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Data Processing for Atmospheric Phase Interferometers

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Abstract

This paper presents a detailed discussion of calibration procedures used to analyze data recorded from a two-element atmospheric phase interferometer (API) deployed at Goldstone, California. In addition, we describe the data products derived from those measurements that can be used for site intercomparison and atmospheric modeling.

Simulated data is used to demonstrate the effectiveness of the proposed algorithm and as a means for validating our procedure. A study of the effect of block size filtering is presented to justify our process for isolating atmospheric fluctuation phenomena from other system-induced effects (e.g., satellite motion, thermal drift). A simulated 24 hr interferometer phase data time series is analyzed to illustrate the step-by-step calibration procedure and desired data products.

Introduction

The phase measurements made by an interferometer allow for observations of differential delay paths through the atmosphere as a function of time. The parameters that principally affect the differential delay path at Ka-Band are, in order of significance: water vapor, temperature, and pressure. Since most atmospheric water vapor is confined to the troposphere (<10 km) with an exponential scale height of 2 km these measurements are primarily affected by the variability in the precipitable water vapor (PWV). The water vapor that is exposed to temporal turbulent air flow conditions in the troposphere generates an irregular (random) distribution of PWV. This results in temporal variation of the refractive indices of the atmospheric irregularities, which leads to variations in the effective electrical path length (phase) of an electromagnetic wave propagating through the atmosphere (ref. 1).

In this paper, we provide a detailed analysis of the effect of block size filtering in detecting and estimating the energy of the atmospheric induced phase fluctuations. The accuracy of the proposed algorithm is then quantitatively described through simulated data with known characteristics.

Interferometer Raw Phase Time Series

The NASA atmospheric phase interferometer (API) has been deployed at the NASA Deep Space Network (DSN) tracking complex at Goldstone, California, since May 2007 (ref. 2). The API records the raw phase data in intervals of 1 sec (86400 points per day). This data collection architecture will be adopted by the proposed algorithm and is the starting point for the analysis described herein.

Besides atmospheric disturbances, the raw phase time series contains “2π wraps”, phase fluctuations due to the orbital motion of the satellite, slowly varying instrument drifts due to temperature changes in transmission lines and receivers, phase noise in the receivers, and errors in the electronic data collection (bad points). Before further analysis can proceed, this satellite motion, as well as other slowly varying system-induced variations must be removed from the raw phase time series data.

Root Mean Square Phase Integration Time

The most fundamentally important quantity that is to be derived from the interferometer phase time series (after calibration) is the root-mean-square (*rms*) value of the phase as a function of time. The *rms* provides a direct estimate of the energy of the atmospheric-induced phase fluctuations on a given time scale.

An interferometer will directly detect atmospheric-induced phase fluctuations on time scales ranging from 0 to (b/v) or larger, where b is the physical baseline distance and v is the average wind speed aloft (ref. 3). The term (b/v) is called the crossing time. This term is defined as the time for a water vapor frozen screen to travel from one antenna to the next assuming a constant wind speed v (ref. 4). In order to accurately compute the *rms* of the phase, it is necessary to integrate over many crossing times (e.g., $> \sim 40 \, x \, b/v$).

The physical baseline distance is a known quantity (e.g., 256 m for the NASA API), but the average wind speed aloft is not an easily obtainable quantity. In order to estimate crossing times for the NASA API we need to make an assumption for the average wind speed aloft at Goldstone, California. A reasonable approximation is to assume a factor-of-two increase with respect to the average surface wind speed (a measurable quantity). The average surface wind speed for one year of measurements (2007 to 2008) at 90 percent of the time was approximately 8 m/s (ref. 5). Given our 256 m baseline, the average crossing time is estimated to be approximately 16 sec. Using the "rule-of-thumb" given above, we require that at least 600 sec be used as the interval for estimating the *rms* of phase fluctuations. Over a 600 sec period, however, there are significant phase variations caused by satellite motion and slowly varying system thermal effects. In order to ensure a minimal contribution of these effects in the *rms* computation of atmospheric phase fluctuations a quadratic fit is utilized for the removal of those effects at each integration period.

Data Calibration Procedure

The Goldstone API stores the raw interferometer phase daily. Each data set contains 86,400 data points (1 record per second). The 24 hr data sets are calibrated by using the following step-by–step process detailed below.

Step 1

The 24 hr time series of phase data is first unwrapped (eliminating all 2π turns). The unwrapped data is segmented into smaller blocks of data. The block size is determined by the *rms* integration time. If we choose 600 sec as the integration time, the 24 hr data set will be segmented into 144 blocks, where each block contains 600 points.

Step 2

A second-order polynomial is fit (least mean square criteria) to each block of data. The polynomial fit is subtracted from the raw data points within each block. The resulting data points form a calibrated block time series. The calibrated blocks are free from satellite motion and any slowly varying system effects. Notice that this step does not eliminate any rapidly varying system effects (e.g., phase noise from oscillators, etc.).

Step 3

Check for bad data blocks. Bad data blocks are defined in our procedure as blocks with missing points, bad data points within the block, and other known instrument or site anomalies. We have removed those entire blocks from any statistical computation of the phase ***rms***.

Description of Data Products

The primary data products that can be determined from the calibrated data blocks include:

1. The block rms. The block *rms* is the most fundamentally important quantity in the analysis of the API phase. The block *rms* is a direct estimate of the energy of the atmospheric-induced phase fluctuations in the block time scale (integration time).

2. The block temporal phase structure function. This is an indirect way to estimate the phase fluctuation *rms* on different block time scales. The maximum resolvable time scale in this product is the block time duration. The minimum resolvable time scale corresponds to the data sampling rate (e.g., 1 sec).

3. The block temporal power spectrum. The block temporal power spectrum provides a display of the power of the atmospheric-induced phase fluctuations as a function of frequency. The area under the curve of the power spectrum plot provides an estimate of the energy of the fluctuation or *rms*.

4. The cumulative distribution function (CDF) and probability density function (PDF) of the rms. The CDF is a measure of the probability that a certain phase *rms* will be present at any given time. This CDF is normally utilized for site comparison and for system design of a widely distributed antenna system.

Data Calibration Applied to a Simulation Case

In order to confirm the validity of the methodology, we applied the procedure to a simulated raw phase data set with known parameters.

The simulated raw interferometer phase is described by the following equations:

$$\phi_{\text{sat}}(n) = 20\sqrt{2}\left[1-\cos\left(\frac{2\pi}{86400}N + 2.2689\right)\right] \rightarrow \text{radians} \tag{1.a}$$

$$\phi_{\text{atm}}(n) 5\sqrt{2}\,\frac{\pi}{180}\left[\sin\left(\frac{2\pi}{10}n\right)+\sin\left(\frac{2\pi}{100}n\right)+\sin\left(\frac{2\pi}{300}n\right)\right] \rightarrow \text{radians} \tag{1.b}$$

$$\phi_{\text{noise}}(n) = \text{Gaussian}\left[86400, \mu, \sigma_{rms}\right] \rightarrow \mu = 0, \sigma_{rms}\, 2\,\frac{\pi}{180} \rightarrow \text{radians} \tag{1.c}$$

$$\phi_{\text{rawphase}}(n) = \phi_{\text{sat}}(n) + \phi_{\text{atm}}(n) + \phi_{\text{noise}}(n) \rightarrow \text{radians} \tag{1.d}$$

The first term (Eq. (1.a)), simulates the effect of satellite motion as detected by the interferometer. The second term (Eq. (1.b)), models the atmospheric-induced phase fluctuation by using three sinusoidal te*rms*. The last equation (Eq. (1.c)) models the system random phase noise by using a Gaussian distribution with zero mean. The three te*rms* are added (superposition applies) to form the basis for simulating the raw interferometer phase time series.

Figure 1(a) displays a simulation (wrapped version of Eq. (1.d)) of a typical phase time series recorded by an interferometer in a 24 hr period. Notice the many 2π turns in the raw data throughout the course of a day. In order to further analyze the data, it is necessary to remove these 2π wraps (Step 1 in the data calibration process).

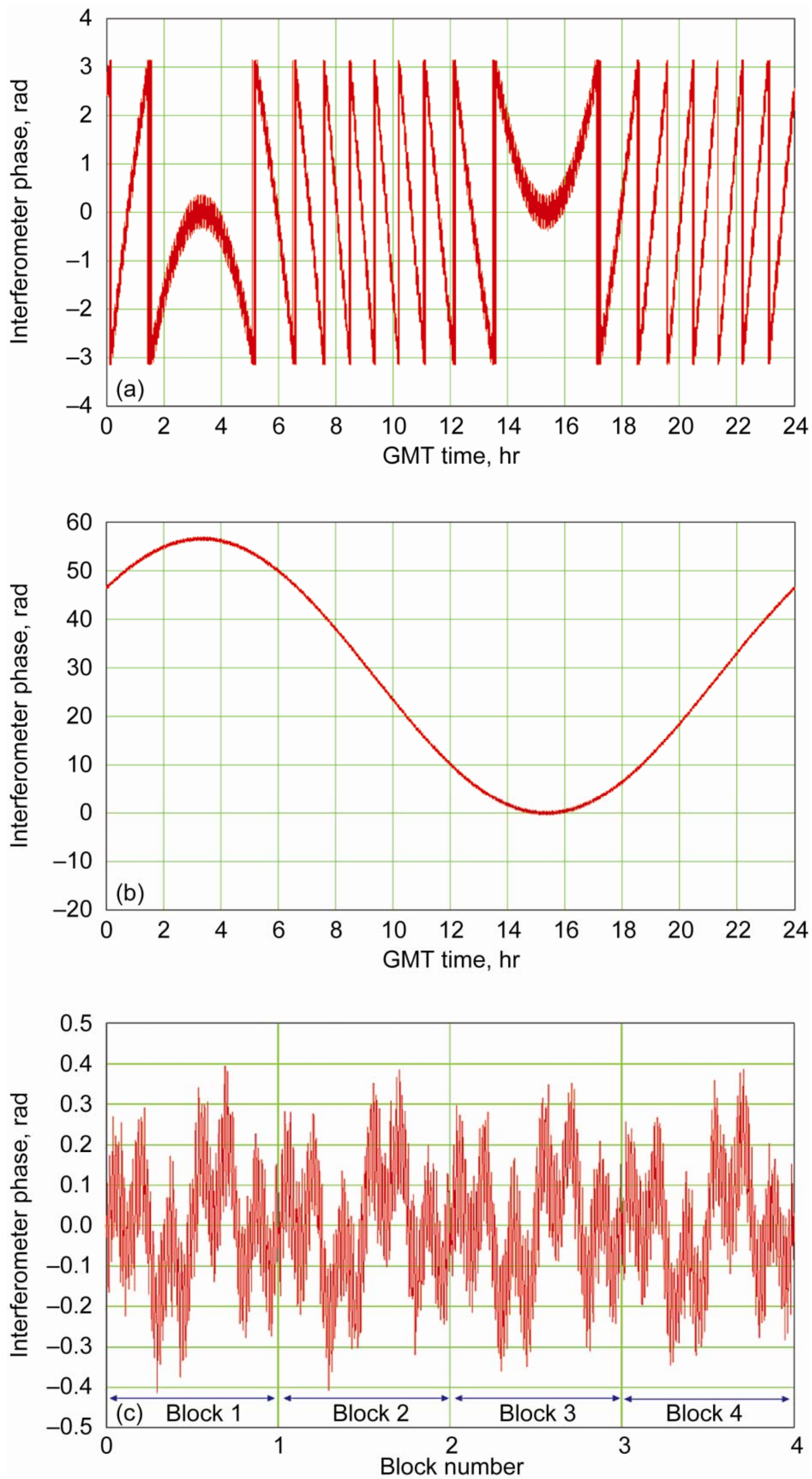

Figure 1.—Simulated cases. (a) “Wrapped” raw interferometer phase. (b) “Unwrapped” raw interferometer phase. (c) Calibrated atmospheric phase (first four blocks).

After the unwrapping function is applied to the data in Figure 1(a) the resulting interferometer raw phase time series will not have any 2π discontinuities, as shown in Figure 1(b).

The next step in the procedure requires that the un-wrapped (Fig. 1(b)) phase time series data be segmented into blocks. We assume an *rms* integration period of 600 sec. This corresponds to 144 blocks in a given 24 hr period (one day). A second-order polynomial is fit to each block (144 blocks) and the difference between the block raw phase and the block polynomial results in a calibrated block (satellite motion removed). The resulting phase time series for the first four calibrated blocks are shown in Figure 1(c).

Effect of Polynomial Fit and Block Size

The process of fitting a second order polynomial to each data block for removing the satellite motion component may add an additional bias or error to the computation of the block *rms*. The error contribution of this procedure can be investigated and simulated by only considering the satellite motion component (Eq. (1.a)). Figure 2 shows the maximum error (unwanted) as function of block size. Notice that as the block size increases, the maximum error in each block also tends to increase. This can be explained by the departure of a satellite motion's shape from second-order. Nevertheless, for block sizes ranging from 600 to 3600 sec, the error contribution from the polynomial fit is negligible.

Effect of Block Size in the Computation of *rms*

In theory, the minimum block size required for detecting the energy of the atmospheric-induced fluctuations is determined by having an *rms* integration time that is much greater than the crossing time. This situation can be numerically investigated by simulating the atmospheric-induced fluctuations by using several sinusoidal te*rms* of fixed frequencies (see Eq. (1.b)). Since the atmospheric-induced fluctuations are known in the simulation, we can compute the error in detecting and estimating the energy that each sinusoid contains as a function of *rms* integration time or block size.

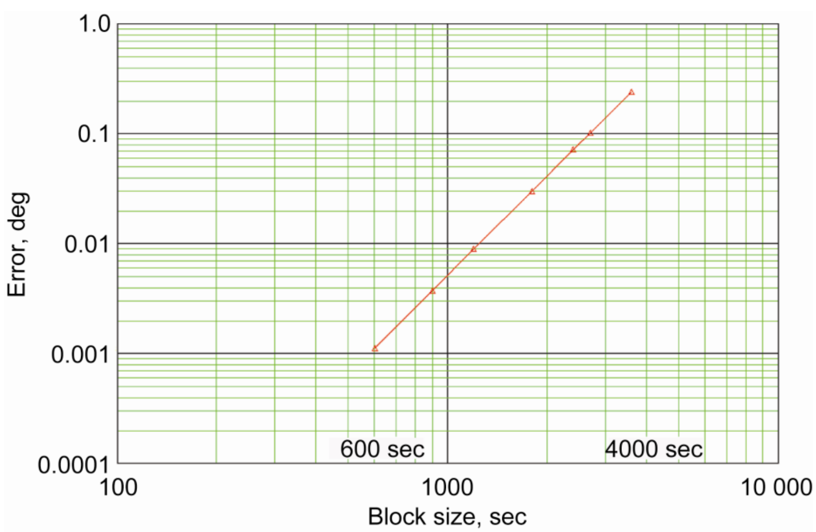

Figure 2.—Maximum error as function of block size.

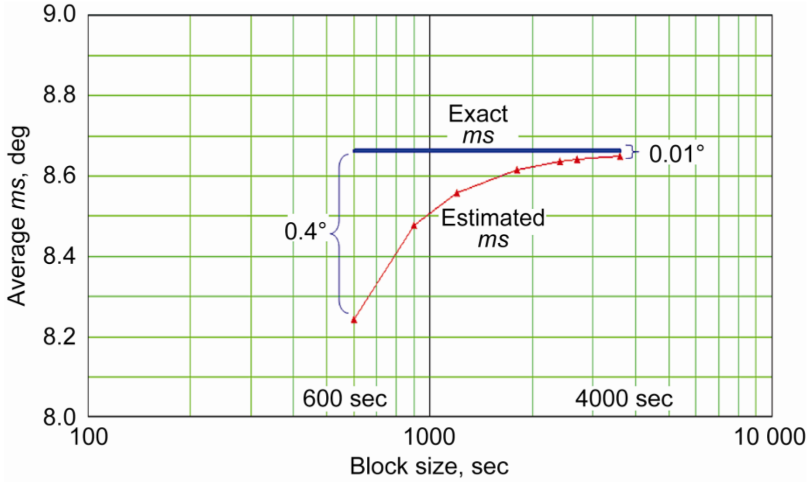

Figure 3.—Maximum error as function of block size.

For the simulation, we selected three sinusoids with periods of 10, 100, and 300 sec, respectively. Each sinusoid has 5° *rms* amplitude. The simulation will not contain any random system noise (Eq. (1.c)). Figure 3 shows the average block *rms* as a function of block size. Notice the average block *rms* converges to the exact *rms* value ($\sqrt{3}\times 5°$) as we increase the block size time.

Practically speaking the *rms* converges for a block size time of ~3600 sec, which is a factor of twelve times of that of the largest sinusoidal period (300 sec) in the simulation. Notice that at 600 sec, the block size error is small (0.4°), which is a factor three smaller than the phase noise for the interferometer.

Derived Products—Simulation Case

The 24 hr *rms* block time series is obtained by computing the standard deviation (*rms* with zero mean) of each calibrated block (144 blocks). The resulting *rms* time series for the entire 24 hr period is presented in Figure 4(a). This product depicts the variation of the energy of the fluctuations (fixed integration time) as a function of time. The random temporal variation of the fluctuations can be easily seen.

In addition to the block *rms* time series, we can also derive the average (over 144 blocks) block temporal structure function and the average (over 144 blocks) block phase power spectra. Figure 4(b) shows the block temporal structure function. Notice that at large time scales the average *rms* is approximately equal to the average block *rms* computed from the block *rms* time series. The periodic structure seen for time scales longer than 100 sec is characteristic of that due to sinusoids. The null structure and peaks of the variation for large time scales is predictable (ref. 6).

The average block power spectrum is depicted in Figure 4(c). Notice that the power levels of the three sinusoidal components show up as spectral peaks with equal strength (as expected). The effectiveness of the block filtering can be indirectly seen in this plot by noticing that the energy at low frequencies is decaying very rapidly below any significant levels. The area under the curve in this plot also provides a measure of the *rms* (the energy of the fluctuations) in any frequency band, therefore it can be also be used to determine the frequency (period) of the fluctuations.

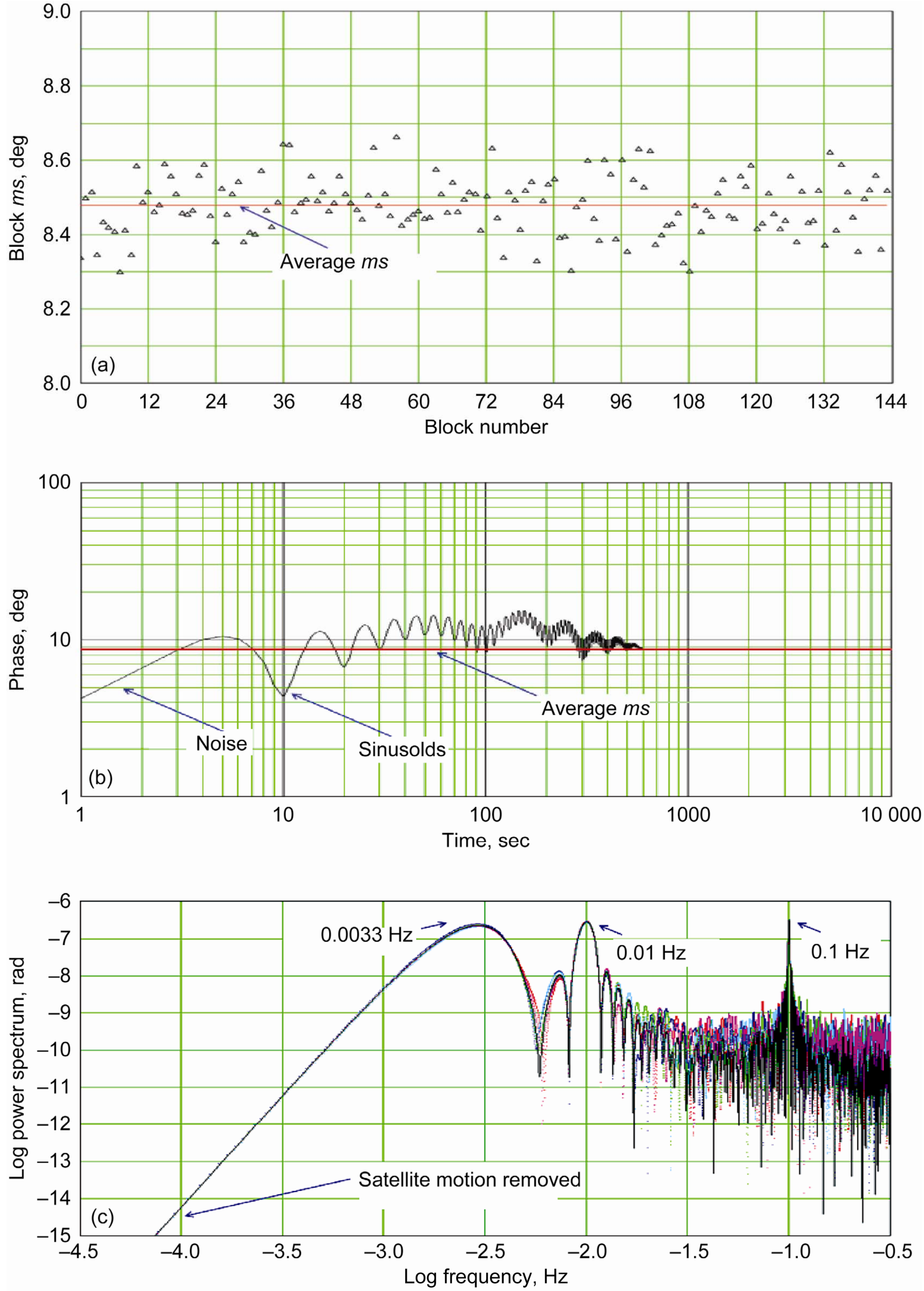

Figure 4.—(a) *rms* time series (144 points). (b) Average block square root temporal structure function (simulated case). (c) Average block power spectrum (also shown are the power spectra of several blocks).

Concluding Remarks

In this paper we described the rationale and validation for calibrating the raw phase time series measured by a two-element atmospheric phase interferometer (API). We discussed the impact of block size (block filtering) in determining the energy of the atmospheric phase fluctuations through simulation. The simulation results showed that a second-order polynomial fit is very effective in removing any slowly varying system and satellite motion on time scales ranging from 600 to 3600 sec. The impact of selecting a block time of 600 sec for the computation of *rms* was found to be at least three times smaller than the random phase noise power found in a typical two-element API.

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This paper presents a detailed discussion of calibration procedures used to analyze data recorded from a two-element atmospheric phase interferometer (API) deployed at Goldstone, California. In addition, we describe the data products derived from those measurements that can be used for site intercomparison and atmospheric modeling. Simulated data is used to demonstrate the effectiveness of the proposed algorithm and as a means for validating our procedure. A study of the effect of block size filtering is presented to justify our process for isolating atmospheric fluctuation phenomena from other system-induced effects (e.g., satellite motion, thermal drift). A simulated 24 hr interferometer phase data time series is analyzed to illustrate the step-by-step calibration procedure and desired data products.

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