Integration durations for ALMA FDM Observations

T.R. Hunter, 21 August 2012

Summary

At the recent Cycle 1 Observing Modes workshop held in Socorro in July 2012, it was recommended that integration durations should remain at 2 seconds for TDM and (as a compromise to limit the data volume) at 6 seconds for FDM observations. Furthermore, these values should be used even if the TelCal-derived water vapor radiometer (WVR) phase corrections are applied online at 1 second intervals. These proposed decisions have led to a concern that (in aggregate) the Cycle 1 data product will exceed the computing specification on the **average** data rate due to the popularity of FDM windows. In response, it has been argued that integrations as short as 6 seconds are not scientifically necessary for FDM observations, and we can simply use longer integrations to avoid the problem with data volume. The purpose of this brief document is: (1) to emphasize the importance of self-calibration to ALMA, (2) to demonstrate that self-calibration on short timescales ($\leq$ 6 seconds) is indeed possible in a significant fraction of observations, and (3) to list a few FDM science cases where self-calibration on timescales of 6 seconds (or even less) will lead to improved results. We conclude that the Phase II Group (P2G) and Contact Scientists (CS) need to be able to apply discretion when choosing the FDM integration time on the basis of the science goals and the science target brightness. To compensate the effect on average data rate, the use of online channel-averaging should be encouraged by the CS for **all** FDM projects to the extent allowable by the science goals.

0.1 The Premise of the Problem

In Cycle 1, we will have the opportunity to apply the WVR corrections computed by TelCal online at the 1 second rate, then time-average the resulting data prior to storage. However, these corrections will not be perfect (even if all WVRs are behaving well) because the conversion coefficients from sky brightness fluctuations into path fluctuations cannot be predicted with complete accuracy (see for example ALMA Memo 592). In other words, there will still be residual atmospheric phase errors in the data. Furthermore, instrumental variations at timescales shorter than the standard phase calibration cycle time will remain as calibration errors in the data. If we average **all** FDM data to 15 second or (heaven forbid) 30 second integration durations, then we can no longer remove errors shorter than these timescales using self-calibration. However, if we store **all** FDM data with integration durations of 6 seconds or less, then we will exceed the average data rate (i.e. the data volume).

0.2 Importance of self-calibration

It has been suggested that the number of sources that can be self-calibrated on intervals shorter than these longer periods is very small. It is simply not true. First, I'd like to emphasize that **every ALMA casaguide** uses self-calibration to obtain improved images (TW Hya, NGC 3256, Antennae galaxies, IRAS 16293). So it is a very common technique with ALMA data. Part of the error that self-calibration removes in CSV and Cycle 0 data can quite clearly be associated with antenna position errors. It is important to remember that as we move to longer baselines, antenna positions will become more difficult to measure, and thus we expect larger errors in the data, and we will increasingly need to rely on self-calibration to remove them. Fortunately, these errors can be removed with self-calibration on long solution intervals (where "long" can be tens of minutes). But these are not the only errors in the data. For the TW Hya casaguide data (reduced by Crystal Brogan), the data were stored with 10 second durations. On the basis of an initial selfcal solution using 30 second intervals, a second round of selfcal with a solution interval of 10 seconds was deemed appropriate and provided the best result. These calibration solutions derived on the continuum channels can then be applied to improve the spectral line channels to also improve those images. One might argue that the CSV targets represented by the casaguides are brighter than typical science targets. So let's examine some actual Cycle 0 data.

0.3 Example of self-calibration used on Cycle 0 projects

Here I present two practical, quantitative examples of self-calibration that has been used on Cycle 0 data delivered to the PIs.

0.3.1 Dynamic-range limited Band 3 observation

The first example is a dynamic-range limited Band 3 extended-configuration observation where self-calibration with a 30 second interval yielded an impressive factor of 9 improvement in dynamic range. Because the data were stored with 6 second integration duration, the data reducer (Steve Myers) was able to use a selfcal interval of 6 seconds instead of 30 seconds, which yielded a further 10% improvement in dynamic range (for a total improvement of a factor of 10 over standard calibration). I suspect that larger potential improvements will be found in the higher bands and for the longer baselines of Cycle 1, and when shorter intervals are possible. Unfortunately, because the integration duration was 6 seconds, we cannot explore the improvements that shorter durations may have allowed. Nevertheless, while a 10% improvement may seem small, thinking about it in terms of sensitivity (in a non-dynamic-range limited case), this level of performance improvement corresponds to 3 more antennas in Cycle 1 (where we will have 32 antennas), or 20% less observing time. This particular Band 3 observation used four 234 MHz FDM windows observing an 8 Jy continuum source. Thus, an equivalent S/N situation will exist in the case of four 1875 MHz FDM windows observing a 2.8 Jy source. One may argue that a source of this flux density is still a rare science target, so let's examine fainter objects.

0.3.2 Noise-limited Band 7 observation

As contact scientist, I have reduced several Band 7 tracks of dozens of high-redshift, lensed objects. Observed with TDM in extended configuration, the objects are resolved into partial or complete rings, with peak intensities ranging from 8 to 30 mJy/beam, and initial image rms of 0.6-1.2 mJy/beam. These objects were observed for 50 seconds each with a system temperature of 230 K, and I find that I have enough S/N to successfully self-calibrate (with a single solution interval) those that are brighter than ~ 12 mJy/beam. This significantly improves the image, sometimes even doubling the dynamic range (i.e. from 10-20 to 20-40). Obviously, brighter objects would afford shorter self-calibration intervals. For 35 mJy sources, one could self-calibrate at 6 second intervals. For 85 mJy sources, one could self-calibrate at 1 second intervals. Thinking about dust emission in Band 7, with a 0.2 arcsec beam (available in Cycle 1), 85 mJy corresponds to only 22K in brightness temperature. Thinking of Galactic astronomy, there are potentially thousands of targets observable by ALMA with dust emission of appreciable opacity that will easily reach this brightness temperature (i.e. hot cores in high-mass star-forming regions and the hot corinos in low-mass star-forming regions). Many of these objects have already been studied with the SMA. Due to their associated spectral line emission, for science reasons they will typically be observed in FDM mode in Cycle 1 and beyond. Thus ALMA observations of these targets should be never be averaged to longer than a few seconds of integration. Indeed, if we were free of constraints on data volume, one could use the practical results from above to define the minimum solution interval and hence the maximum recommended integration duration ($t_{\max}$) in terms of the system temperature ($T_{\rm sys}$), total bandwidth ($\Delta\nu$), and peak intensity (I) by the following scaling relation:

$$t_{\max}(\mathrm{sec}) = 1.0\left(\frac{100\mathrm{mJy/beam}}{I}\right)^2\left(\frac{1\mathrm{GHz}}{\Delta\nu}\right)\left(\frac{T_{\rm sys}}{100}\right)^2$$

0.3.3 Other future targets

Another obvious example of science targets that should not be overlooked is H_2O and SiO masers, whose spectral line peaks can be thousands of Jy. In a process reverse to that applied in the TW Hya casaguide, self-calibration solutions from these line channels can be applied to the entire dataset to reveal faint continuum sources in the field. Indeed, I used this technique in my first three science papers in radio astronomy (VLA A-configuration, K-band). Observations of these maser targets, which have been proposed for Cycle 1, will allow self-calibration at the shortest imaginable data dump rates, and thus have the potential for telling us just how much short timescale error remains in ALMA data.

Finally, there are FDM planet observations in Cycle 0 (and no doubt in Cycle 1), and these sources have plenty of continuum flux that they can be self-calibrated at short timescales. In fact, they currently *require* self-calibration due to remaining problems on ephemeris targets in the online system. Obviously there will be more FDM planet observations in Cycle 1, and these too will benefit from short integration durations.

0.4 Conclusion

We conclude that the Phase II Group (P2G) and Contact Scientists (CS) need to be able to apply discretion when choosing the FDM integration duration. It should not be a strict rule where we use a long duration in all projects simply satisfy the data volume. It should be made on the basis of the science goals and the science target brightness, in the course of the normal consultation with the PI during the P2G process. The use of short durations in **some** FDM projects should be compensated by using online channel-averaging in **all** FDM projects to the extent allowed by the science, again in consultation with the PI. The CS can encourage channel-averaging by the PI by noting the reduction in time and space to transfer and store calibrated datasets. We can also compensate by setting the default the integration time for faint-source FDM projects to values larger than 6 seconds (such as 15 seconds).