Phase Characteristics of the ALMA 3 km Baseline Data

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ABSTRACT
We present the phase characteristics study of the Atacama Large Millimeter/submillimeter Array (ALMA) long (up to 3 km) baseline, which is the longest baseline tested so far using ALMA. The data consist of long time-scale (10 – 20 minutes) measurements on a strong point source (i.e., bright quasar) at various frequency bands (bands 3, 6, and 7, which correspond to the frequencies of about 88 GHz, 232 GHz, and 336 GHz). Water vapor radiometer (WVR) phase correction works well even at long baselines, and the efficiency is better at higher PWV (> 1 mm) condition, consistent with the past studies. We calculate the spatial structure function of phase fluctuation, and display that the phase fluctuation (i.e., rms phase) increases as a function of baseline length, and some data sets show turn-over around several hundred meters to 1 km and being almost constant at longer baselines. This is the first millimeter/submillimeter structure function at this long baseline length, and to show the turn-over of the structure function. Furthermore, the observation of the turn-over indicates that even if the ALMA baseline length extends to the planned longest baseline of 15 km, fringes will be detected at a similar rms phase fluctuation as that at a few km baseline lengths. We also calculate the coherence time using the 3 km baseline data, and the results indicate that the coherence time for band 3 is longer than 400 seconds in most of the data (both in the raw and WVR-corrected data). For bands 6 and 7, WVR-corrected data have about twice longer coherence time, but it is better to use fast switching method to avoid the coherence loss.

Keywords: Atacama Large Millimeter/submillimeter Array (ALMA), Commissioning, Long Baseline, Phase Stability, Water Vapor Radiometer (WVR), Phase Correction

1. INTRODUCTION
Atacama Large Millimeter/submillimeter Array (ALMA\textsuperscript{5}) has recently become the world’s largest millimeter-/submillimeter-wave (mm-/submm-wave) interferometer, and currently commissioning and Early Science observations are ongoing in parallel. One of the most important commissioning items before the full science operation of ALMA is the commissioning of long baselines.

The difficulty of long baseline interferometry in mm-/submm-wave comes mainly from the large phase fluctuation caused by water vapor in the atmosphere. Refraction of water vapor causes the change of phase (and amplitude) of electromagnetic wave. Water vapor is believed to be distributed as clumps that have a power-law size distribution and an upper limit of size at some point. The difference of path lengths through water vapor clumps in the line-of-sight between two antennas causes a phase difference, and the change of this difference caused by the flow of water vapor clumps creates phase fluctuation. Due to the power-law size distribution and

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the upper limit of the size of the water vapor clumps, the phase fluctuation is expected to increase with baseline length, and at some point, phase fluctuation does not become larger any more (see Ref. [2] for more details).

This phase fluctuation can be reduced using the 183 GHz Water Vapor Radiometer (WVR). WVRs are installed in each of the 12-m diameter ALMA antennas, and they measure the line-of-sight atmospheric water vapor content precisely. The difference of the water vapor content between antennas corresponds to the difference of path lengths due to the water vapor clumps, and therefore it is possible to estimate the phase difference between antennas. Correcting this estimated phase difference will correct the phase fluctuation caused by water vapor in the atmosphere. This phase correction method using WVRs has been shown to work successfully on the past shorter baseline ALMA data.

For the commissioning of ALMA long baseline, it is important to know how large the phase fluctuation can be as a function of baseline length, at which baseline length the phase fluctuation turns over (i.e., stops increasing), and whether the WVR phase correction works well even at the long baseline. In this paper, we discuss these topics.

2. MEASUREMENTS AND DATA ANALYSIS

To characterize the mm-/submm-wave phase fluctuation at long baselines (up to 3 km), we stared at a strong point source, namely a strong radio-loud quasar, using ALMA for 10 – 20 minutes at frequency bands 3 (∼88 GHz), 6 (∼232 GHz), and 7 (∼336 GHz) under various precipitable water vapor (PWV) conditions of 0.5 – 2.0 mm. Note that the PWV values are from the WVR output, so that those are the values along the line-of-sight. We only used the 12 m diameter antennas, since the 7 m antennas do not have WVRs.
Table 1. Details of the 3 km baseline measurements. (1) Data identification number. (2) ALMA band name (number). (3) Measurement frequency in GHz. (4) Measurement date. (5) Precipitable water vapor in mm. (6) Observed source name. (7) Total observation time in minute. (8) Integration time of each data point in second. (9) Number of antennas used in the measurement.

| Data No. | Band | Freq. [GHz] | Date [YYYY/MM/DD] | PWV [mm] | Source Name | Obs. Time [min] | Int. Time [sec] | Ant. No. |
|----------|------|-------------|-------------------|----------|-------------|----------------|----------------|---------|
| 1        | 3    | 88.0        | 2013/06/03        | 0.68     | 1058+015    | 9.6            | 0.96           | 28      |
| 2        | 3    | 88.0        | 2013/06/06        | 0.54     | NRAO 530    | 9.6            | 0.96           | 29      |
| 3        | 3    | 88.1        | 2013/06/06        | 0.55     | 1924-292    | 9.6            | 0.96           | 28      |
| 4        | 3    | 88.1        | 2013/06/06        | 0.55     | 2348-165    | 9.6            | 0.96           | 26      |
| 5        | 6    | 232.4       | 2013/06/06        | 0.54     | 2348-165    | 9.6            | 0.96           | 26      |
| 6        | 7    | 335.6       | 2013/06/06        | 0.57     | 2348-165    | 9.6            | 0.96           | 26      |
| 7        | 3    | 88.1        | 2013/06/07        | 1.46     | 1924-292    | 9.6            | 0.96           | 32      |
| 8        | 6    | 232.4       | 2013/06/07        | 1.42     | 1924-292    | 9.6            | 0.96           | 32      |
| 9        | 7    | 335.6       | 2013/06/07        | 1.39     | 1924-292    | 9.6            | 0.96           | 32      |

Table 2. Details of the 2 km baseline measurements.

| Data No. | Band | Freq. [GHz] | Date [YYYY/MM/DD] | PWV [mm] | Source Name | Obs. Time [min] | Int. Time [sec] | Ant. No. |
|----------|------|-------------|-------------------|----------|-------------|----------------|----------------|---------|
| 1        | 6    | 232.3       | 2012/05/02        | 1.54     | 1924-292    | 19.2           | 0.96           | 14      |
| 2        | 6    | 232.3       | 2012/05/02        | 1.65     | 1924-292    | 19.2           | 0.96           | 14      |
| 3        | 6    | 232.3       | 2012/05/10        | 0.98     | 3C279       | 19.2           | 0.96           | 15      |
| 4        | 6    | 232.3       | 2012/05/10        | 0.86     | 2258-279    | 19.2           | 0.96           | 14      |
| 5        | 3    | 88.0        | 2012/05/10        | 1.96     | 0522-364    | 19.2           | 0.96           | 17      |
| 6        | 3    | 88.0        | 2012/05/11        | 1.78     | 1924-292    | 19.2           | 0.96           | 15      |
| 7        | 3    | 88.0        | 2012/05/12        | 1.91     | 3C279       | 19.2           | 0.96           | 17      |
| 8        | 3    | 88.0        | 2012/05/12        | 1.14     | 3C454.3     | 19.2           | 0.96           | 14      |
| 9        | 7    | 335.6       | 2012/05/12        | 1.30     | 3C454.3     | 19.2           | 0.96           | 14      |
| 10       | 3    | 88.0        | 2012/05/15        | 1.69     | 3C279       | 19.2           | 0.96           | 21      |
| 11       | 3    | 95.8        | 2012/05/15        | 1.56     | 3C279       | 21.1           | 1.056         | 20      |
| 12       | 3    | 95.8        | 2012/05/15        | 1.46     | 3C279       | 21.1           | 1.056         | 19      |
| 13       | 3    | 95.8        | 2012/05/15        | 0.69     | 3C454.3     | 21.1           | 1.056         | 19      |
| 14       | 3    | 88.0        | 2012/05/26        | 1.97     | 1924-292    | 19.2           | 0.96           | 16      |

There were two long baseline campaigns, one was for the maximum baseline of ~3 km performed on June 2013, and another of ~2 km on May 2012. For both campaigns, most of the antennas were located at the central cluster with the longest baselines of ~500 m, but for the former case, three antennas were located at north (antenna name DV25), north-west (DV07), and west (DV19) of the central cluster with the distance of about 1 km from the central cluster, and one antenna located at south-east (DV24) with the distance of about 2 km (see Fig. 1 Right for the actual antenna configuration). For the latter case, one antenna (PM03) was located at north with the distance of about 2 km from the central cluster (Fig. 1 Left). The details of the measurements are listed in Table 1 and 2 for the 3 km and 2 km baseline tests, respectively.

All the data sets have been reduced under the Common Astronomy Software Applications (CASA) package environment. The WVR phase correction has first been applied to the obtained data sets using the `wvrgcal` program. For the 3 km baseline test data sets, the precise position for the south-east antenna (DV24) was determined after these measurements, so that we applied the correct antenna position at this point.

For the phase characterization, we calculate the spatial structure function (hereafter SSF) of the phase fluctuation (i.e., root-mean-square [rms] phase) using personally developed python programs under CASA. The
Figure 2. Example plots of the phase improvement ratio (the ratio of averaged rms phase between the raw and the WVR corrected data) as a function of baseline length. (a) A case of the ratio increases up to the baseline length of several hundred meters, and decreases at longer baselines. Most of the data shows this pattern. (b) A case of the ratio increases monotonically as the baseline length increases. (c) A case of the ratio decreases almost monotonically as the baseline length increases. (d) A case of the ratio does not depend on the baseline length.

SSF of rms phase for each baseline can be calculated as

$$\sigma_\phi = \sqrt{\frac{<\{\phi(x+d) - \phi(x)\}^2>}{2}},$$

where $\phi$ is a phase output from an antenna, $x$ is an arbitrary antenna location, $d$ is the baseline length, and $< ... >$ means an ensemble average. Original data output has an integration time of $\sim 1$ second (see Tables 1, 2), but for this calculation, we averaged for 10 seconds to suppress noise with white-spectrum characteristics such as that intrinsically arising within the mixers of the ALMA receivers when measuring the phase from the astronomical signals. For the 10 second data binning, if the data points are less than 70% of the number of the data points should be, this binned data point has been discarded. Since there are limited number of baselines, especially for long baselines, we did not bin the data along the baseline length.

3. EFFECTIVENESS OF WATER VAPOR RADIOMETER PHASE CORRECTION

To evaluate the effectiveness of the WVR phase correction on the long baseline data, we first calculated the ratio of averaged rms phase between the raw (not WVR corrected) and the WVR corrected data (hereafter, we refer
this as a phase improvement ratio) for each baseline. Fig. 2 displays some example plots of the phase improvement ratio as a function of baseline length. Many (15 out of 25 data, or 60%; Fig. 2a) of the data show increment of the ratio as a function of baseline length up to around several hundred meters to 1 km and then either being constant or decrease at longer baselines. On the other hand, small amount of data exhibit a constant increment (5 out of 25, or 20%; Fig. 2b), constant decrement (2 out of 25, or 8%; Fig. 2c), or even no trend (3 out of 25, or 12%; Fig. 2d). This statistics tells that in most cases, the WVR phase correction works effectively at some certain baseline length, but at longer baseline length, this effectiveness being constant or decreases. The baseline length of this effectiveness bending roughly matches the turn-over baseline length in the structure functions (see next section). This suggests that the decrease of the effectiveness of the WVR phase correction at the baseline lengths longer than the turn-over is due to the change in the characteristics of phase fluctuation. On the other hand, it can be due purely to the instrumental characteristics of WVRs on the long baseline antennas, since the long baseline data points rely only on a few antennas, and if one WVR has lower sensitivity, then many long baseline data points will appear to have low effectiveness of the WVR phase correction.

We then averaged over all the baselines in each data set. This tells the overall degree of improvement of rms phase with applying the WVR phase correction. Fig. 3 exhibits the averaged rms phase ratio between the raw and the WVR-corrected data as a function of PWV. There is a slight trend that higher PWV (PWV > 1 mm) data improves better than lower PWV (PWV < 1 mm) data. Indeed, the average ratio (i.e., improvement factor) for the higher PWV data is 2.4, higher than that of the lower PWV data of 1.6. This trend is consistent with that reported in the previous papers, namely the WVR phase correction work well under some amount of water vapor in the atmosphere, but will be limited under drier (i.e., too less water vapor in the atmosphere) conditions. This figure also differentiates the frequency bands, but there is no significant difference between the bands (although there are not much data points for each band).
Figure 4. Example plots of the spatial structure function (SSF) derived using the 3 km baseline data sets. Black and grey points are the raw and the WVR-corrected data points, respectively. Grey and black solid lines are the fitted slopes for the raw and the WVR-corrected data, respectively, using the data points at the baseline length shorter than 500 m. (a) A case that shows the turn-over in both the raw and WVR-corrected data. (b) A case that shows the turn-over only in the raw data. (c) A case that shows the turn-over only in the WVR-corrected data. (d) A case that does not show any turn-over in both the raw and the WVR-corrected data.

4. SPATIAL STRUCTURE FUNCTION

Fig. 4 shows a few examples of SSF derived using the 3 km baseline data sets. Black and grey points are the raw and the WVR-corrected data points, respectively. For the first time, we have observed the turn-over of SSF in the submillimeter-wave regime as in Fig. 4(a). The turn-over is often observed around the baseline length of several hundred meters to 1 km. This suggests that for the baselines longer than this turn-over, the phase fluctuation does not become larger than that measured around the turn-over, and therefore assure the success of detecting fringes at longer baseline, even for the longest baseline of ALMA of 15 km.

On the other hand, not all the data show the turn-over; some shows either only in the raw data (i.e., turn-over does not exist in the WVR-corrected data; Fig. 4(b)) or in the WVR-corrected data (Fig. 4(c)), and some does not show in both the raw and WVR-corrected data (Fig. 4(d)). The data sets that show the turn-over in both the raw and the WVR-corrected data are 3 out of 25 data sets (12%), in only the raw data 8 out of 25 data sets (32%), in only the WVR-corrected data 1 out of 25 data sets (4%), and that do not show the turn-over are 13 out of 25 data sets (52%). This suggests that most of the WVR-corrected data do not exhibit the turn-over. However,
the difficulty of judging the turn-over is that the number of the long baseline data points is very limited due to the limited number of antennas at the long baselines, so that the accuracy of the location of the turn-over is not high. Hereafter, we concentrate on the analysis of the slope of SSF.

We fit the slope of SSF using the data points at the baseline length shorter than 500 m. The solid lines in Fig. 4 are the fitted slopes. Fittings have been done to all the data sets, and the histogram of the number of the data sets as a function of slope are displayed in Fig. 5(a). It is obvious that the peak of the histogram for the raw data are larger (average = 0.61) than that of the WVR-corrected data (0.51), namely the WVR-corrected data have shallower slope than that of the raw data. Note that the average (50% quartile) slope of the temporal structure function derived from the 11.2 GHz radio seeing monitor (RSM) data used for the ALMA site testing exhibits 0.63, agrees well with our result for the raw data. The RSM result is from the long term monitoring (taken between 1996 July and 1999 March), and the agreement of the average values for the raw data therefore suggests that our data represent the typical phase fluctuation condition (at least for the slope of the structure function) at the ALMA site.

We then plot the slopes as a function of PWV (Fig. 5b). For the data with the lower PWV of $<1$ mm, there is almost no difference between the raw and the WVR-corrected data (average of 0.58 and 0.55, respectively), but for the data with the higher PWV of $>1$ mm, the WVR-corrected data exhibit obviously shallower slopes of 0.49 than that for the raw data of 0.63. We again differentiate the frequency bands in this figure, but there is no significant difference between the bands; the aforementioned trends are all true for all the bands.

Based on theoretical studies, steeper slope of 0.83 suggests the three-dimensional Kolmogorov turbulence, and shallower slope of 0.33 suggests the two-dimensional Kolmogorov turbulence. The slopes of our data for both raw and WVR-corrected ones are mostly in between these values, although the WVR-corrected data have shallower slopes than that of the raw data. This suggests that the WVR phase correction makes the effect of turbulence in phase fluctuation closer to two-dimensional turbulence. On the other hand, if the phase fluctuation purely caused by the water vapor in the atmosphere, the WVR phase correction will eliminate all the phase fluctuation, and the slope should be flat within the timescale of the WVR phase correction (which is 1 second). All the obtained data exhibit, however, significant slopes, suggesting other cause(s) for the atmospheric phase fluctuation. The most likely cause of this is due to the dry component (O₂ or N₂) in the atmosphere. This, however, contradicts with the above discussion; the scale height of the dry air ($\sim$ 8 km) is much larger than that of the water vapor ($\sim$ 2 km), so that the turbulence in the dry air will more likely to be three-dimensional, namely it seems natural to have steeper slope. But the obtained slopes tend to have shallower slopes, rather close to the two-dimensional turbulence. The alternative explanation may be the multiple layers of two-dimensional Kolmogorov turbulence, which leads to the slopes to be in the middle of two-dimensional and three-dimensional Kolmogorov turbulence slopes. This might be the most plausible solution, since the atmosphere consists of multiple layers. On the other hand, imperfect WVR phase correction due either to instrumental causes or to
incorrect assumptions in the phase correction method cannot be ignored. There is also a possibility of phase fluctuation caused by instruments, but it is usually difficult to produce baseline-base phase fluctuation so it is less likely.

5. COHERENCE TIME

Since some of the data show the turn-over in the slope of SSF, it is worth to calculate the coherence time at the longest baseline length of 3 km, because it assures that there is no increment of the coherence time even for longer baselines (even for the very long baseline interferometry [VLBI] observations, which is considered as one of the near future plans for ALMA). Here we assume that the coherence time corresponds to the amplitude decrement of 10% from the original amplitude due to the phase decorrelation. We only use the 3 km baseline length data for this calculation. We also calculate the coherence time for all the frequency bands using the original data, assuming that the phase fluctuation linearly increases with the frequency increase (i.e., non-dispersive assumption). This assumption is valid, since the WVR phase correction works at all the frequency bands in our data, which also assumes the non-dispersive characteristics of the phase at the observation frequencies. Due to the limited observation time (and therefore the statistics for each time length), we limit the calculation of the coherence time up to $\sim 400$ seconds.

An example plot of coherence as a function of time for each band is displayed in Fig. 6 and the coherence time as a function PWV is displayed in Fig. 7. Most (7 out of 8) of the raw data and all of the WVR-corrected data of band 3 have coherence time longer than $\sim 400$ seconds, namely it is possible to have a switching time between a target source and a calibrator of at least 6.5 minutes for the most of the data (as far as the PWV of less than 2 mm; no data so far for PWV larger than 2 mm) without significant phase decorrelation for band 3. This is also true for VLBI observations; it is possible to integrate at least 6.5 minutes for the most of the band 3 data at the ALMA site.

For bands 6 and 7, the average coherence time is 108 and 57 seconds, respectively, for the raw data and $> 273$ and 125 seconds for the WVR corrected data. This tells that for these higher frequency observations, especially for band 7 (or higher frequency bands), it is better to observe with fast switching calibration technique to keep coherence loss less than 10%. This results do not reject to observe slow switching observation, but the data taken with the slow switching will have some degree (more than 10%) of coherence loss.

It is obvious that the WVR phase correction extends the coherence time significantly (more than a factor of 2) from the non-WVR corrected data. This also suggests that the WVR phase correction helps a lot for VLBI observations. But still it is better to operate with fast switching calibration, especially for higher frequency bands (higher than band 7) to have low coherence loss data.
Figure 7. Coherence time as a function of PWV. Circle, square, and diamond marks are the data from bands 3, 6, and 7, respectively. Black and grey color indicates the raw and WVR-corrected data, respectively. Data points around the coherence time of 400 seconds are the data that do not degrade to the coherence of 0.9, namely the coherence time of ~ 400 seconds are the lower limit for these data. This limitation is caused by the limited measurement time length.

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