# Fast-switching in the Submillimeter Array: a step toward gain calibration in ALMA

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**Abstract** Fluctuations of water vapour content in the troposphere are one of the worst enemies of millimeter/submillimeter aperture synthesis observations, being responsible of loss of coherence in the radio signal and limiting the spatial resolution. The use of the fast switching technique tries to minimize this effect through fast and succesive cycles between calibrator and source. Here we present fast-switching tests in millimeter/submillimeter wavelengths carried out at the Submillimeter Array (SMA) on top of Mauna Kea, in order to shed light into the optimization of calibration cycle as a function of different atmospherical conditions. We have found that fast switching with calibration cycles of a few minutes slightly improve ($\sim$ 15%) the signal-to-noise ratio in the image plane with respect to the standard calibration time of 20–30 min, under relatively good weather conditions. For worse weather conditions, the fast switching technique does not have any relevant effect. This confirms previous findings that most of the fluctuations must be shorter than 2 minutes under normal conditions in the Mauna Kea site and baseline range from $\sim$ 20 - 200 m.

## 1 Introduction

In the millimeter and submillimeter range, turbulence on the troposphere water vapor content is the main responsible of atmospherical electrical path fluctuations,

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causing distortions on the phase of the signal. This is the main factor that causes loss of coherence and limits imaging resolution in millimeter/submillimeter wave interferometers [1].

In order to minimize these effects several gain calibration techniques have been used in the past. Usually standard gain calibration is used in millimeter/submillimeter observations with cycles between source and calibrator of the order of 20-30 minutes, although a more precise tracking of the phase variations introduced by the atmosphere is needed in order to obtain results closer to the diffraction limit [2], [3].

A more precise tracking of the phase variations introduced by the atmosphere is usually obtained by the application of Water Vapor Radiometry (WVR) [4] and Fast Switching (FS) [5]. WVR has been proven to be a very useful technique to reduce the phase fluctuations, especially for very short time ($\sim$1 second) variations. It however needs frequent gain calibration to convert accurately from water vapor content to path delay, and it also relies on atmospheric models. This usually restricts its applicability to relatively short time scale fluctuations ($<$1min) (e.g., [6]). The FS calibration technique, on the other hand, can be used in order to efficiently track the larger time scale atmospheric fluctuations [5], [7], [8]. It consists on observing frequently a closeby and bright calibrator as a reference, with calibration cycles that may range between tens of seconds to a few minutes. Moreover, this calibration corrects phase fluctuations that are related to the instrumentation rather than just to the atmosphere. Therefore, the combination of these two techniques should reduce most of the atmospheric phase fluctuations.

We explore the applicability of the FS technique in the Submillimeter Array (SMA), the first interferometer dedicated to submillimeter observations[1] [9]. The SMA consists of eight 6 m antennas with baselines up to 500 m and receivers covering the frequency range of 200 - 700 GHz so far. SMA antennas are designed in such a way they can perform a fast slewing between sources, which is essential for a satisfactory fast-switching implementation. Vir Lal, Matsushita & Lim (2007) have analysed two FS datasets from the SMA and show that although temporal changes in the water vapor content cause phase variations, FS with calibration cycles between 90 seconds to 22 minutes does not improve significantly the quality of the generated images with either very bad or good weather conditions. Here we present the results of new fast-switching tests performed at the SMA that contribute to bridge between these two extreme weather conditions.These tests are of interest before the advent Atacama Large Millimeter Array[2] (ALMA) is operative, which will be the largest millimeter and submillimeter interferometer in the world.

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[2] http://www.eso.org/sci/facilities/alma/index.html

## 2 Observations and Data Reduction

The observations have been carried out at the SMA in its compact and extended configurations (baselines ranging from 20 to 80 m, and 40 to 230 m, respectively) during September 2, 4, 5 and 6, 2004. A 2 GHz sideband have been used in order to obtain the continuum of the complex visibilities. A total of 5 datasets were obtained during 4 days.We have followed the same method as the observations performed in [2]. Observations of three different bright quasars with small angular separations ($<$ 20 degrees), were taken at 230 or 345 GHz (1.3 and 0.8 mm, respectively).

We have observed the following sets of bright quasars: (3C279, 1244-255, 1334-127), (3C454.3, 2230+114, 2145+067) and (1908-210, 1908-210, nrao530). One of these sets was selected for a given track depending on the time when the sources were observable. In each pointing, a quasar was observed for a total of 4 integrations of 5 seconds each. A sequential cycle of the three quasars was performed.Taking into account the time used to switch between sources, each cycle takes about 1 minute 40 seconds.

We list in Table 1 the basic information of the different datasets, including average opacities, available antennas, observed frequencies, set of observed quasars as well as their fluxes at the moment of the observations.

**Table 1** Log of SMA observations for the different datasets

| Calibration | Dataset I | Dataset II | Dataset III | Dataset IV | Dataset V |
|---|---|---|---|---|---|
| Observation date | 02/09/04 | 02/09/04 | 04/09/04 | 05/09/04 | 06/09/04 |
| Opacity | 0.08-0.10 | 0.13 | 0.1 | 0.1-0.14 | 0.17 |
| Antennas | 1,2,3,4,7,8 | 1,2,3,4,7,8 | 1,2,3,4,5,6,7,8 | 1,2,3,4,5,6,7,8 | 1,2,3,4,5,6,7,8 |
| Receiving bands | 345 GHz | 345 GHz | 230 GHz | 230 GHz | 230 GHz |
| Quasars : Flux (Jy) | 3c454.3: 3.4 | 1921-293: 5.6 | 3c279: 7.3 | 3c279: 7.3 | 3c279: 7.3 |
| | 2145+067: 3.8 | 1908-201: 1.7 | 1334-127: 4.2 | 1334-127: 4.2 | 1334-127: 4.2 |
| | 2230+114: 7.4 | nrao530: 1.5 | 1244-255: 0.7 | 1244-255: 0.7 | 1244-255: 0.7 |
| Gain calibrator | 2230+114 | 1921-293 | 3c279 | 3c279 | 3c279 |

We choose the brighter source as the gain calibrator, and use it to map the other two weaker quasars. We take into account different calibration cycles by flagging interleaved sets of integrations on the gain calibrator. For example, by flagging half the interleaved sets of integrations to the gain calibrator, the calibration cycle is approximately 3 minutes 20 seconds. By using different alternating combinations of flagged sets of integrations, we gradually take into account calibration cycles from 1 minute 40 seconds up to 20 minutes 40 seconds (see Table 2).

The flagging and gain calibration using the brighter of the quasars on the two other sources was performed with the data reduction package MIR/IDL for SMA[3].

[3] http://cfa-www.harvard.edu/∼cqi/mircook.html, MIR is a software package to reduce data taken with the Smithsonian Submillimeter Array (SMA). The MIR package was originally developed by Nick Scoville at Caltech.

**Table 2** Calibration cycles

| Calibration Number | Interleaved integrations to the calibrator | Calibration time |
|---|---|---|
| 1 | All | 1min 43sec |
| 2 | 1 of each 2 | 3min 26sec |
| 3 | 1 of each 3 | 5min 10sec |
| 4 | 1 of each 5 | 8min 36sec |
| 5 | 1 of each 6 | 10min 20sec |
| 6 | 1 of each 7 | 12min 3sec |
| 7 | 1 of each 10 | 17min 12sec |
| 8 | 1 of each 12 | 20min 40sec |

Once the data for the two quasars are calibrated, we have imaged them in a standard way using Miriad (Sault et al., 1995) for each of the switching cycles.

## 3 Results

We have derived parameters in the image plane, such as the signal to noise ratio (S/N) and offsets of the main peaks with respect to the phase center. In Fig. 1 and Fig. 2 we present the S/N as a function of the calibration cycle time for two of the most representative cases.

Fig. 1 corresponds to the S/N versus switching cycle for the first dataset obtained on September 2, 2004. The observed sources were 3c454.3, 2145+067 and 2230+114 (used as calibrator), at 345 GHz (0.8 mm), and took place under quite good atmospherical conditions (opacities $\sim$ 0.08 - 0.10). Fluxes of the sources are 3.4, 3.8 and 7.4 Jy, respectively. Overall, it contains the data with the best S/N ratios among all the datasets. The S/N decreases as we increase the calibration cycle time. When phase fluctuations are poorly tracked the image's quality degrade: there is a difference in S/N of about 4 ( 15%) between calibration times of the order of 20 minutes and 2 minutes. In addition, we find a trend in the continuum peak to be offset from the phase center as the calibration time increases.

Fig. 2 shows a much worse scenario for observations done the same day but immediately after the previous one. The observed sources were 1908-210, NRAO530 and 1921-293 (calibrator), this time under worse atmospherical conditions (opacities $\sim$ 0.13, and much more humid conditions), and obvious bad phase stability. Fluxes of the sources are 1.7, 1.5 and 5.6 Jy, respectively. In this case the FS technique does not improve the image quality, from calibration cycles spanning from about 2 minutes to 20 minues. Smaller switching cycles would be required in order to improve the quality of the images.

The other three datasets are intermediate cases between these two, with opacities ranging 0.1 – 0.2, and different humid conditions. In all the cases the improvement

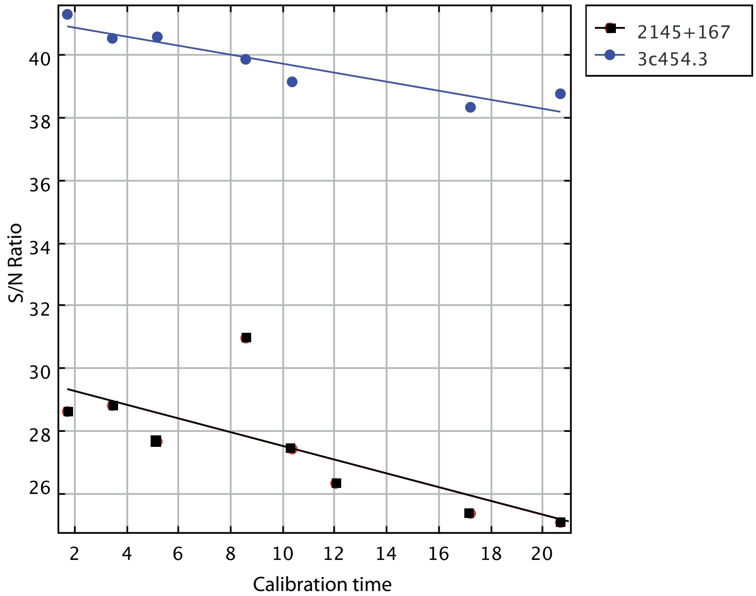


**Fig. 1** Figure showing the signal to noise ratio (S/N) in the image plane for quasars 3C454.3 and 2145+167 versus the calibration cycle (in minutes), using 2230+114 as gain calibrator. Dataset taken on September 2, 2004 (Dataset I in Table 1) at the SMA. A linear fit to the data points is presented. This case represents an improvement of the fast switching technique.

in the image's quality by using calibration cycles as short as 2 minutes is less than 10%.

## 4 Conclusion

Overall, we only see a small improvement in the S/N ratios under relatively good weather conditions. We also find a trend of an increase in peak offsets for the different sources as the calibration cycle increases. Under bad weather conditions, the application of short calibration cycles does not improve the S/N ratios at all. This confirms that most of the fluctuations must be shorter than $\sim 2$ minutes for baselines ranging from 20 – 200 m, in agreement with [2]. Thus, such short calibration cycles are required in order to improve considerably aperture synthesis image's quality at these wavelengths, at least under normal conditions in Mauna Kea.

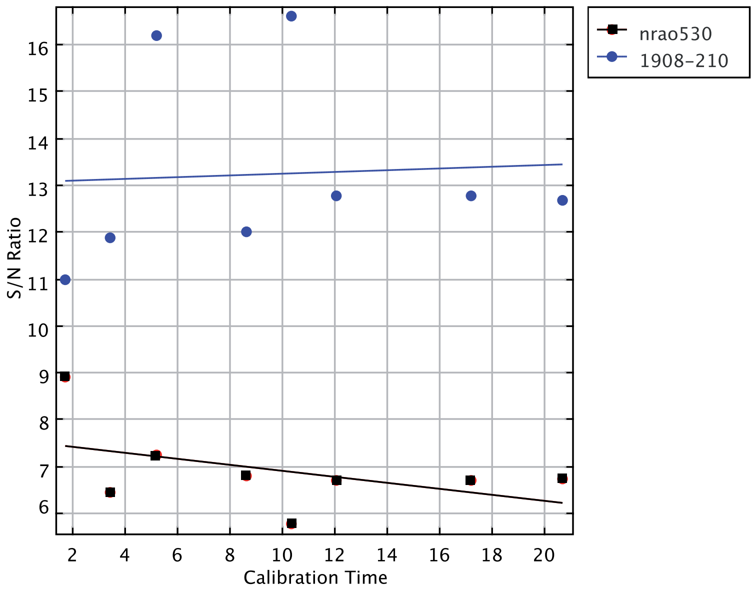


**Fig. 2** Same as Figure 1 butfor quasars nrao530 and 1908-210, using 1921-293 as gain calibrator. Dataset taken on September 2, 2004 (Dataset II in Table 1) at the SMA.

## References


1. A.R. Thompson, G.W. Svenson, J.M. Moran, *Interferometry and Synthesis in radio Astronomy* (Wiley, New York, 2001)
2. D. Vir Lal, S. Matsushita, J. Lim, arXiv:0706.0149 (2007)
3. J.B. Battat, R. Blundell, J.M. Moran, S. Paine, ApJ **616**, L71 (2004). DOI 10.1086/423932
4. C.L. Carilli, O. Lay, S.E. C. Radiometric phase correction. ALMA memo No. 210 (1998)
5. C.L. Carilli, M.A. Holdaway, Radio Science **34**, 817 (1999). DOI 10.1029/1999RS900048
6. O.P. Lay, A&AS **122**, 547 (1997)
7. M.A. Holdaway, et al. Fast switching phase calibration: Effectiveness at mauna kea and chajnantor. ALMA memo No. 139 (1995)
8. C.L. Carilli, M.A. Holdaway, K. Sowinsky. Faster switching at the vla. VLA Scientific Memo No. 169 (1996)
9. P.T.P. Ho, J.M. Moran, K.Y. Lo, ApJ **616**, L1 (2004). DOI 10.1086/423245