The Effect of Atmospheric Phase Fluctuations on Uplink Arraying

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This article investigates the effect of atmospheric phase variations on uplink array losses if the phase variations are not measured and corrections applied to the signals radiated from individual antennas. For an interferometer with a baseline of about 1.6 km and working at 7.2 GHz (X-band), the loss of signal due to phasing errors caused by atmospheric variations, if not corrected, is expected to be ≤0.7 dB for 95 percent of the time at elevations ≥18 deg at Goldstone. Therefore, it may not be necessary to continuously monitor the atmospheric variations and apply the phase corrections for arrays smaller than about a kilometer at X-band. However, for arrays spread over much larger areas or for an array of even one kilometer working at higher frequencies, such as 32 GHz (Ka-band), it may be necessary to monitor the atmospheric variations and apply the corrections to keep the phasing losses below an acceptable level (say, about 1 dB).

I. Introduction

Uplink arraying signals transmitted from various antennas of the array should coherently add and produce a maximum signal power at a target. This can be achieved by adjusting phase and delay of the signal transmitted from each antenna and by maximizing the signal received at the target using a power monitor. However, it may not be possible to use a power monitor on every target due to cost or round-trip signal travel time. In that case, one would like to measure the path length from each transmitter to a calibration target in the sky and then calculate adjustments required for the path lengths for a given direction/target using knowledge of the geometry of the array, calibrator, and the target of interest. One has to be careful about the difference in atmospheric phase while looking at the calibrator and at the target. Moreover, in uplink arraying, we may not be able to monitor how well signals are coherently adding at the target. Therefore, we need to have a way to monitor the atmospheric variations or have a good understanding and estimate of the atmospheric phase variations with time. We need an estimate of the fraction of time the signal is reduced by a given amount by these phase fluctuations.

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II. Approach

We adopt the following approach to estimate the expected maximum loss due to lack of correct phasing of the transmit signals at a target for a given fraction of time if the delay fluctuations are not measured and proper corrections applied. We use water-vapor radiometer (WVR) data to estimate temporal fluctuations of the path length. The temporal fluctuations are used to estimate spatial fluctuations over an array, assuming that the path-length variations caused by water-vapor irregularities are frozen into the medium and blown over the antennas by wind.

III. Data

Keihm [2] has analyzed one year of water-vapor radiometer data at Goldstone and has given plots of Allan standard deviations for four time intervals (200 s, 800 s, 3200 s, and 12,800 s), as shown in Fig. 1. He also compares average values of the Allan standard deviations for nighttime and the entire day over one year (Fig. 2). Also, Shambayati [4] has reported water-vapor radiometer data at both Goldstone and Madrid for several years. These data have been used by Resch[2] to plot cumulative probability distribution for atmospheric turbulence (temporal fluctuations) for Goldstone in 1994 (Fig. 3) for 200-s, 400-s, 800-s, 1600-s, 3200-s, 6400-s, and 12,800-s time intervals.

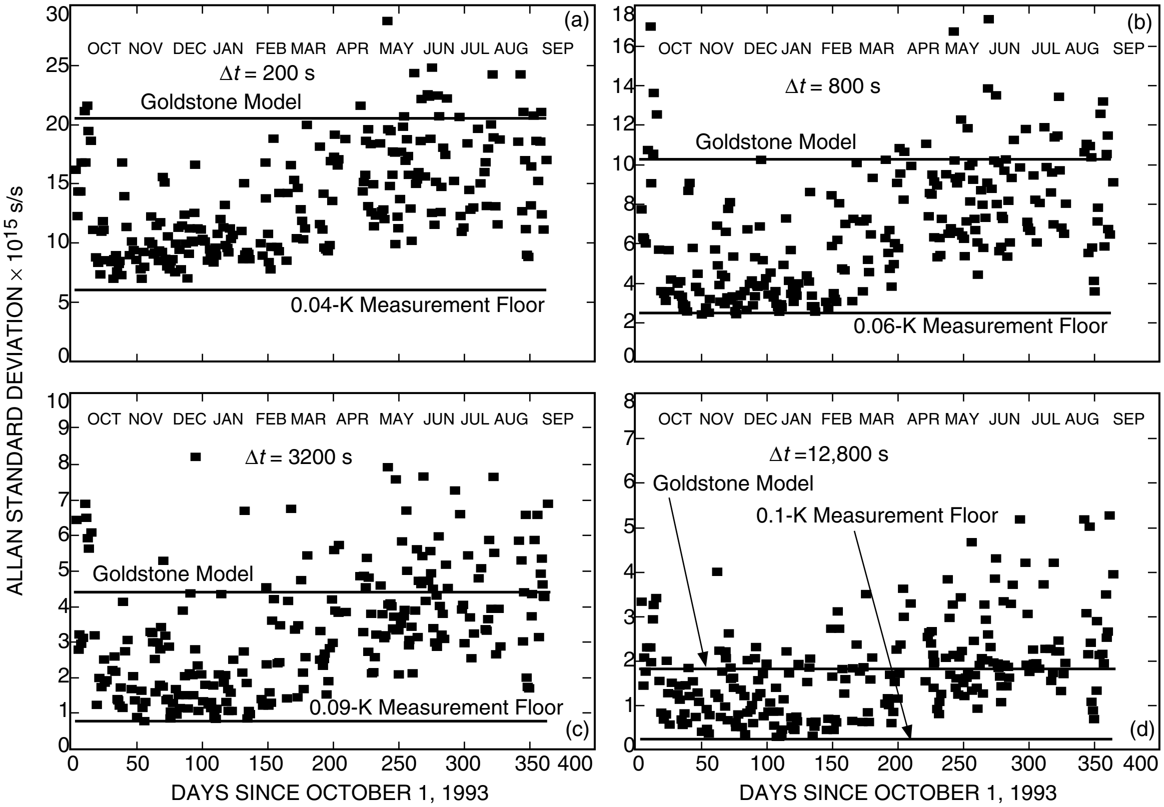

Fig. 1. WVR-derived Allan standard deviation of one-way zenith path delay at DSS 13, October 1993 through September 1994. Each data point represents the ASD calculated from about 24 hours of continuous cloud-free measurements: (a) Δt = 200 s, (b) Δt = 800 s, (c) Δt = 3200 s, and (d) Δt = 12,800 s. Taken from [2].

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[2] G. Resch, personal communication, Jet Propulsion Laboratory, Pasadena, California, November 2001.

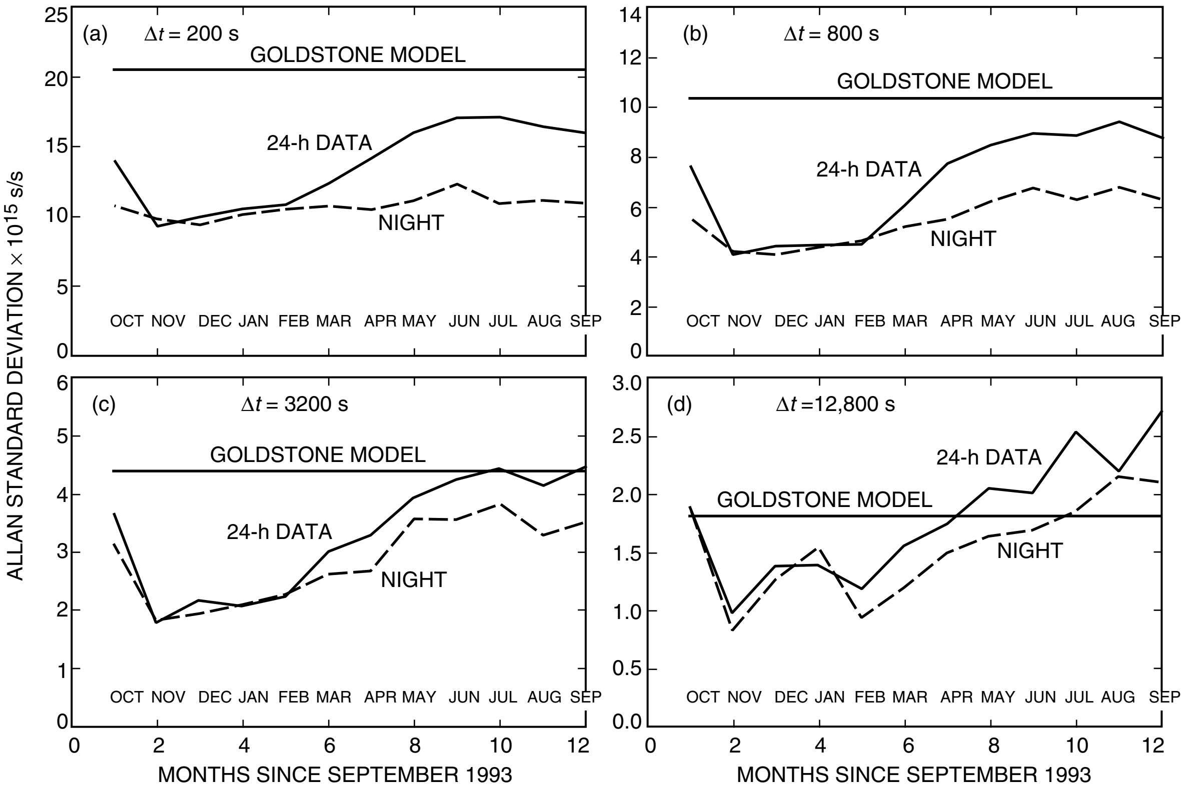

Fig. 2. Monthly averaged Allan standard deviation of one-way zenith path delay at DSS 13. The "night" data refer to calculations that used only 9 p.m. through 5 a.m. local time WVR measurements: (a) $\Delta t = 200$ s, **(b)** $\Delta t = 800$ s, **(c)** $\Delta t = 3200$ s, **and (d)** $\Delta t = 12{,}800$ s. **Taken from [2].**

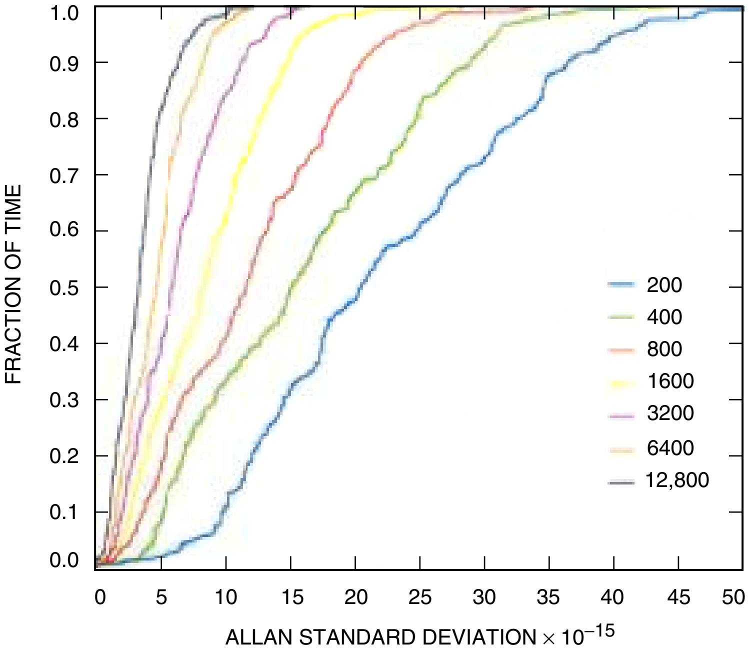

Fig. 3. Cumulative probability distribution for atmospheric turbulence at Goldstone for time intervals from 200 s to 12,800 s, two-way measurement. From G. Resch.

We use these plots to determine the maximum delay fluctuations for Goldstone for separation between antennas corresponding to these intervals. We assume a frozen flow of water-vapor irregularities in the wind and further assume that spatial fluctuations of delay can be obtained from temporal fluctuations using a typical wind speed of 8 m/s for Goldstone [5]. This allows us to determine delay fluctuations and, knowing the delay fluctuations, loss in coherence is calculated using $\exp(-\phi^2/2)$, where ϕ is rms phase variations due to path-length fluctuations. The estimated maximum loss for different antenna spacing for times of 90 and 95 percent looking at zenith are plotted in Fig. 4. For estimating path-length fluctuations at other zenith angles, we multiply the zenith variations by secant zenith angle, assuming that fluctuations are proportional to slant-path length through the troposphere. The estimated maximum losses for different antenna spacings along the wind direction for 90 and 95 percent times for an elevation (EL) of 18 deg are plotted in Fig. 5.

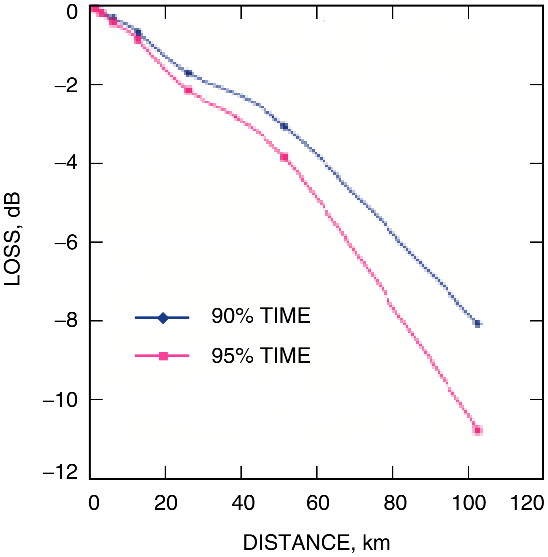

Fig. 4. Estimated maximum loss of uplink array signal at 7.2 GHz while looking at zenith for 90 and 95 percentile time due to phasing errors caused by water-vapor fluctuations at Goldstone.

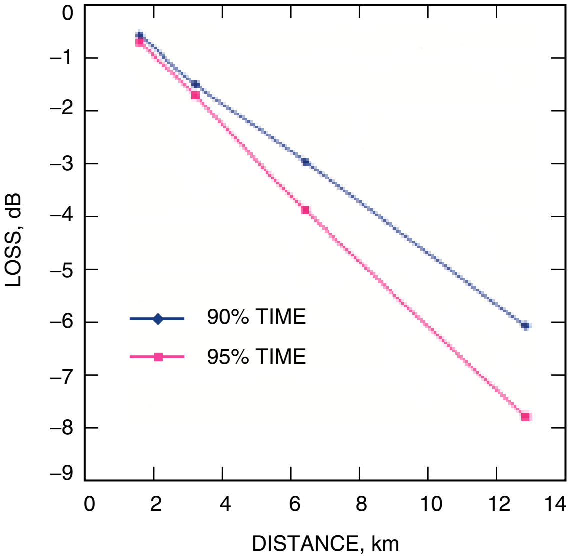

Fig. 5. Estimated maximum loss of uplink array signal at 7.2 GHz while looking at EL = 18 deg for 90 and 95 percentile time due to phasing errors caused by water-vapor fluctuations at Goldstone.

IV. Discussion

A. Results

The expected loss is <0.7 dB for a time of 95 percent for antenna spacing of 1.6 km at an elevation angle of 18 deg at 7.2 GHz (X-band). At longer distances at X-band, and even at a kilometer at higher frequencies, such as 32 GHz (Ka-band), phasing loss could become very large, especially at lower elevations (see Fig. 5). This means that to maintain low loss we have to measure the phase fluctuations and correct for the variations to maintain coherence of the uplink. This can be done in the following way.

If the spacecraft downlink has a reasonable signal-to-noise ratio, the interferometer phase can be measured from the downlink signals and then can be used to estimate the uplink phase correction. Because the troposphere is not dispersive to first order, this can be accomplished even if the uplink and downlink signals are at different frequencies. However, if the spacecraft downlink signal is very weak, then it may be necessary to use a fraction of the array antennas to monitor phase fluctuations using natural compact radio sources in a direction nearby the spacecraft. These measured phase fluctuations would then be used to correct the uplink signals on the remaining antennas.

B. How Good Are These Assumptions?

1. Estimating Spatial Fluctuations from Temporal Variations. Delgado et al. [1] have reported on the correlation between temporal fluctuations estimated using a 183-GHz water-vapor radiometer and spatial fluctuations measured using an interferometer looking at a geo-stationary satellite beacon at about 12 GHz, both co-located at an Atacama Large Millimeter Array (ALMA) site in Chile, as a function of the time of day for several days; this is shown in Fig. 6 [1]. The data show correlation between the path-length fluctuations estimated using the two methods over the time of the day over several days. Figure 7 shows the average correlation coefficient for the available data over the three-week period. It demonstrates a reasonable correlation between the path-length fluctuations using the two methods, although the correlation is far from perfect. The WVR method measures radiation from water vapor and therefore depends on the temperature and pressure in the region where the radiation is generated; however, the phase change produced by the water vapor is independent of the temperature and pressure. Thus, we are likely to have different effects in the two cases, and, therefore, it is not surprising that we see only partial correlation between the two.

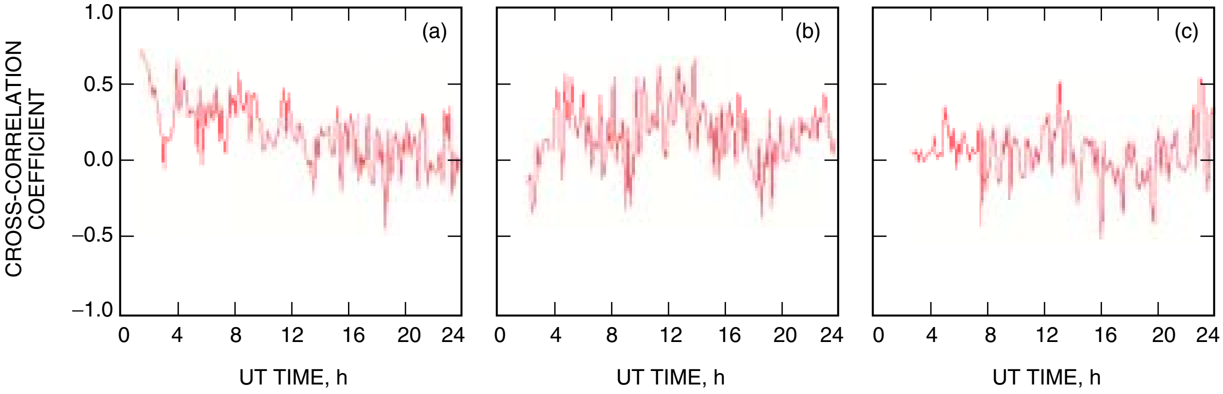

Fig. 6. Cross-correlation of a linear relation between interferometer measured phase and radiometer estimated phase; typical examples for 3 days: (a) November 1, 1999, (b) November 2, 1999, and (c) November 3, 1999. Taken from [1].

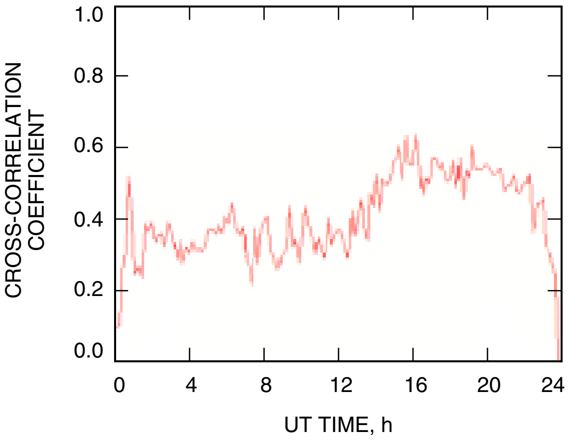

Fig. 7. Average correlation coefficient for the available data for the period from November 1 to November 21, 1999. Taken from [1].

2. Wind Speed of 8 m/s. Truehaft and Lanyi [5] give this as a typical value, and it has been used by most users. Higher wind speeds will cause more rapid reduction in uplink power.

3. Multiplication by Secant of the Zenith Angle. This assumes the troposphere is a flat slab (horizontally stratified) and further assumes that the number of irregularities is proportional to the total path length traversed through the medium. Therefore, change in the path length is proportional to the secant of the zenith angle.

C. What Else Can Be Done?

One way to better characterize the Goldstone site for phase fluctuations is to set up a site testing the interferometer looking at a geo-stationary satellite beacon to monitor atmospheric phase fluctuations, as has been done at the ALMA site or at the Very Large Array (VLA). This can be done with modest resources, but one would need to collect and analyze data over at least one year.

D. How Well Can You Expect to Maintain Array Phasing at Ka-Band Using Radio Sources?

To determine how well phasing can be maintained using radio sources for calibrating adjacent antennas and using these corrections on the nearby antennas looking at a spacecraft, we first estimate a typical angular separation between a calibrator and spacecraft. From the radio source counts at X-band (the Merlin catalog of radio sources at X-band [3,6]), we have about 235 compact sources with flux density more than 0.4 Jy over 2.5 steradians or at least one calibrator source within about 4 deg from any direction in the sky. These sources are mostly compact, flat spectrum sources with spectral index, α, of flux density S_ν (given by $S_\nu \propto \nu^{-\alpha}$, where ν = frequency), given by $\alpha \approx 0.4$. This gives a 0.25-Jy calibration source within about 4 deg from any position in the sky at Ka-band. This is of sufficient strength to calibrate the phase of antennas of $\geq$10-m diameter using only two antennas with a 500-MHz correlator and a 10-s integration time.

Assuming a thin-screen model for effective tropospheric layer at a scale height of about 2 km suggests an effective line-of-sight separation at a screen height of about 140 m. Assuming roughly similar separation on the ground between the two antennas, give a maximum separation of about 280 m for estimating the tropospheric phase fluctuations. Now, using the plots in Fig. 5, we can estimate how much attenuation will be introduced at X-band for a 280-m separation and scale it based on the ratio of the square of the frequency for Ka-band (the loss is proportional to the square of the phase error). This gives a maximum attenuation of about 0.3 dB at Ka-band at Goldstone for 95 percent of time at an elevation of 18 deg using phase calibrations based upon adjacent antennas at a 140-m separation on the ground and with the calibration source up to about 4 deg away in the sky.

This implies that, when the spacecraft downlink does not have enough signal to determine atmospheric phase fluctuations in the receive mode, we may have to take out a fraction of the antennas (about 10 percent) to measure atmospheric fluctuations by looking at a nearby radio astronomy calibrator to correct atmospheric variations, and we may further lose up to about 7 percent (95 percentile time) due to phasing accuracies.

Also, it should be pointed out that to calibrate on a 0.25-Jy source with small antennas, one would need a broadband (>500-MHz) correlator. This correlator would need to process only 10 percent of the antennas in the array. A much larger correlator for all antennas in the array would be desirable to perform astronomical observations using synthesis imaging.

V. Conclusion

For an uplink array at Goldstone working at X-band and spread over distances up to about a kilometer, it is not necessary to have a real-time atmospheric phase measurement and correction system for atmospheric phase variations because phasing loss is expected to be <1 dB for at least 95 percent time down to 18-deg elevations. However, for larger array sizes at X-band and even for one kilometer at Ka-band, coherence loss could be appreciable unless real-time measurements of the phase fluctuations are made and corrections are applied to the uplink signals.

Acknowledgments

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