

Test-observation request

Water-vapor variations inferred from the science SPWs

1. Introduction/motivation

Based on idea of Richard Hills (2019) we have developed a method for estimation of the time-varying water-vapor column from the signal contained in the science SPWs in Band 5 – either auto-correlation (AC) signal or SQLDs. Expression for the differential (the difference w.r.t. the average value of PWV over a scan) PWV is as follows:

$$dw(t) = - \frac{\int_{BW} \frac{1}{G(f)} \cdot (P(t, f) - \langle P(f) \rangle) df}{\int_{BW} \left(\frac{\langle P(f) \rangle}{G(f)} - T_{inst}(f) - T_{atm} \right) \tau_1(f) df} \quad (1)$$

We refer to this quantity $dw(t)$ as “dPWV proxy” in the following. Here, $P(t, f)$ is the signal directly measured in the AC or SQLD SPWs, ‘ $\langle \rangle$ ’ means time averaging over a scan, $\tau_1(f)$ is the specific wet opacity for 1mm of PWV, and T_{inst} is the ‘instrumental temperature’ – it equals to T_{rx} for the AC SPWs, while for the SQLDs it (moreover) contains the power offset, present in the SQLD data even in absence of any signal. The gain $G(f)$ and $T_{rx}(f)$ have been determined using dual-load (hot/ambient) calibration done in preceding ATM scan. Finally, T_{atm} is found by meteo measurements using the ATM model implemented in the *atmosphere* CASA tool. Details can be found in the draft of the *Final report* for ESO ALMA Development Study “High-resolution solar imaging with ALMA”.

Similarly to the standard WVR measurements, which are normally used for the same purpose, the dPWV proxy can be recalculated to (atmospheric-turbulence induced) phase delays and used for their corrections. Fig. 1 demonstrates application of this technique to band-pass (BP) calibrator observed during the test observation in December 2023 in frame of the project 2022.1.00031.CSV (see JIRA ticket <https://jira.alma.cl/browse/CSV-3832>). As it can be seen, both WVR- and dPWV-based corrections to the phase variations work quite well for this antenna, reducing the original large variations (note: Observation has been performed under marginal weather conditions for Band 5, with PWV=4.7mm) significantly.

Equation (1) is devised such a way that it should work for both relatively weak sources, like the BP calibrator presented in Fig. 1, where the signal is dominated by atmospheric WV emission, and as well for the Sun, where increased WV column causes diminishing of the signal in the science SPW by WV absorption of the much stronger solar radiation. The sign (plus or minus) is regulated by the sign of the denominator, which is positive in the solar case and negative for the quasar used as BP calibrator. Nevertheless, **we are not able to make similar comparison as in Fig. 1 for the Sun** because: (i) the WVR data for the Sun are strongly contaminated (frequently, in case of direct exposition of WVR by sun-light, even saturated), (ii) also the raw, uncorrected phases of the Sun can be determined solely by self-calibration, which is not trivial nor unambiguous procedure for the solar target, with its complex

spatial structure and relatively fast (on timescale of 1-2 sec) intrinsic dynamics.

To that end, we propose one more test observation with specific setup described below, whose purpose would be to **compare the direct WVR measurements with the dPWV proxy** inferred by Eq. (1) from co-temporally observed solar target. Because WVR can be measured only with antennas pointed off the Sun, we suggest to set a small fraction of 12m array to be pointed to different directions.

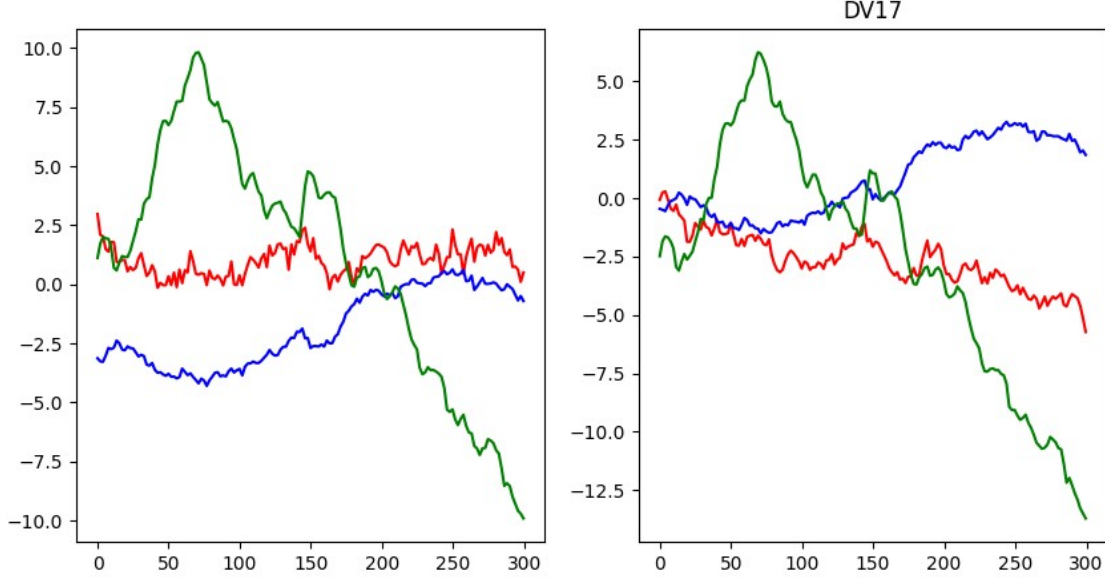


Figure 1: Comparison among (i) Raw phases for the band-pass calibrator – green, (ii) the same phase after being corrected by our proxy dPWV method – red, and (iii) the phases after being corrected by applying WVR-based `wvrgcal()` table – blue. Phases (y-axis) are in radians(!). This is an example of well-working antenna DV17. Left panel: XX, right: YY. Time (x-axis) is in secs since the BP-cal scan beginning.

2. Specific array setup

As explained in *Introduction*, our goal is to compare dPWV proxy signal ON_SOURCE with simultaneous WVR data OFF_SOURCE. For that sake, we are selecting close pairs or triplets of antennas in the 12m array such a way, that one antenna in each close pair/triplet observes the solar target and the second one points to the nearby OFF_SOURCE position (in case of triplets we have two off-source positions in order to check the methodology – see the next paragraph). Tabs. 1 and 2 below show these pairs/triplets identified in configurations C-6 and C-5 (see also the Figs. 2 and 3). To be clear: We suggest just a single test observation, but in order to achieve better scheduling flexibility, we present two alternative configurations C-6 and C-5. The rest of the antennas (including the 7m array) observes the solar target. Configurations C-6 or, alternatively, C-5 are proposed for the following reason: The study aims at extending the so far limit for max. baseline lengths in solar ObsMode. Our simulations as well as Dec. 2023 test has shown that for Band 5 the limiting still feasible array extension is C-6. Therefore we prefer this configuration in order to test the dPWV vs WVR techniques

at the longest feasible baselines. The C-5 array represents the next smaller alternative and as its is scheduled immediately after C-6 (Nov – Dec 2025), its choice extends the time window for performing the test. C-5 has smaller extent, on the other hand, thanks to higher density in uv -space it is less sensitive to missing antennas, which me absent either deliberately, because of selecting them for the parallel WVR measurements, or accidentally (technical shutdown, flagging).

In order to verify that this comparison can be done at all, one pair of antennas in C-6 (the last row in the C-6 table) is devoted to two distinct OFF_SOURCE positions as a ‘control sample’. Should there be a significant difference between the WVR signals from those control-sample pair of antennas, we cannot say anything about possible difference (if found) between our dPWV proxy and WVR in the remaining pairs: It could be attributed just to the fact that we observe two slightly different positions at the sky with two not exactly co-located antennas. In C-6 there is no really close triplet of antennas, so we check the methodology this way. On the other hand, in C-5 we have identified a triplet of antennas at pads A042, A043, and A011, so the methodology test can be done more clever way: One antenna is pointing to the Sun and two remaining to two distinct OFF_SOURCE positions. The locations of the OFF_SOURCE pointings relative to the solar target are discussed below in Section 3 “Pointings”.

The following Tab. 1 and Tab. 2 shows the selection of antennas for the off-source (WVR) measurements in left column and their adjudged antennas to be used for dPWV calculation in right for two alternative configurations C-6 (scheduled to late November 2025) and C-5 (early December 2025):

Configuration C-6

Table 1: Suggested array splitting in configuration C-6. Pairs of antennas (identified by the pad number) for the WVR and the Sun.

WVR (off source)		Sun
A042 – off-source-0		A043
A015 – off-source-0		A007
A073 – off-source-0		A069
A070 – off-source-0	A074 – test position	-

In total 5 antennas are deliberately picked from the array. Typically, 1 – 2 more are flagged, having 6 – 7 antennas missing.

Configuration C-5

Table 2: Suggested array splitting for alternative configuration C-5. Pairs/triplets of antennas (identified by the pad number) for the WVR and the Sun.

WVR (off source)		Sun
A042 – off-source 1	A011 – off-source 2	A043
A033 – off-source-0		A027
A022 – off-source-0		A066
A015 – off-source-0		A007
A062 – off-source-0		A058

In total 6 antennas are deliberately picked from the array. Typically, 1 – 2 more are flagged, having 7 – 8 antennas missing. With higher uv density in C-5 we can afford it as we have tested by simulations.

The selection of antennas described in Tabs. 1 and 2 is illustrated in Figs. 2 and 3.

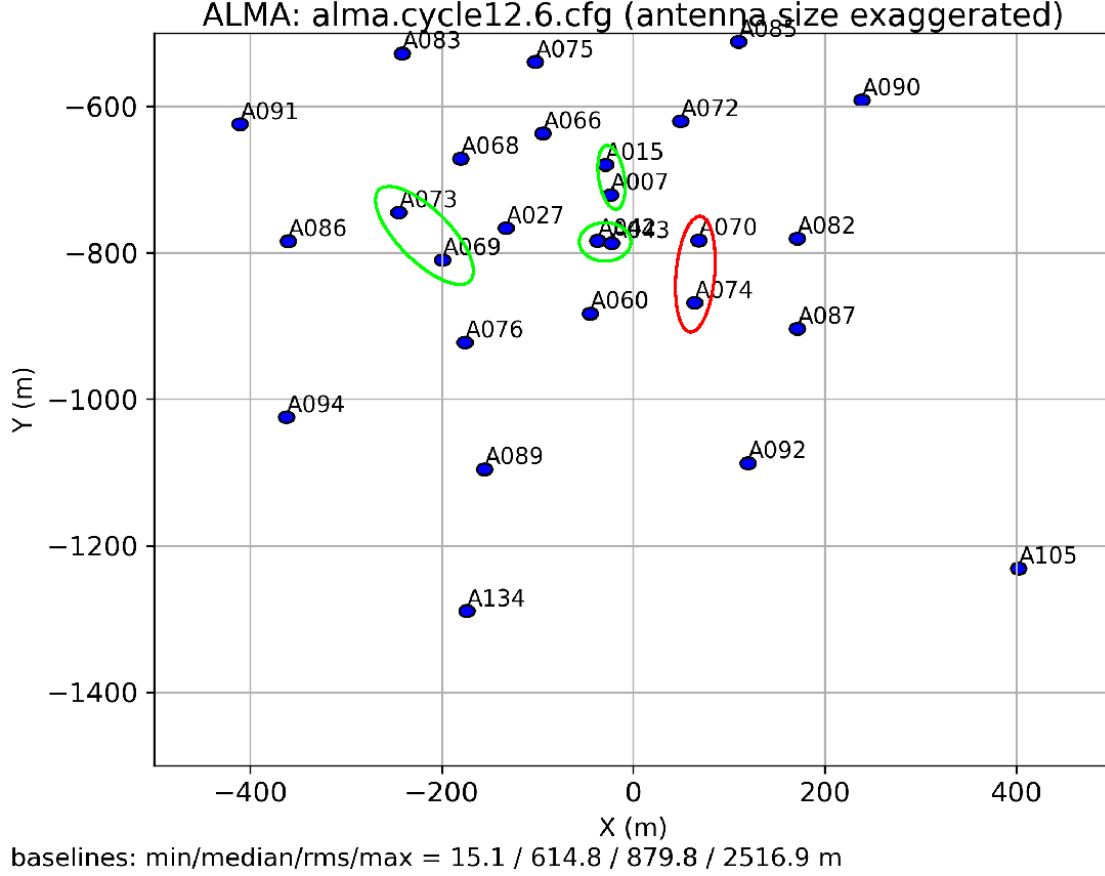


Figure 2: Zoomed view of the central part of the 12m array in C-6. Antenna pairs to be split for co-temporal observation of the Sun and adjacent off-source positions are marked by green ellipses. The red ellipse marks the control pair used for testing validity of the approach. See Tab. 1 for C-6.

As it can be seen from the phase-screen simulation in Fig. 3, close pairs of antennas are really following very similar patterns of the atmospheric phase delays – this indicates that the method is viable, at least from the point of view of not exactly co-spatial points of observation. Still there is question, whether also not exactly co-located pointings cannot lead to a significant difference of the WVR signal. Assuming the main atmospheric features (‘bubbles’) influencing the phase delays are formed in the heights up to 3km above the ground, then 2 deg separation in pointings (see Section 3) would mean ~ 100 m linear distance in the upper atmosphere, which is the scale comparable with the distance of antennas in our close pairs. As Fig. 4 indicates that this distance does not change the delay significantly, we hope that the methodology should work. Anyway, we keep the ‘control sample’

antenna pair pointing to two different off-source directions in order to check it, as described above.

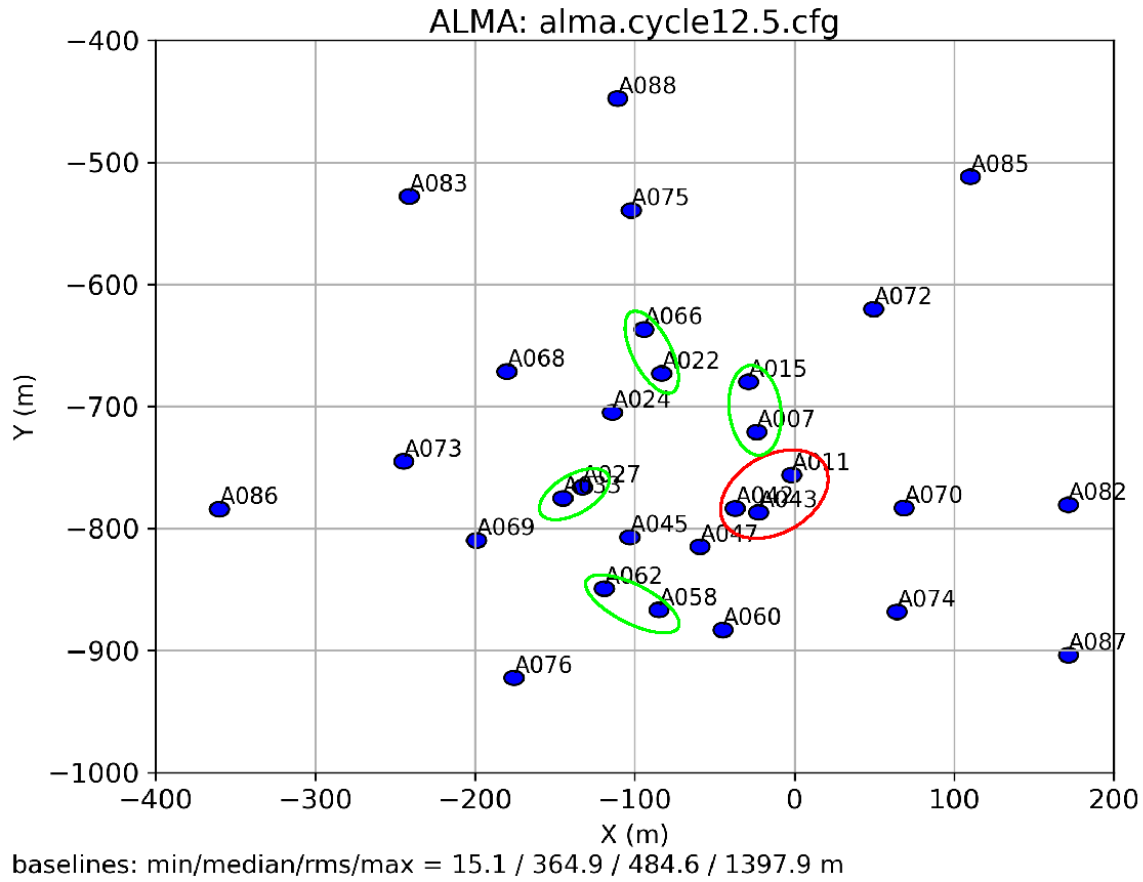


Figure 3: Like Fig. 2, now for alternative configuration C-5 (Tab. 2). The red circle marks the triplet of antennas, where one is pointing to the Sun and two remaining to the two distinct off-source positions - see Fig. 7.

Correlator setup

This setup has been suggested by Neil Phillips <nphillip@eso.org> and approved by the study advisory board:

- One array for observing Sun, WVR antennas not in that array
- Run a second manual mode observation (correlator subarray) to record WVR data to an ASDM

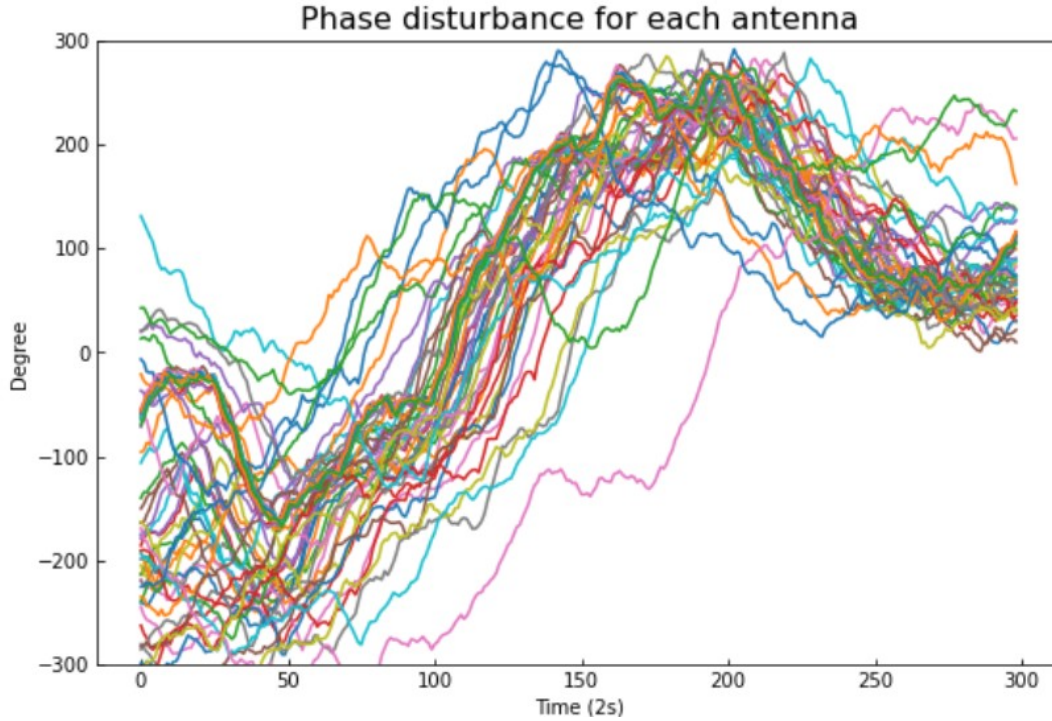


Figure 4: Phase delays for antennas in configuration C-6 as simulated by the phase-screen model of atmospheric turbulence with 1-minute phase RMS of 30 degs. The transport wind velocity has been set to 10ms/s – see the Final report draft. The neighboring antennas follow similar time profile of the phase delays, which justifies the suggested methodology of using two close antennas for comparison of WVR vs. dPWV measures of water-vapor variations.

3. Pointigs

In order to scan the turbulence through at least similar/adjacent atmospheric volumes, not only the antennas for the on-source (target) and off-source (WVR) observations need to be as close as possible, but also the off-source pointing(s) should be nearby the target. A question arises up, how close to the Sun we can go for the WVR measurements, still not destroying significantly the atmospheric WV emission by the strong solar radiation contribution.

As the first guess we have checked the off-source positions taken for (1) ATM/Tsys scan no. 8 preceding the scan no. 9 in our December 2023 Band 5 data (project 2022.1.00031.CSV) , and (2) two sub-scans of the solar scan no. 9 that are taken with intent OBSERVE_TARGET#OFF_SOURCE – they represent basically again ATM/Tsys observation, but now with the attenuation level optimized for the on-source solar scan. We have found that the **separation of the off-source pointings was 1.96 deg from the solar disc center.**

As a next step we have checked the raw WVR signal contained in the SPW=4 in the solar scan no. 9 and compare it with the same WVR for scan no. 5 – the band-pass calibrator, all in the same MS

described above. Results are shown in Figs. 5 and 6. By chance, the WVR has been apparently pointing slightly off the solar disc, so its signal is not fully saturated even during the ON_SOURCE subscan (the middle part of the curves at Fig. 5), just contaminated by the solar illumination. Anyway, the short OFF_SOURCE subscans at the very beginning and very end of the solar scan in Fig. 5, taken in the position ~ 2 degs of the solar disc center, show much closer values of the WVR temperatures to the ‘control’ measurement for the band-pass calibrator displayed in Fig. 6.

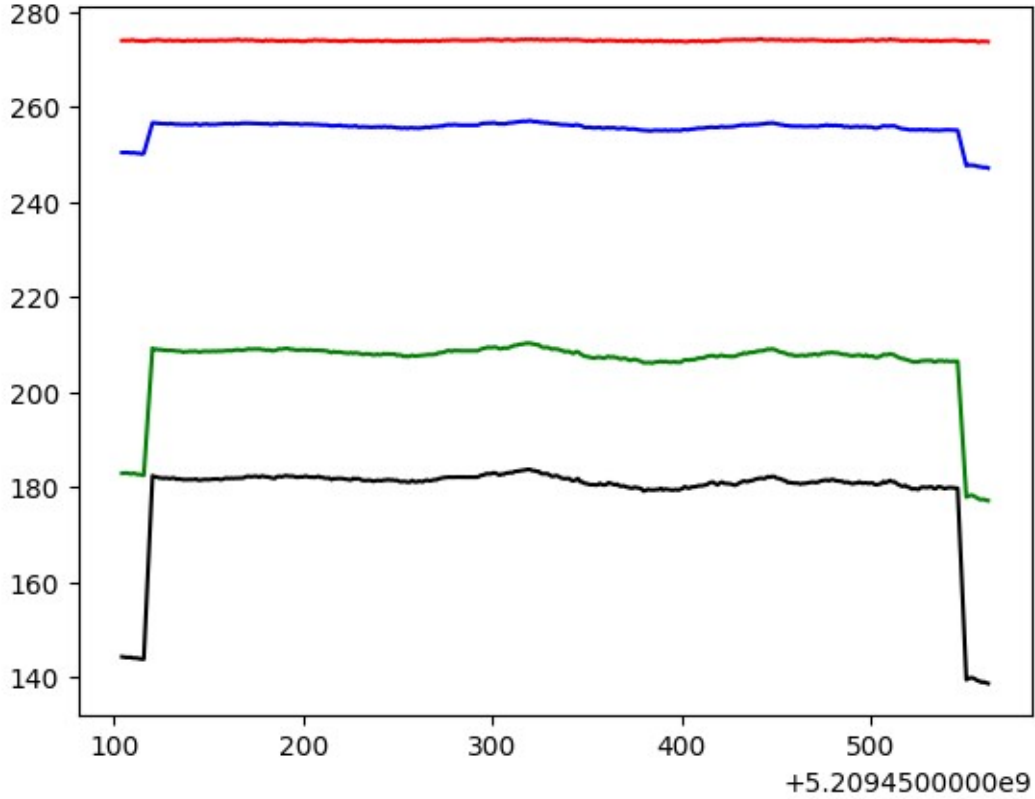


Figure 5: The raw WVR data as recorded in SPW=4 for the solar scan. Time at x-axis is in MJD secs, the red, blue, green, and black curves show the WVR channels 1, 2, 3, and 4, respectively. The very beginning and very end of each curve corresponds to OBSERVE_TARGET#OFF_SOURCE position, which has been identified to be ~ 2 degs apart of the solar disc center. The middle part corresponds to receiver being pointed to the target at the western solar limb. Obviously, the WVR was pointing not fully to the Sun, so the WVR signal is contaminated – i.e. significantly boosted in the middle part of the curve – but still not saturated. The values of WVR temperatures for the off-source subscans are to be compared with the next Fig. 6, where the same curves are shown for the band-pass calibrator scan.

As a result, we think that the 2 deg separation of the off-source position from the solar center is acceptable and suggest it for calculation of pointing positions displayed in Fig. 7.

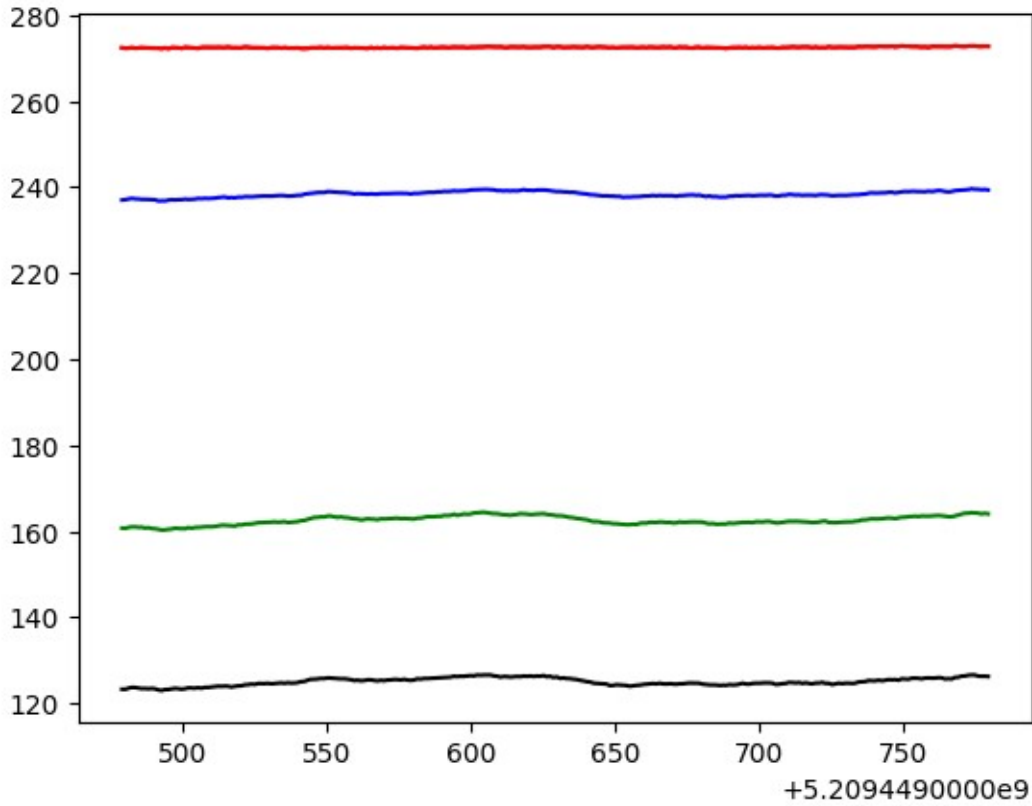


Figure 6: Like in Fig. 5, now for the band-pass calibrator scan. As it can be seen, this 'control' values are by some 15 - 20 K lower than the off-source values (the edge of the curves in Fig. 5) for the Sun.

Fig. 7 shows the pointings as indicated in the Tables 1 and 2 for two alternative configurations C-6 and C-5. Suggested angular separations are indicated by numbers, the figure is not to scale.

The OFF-POS-1 and OFF-POS-2 apply only for the configuration C-5 for antennas A042 and A011 in the first row of the C-5 table at page 1. They are intended to form an equilateral triangle with the solar disc center, with the side length of 2 degs. The PA arm towards the target should form a bisector of that triangle.

Vice versa, TEST-POS is intended for the alternative using the C-6 configuration only, for the antenna A074 as indicated in the last row of the C-6 table at page 1. The 2 deg separation has been chosen patterned by the off-source position for ATM/Tsys/target-off-source as used in the standard solar observations – see above.

The TARGET radius 600 arcssec from the solar center has been chosen as a compromise between the demand to limit the projection effects close to the solar limb and our wish to minimize the separation between the off-source WVR position and the target. We would like to leave the PA angle free until close to the observations in order to avoid some very specific features (sunspot or hot area) in the target position.

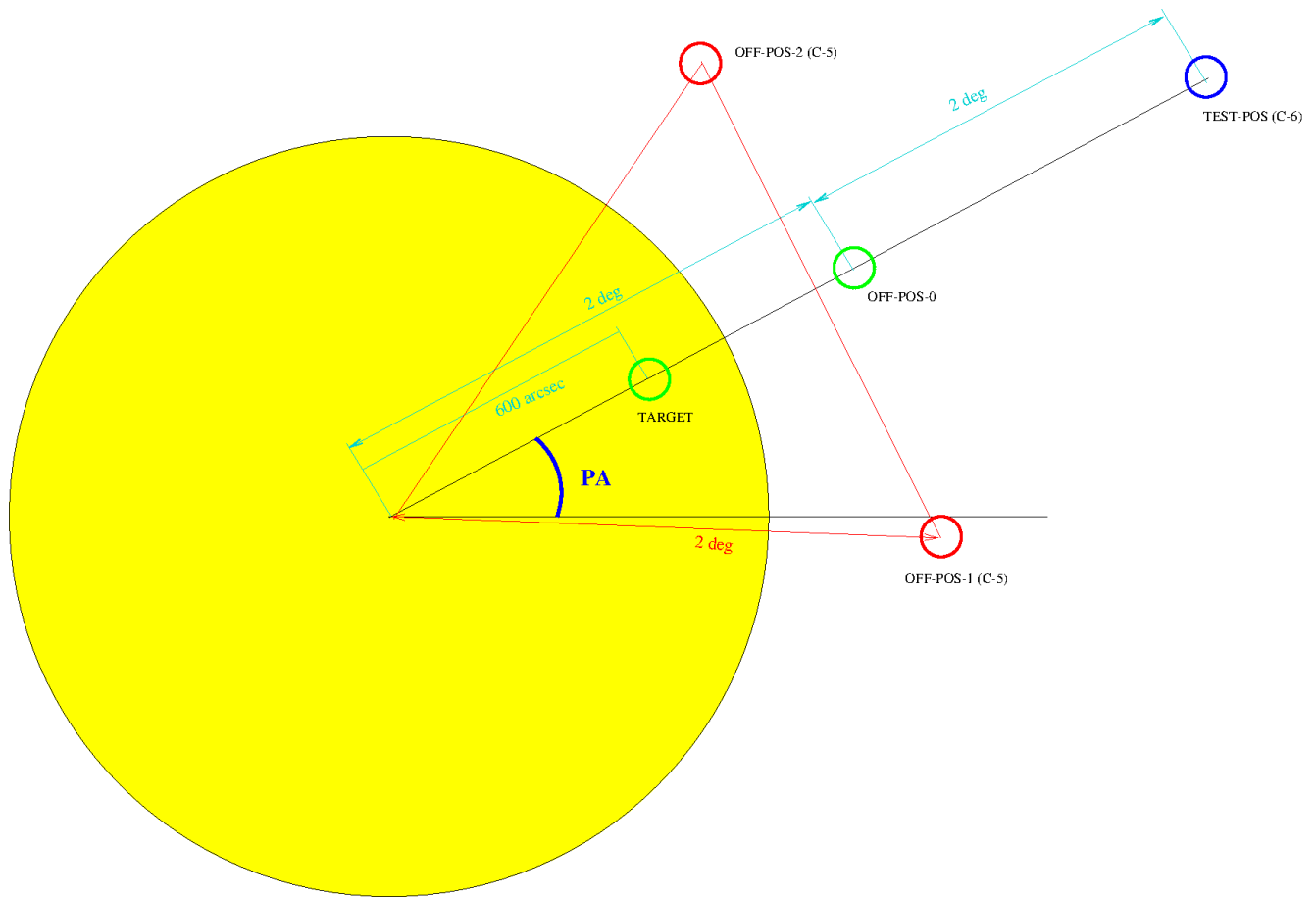


Figure 7: Pointing positions for the target and off-source and control/test positions as indicated in Tabs. 1 and 2 for two alternative configurations C-6 and C-5. The black horizontal line from the solar center to the right indicates the Right Ascension/Hour-angle axis, the position angle PA is measured w.r.t. to it.

4. Spectral setup, timing etc.

Remaining settings are suggested to copy our last test in Band 5 in project 2022.1.00031.CSV (<https://jira.alma.cl/browse/CSV-3832>). From those crucial are

- **Integration time of 0.192 sec.**
- As much complete array as possible – the **uv-coverage is essential**.
- The spectral setup is the standard one for Band 5 with LO at 198 GHz and the science SPWs as follows:

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			

- As we do not need TP co-observation in order to achieve the main goal of the test, the timing is limited by the standard solar observation requirements, which demand the elevation of the Sun to be between 40 and 70 degrees. In order to limit the projection effect to the uv-mapping, we slightly prefer rather higher elevation (50-60 degs).
- One scan with 7 min target on-source is enough, like in the Dec. 2023 test.
- Weather conditions may be medium to worse – 3rd or 4th quartil with median PWV ranging from 2.5mm to 5mm are OK.