Technical Description and Implementation of Band to Band Phase Transfer

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Band to Band Phase Transfer

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Summary:

Band to band phase transfer is successful because: the instrumental phase variation of all ALMA bands are small; and virtually all other phase changes are associated with delay changes.

Image improvement from several band 3,6 to band 7,9,10 transfers occurs under the proper conditions which are still being determined.

B2B works best if the distance of the low frequency calibration is less than (1/R) of the distance to the nearest high frequency calibrator, where R is the ratio of the high to low frequency.

A band-to-band observing sequence is suggested for which about 10 minutes of observations of the high/low frequency calibrator is needed.

Minimum flux densities for the band to band calibrator at the high frequencies are given.

Additional tests are suggested.

1 Introduction:

When imaging a target using phase referencing, the closer the phase calibrator is to the target, the more accurately is the phase/gain calibration with the result of a significantly higher quality image. At ALMA frequencies above 300 GHz there is a low probability of finding a sufficiently strong calibrator that is within 5° of the target when atmospheric and other phase differences between the calibrator and target are small.

It is possible to use phase calibrator observations at a low frequency, where it is more likely to find one close to the target, and then scale the phases to what would be obtained at the target higher frequency. The scaling properties are determined from occasional observations of a strong calibrator (DGC for DiffGainCalSource) that may be tens of degrees from the target but easily detectable at the higher frequency.

2 Band to Band Phase Transfer Method:

This calibration procedure is called band-to-band phase transfer (B2B) and the method has been recently tested for various frequency pairs from 100 GHz to 650 GHz. The analysis of the method, the results and the recommendations are summarized here.

2.1 Band3/Band9 Data set:

An observation on June 23, 2014 was observed for 70 min making the asdm uid___A002_X8505d8_X14aa. In addition to the usual apriori calibration observations, four short observation periods of the DGC, switching between 92.3 GHz (band 3) and 644 GHz (band 9) were made to determine the phase difference between the two bands. The remainder of the experiment contained observations of the phase calibrator at band 3, switching with the target at band 9.

After the usual apriori calibrations (amp calibration, bandpass calibration, wvr correction), the antenna-based phases of the DGC and phase cal were determined for each spw and polarization, for each scan of 30 sec. At one selected time, t_0, during the observations, the DGC phase for each spw and polarization at both frequencies were determined and removed from the entire data set. Care was taken to obtain the band 3 and band 9 phases at the **same** average time (more on this later). The residual phases for the DGC and phase calibrator were then determined for the entire experiment for each band since the data for each spw and polarization were coherent after the t_0 phases were removed.

These residual phases are shown in the upper left of the figure for one of the longer baselines in this experiment. The phase drift over the 70-min observation period is clear, especially with the band 9 DGC observations. The DGC phase offset scaling within the fluctuations and slight time offsets are consistent with the frequency ratio of 644/92.3, since virtually all changes are caused by delay-like effects in the antenna system (position errors) or troposphere. It also assumes that any temporal instrumental phase changes at the two bands are small (a few degrees per hour) which has been established by many test observations.

The phase calibrator low frequency phases at band 3 are stable, but are similar to that of the DGC. The offset phase at t_0 is a measure of the difference in the delay between the DGC and the phase calibrator at that time, caused by antenna position errors and the atmosphere delay that differ between the two directions. When this difference is removed from the phase calibrator phases (to simulate the its high and low phase difference would have been at t_0, its phases are scaled by 644/92.3 to determine the expected phase calibrator value at band 9, and this is shown by the connected blue line. Its phase trend does follow the DGC high frequency phase, but is differs by about 50° from the DGC high frequency phase.

On the right in the figure, the phases for a shorter baseline are shown. The phase range is much less and the phase calibrator calculated phase at band 9 is similar to that obtained with the DGC which is expected if the systematics and the troposphere effects associated with this antenna are small.

The interferometric analysis of the above procedure is shown in section 3. The two assumptions for B2B to be successful are: (1) The instrumental phase difference between the two bands are nearly constant in time; (2) All other instrumental and tropospheric phase changes at both frequencies are delay-like and scale with frequency.

2.2 Using The DiffGainCalSource:

The recommendation of the above and other B2B tests are that it is sufficient to determine the DGC phase difference at the two frequencies at one time stamp. This phase difference removes the constant instrumental and DGC delay offset at this time. Further DGC observations show a changing phase between the two frequencies, but these changes can be removed more accurately by the phase calibrator observations at band 3 after applying the offset phase at t_0 and scaling to band 9 (see section 3).

The minimum needed DGC observations is a sequence near the middle of the experiment of about 4 min, such as

```
Dh(60s)--Dl(20s)--Dh(60s)--Dl(20s)--Dh(60s)   where
     Dh(60s) = 60 second scan of DGC at the high frequency
     Dl(20s) = 20 second scan of DGC at the low frequency
```

From these data, the average antenna-based phases at each frequency can be determined at nearly the same time, t_0, somewhere near the middle of the set of scans. The SNR for the antenna-based solutions for the 60 sec integration at the high frequency should be greater than 10 (giving a 5° rms) over each spw of 2 GHz and each polarization. This averaging could be done with only three scans. What is important is that the high frequency and low frequency data that are averaged have the same average time in at both frequencies to simulate a simultaneous measurement. For redundancy, this burst of the DGC can be made twice during the experiment, but there is little need to observe the DGC more than that recommended above.

The usual phase stability criterion applies. If the atmospheric phase fluctuations for the longer baselines during a 60-sec period are larger than about 30°, normally assessed from the DGC observations, the image quality will have a dynamic range less than 10:1. Regardless of the calibration method, this experiment should be aborted.

2.3 The Phase Calibrator at Low Frequency:

The remainder of the experiment consists of the nodding observations between the phase calibrator, observed only at low frequency (Cl), and the target source (Th), observed only at high frequencies. Various bandpass, tsys and other calibrations are applied before doing the phase analysis.

For the B2B procedure to be accurate, the estimate of the low frequency calibrator phase must be determined at t_0 which is usually specified near the middle of the DGC observation burst. Hence, an observing sequence with the DGC observations recommended is:

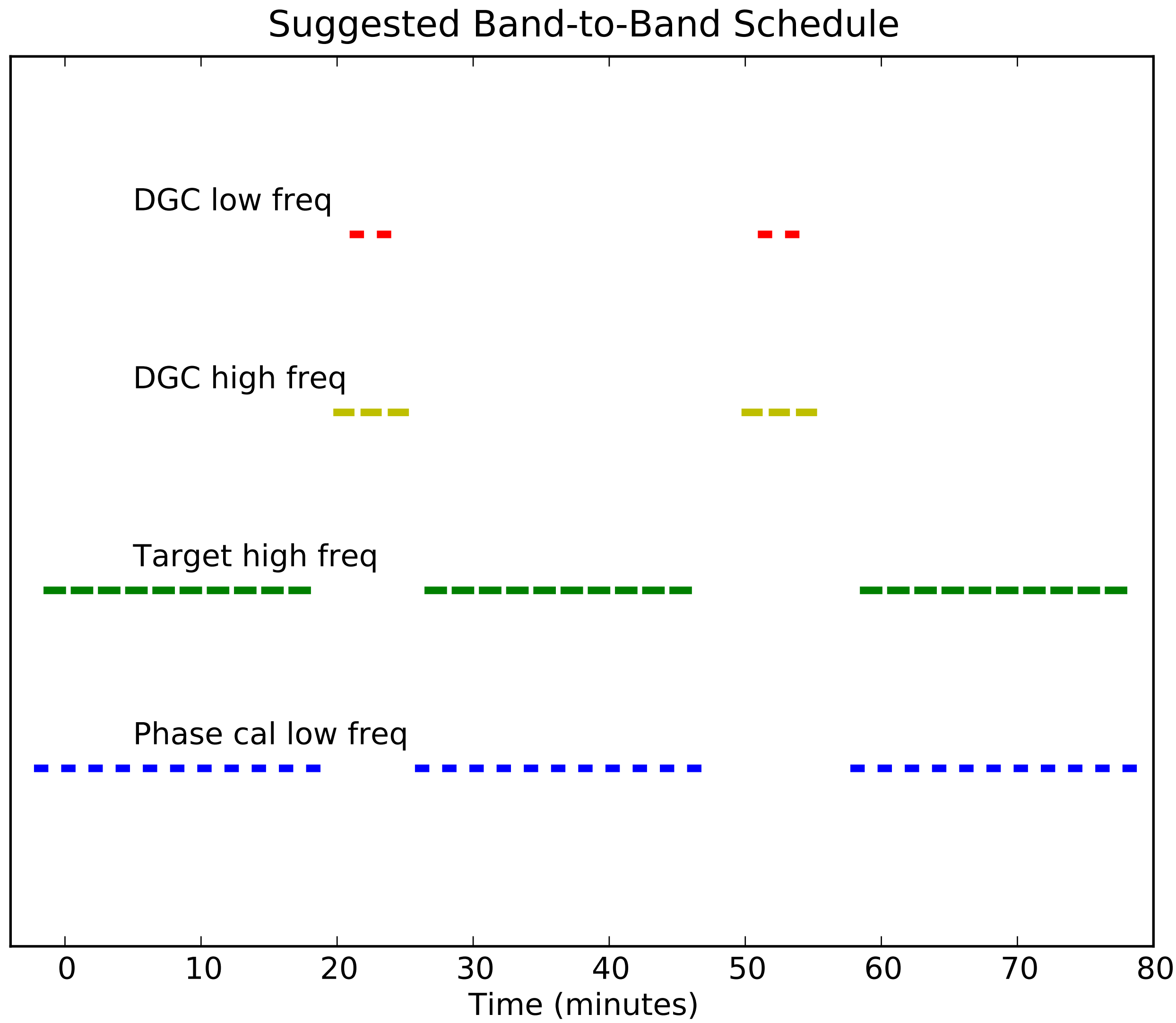
```
...Th(150s)--Cl(30s)--Dh(60s)--Dl(20s)--Dh(60s)--DG(20s)--DG(60s)--Cl(30s)--Th(150s)-...
         Th(150s= 120 second scan of target at high frequency
         Cl(30s) = 30 second scan of phase cal at low frequency
```

The two scans of the low frequency calibrator at about 4 min apart, and the average phase should be sufficiently accurate to estimate its phase at t_0. This estimate is made *after* the DGC phase corrections at t_0 are applied to remove the spw and polarization offsets and the instrumental phases at this time.

2.4 Suggested Schedule:

The suggested schedule for a B2B experiment is shown in the following figure. We assumed that the target source needs about 60 in integration at the high band to reach the desired rms noise level. Each DGC-source segment consists of five scans; three one-min scans observed at the high frequency, alternating with two 20-sec scans at the low frequency. There should be two such segments in each experiment, although only one is needed to determine the high/low frequency phase different at t_0. The typical cycling between target at high frequency and phase calibrator at low frequency should cover approximately 20 to 30 min segments with the phase calibrator scan of 30 sec and the target scan at 150 sec. These times scales are recommendations.

Additional calibrations are not included in the diagram. They will be: an amplitude calibrator at the high frequency only (solar system object or grid source). a bandpass observation at the high frequency (perhaps the DGC for about 10 minutes near the beginning of the observation). A bandpass observation at the lower frequency is not needed since it can be obtained from the observations of phase calibrator. Tsys observations are needed near most of the high frequency observations (but not for the low frequency observations), although those associated with the target need be done only every 10 minutes. Pointing and focus, probably on the DGC are probably sufficient just before each DGC high/low frequency segment.



The approximate rms sensitivities and minimum suggest flux densities for the DGC at the high frequency and the phase calibrator at the low frequency are given in the table below. The table assumes a scan length of 1 min for the DGC, and the sensitivities are for a 2-GHz spw and one polarization since the phase offset of each need bet determined at t_0. For the Phase-calibrator at band 3 and 6, the scan length assumed is 20 sec and all spw/pol have been combined coherently.

RMS AND MINIMUM FLUX DENSITIES

	BAND 7		BAND 9		BAND 10		
	RMS	MIN FLUX	RMS	MIN FLUX	RMS	MIN FLUX	
DGC 34 12m antennas-1m	3.5	18	30	150	120	500	mJy
DGC 9 7m antennas-1m	20	100	140	700	560	2800	mJy

	BAND 3		BAND 6		
	RMS	MIN FLUX	RMS	MIN FLUX	
Phase cal 34 12m 30sec	1.0	5.0	3.0	15	mJy
Phase cal 9 7m 30sec	6.0	30.0	16	80	mJy

2.5 Images for this Experiment:

Three images are shown for the target in this experiment. In the figure on the lower left, the image using only the DGC at high frequency is shown This is not a particularly good calibration scheme since the DGC source was observed every 20 min. Future comparison tests will make an independent observation of the DGC with a more typical cycle time of 5 min for a more valid high frequency image. The middle image shows the result from the B2B calibration scheme. The image on the right shows the self-calibrated image which should be perfect within the signal to noise. The peak flux densities for the self-cal, B2b and DGC, B2B and self-cal images are 0.14, 0.27 and 0.31 Jy/beam (the resolution is approximately 0.18") and the differences in the quality of the images are obvious. The image rms's are 0.0072, 0.0036, 0.0016 Jy/beam. Although the B2B image is somewhat worse than the self-cal 'perfect' image, the quality improvement from the normal high frequency calibration to the B2B calibration is clear. One caveat is that this experiment was not optimized for the normal high frequency calibration.

The separations among the sources for this test are typical of the circumstances for ALMA observing. A distance of 15° is about the distance that a target will be from a suitably bright quasar at a frequency greater than 500 GHz. At band 3, a suitable calibrator will often be found within about 4° of the target. However, the DGC, phase calibrator and target are atypically strong in order to assess the quality of the method. Further testing of weaker phase calibrators and targets are underway.

B2B SOURCE PARAMETERS

TYPE	NAME	RA (J2000)	DEC	Sep from target	Flux (650)
DGC source	J1751+0939	17:51:32.8185	+09.39.00.728	14.2 deg	0.7
Phase cal	J1745-0753	17:45:27.1049	-07.53.03.947	4.2 deg	
Target	J1743-0350	17:43:58.8552	-03.50.04.632	---	0.31

2.6 Preliminary Recommendations when to use Band to Band

3 Band to Band Transfer Assumptions and Equations:

3.1 DiffGainCalSource:

This section goes through the interferometric phase equations to demonstrate the calibration sequences that are suggested. The antenna-based phases (the visibility phase of the antenna versus some reference antenna) measured for a point source of known position at two frequencies are:

$$\begin{aligned} \theta^h(t) &= \phi_i^h + \psi^h(t) \\ \theta^l(t) &= \phi_i^l + \psi^l(t) \end{aligned} \tag{1}$$

where θ^f = measured visibility phase at freq f, with the frequency = h (high) or l (low), ϕ_i^f = instrumental system/receiver phase at freq f, and $\psi^f(t)$ = all other variable phase change at each frequency, most of which are caused by the troposphere or other calibration errors.

The two assumptions of the property of these phases are: 1) the instrumental phase $\phi_i^{h,l}$ are essentially constant over many hours; and 2) the variable phase component at each frequency is non-dispersive (associated with a delay) which means they scale linearly with frequency.

$$\psi^h(t) = 2\pi\nu^h\tau(t); \qquad \psi^l(t) = 2\pi\nu^l\tau(t) \tag{2}$$

The instrumental phase stability of ALMA over several hours has been demonstrated in many experiments. A check on the two assumptions can be confirmed by making a plot of

$$\Delta\theta^h_D(t)/\nu^h - \Delta\theta^l_D(t)/\nu^l \approx 0 \tag{3}$$

Even when antenna instabilities occur (for example if the line length compensator is faulty), often delay-like changes occur and these are calibrated using the B2B method.

The DiffGainCalSource (DGC) is a strong point source of known position that is used to measure the phase at the two frequencies almost simultaneously. If the phase at each frequency is determined at a fiducial time, t_0, then the phase change from this fiducial time at the high and low frequencies becomes,

$$\begin{aligned} \Delta\theta^h_D(t) &= \theta^h_D(t) - \theta^h_D(t_0) = 2\pi\nu^h\Big(\tau_D(t) - \tau_D(t_0)\Big) \\ \Delta\theta^l_D(t) &= \theta^l_D(t) - \theta^l_D(t_0) = 2\pi\nu^l\Big(\tau_D(t) - \tau_D(t_0)\Big) \end{aligned} \tag{4}$$

where the assumed constant instrumental phases drop out and the phase change with time from the fiducial point scale precisely with frequency.

3.2 Phase Reference Source:

The same formulation applies to the phase calibrator (C)

$$\begin{aligned} \Delta\theta^h_C(t) &= \theta^h_C(t) - \theta^h_C(t_0) = 2\pi\nu^h\Big(\tau_C(t) - \tau_C(t_0)\Big) \\ \Delta\theta^l_C(t) &= \theta^l_C(t) - \theta^l_C(t_0) = 2\pi\nu^l\Big(\tau_C(t) - \tau_C(t_0)\Big) \end{aligned} \tag{5}$$

Notice that the calibrator phase must is normalized at t_0 which is a time stamp where the DGC high and low frequencies have been observed. The question for successful band-to-band observations is:

If the phase calibrator is observed only at the low frequency, how can its high frequency phase be inferred from the DGC observations at two frequencies?

Taking the temporal phase difference between the DGC (D) and phase cal (C), gives

$$\begin{aligned} \Delta\theta^h_D(t) - \Delta\theta^h_C(t) &= 2\pi\nu^h(\Delta\tau_D(t) - \Delta\tau_C(t)) \\ \Delta\theta^l_D(t) - \Delta\theta^l_C(t) &= 2\pi\nu^l(\Delta\tau_D(t) - \Delta\tau_C(t)) \end{aligned} \tag{6}$$

where $\Delta\tau_{D,C}(t)$ is the change of delay for each source. By multiplying the top equation by ν_l and the bottom equation by ν_h, and differencing gives,

$$\Delta\theta^h_C(t) = \theta^h_C(t) - \theta^h_C(t_0) = \frac{\nu^h}{\nu^l}\Big(\theta^l_C(t) - \theta^l_C(t_0)\Big) \tag{7}$$

so the expected high frequency phase of the calibrator is a simple scaling of the measured low frequency phase by the ratio of the frequencies, $\Delta\theta^h_C(t)$.

4 Conclusion:

The band-to-band phase referencing scheme has been demonstrated to improve the image quality when compared with normal phase calibration at high frequencies. Additional work is needed: 1) to compare the high frequency calibration results to the b2b results as a function of relative distance of the DGC and low frequency calibrators from the target. 2) to apply the technique to band 10 where low SNR and larger phase variations occur. 3) to determine the preference for B2B at B3/B9 or B6/B9. 4) to recommend the parameters for accurate calibrator queries for the DGC and the phase calibrator that include the effect of frequency scaling. 5) and to simplify the nominal SB will also produce a more efficient schedule with more integration time on the target.

5 Acknowledgements:

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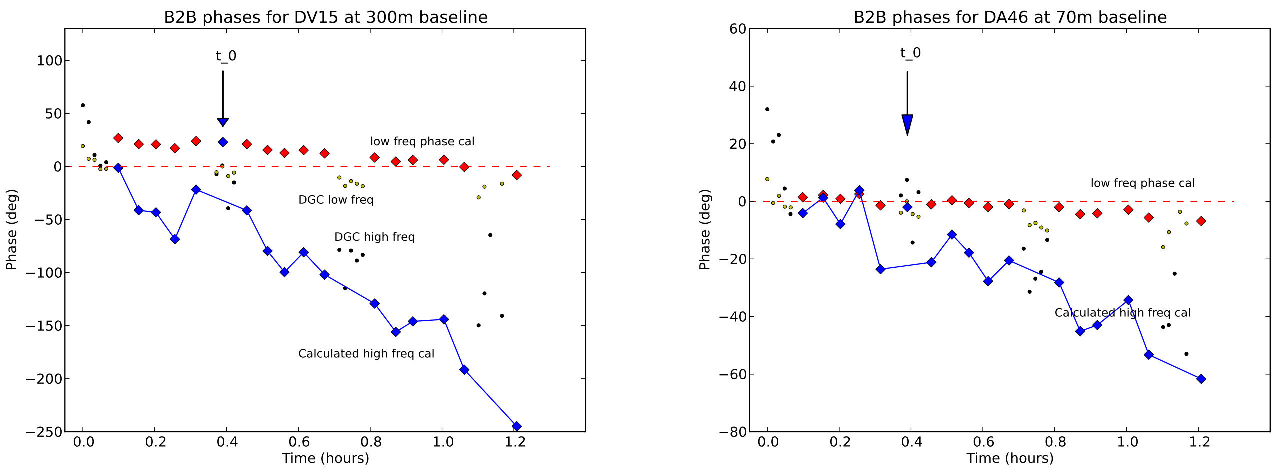
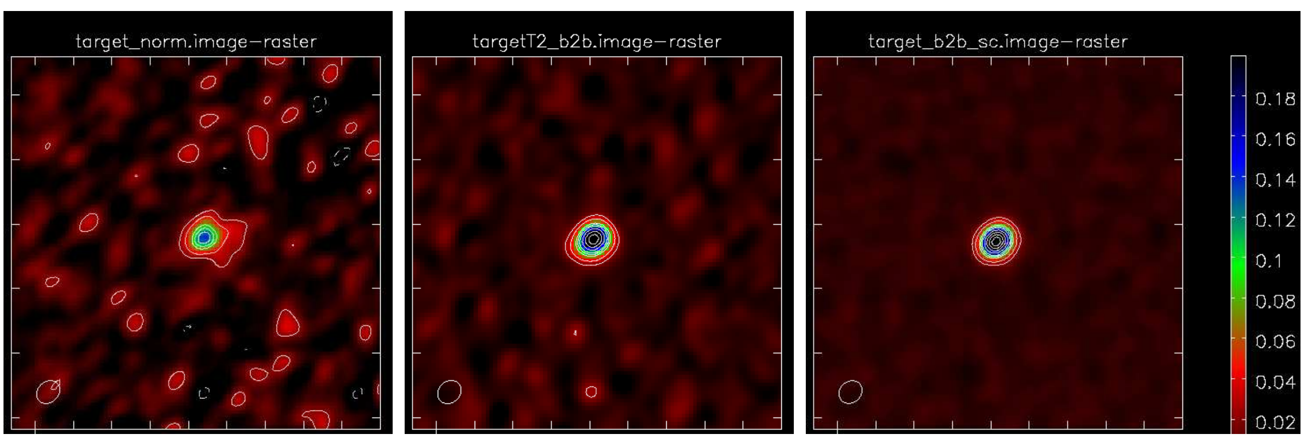

B2B phases for DV15 at 300m baseline
t_0
low freq phase cal
DGC low freq
DGC high freq
Calculated high freq cal
Phase (deg)
Time (hours)
B2B phases for DA46 at 70m baseline
t_0
low freq phase cal
Calculated high freq cal
Phase (deg)
Time (hours)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targetT2_b2b.image−raster
target_b2b_sc.image−raster
0.18
0.16
0.14
0.12
0.1
0.08
0.06
0.04
0.02