796875.0	187005.3750	2	XX	YY				
21	X498997425#ALMA_RB_05#BB_3#SW-01#FULL_RES	128	TOPO	207986.812	15625.000			
2000000.0	208979.0000	3	XX	YY				
22	X498997425#ALMA_RB_05#BB_3#SW-01#CH_AVG	1	TOPO	208963.375	1796875.000			
1796875.0	208963.3750	3	XX	YY				
23	X498997425#ALMA_RB_05#BB_4#SW-01#FULL_RES	128	TOPO	207986.812	15625.000			
2000000.0	208979.0000	4	XX	YY				
24	X498997425#ALMA_RB_05#BB_4#SW-01#CH_AVG	1	TOPO	208963.375	1796875.000			
1796875.0	208963.3750	4	XX	YY				
25	X498997425#ALMA_RB_05#BB_1#SQLD	1	TOPO	196021.000	2000000.000			
2000000.0	196021.0000	1	XX	YY				
26	X498997425#ALMA_RB_05#BB_2#SQLD	1	TOPO	197979.000	2000000.000			
2000000.0	197979.0000	2	XX	YY				
27	X498997425#ALMA_RB_05#BB_3#SQLD	1	TOPO	208021.000	2000000.000			
2000000.0	208021.0000	3	XX	YY				
28	X498997425#ALMA_RB_05#BB_4#SQLD	1	TOPO	209979.000	2000000.000			
2000000.0	209979.0000	4	XX	YY				
29	X498997425#ALMA_RB_05#BB_1#SW-01#FULL_RES	128	TOPO	197013.188	-15625.000			
2000000.0	196021.0000	1	XX	YY				
30	X498997425#ALMA_RB_05#BB_1#SW-01#CH_AVG	1	TOPO	195997.562	1781250.000			
1781250.0	195997.5625	1	XX	YY				
31	X498997425#ALMA_RB_05#BB_2#SW-01#FULL_RES	128	TOPO	198971.188	-15625.000			
2000000.0	197979.0000	2	XX	YY				
32	X498997425#ALMA_RB_05#BB_2#SW-01#CH_AVG	1	TOPO	197955.562	1781250.000			
1781250.0	197955.5625	2	XX	YY				
33	X498997425#ALMA_RB_05#BB_3#SW-01#FULL_RES	128	TOPO	207028.812	15625.000			
2000000.0	208021.0000	3	XX	YY				
34	X498997425#ALMA_RB_05#BB_3#SW-01#CH_AVG	1	TOPO	207997.562	1781250.000			
1781250.0	207997.5625	3	XX	YY				
35	X498997425#ALMA_RB_05#BB_4#SW-01#FULL_RES	128	TOPO	208986.812	15625.000			
2000000.0	209979.0000	4	XX	YY				
36	X498997425#ALMA_RB_05#BB_4#SW-01#CH_AVG	1	TOPO	209955.562	1781250.000			

1781250.0 209955.5625

4 XX YY

Sources: 300

ID	Name	SpwId	RestFreq (MHz)	SysVel (km/s)
0	Sun	0	-	-
0	Sun	1	-	-
0	Sun	2	-	-
0	Sun	3	-	-
0	Sun	4	-	-
0	Sun	37	-	-
0	Sun	38	-	-
0	Sun	39	-	-
0	Sun	40	-	-
0	Sun	41	-	-
0	Sun	42	-	-
0	Sun	43	-	-
0	Sun	44	-	-
0	Sun	45	-	-
0	Sun	46	-	-
0	Sun	47	-	-
0	Sun	48	-	-
0	Sun	49	-	-
0	Sun	50	-	-
0	Sun	51	-	-
0	Sun	52	-	-
0	Sun	53	-	-
0	Sun	54	-	-
0	Sun	55	-	-
0	Sun	56	-	-
0	Sun	57	-	-
0	Sun	58	-	-
0	Sun	59	-	-
0	Sun	60	-	-
0	Sun	61	-	-
0	Sun	62	-	-
0	Sun	63	-	-
0	Sun	64	-	-
0	Sun	65	-	-
0	Sun	66	-	-
0	Sun	67	-	-
0	Sun	68	-	-
0	Sun	69	-	-
0	Sun	70	-	-
0	Sun	71	-	-
0	Sun	72	-	-
0	Sun	73	-	-
0	Sun	74	-	-
0	Sun	75	-	-
0	Sun	76	-	-
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0	Sun	86	-	-
0	Sun	87	-	-
0	Sun	88	-	-
0	Sun	5	191000	0
0	Sun	6	191000	0
0	Sun	7	193000	0
0	Sun	8	193000	0
0	Sun	9	203000	0
0	Sun	10	203000	0
0	Sun	11	205000	0
0	Sun	12	205000	0

0	Sun	13	-	-
0	Sun	14	-	-
0	Sun	15	-	-
0	Sun	16	-	-
0	Sun	17	191000	0
0	Sun	18	191000	0
0	Sun	19	193000	0
0	Sun	20	193000	0
0	Sun	21	203000	0
0	Sun	22	203000	0
0	Sun	23	205000	0
0	Sun	24	205000	0
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1	J1256-0547	6	191000	0
1	J1256-0547	7	193000	0

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2	J1624-3213	5	191000	0
2	J1624-3213	6	191000	0
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2	J1624-3213	8	193000	0
2	J1624-3213	9	203000	0
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3	J1700-2610	1	-	-
3	J1700-2610	2	-	-
3	J1700-2610	3	-	-
3	J1700-2610	5	191000	0
3	J1700-2610	6	191000	0
3	J1700-2610	7	193000	0
3	J1700-2610	8	193000	0
3	J1700-2610	9	203000	0
3	J1700-2610	10	203000	0
3	J1700-2610	11	205000	0
3	J1700-2610	12	205000	0

Antennas: 52:

ID	Name	Station	Diam.	Long.	Lat.	Offset from array center (m)	
ITRF Geocentric coordinates (m)						East	North
Elevation			x	y	z		
0	CM01	N602	7.0 m	-067.45.17.4	-22.53.22.3	8.8037	-527.8580
22.2055	2225080.355228		-5440132.958128	-2481524.789864			
1	CM02	J502	7.0 m	-067.45.17.7	-22.53.23.0	2.1071	-549.4456
22.1477	2225070.958281		-5440127.672185	-2481544.655258			
2	CM03	J503	7.0 m	-067.45.17.4	-22.53.23.2	9.2481	-555.0631
22.1325	2225076.735107		-5440122.933576	-2481549.824492			
3	CM04	N605	7.0 m	-067.45.17.4	-22.53.23.9	9.6880	-575.8356
22.0879	2225074.068012		-5440115.250608	-2481568.943967			
4	CM06	N606	7.0 m	-067.45.17.1	-22.53.23.6	19.1994	-566.5678
22.1031	2225084.241158		-5440114.999494	-2481560.411854			
5	CM07	N601	7.0 m	-067.45.17.0	-22.53.22.5	21.0632	-532.5809
22.1877	2225091.000261		-5440126.601762	-2481529.134056			
6	CM09	N603	7.0 m	-067.45.17.7	-22.53.22.3	-0.0497	-527.8645
22.1928	2225072.155639		-5440136.296531	-2481524.791008			
7	CM10	J501	7.0 m	-067.45.17.4	-22.53.22.9	10.0861	-545.4953
22.1622	2225078.929912		-5440126.086166	-2481541.021606			
8	CM11	N604	7.0 m	-067.45.17.8	-22.53.23.7	-0.2657	-571.8963
22.0852	2225065.434567		-5440120.434627	-2481565.313800			
9	DA41	A083	12.0 m	-067.45.22.8	-22.53.21.0	-143.5434	-488.2362
25.7594	2224946.423770		-5440207.923211	-2481489.670186			
10	DA42	A047	12.0 m	-067.45.16.4	-22.53.30.3	38.4531	-775.2182
21.5979	2225071.159752		-5440032.160449	-2481752.434638			
11	DA44	A016	12.0 m	-067.45.16.4	-22.53.25.1	37.4651	-614.5603
21.7887	2225093.970126		-5440090.538761	-2481604.502872			
12	DA45	A101	12.0 m	-067.45.24.0	-22.53.10.5	-177.3499	-163.1864
25.7562	2224962.988323		-5440337.730653	-2481190.209469			
13	DA46	A122	12.0 m	-067.45.55.6	-22.53.04.3	-1079.8558	29.4330
6.2507	2224149.167422		-5440732.003760	-2481005.166290			
14	DA47	A022	12.0 m	-067.45.17.2	-22.53.25.7	14.4394	-633.3728
21.9426	2225069.942470		-5440092.613603	-2481621.893817			
15	DA48	A082	12.0 m	-067.45.08.3	-22.53.29.2	269.0423	-740.9535
16.2833	2225287.767033		-5439952.669973	-2481718.801163			

16	DA49	A066	12.0 m	-067.45.17.6	-22.53.24.6	3.3950	-597.3309
21.8251	2225064.986682	-5440109.670174	-2481588.644429				
17	DA51	A135	12.0 m	-067.45.02.2	-22.53.16.5	442.8905	-348.0857
12.9372	2225505.357228	-5440025.428568	-2481355.567250				
18	DA52	A015	12.0 m	-067.45.15.3	-22.53.26.0	68.8256	-640.1823
21.5282	2225119.131525	-5440069.220242	-2481628.005984				
19	DA53	A085	12.0 m	-067.45.10.5	-22.53.20.5	207.6862	-472.2073
16.8002	2225270.737975	-5440073.091611	-2481471.418756				
20	DA55	A134	12.0 m	-067.45.20.4	-22.53.45.6	-76.0039	-1249.4239
24.2069	2224896.300495	-5439906.962910	-2482190.302240				
21	DA56	A062	12.0 m	-067.45.18.5	-22.53.31.4	-21.4628	-809.5726
22.5655	2225010.984344	-5440043.297652	-2481784.459798				
22	DA57	A094	12.0 m	-067.45.27.0	-22.53.37.1	-264.4594	-984.7315
19.8550	2224759.344760	-5440069.898985	-2481944.768298				
23	DA58	A076	12.0 m	-067.45.20.5	-22.53.33.8	-77.9916	-882.7187
24.5723	2224948.593622	-5440040.070937	-2481852.625688				
24	DA59	A093	12.0 m	-067.45.14.7	-22.53.14.5	86.9869	-286.0414
22.1124	2225188.290980	-5440190.332841	-2481301.976054				
25	DA62	A069	12.0 m	-067.45.21.3	-22.53.30.2	-101.4810	-770.1050
23.8043	2224943.168875	-5440088.854228	-2481748.582478				
26	DA64	A110	12.0 m	-067.45.09.2	-22.53.54.8	244.7432	-1530.9482
13.5074	2225147.947357	-5439675.039018	-2482445.481380				
27	DA65	A045	12.0 m	-067.45.17.9	-22.53.30.1	-5.4184	-767.4395
22.6051	2225032.052228	-5440052.427624	-2481745.660395				
28	DV01	A011	12.0 m	-067.45.14.4	-22.53.28.4	95.9112	-716.4989
21.0931	2225132.809848	-5440031.119522	-2481698.143402				
29	DV02	A024	12.0 m	-067.45.18.3	-22.53.26.8	-16.3966	-665.3089
21.5565	2225036.565223	-5440092.459725	-2481651.164861				
30	DV03	A027	12.0 m	-067.45.19.0	-22.53.28.7	-35.0467	-726.6009
21.6047	2225010.295225	-5440077.493756	-2481707.648797				
31	DV04	A042	12.0 m	-067.45.15.6	-22.53.29.3	60.4757	-743.9313
20.6733	2225095.827142	-5440034.299665	-2481723.252096				
32	DV05	A092	12.0 m	-067.45.10.1	-22.53.39.1	217.6020	-1047.7078
20.8520	2225196.572935	-5439865.592923	-2482003.171782				
33	DV06	A096	12.0 m	-067.45.29.9	-22.53.15.7	-347.1456	-322.7952
22.7984	2224781.300736	-5440342.024685	-2481336.103148				
34	DV07	A086	12.0 m	-067.45.27.0	-22.53.29.3	-262.5029	-744.4838
26.4714	2224798.839058	-5440161.303679	-2481726.016465				
35	DV08	A087	12.0 m	-067.45.08.3	-22.53.33.2	269.0949	-864.0691
16.2389	2225269.667982	-5439908.285863	-2481832.203194				
36	DV09	A073	12.0 m	-067.45.22.9	-22.53.28.1	-147.0734	-705.3304
23.7576	2224910.493113	-5440129.394064	-2481688.890878				
37	DV10	A043	12.0 m	-067.45.15.1	-22.53.29.4	75.1901	-747.1637
20.6663	2225108.967309	-5440027.559553	-2481726.227190				
38	DV11	A007	12.0 m	-067.45.15.1	-22.53.27.3	74.0150	-681.2930
21.3248	2225117.809595	-5440052.281397	-2481665.800107				
39	DV12	A121	12.0 m	-067.44.36.3	-22.53.19.3	1181.3913	-435.7649
-24.4919	2226162.864243	-5439682.292505	-2481421.785374				
40	DV14	A074	12.0 m	-067.45.12.1	-22.53.32.0	161.8142	-828.6189
18.7740	2225176.483822	-5439963.825760	-2481800.531180				
41	DV15	A105	12.0 m	-067.45.00.2	-22.53.43.8	500.1150	-1191.4347
14.9707	2225434.811677	-5439701.866358	-2482133.288250				
42	DV16	A108	12.0 m	-067.44.52.4	-22.53.25.7	722.5812	-632.9600
1.9541	2225718.424978	-5439807.607943	-2481613.738634				
43	DV17	A116	12.0 m	-067.44.49.8	-22.53.07.3	796.8150	-62.7364
2.4465	2225871.284785	-5439985.176851	-2481088.601483				
44	DV18	A070	12.0 m	-067.45.11.9	-22.53.29.3	166.1828	-743.4929
19.3809	2225193.275369	-5439993.337992	-2481722.345469				
45	DV19	A104	12.0 m	-067.45.36.4	-22.53.21.2	-530.9026	-492.4907
20.3387	2224585.379851	-5440348.386669	-2481491.481328				
46	DV20	A072	12.0 m	-067.45.12.6	-22.53.24.0	147.1735	-580.5877
18.1844	2225199.254476	-5440058.163787	-2481571.803516				
47	DV21	A068	12.0 m	-067.45.20.6	-22.53.25.7	-82.4247	-631.7802
23.0805	2224980.922220	-5440130.825161	-2481620.869248				
48	DV22	A088	12.0 m	-067.45.18.2	-22.53.18.4	-13.0909	-408.0098
23.6750	2225078.250111	-5440185.644924	-2481414.949662				
49	DV23	A060	12.0 m	-067.45.15.9	-22.53.32.5	52.7921	-843.4863
21.7260	2225074.421988	-5440002.261967	-2481815.375939				

50	DV24	A111	12.0 m	-067.45.03.9	-22.53.03.1	394.2957	66.9171
17.6692	2225523.141145	-5440197.241490	-2480975.072800				
51	DV25	A033	12.0 m	-067.45.19.4	-22.53.29.0	-47.3625	-735.6347
21.8852	2224997.664006	-5440079.142558	-2481716.080288				

QA2 REPORT

MEDIAN TSYS WITH SOURCE/ELEVATION

(see plots for details)

Scan	Fid	Source	Elev	Median T_x	Median T_y
1	0	Sun	46.1	1249	1253
4	1	J1256-0547	62.6	1094	1083
8	0	Sun	49.4	1236	1240

MEDIAN TSYS versus ANTENNA/SPW and OUTLIERS

TSYS MEDIAN				>3-sigma OUTLIERS			
XPOL		YPOL		OUTLIERS			
SPW	T	rms	T	rms	antenna	Pol	tsys n-sigma
0	5	1426 1190	1450 1229		No outliers		
1	7	1159 944	1140 990		No outliers		
2	9	985 852	966 1048		No outliers		
3	11	1244 1702	1206 1718		No outliers		

* * * * *

SUMMARY INFORMATION FOR uid___A002_X110fd13_X1099e.ms.split

Experiment Duration: 2023/12/16/13:17:58 to
2023/12/16/13:37:13

Processed from ms: uid___A002_X110fd13_X1099e.ms.split
Written to file: NewListobs.txt

SCAN LISTING

Scan	FdId	srcId	FieldName	StartTime	StopTime	Int(s)	Elev	ScanIntent
5	1	1	J1256-0547	13:17:58.5 -	13:23:00.9	0.19	62.0	Cal Bandpass
7	3	3	J1700-2610	13:26:45.4 -	13:27:45.8	0.19	56.7	Cal Phase
9	0	0	Sun	13:28:40.4 -	13:35:47.0	0.19	50.3	Obs Target
10	3	3	J1700-2610	13:36:13.0 -	13:37:13.4	0.19	58.8	Cal Phase

FIELD INFORMATION

Fid	Srd	Field	RA (J2000)	DEC	Fld Time (min)	#Scans
0	0	Sun	00:00:00.00000	+00.00.00.0000	7.11	1
1	1	J1256-0547	12:56:11.16657	-05.47.21.5252	5.04	1
2	2	J1624-3213	16:24:59.61963	-32.13.24.4383	0.00	0
3	3	J1700-2610	17:00:53.15406	-26.10.51.7254	2.02	2

FREQUENCY INFORMATION

spw	nchan	----Frequencies (GHz)-----			--Channel Width--		
		First	Last	Bandwidth	MHz	km/s	POLN
0	128	192.013187	190.028812	2.000	-15.625	-24.39	['XX', 'YY']
1	128	193.971188	191.986813	2.000	-15.625	-24.14	['XX', 'YY']
2	128	202.028812	204.013187	2.000	15.625	23.18	['XX', 'YY']
3	128	203.986813	205.971188	2.000	15.625	22.96	['XX', 'YY']

ANTENNA INFORMATION

ID	Name	Pad	Size (m)	Longitude	Latitude	E-off (m)	N-off (m)	Elev (m)
0	CM01	N602	7.0	-67.45.17.44	-22.53.22.32	-12.8	15768.3	8.2
1	CM02	J502	7.0	-67.45.17.67	-22.53.23.02	-19.5	15746.7	8.2
2	CM03	J503	7.0	-67.45.17.42	-22.53.23.20	-12.3	15741.1	8.1
3	CM04	N605	7.0	-67.45.17.40	-22.53.23.87	-11.9	15720.3	8.1
4	CM06	N606	7.0	-67.45.17.07	-22.53.23.57	-2.4	15729.6	8.1
5	CM07	N601	7.0	-67.45.17.01	-22.53.22.47	-0.5	15763.5	8.2
6	CM09	N603	7.0	-67.45.17.75	-22.53.22.32	-21.6	15768.3	8.2
7	CM10	J501	7.0	-67.45.17.39	-22.53.22.89	-11.5	15750.6	8.2
8	CM11	N604	7.0	-67.45.17.75	-22.53.23.74	-21.8	15724.2	8.1
9	DA41	A083	12.0	-67.45.22.78	-22.53.21.04	-165.1	15807.9	11.8
10	DA42	A047	12.0	-67.45.16.39	-22.53.30.32	16.9	15520.9	7.6
11	DA44	A016	12.0	-67.45.16.43	-22.53.25.12	15.9	15681.6	7.8
12	DA45	A101	12.0	-67.45.23.97	-22.53.10.53	-198.9	16132.9	11.8
13	DA46	A122	12.0	-67.45.55.64	-22.53.04.30	-1101.4	16325.6	-7.7
14	DA47	A022	12.0	-67.45.17.24	-22.53.25.73	-7.1	15662.8	8.0
15	DA48	A082	12.0	-67.45.08.30	-22.53.29.21	247.5	15555.2	2.3
16	DA49	A066	12.0	-67.45.17.63	-22.53.24.57	-18.2	15698.8	7.8
17	DA51	A135	12.0	-67.45.02.20	-22.53.16.51	421.3	15948.0	-1.0
18	DA52	A015	12.0	-67.45.15.33	-22.53.25.95	47.3	15655.9	7.5
19	DA53	A085	12.0	-67.45.10.46	-22.53.20.52	186.1	15823.9	2.8
20	DA55	A134	12.0	-67.45.20.41	-22.53.45.65	-97.6	15046.7	10.2
21	DA56	A062	12.0	-67.45.18.50	-22.53.31.43	-43.0	15486.6	8.6
22	DA57	A094	12.0	-67.45.27.02	-22.53.37.09	-286.0	15311.4	5.9
23	DA58	A076	12.0	-67.45.20.48	-22.53.33.79	-99.6	15413.4	10.6
24	DA59	A093	12.0	-67.45.14.69	-22.53.14.50	65.4	16010.1	8.1
25	DA62	A069	12.0	-67.45.21.31	-22.53.30.15	-123.0	15526.0	9.8
26	DA64	A110	12.0	-67.45.09.16	-22.53.54.75	223.2	14765.2	-0.5
27	DA65	A045	12.0	-67.45.17.93	-22.53.30.07	-27.0	15528.7	8.6
28	DV01	A011	12.0	-67.45.14.38	-22.53.28.42	74.3	15579.6	7.1
29	DV02	A024	12.0	-67.45.18.32	-22.53.26.76	-38.0	15630.8	7.6
30	DV03	A027	12.0	-67.45.18.97	-22.53.28.75	-56.6	15569.5	7.6
31	DV04	A042	12.0	-67.45.15.62	-22.53.29.31	38.9	15552.2	6.7
32	DV05	A092	12.0	-67.45.10.11	-22.53.39.13	196.0	15248.4	6.9
33	DV06	A096	12.0	-67.45.29.93	-22.53.15.69	-368.7	15973.3	8.8
34	DV07	A086	12.0	-67.45.26.96	-22.53.29.32	-284.1	15551.6	12.5
35	DV08	A087	12.0	-67.45.08.30	-22.53.33.19	247.5	15432.1	2.3
36	DV09	A073	12.0	-67.45.22.91	-22.53.28.06	-168.6	15590.8	9.8
37	DV10	A043	12.0	-67.45.15.11	-22.53.29.41	53.6	15549.0	6.7
38	DV11	A007	12.0	-67.45.15.15	-22.53.27.28	52.4	15614.8	7.3
39	DV12	A121	12.0	-67.44.36.29	-22.53.19.34	1159.8	15860.4	-38.5
40	DV14	A074	12.0	-67.45.12.07	-22.53.32.04	140.2	15467.5	4.8
41	DV15	A105	12.0	-67.45.00.19	-22.53.43.77	478.5	15104.7	1.0
42	DV16	A108	12.0	-67.44.52.39	-22.53.25.72	701.0	15663.2	-12.0
43	DV17	A116	12.0	-67.44.49.78	-22.53.07.28	775.2	16233.4	-11.5
44	DV18	A070	12.0	-67.45.11.91	-22.53.29.29	144.6	15552.6	5.4
45	DV19	A104	12.0	-67.45.36.38	-22.53.21.18	-552.5	15803.6	6.4
46	DV20	A072	12.0	-67.45.12.58	-22.53.24.03	125.6	15715.5	4.2
47	DV21	A068	12.0	-67.45.20.64	-22.53.25.68	-104.0	15664.3	9.1
48	DV22	A088	12.0	-67.45.18.20	-22.53.18.45	-34.7	15888.1	9.7
49	DV23	A060	12.0	-67.45.15.89	-22.53.32.52	31.2	15452.6	7.7
50	DV24	A111	12.0	-67.45.03.91	-22.53.03.09	372.7	16363.0	3.7
51	DV25	A033	12.0	-67.45.19.41	-22.53.29.04	-68.9	15560.5	7.9

MEDIAN GAIN VALUE = 0.168

RELATIVE ANTENNA GAIN FOR BANDPASS OBSERVATION

Antenna	SPW 0		SPW 1		SPW 2		SPW 3	
	X	Y	X	Y	X	Y	X	Y
0-CM01	0.58**	0.61**	0.58**	0.61**	0.58**	0.61**	0.57**	0.61**
1-CM02	0.57**	0.60**	0.57**	0.61**	0.57**	0.60**	0.57**	0.60**

2-CM03	0.58**	0.61**	0.58**	0.60**	0.58**	0.60**	0.58**	0.61**
3-CM04	0.57**	0.61**	0.57**	0.61**	0.57**	0.60**	0.58**	0.60**
4-CM06	0.56**	0.61**	0.57**	0.61**	0.57**	0.60**	0.57**	0.61**
5-CM07	flagged	flagged	flagged	flagged	flagged	flagged	flagged	flagged
6-CM09	0.57**	0.58**	0.57**	0.59**	0.58**	0.60**	0.56**	0.57**
7-CM10	0.57**	0.60**	0.57**	0.60**	0.57**	0.60**	0.57**	0.60**
8-CM11	0.55**	0.59**	0.56**	0.60**	0.56**	0.58**	0.56**	0.59**
9-DA41	0.98	1.04	0.98	1.04	0.98	1.03	0.99	1.03
10-DA42	0.97	1.03	0.98	1.03	0.97	1.02	0.97	1.02
11-DA44	0.99	1.04	0.98	1.04	0.99	1.04	0.98	1.04
12-DA45	0.95	1.03	0.97	1.03	0.99	1.03	0.97	1.04
13-DA46	0.95	1.05	0.99	1.04	0.99	1.04	0.98	1.04
14-DA47	0.99	1.05	1.00	1.05	1.00	1.04	0.99	1.06
15-DA48	flagged	flagged	flagged	flagged	flagged	flagged	flagged	flagged
16-DA49	0.97	1.04	0.99	1.04	0.99	1.03	0.98	1.03
17-DA51	0.96	1.00	0.97	1.02	0.96	1.02	0.97	1.01
18-DA52	0.97	1.04	0.99	1.05	0.98	1.05	0.98	1.06
19-DA53	0.97	1.03	0.98	1.03	0.96	1.02	0.97	1.03
20-DA55	0.99	1.03	0.99	1.04	0.98	1.03	0.98	1.03
21-DA56	0.98	1.02	0.98	1.03	0.97	1.02	0.96	1.02
22-DA57	0.99	1.05	0.99	1.05	0.99	1.04	0.99	1.04
23-DA58	0.99	1.04	0.99	1.04	0.99	1.03	0.99	1.04
24-DA59	0.99	1.03	0.99	1.03	0.98	1.03	0.98	1.03
25-DA62	0.98	1.03	0.99	1.04	0.98	1.04	0.99	1.04
26-DA64	0.99	1.05	1.00	1.05	0.99	1.04	0.99	1.05
27-DA65	0.99	1.04	1.00	1.04	0.98	1.04	0.99	1.03
28-DV01	1.01	1.06	1.01	1.07	1.01	1.07	1.01	1.07
29-DV02	1.00	1.05	1.01	1.06	1.01	1.07	1.00	1.06
30-DV03	1.00	1.05	1.01	1.06	1.00	1.05	1.00	1.06
31-DV04	1.01	1.06	1.01	1.06	1.01	1.06	1.01	1.07
32-DV05	1.01	1.06	1.01	1.05	0.99	1.04	1.00	1.03
33-DV06	1.00	1.06	1.00	1.06	1.00	1.06	1.00	1.05
34-DV07	1.00	1.04	0.99	1.06	1.00	1.05	0.99	1.04
35-DV08	0.99	1.04	1.00	1.05	0.99	1.04	0.99	1.04
36-DV09	1.01	1.03	1.02	1.05	1.01	1.07	1.01	1.05
37-DV10	1.00	1.06	1.01	1.06	1.00	1.06	1.01	1.06
38-DV11	1.00	1.06	1.01	1.06	0.99	1.05	1.00	1.05
39-DV12	0.97	1.04	0.99	1.04	0.97	1.03	0.98	1.03
40-DV14	1.00	1.06	0.99	1.05	1.00	1.05	1.00	1.06
41-DV15	0.99	1.03	0.99	1.04	0.99	1.05	0.99	1.04
42-DV16	0.96	1.04	0.98	1.03	0.99	1.04	0.98	1.04
43-DV17	0.98	1.02	0.99	1.04	0.99	1.03	0.98	1.04
44-DV18	0.99	1.05	1.01	1.05	0.99	1.05	0.99	1.04
45-DV19	0.99	1.03	1.00	1.05	0.99	1.05	0.99	1.05
46-DV20	0.98	1.04	0.98	1.03	0.97	1.00	0.98	0.99
47-DV21	0.99	1.05	0.99	1.04	1.00	1.05	1.00	1.03
48-DV22	0.99	1.05	1.00	1.05	0.99	1.05	1.00	1.05
49-DV23	1.01	1.05	1.00	1.06	1.00	1.05	0.99	1.04
50-DV24	0.95	1.00	0.96	1.00	0.94	1.00	0.94	0.99
51-DV25	0.99	1.02	0.99	1.04	1.00	1.02	1.00	1.01

** means outside of normalized range: 0.90 to 1.10

NORMALIZED BANDPASS AMPLITUDE RMS OVER 128 CHANNELS
using table uid____A002_X110fd13_X1099e.ms.split.bandpass

Antenna	SPW0		SPW1		SPW2		SPW3	
	X	Y	X	Y	X	Y	X	Y
0-CM01	2.507	2.359	2.483	2.362	2.488	2.361	2.515	2.367
1-CM02	2.530	2.372	2.531	2.362	2.533	2.380	2.536	2.388
2-CM03	2.504	2.337	2.488	2.374	2.500	2.397	2.486	2.358
3-CM04	2.553	2.365	2.511	2.370	2.520	2.391	2.490	2.386
4-CM06	2.564	2.367	2.511	2.364	2.511	2.377	2.534	2.365

5-CM07	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000
6-CM09	2.513	2.466	2.525	2.415	2.501	2.392	2.563	2.514
7-CM10	2.532	2.383	2.544	2.375	2.543	2.394	2.550	2.414
8-CM11	2.632	2.433	2.600	2.414	2.604	2.461	2.586	2.431
9-DA41	1.355	1.270	1.356	1.268	1.364	1.276	1.351	1.278
10-DA42	1.373	1.276	1.369	1.280	1.384	1.299	1.377	1.301
11-DA44	1.347	1.262	1.356	1.266	1.349	1.270	1.356	1.267
12-DA45	1.409	1.285	1.374	1.287	1.350	1.285	1.379	1.261
13-DA46	1.413	1.251	1.345	1.274	1.343	1.263	1.369	1.271
14-DA47	1.339	1.252	1.330	1.258	1.330	1.264	1.349	1.241
15-DA48	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000
16-DA49	1.371	1.268	1.352	1.266	1.351	1.275	1.361	1.278
17-DA51	1.387	1.326	1.378	1.298	1.386	1.301	1.383	1.312
18-DA52	1.373	1.260	1.339	1.252	1.357	1.248	1.357	1.238
19-DA53	1.380	1.284	1.366	1.285	1.387	1.289	1.379	1.289
20-DA55	1.345	1.277	1.351	1.270	1.361	1.282	1.359	1.280
21-DA56	1.367	1.298	1.369	1.287	1.376	1.295	1.388	1.297
22-DA57	1.342	1.249	1.343	1.253	1.345	1.261	1.348	1.266
23-DA58	1.341	1.271	1.337	1.274	1.348	1.277	1.343	1.262
24-DA59	1.351	1.274	1.345	1.277	1.364	1.281	1.353	1.285
25-DA62	1.353	1.280	1.347	1.268	1.363	1.272	1.347	1.259
26-DA64	1.341	1.253	1.334	1.253	1.339	1.264	1.344	1.255
27-DA65	1.338	1.262	1.329	1.271	1.353	1.264	1.343	1.279
28-DV01	1.309	1.240	1.312	1.227	1.305	1.225	1.308	1.217
29-DV02	1.326	1.253	1.307	1.238	1.317	1.231	1.327	1.238
30-DV03	1.334	1.253	1.317	1.238	1.329	1.248	1.323	1.243
31-DV04	1.318	1.239	1.319	1.240	1.317	1.238	1.318	1.228
32-DV05	1.310	1.241	1.312	1.251	1.337	1.269	1.329	1.286
33-DV06	1.324	1.241	1.326	1.240	1.328	1.241	1.335	1.247
34-DV07	1.329	1.268	1.340	1.240	1.335	1.258	1.343	1.273
35-DV08	1.343	1.270	1.322	1.256	1.347	1.262	1.340	1.260
36-DV09	1.308	1.276	1.304	1.249	1.305	1.230	1.308	1.249
37-DV10	1.322	1.232	1.316	1.233	1.325	1.236	1.310	1.241
38-DV11	1.326	1.233	1.315	1.234	1.339	1.246	1.332	1.250
39-DV12	1.374	1.266	1.348	1.263	1.383	1.279	1.365	1.280
40-DV14	1.322	1.238	1.337	1.248	1.335	1.251	1.333	1.244
41-DV15	1.341	1.282	1.341	1.269	1.344	1.254	1.337	1.274
42-DV16	1.401	1.269	1.364	1.276	1.352	1.273	1.359	1.264
43-DV17	1.361	1.296	1.348	1.269	1.349	1.279	1.355	1.265
44-DV18	1.344	1.247	1.319	1.249	1.349	1.251	1.343	1.260
45-DV19	1.341	1.278	1.333	1.249	1.344	1.257	1.349	1.258
46-DV20	1.359	1.265	1.357	1.278	1.371	1.321	1.363	1.349
47-DV21	1.341	1.256	1.340	1.269	1.325	1.258	1.325	1.279
48-DV22	1.343	1.249	1.324	1.254	1.336	1.258	1.328	1.249
49-DV23	1.315	1.252	1.322	1.238	1.333	1.247	1.338	1.266
50-DV24	1.408	1.331	1.403	1.332	1.427	1.335	1.431	1.351
51-DV25	1.344	1.296	1.338	1.262	1.334	1.292	1.334	1.311

BANDPASS RMS MEDIAN VALUE = 1.325

Consider using BPOLY, or B with pre-averaging (e.g. solint="8MHz")

RMS OUTLIERS >3.0 SIGMA

SPW	Xpol		Ypol		OUTLIERS
	mean	rms	mean	rms	
0	1.3445	0.5219	1.2682	0.4897	No Outliers
1	1.3420	0.5179	1.2669	0.4885	No Outliers
2	1.3491	0.5166	1.2692	0.4922	No Outliers
3	1.3487	0.5190	1.2690	0.4949	No Outliers

Flux Density Determinations

Reference source J1256-0547

J1700-2610 in SpW=0 (1.91021e+11 Hz) is: 0.715959+-0.00749206 (SNR=95.5624, N=100)
J1700-2610 in SpW=1 (1.92979e+11 Hz) is: 0.690351+-0.00681293 (SNR=101.329, N=100)
J1700-2610 in SpW=2 (2.03021e+11 Hz) is: 0.647312+-0.00554967 (SNR=116.64, N=100)
J1700-2610 in SpW=3 (2.04979e+11 Hz) is: 0.643687+-0.00657912 (SNR=97.8378, N=100)
Fit spectrum J1700-2610: 0.673232+-0.00379604 (197.907 GHz) spidx: a_1 (spectral index)
=-1.42638+-0.187176 covariance matrix the fit: covar(0,0)=2.36333e-05 covar(0,1)=-0.000142162
covar(1,0)=-0.000142162 covar(1,1)=0.138079

FLAGGING STATISTICS

Overall -> 33.41 percent

Per spw (over total of dataset):

0 -> 9.23
1 -> 8.05
2 -> 8.23
3 -> 7.90

Per antenna (over total of dataset):

CM01 -> 1.64
CM02 -> 0.99
CM03 -> 0.99
CM04 -> 0.98
CM06 -> 1.06
CM07 -> 3.77
CM09 -> 2.32
CM10 -> 0.99
CM11 -> 0.98
DA41 -> 1.30
DA42 -> 0.98
DA44 -> 0.98
DA45 -> 0.98
DA46 -> 0.98
DA47 -> 0.98
DA48 -> 3.77
DA49 -> 0.98
DA51 -> 0.98
DA52 -> 0.98
DA53 -> 0.98
DA55 -> 1.30
DA56 -> 0.98
DA57 -> 0.98
DA58 -> 0.98
DA59 -> 0.98
DA62 -> 0.98
DA64 -> 0.98
DA65 -> 0.98
DV01 -> 0.98
DV02 -> 0.98
DV03 -> 0.98
DV04 -> 2.31
DV05 -> 1.80
DV06 -> 0.98
DV07 -> 0.98
DV08 -> 0.98
DV09 -> 0.98
DV10 -> 0.98
DV11 -> 0.98
DV12 -> 1.97
DV14 -> 0.98
DV15 -> 0.98
DV16 -> 1.29
DV17 -> 1.29

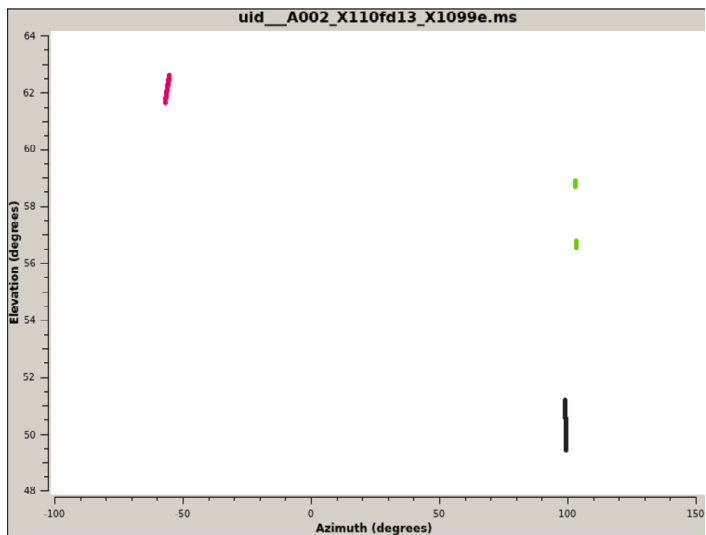
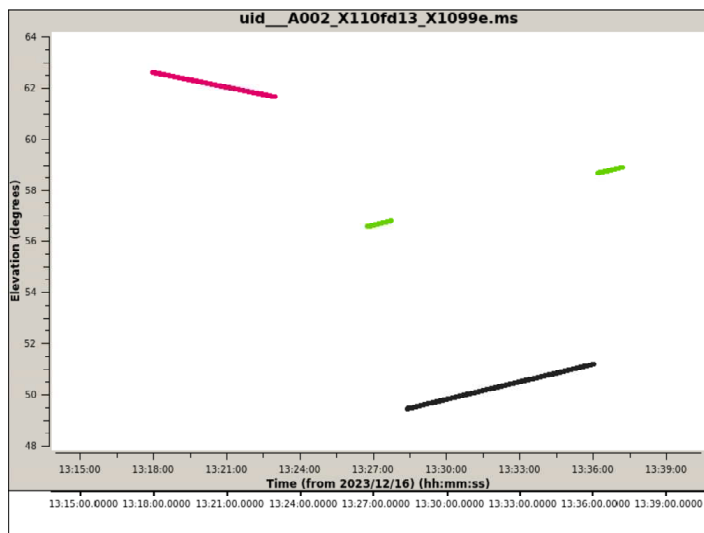
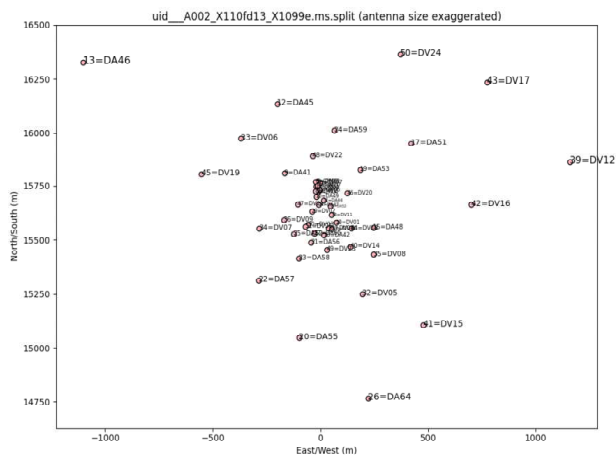
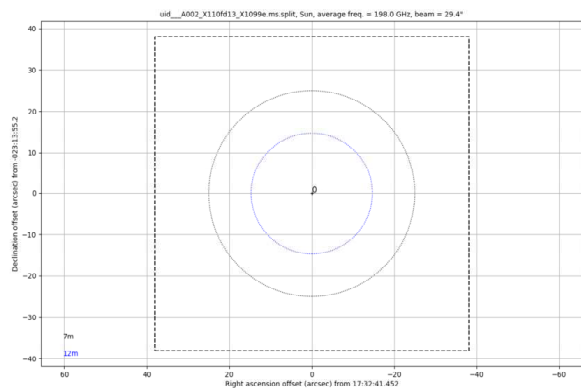
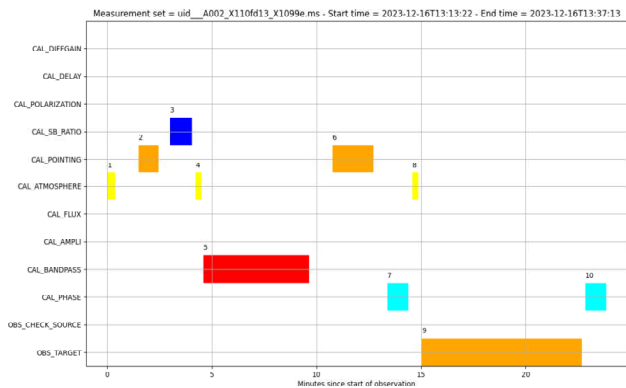
DV18 -> 0.98
DV19 -> 0.98
DV20 -> 0.98
DV21 -> 0.98
DV22 -> 0.98
DV23 -> 0.98
DV24 -> 0.98
DV25 -> 0.98

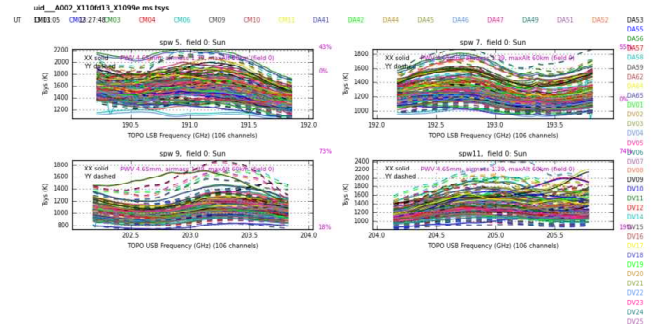
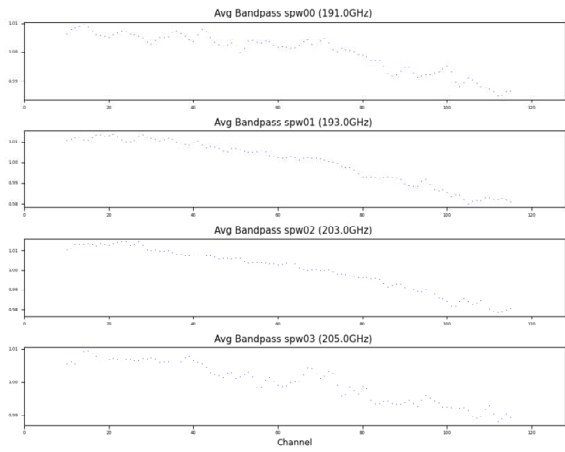
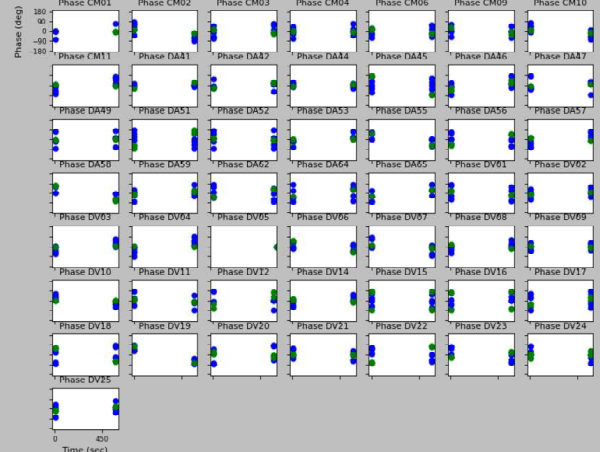
CHECK OF A TARGET IMAGE AND SENSITIVITY

longest baseline = 2308.8 (meters)
recommended cellsize = 0.0300 (arcsec)
primary beam FWHM = 31.25 (arcsec)
recommended image size = 1600

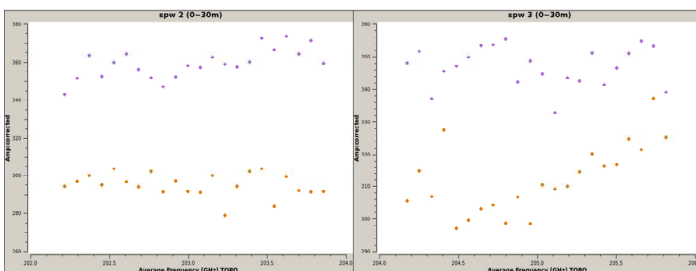
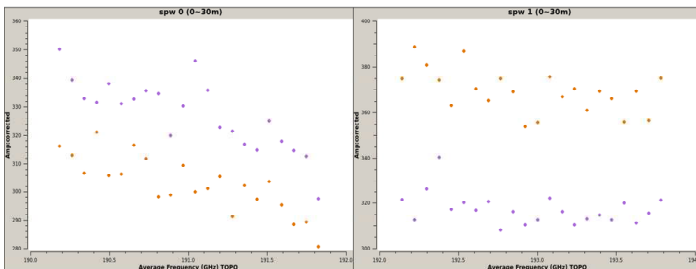
target = 0
resolution = 0.438 x 0.310 in pa 73.2
time on target = 7.08 (min)
peak on image = 2924.497 (mJy)
rms on image = 1195.578 (mJy)
expected sensitivity = 0.428 (mJy) (aggregate bandwidth)

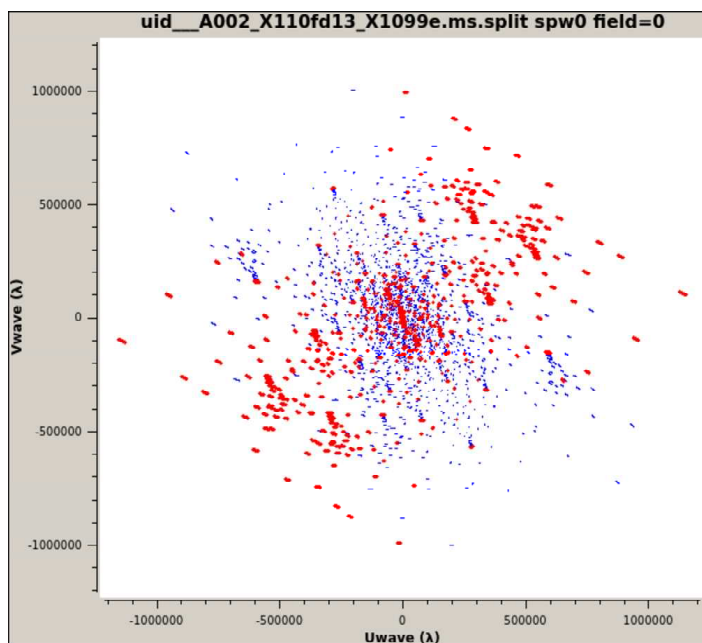
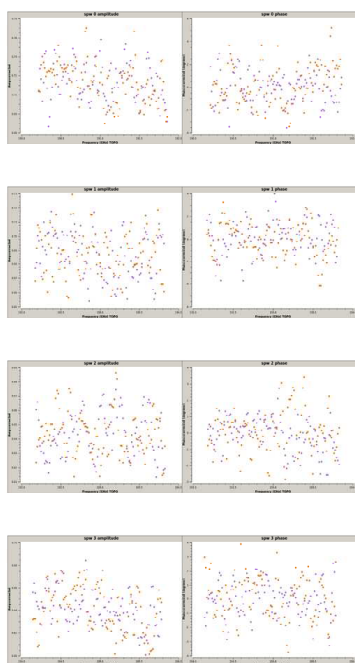
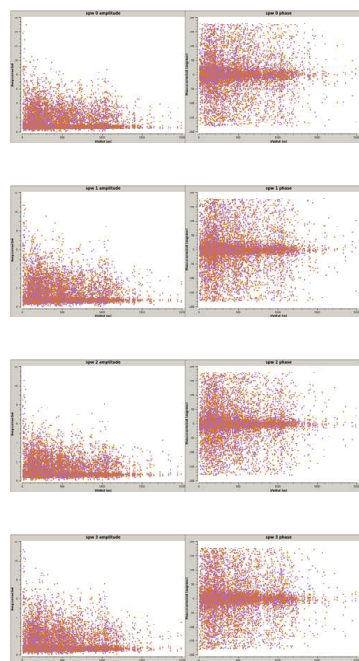
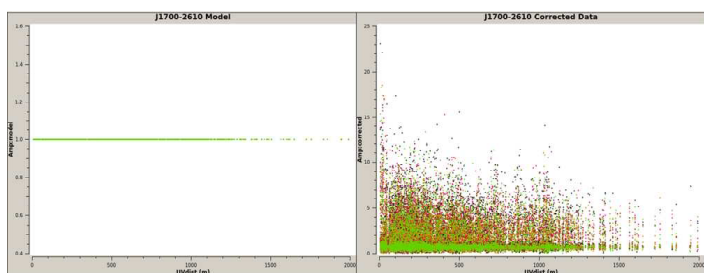
<!-- No flux measurements for the ALMA database since no intent CALIBRATE_FLUX#ON_SOURCE was found -->



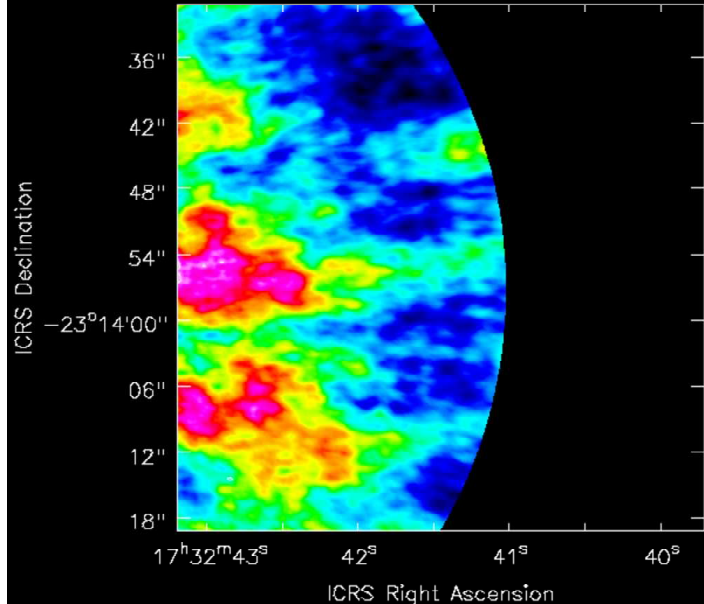


uid_A002_X110613_X1096e.ms ObsData=2023-12-16 plotbandpass3 v2.6: 2023/04/15 21:58, C6.4.1.12





target_check.image--raster



target_check.psf--raster

