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| Application, Validation AND DATA PROCESSING of atmospheric path length standard deviation statistics for ground-based antenna array performance predictions | |

# 1 Introduction

This document contains background information and data processing techniques for the application of atmospheric-induced path length statistics provided in Table II-11 in the Recommendation ITU-R P.311 Databanks. A preliminary model is provided to compute the average array loss for an antenna array of arbitrary geometry due to fluctuations of water vapour resulting from atmospheric turbulence. This represents the dominant dynamic path length variation component. Validation of the assumptions required for the use of the proposed model, as well as the measurements themselves, are also provided.

The model takes as input, the atmospheric-induced path length variation statistics defined in Table II-11 to derive the array loss factor (in dB) for an arbitrary geometry array at a given elevation angle and operational frequency. The basis of this model is derived from well accepted atmospheric frequency scaling parameters and Kolmogorov turbulence theory.

Section 2 describes the problem statement and provides a proposed procedure for translating path length statistics to array loss factor. Section 3 provides some data to validate the assumptions needed for use of the proposed model. Section 4 describes an example experimental setup and the data processing techniques employed to measure path length turbulence. Section 5 provides validation of the measurement of the site test interferometer with two collocated water vapour radiometers. Section 6 provides validation of the phase statistics scaling procedure via comparison of two separate STIs on two unique baseline separations at the same site. Section 7 provides estimates of the expected array loss due to the atmospheric path length variations for a 3-element antenna array located at the Goldstone Deep Space Communications Complex (GDSCC). References dealing with these derivations and further validation of the approach are listed in Section 8 of this document.

# 2 Array loss due to atmospheric turbulence: Derivation

For the purposes of (1) generating statistical models, and (2) predicting the performance of communications systems in a widely distributed ground-based antenna array architecture, it becomes necessary to define the impact of path length (phase) turbulence, as induced by the atmosphere, on array combining losses. Atmospheric-induced path length variations are directly correlated with the spatiotemporal variations in tropospheric water vapour that occur along the line of sight path for individual antenna elements comprising an array. Turbulence in the troposphere result in short timescale variations of the refractive index of the atmospheric channel which can be unique to each antenna element and directly impact the array combining efficiency of a ground-based antenna array via distortions of the phase front received and transmitted, as indicated in the diagram of Figure 1, for the transmit case.

The *average loss* of an array in the presence of atmospheric turbulence integrated over a finite time interval can be described by a generalized form of the Ruze equation,

where,

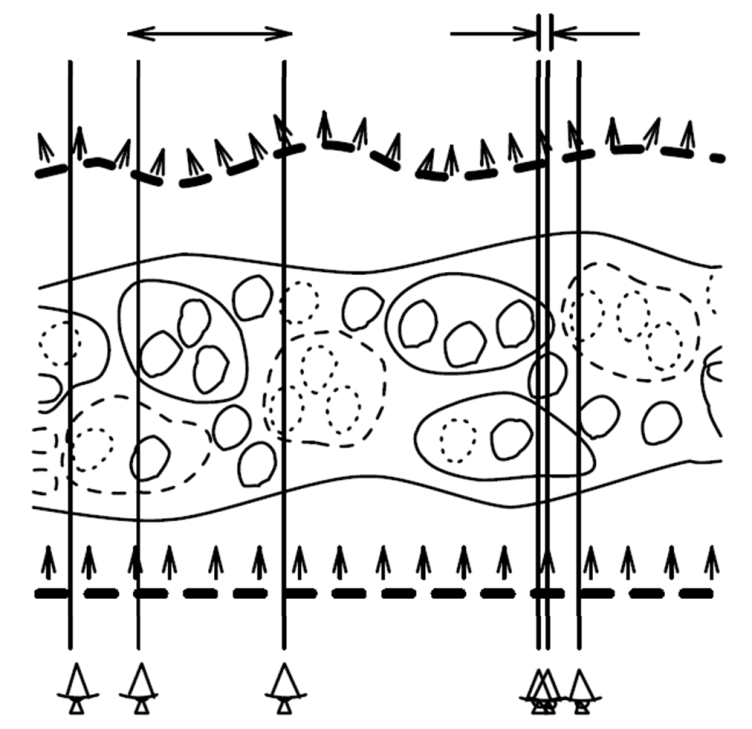
is the average loss of the array due to atmospheric phase turbulence

is the number of elements in the array

is the phase variance (in radians) between elements *m* and *n* in the array

Figure 1

Distortion of phase front of transmitted wave induced by variation in water vapor content along the line of  
sight path of each element of an antenna array.



Therefore, the primary parameter of interest for determining array loss in the presence of atmospheric turbulence is the phase variance term, , which is a function of elevation angle, frequency, and separation distance between antenna elements.

For a given set of measured path length statistics, at a fixed elevation angle and separation distance, the phase variance (in radians) can be scaled to other frequencies, separation distances, and elevation angles via,

where,

is the square of the path length standard deviation provided in Table II-11 of the Recommendation ITU-R P.311 databanks (in mm2)

is the desired frequency and the measurement frequency, respectively (in Hz)

is the speed of light (m/s)

is the desired elevation angle and the measurement elevation angle, respectively

is the desired baseline and the measurement baseline, respectively

is the phase structure function exponent (given by Kolmogorov turbulence theory)

is an exponent equal to 1 for thick screen approximation and 2 for thin screen

The linear scaling parameter for the rms phase is due to the fact that the atmosphere can be considered as non-dispersive away from absorption line centres. The exponents and are necessary for scaling of the phase variance term to different baseline separations and elevation angles, respectively, and are dependent on the dimensionality and outer scale of the turbulence process occurring (and hence, the local site climatology). Typical theoretical values for and are given by Kolmogorov turbulence theory, as described in Table 1, and are recommended for general application of the phase statistics table. For baseline separation distances longer than the scale height of the turbulent layer (defined as *H* in Table 1), approaches a value of unity. In reality, the true scaling parameters may lie between these extremes and may possess some seasonal variation for a given site. The inclusion of statistical site-dependent scaling parameters will be investigated in future work.

Table 1

Bounded values of α and γ for scaling of phase variance for array combining loss

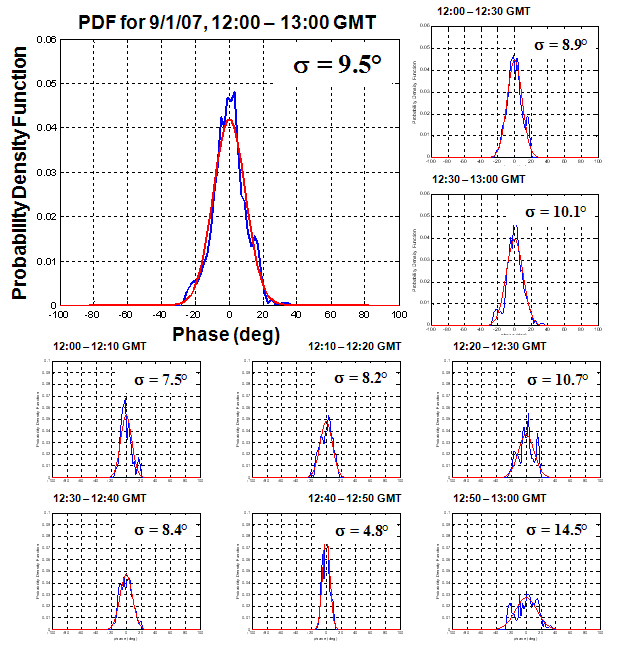
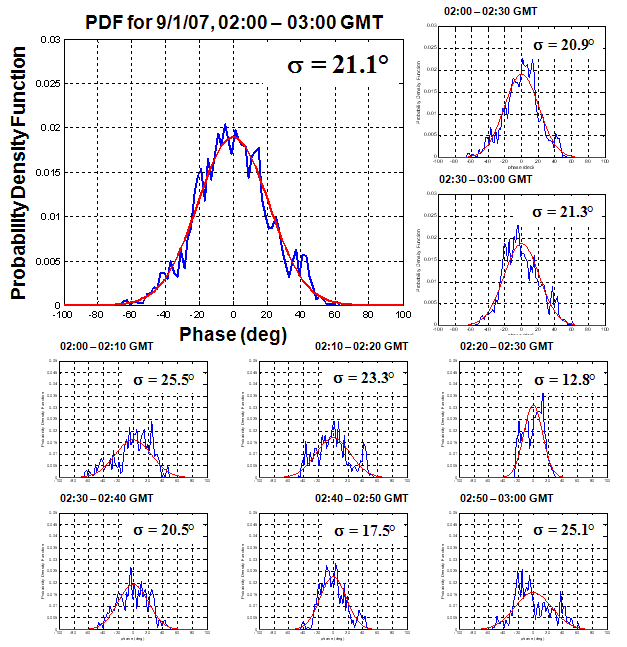
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| --- | --- | --- |
| **Parameter** | **Thick Screen Model**  **(3D Turbulence – warm, humid climates)** | **Thin Screen Model**  **(2D Turbulence – high altitude, dry climates)** |
| *β* | 5/3 (for *d* < *H*) | 2/3 (for *d* >*H*) |
| γ | 1 | 2 |

# 3 Validation of assumptions

For application of interferometric-measured phase statistics converted to array loss prediction via the Ruze equation, it must be assumed that the phase statistics can be described by a zero-mean Gaussian process. Validation of this assumption is shown in the probability density function (PDF) of measured site test interferometer data at the Venus site located in Goldstone, CA, as shown in Figure 2. For various time scales, it is evident that this assumption holds. Slight deviations of this assumption at the shortest time scales is due to the reduced number of samples available.

Figure 2

PDF's of phase fluctuations for 1 hr (top left, 1), 30 mins (top right, 2), and 10 mins (bottom center, 6)  
at (a) 02:00 - 03:00 GMT and (b) 12:00 - 13:00 GMT on 9/1/07.

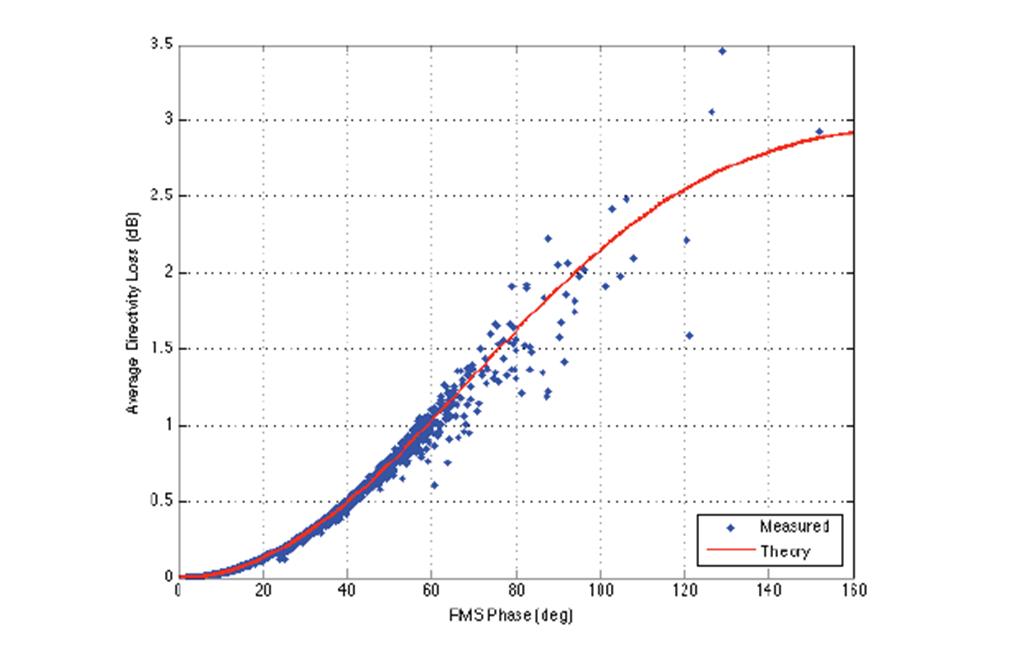


**(a) (b)**

The plot of Figure 3 shows the comparison between the predicted array loss for a given rms phase and the measured time-averaged array loss for the two-element array at Goldstone, CA, for   
an entire year. From the plot, we observe excellent agreement between the two curves, indicating the correctness of the theoretical derivation for array loss in the presence of atmospheric-induced phase fluctuations and the justification to utilize differential phase statistics to predict overall array performance for an arbitrary geometry. Deviations from the theoretical curve are likely due to the lack of resolution to effectively determine a normal distribution over the particular time scale.

Figure 3

Measured vs. theoretical array loss for varying rms phase as recorded from May 2007-May 2008   
at Goldstone, CA.



# 4 Experimental setup and data processing procedure

A typical method to measure path length turbulence statistics is through the use of a site test interferometer (STI). An example setup is the STI located at the Venus Site (35.248 °N, 116.791 °W) of the Goldstone Deep Space Network Tracking Complex which is comprised of a two‑element beacon receiver separated on a 256-m E-W baseline and is shown in the photographs of Figure 4. The system utilizes two 1.2-m offset-fed reflector antennas to receive an unmodulated beacon signal broadcast from the geostationary satellite, Anik F2 (longitude 248.9 E), at 20.2 GHz. The receivers perform time-synchronous Fast Fourier Transforms to measure the in-phase and quadrature (I/Q) components of the receive signal every second. From this information, the differential phase, between the two STI elements is derived in post-processing. The noise floor of

this system was tested via a zero-baseline test and resulted in a phase (path length) rms noise floor of 1.8° (0.0742 mm ). A detailed description of the STI hardware and receiver operations can be found in [6].

FIGURE 4

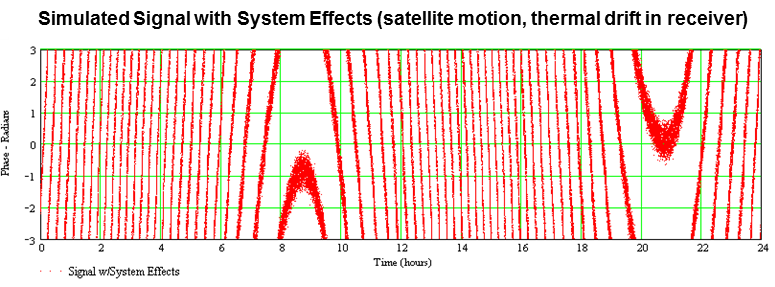
Goldstone Venus Site STI layout (left) and close-up of individual receiver element of the STI (right)

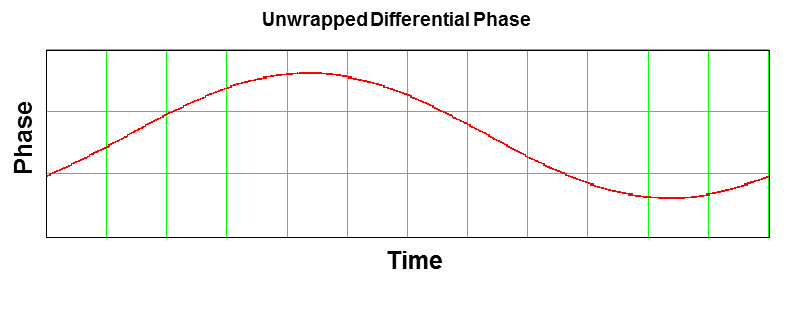
 

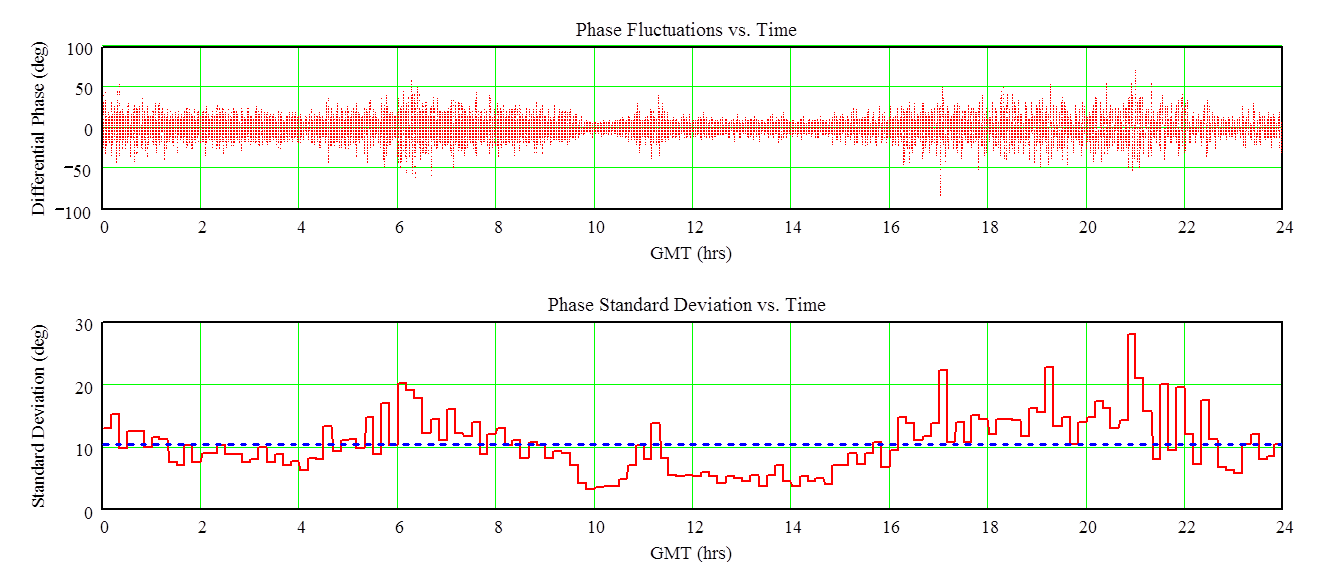
Fundamentally, the measurement of differential phase as recorded by the STI includes the relative motion of the satellite, as well as slow-varying system effects (i.e., thermal variations, instrument drift), which are removed via a second order polynomial fit over 10-min blocks on the unwrapped phase. The calibration process has been validated and shown to have negligible impact in the processed data [7]. Once these effects are removed, only the dynamic variations due solely to the atmosphere remain. Over the 10-min blocks, the standard deviation of the phase variations is calculated. This process is shown pictorially in Figure 5 and described completely in [7-8].

Figure 5

Data calibration procedure







Data is stored locally on a central site computer and bad data blocks are removed in post-processing utilizing the following conditions. For a given 10-min block of data,

– Data is flagged and removed if the rms value over that block is less than or equal to the measured zero-baseline phase rms noise floor.

– Phase rms values greater than 180° are removed

– During routine maintenance activities, data blocks are flagged and removed.

– Blocks in which the individual receiver FFT bins differed from each other were recorded by the receivers are flagged and removed.

# 5 Validation of measurements with collocated water vapour radiometers

In August 2008, two water vapour radiometers (WVRs) were collocated with the two-element site test interferometer (STI) located at the Venus site of the Goldstone Deep Space Communications Complex (GDSCC) described in Section 4. The differenced path delay between the two WVR units forms an additional data type that can be used to validate the STI phase fluctuations and confirm the atmospheric nature of these fluctuations. The use of two WVRs allows estimation of their differenced path delay, which produces a data type that could be correlated directly against the STI phase difference fluctuations. The details of this experiment are more fully described in [9]. A comparison of the rms temporal delay (which is directly related to the rms path delay) for the differenced WVRs and the STI on the same baseline for the month of August 2008 is shown in Figure 6 and a zoomed-in view for a one week period in August 2008 is shown in Figure 7.

Figure 6

Goldstone Venus STI and DWVR zenith differenced path delay scatter (standard deviation in 1200-s blocks) for August 2008 (thermal noise estimates removed).



Figure 7

Expanded view of STI and DWVR zenith differenced path delay standard deviation (in 1200-s blocks) time series for the selected several-day period of August 17–25, 2008.



# 6 Validation of array loss model with separate interferometer measurements on different baselines

Considering that two independent measurements of atmospheric phase turbulence were collected at the Goldstone Deep Space Communications Complex at two different baselines and at two different physical locations, validation of the array loss model can be performed. The data utilized for this comparison are provided in Table II-11 in the Recommendation ITU-R P.311 Databanks.

The Venus STI (described in Section 4) utilizes a 250-m baseline and a measurement frequency of 20.2 GHz, while the Apollo STI has a baseline of 190-m and a measurement frequency of 12.45 GHz. The elevation angles of the two instruments are comparable. Following the scaling procedure of the STI-measured statistics and the array loss model described in this document, we can derive the expected attenuation for the two-element array on a common baseline and common frequency. Figure 8 shows a comparison of the derived monthly cumulative distribution curves for the Apollo and Venus STIs, scaled to 7.15 GHz (DSN operational frequency), 20 deg elevation angle, and 190-m baseline. The comparison of the curves implementing the scaling and array loss models show reasonably good agreement between the two separate STI instruments. Differences in the two curves are hypothesized to be due to differences in the relative altitudes of the two sites, which is not directly considered in the currently proposed phase statistics scaling model.

Figure 8

Monthly comparison of predicted two-element array loss from two STIs in operation at GDSCC scaled to a common 7.15 GHz frequency, 20 deg elevation angle, and 190-m separation distance.



# 7 Example predicted array loss due to atmospheric turbulence statistics

The annual cumulative distribution function (CDF) for the path length rms as measured by the GDSCC Venus site data from Table II-11 is plotted in Figure 9, with the statistics of the mean year, and an example monthly CDF for 2009‑ plotted in Figure 10. We observe that, on a yearly basis, the statistics appear to be very well behaved and agree with expectations based on our knowledge of the physics governing atmospheric turbulence. Furthermore, on a monthly basis, we observe that summer months possess higher path length variability than winter months, which agrees precisely with expectations.

The geometry of the 3-element array at the Goldstone Deep Space Communications Complex is shown in the aerial photograph of Figure 11. Figure 12 shows the predicted array loss employing the proposed array loss model for two specific frequencies as a function of elevation angle for the 3-element array shown in Figure 11.

There are currently unpublished results showing good agreement between adjusted STI phase fluctuations with those obtained from demonstrations of DSN arrays tracking spacecraft over a wide range of elevation angles and baseline projections against spacecraft source.

Figure 9

Plot of annual path length rms CDF for Goldstone, CA

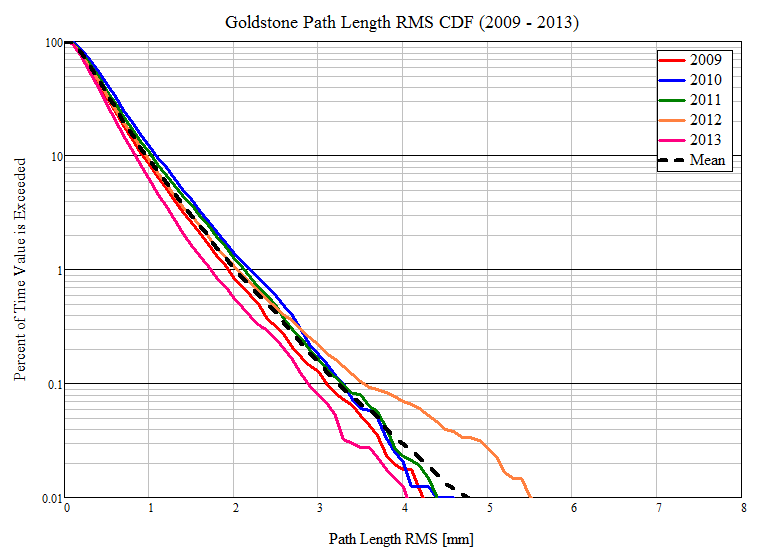


Figure 10

Plot of monthly path length rms CDFs for Goldstone, CA for 2009

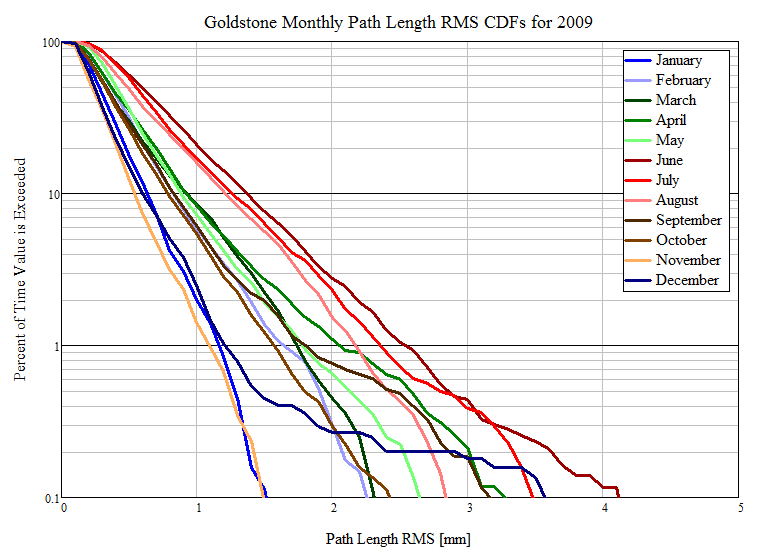
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Figure 11

Geometry of the 3-element array at the Goldstone Deep Space Communications Complex.

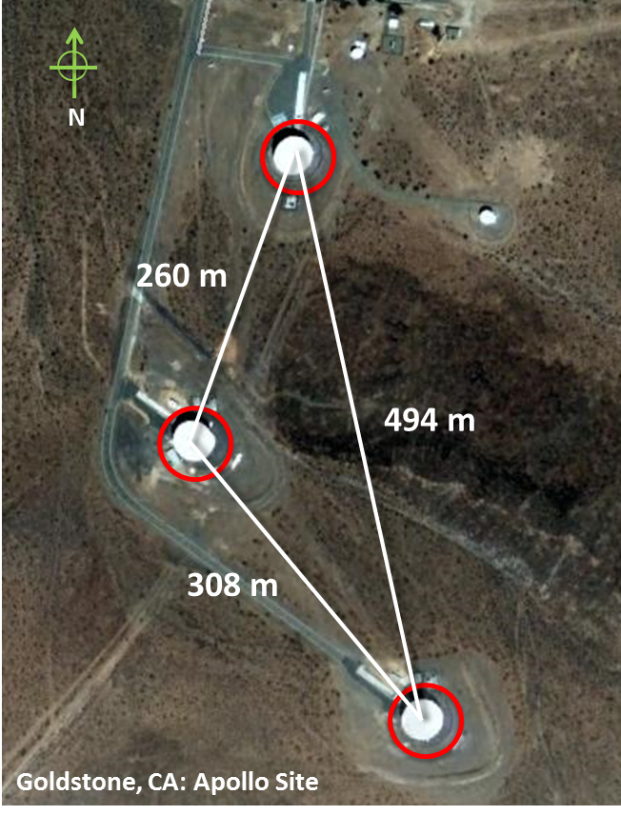
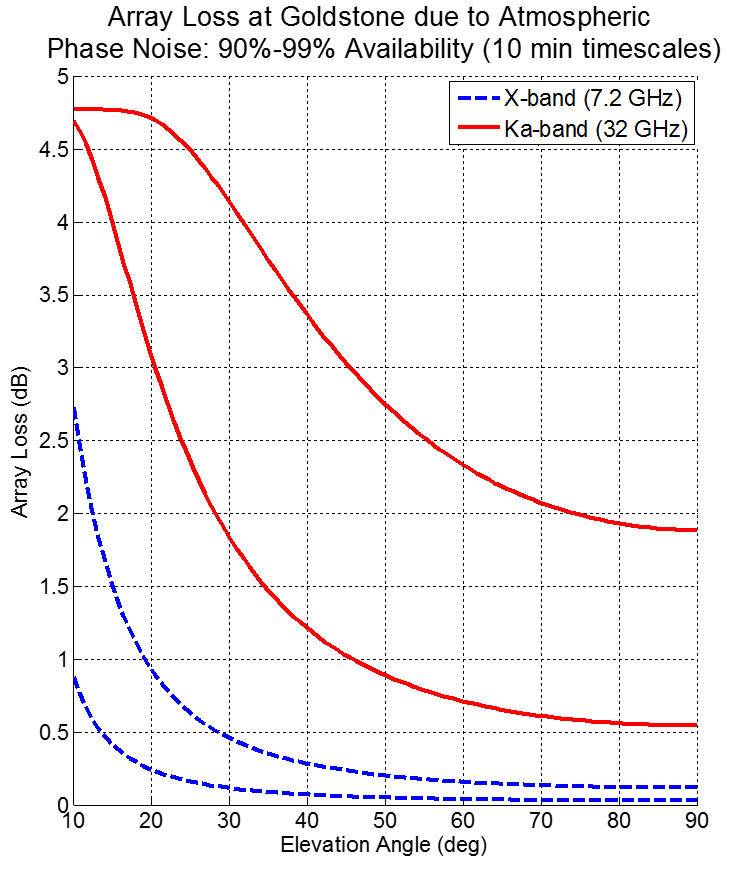


Figure 12

Predicted average array loss as a function of elevation angle for two operational frequencies for 90% (1 mm rms) and 99% (2 mm rms) average annual phase statistics from the Venus STI measured data for  
the 3-element array geometry shown in Figure 11.



# 8 References

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