TWO YEARS OF SIMULTANEOUS K_a-BAND MEASUREMENTS: GOLDSTONE, CA; WHITE SANDS, NM; AND GUAM, USA

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Abstract

In order to statistically characterize the effect of the Earth's atmosphere on K_a-Band links, site test interferometers (STIs) have been deployed at three of NASA's operational sites to directly measure each site's tropospheric phase stability and rain attenuation. These STIs are composed of two antennas on a short baseline (less than 1km) that observe the same unmodulated beacon signal broadcast from a geostationary satellite (e.g., Anik F2). The STIs are used to measure the differential phase between the two received signals as well as the individual signal attenuation at each terminal.

There are currently three NASA sites utilizing STIs; the Goldstone Deep Space Communications Complex near Barstow, California; the White Sands Complex in Las Cruces, New Mexico; and the Guam Remote Ground Terminal on the island of Guam. The first two sites are both located in desert regions that have highly similar climates in terms of their seasonal temperatures, average humidity, and annual rain fall (the primary factors in determining phase stability). In contrast, Guam is in a tropical region with drastically higher annual rainfall and humidity. Five station years of data have been collected in Goldstone, three in White Sands, and two in Guam, yielding two years of simultaneous data collection across all three sites.

During this period of simultaneous data collection, the root-mean-square (RMS) of the time delay fluctuations stayed under 2.40 picoseconds for 90% of the time in Goldstone, under 2.07 picoseconds for 90% of the time in White Sands, and under 10.13 picoseconds for 90% of the time in Guam. For the 99^{th} percentile, the statistics were 6.32 ps, 6.03 ps, and 24.85 ps, respectively. These values, as well as various other site quality characteristics, will be used to determine the suitability of these sites for NASA's future communication services at K_a-Band.

I. Introduction

NASA's Space and Deep Space Networks currently employ X-band (8 - 12 GHz) and K_u-band (12 – 18 GHz) radio frequencies for communication with spacecraft, but a migration to the higher frequency K_a-band (26.5 – 40 GHz) is anticipated by 2018 **[1]**. This transition will reduce spectrum congestion at lower frequencies while increasing available speeds from megabit to gigabit data rates, but it comes at the expense of increased atmospheric attenuation and distortion.

In order to design networks that are cost effective and can operate at K_a-band with availability comparable to the current networks (over 99%), the atmospheric phase stability and attenuation distribution function of a particular ground station site must be well known. This enables these negative atmospheric effects to be mitigated when designing the system, which reduces cost and further increases system margin **[2]**. In particular, the phase stability of a site will determine whether or not the site is a suitable location for an array of smaller antennas, rather than a single large and expensive reflector. The attenuation distribution determines the margin needed to operate at the site, as well as whether or not additional mitigation techniques (e.g. site diversity) would be beneficial.

These studies must be done on a site-by-site basis due to the wide variety of climates and weather conditions at each ground terminal.

NASA Glenn Research Center, in collaboration with the Jet Propulsion Laboratory and Goddard Space Flight Center, has constructed and deployed Site Test Interferometers (STIs) to three operational sites: the Goldstone Deep Space Communications Complex near Barstow, California; the White Sands Ground Terminal at the White Sands Complex in Las Cruces, New Mexico; and the Guam Remote Ground Terminal on the island of Guam. The data collected through this research will determine the phase quality measurements needed to conclude the site's suitability for antenna arraying, as well as determine the necessary system design parameters (e.g. system availability and the corresponding system margin) and identify possible mitigation techniques (e.g., site diversity) to optimally operate a K_a-band system at these locations.

II. Terminal Design & Data Collection

The Site Test Interferometers (STIs) deployed to Goldstone, White Sands and Guam each consist of a two-element interferometer observing an unmodulated K_a-band beacon signal from a geostationary satellite. The STI is capable of measuring phase instability between the two elements, as well as measuring the amplitude attenuation observed at each individual antenna.

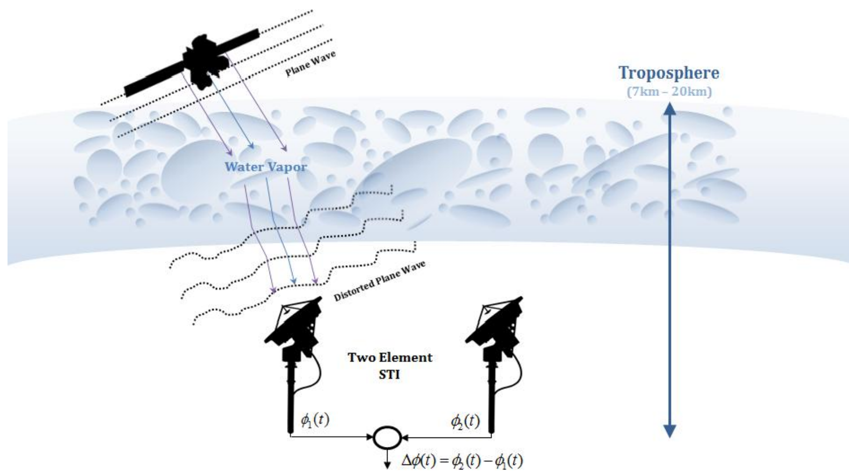

Fig. 1. *Phase fluctuations can be measured with a two-element STI and are primarily induced by water vapor in the troposphere.*

Phase instability occurs because the earth's troposphere (the layer of the atmosphere from the surface to approximately 20km above, comprising the majority of weather phenomena) contains a large amount of inhomogeneous cells of water vapor exposed to turbulent air flow **[2]**. This water vapor content changes the refractivity of the air and leads to variations in the effective path length of an electromagnetic wave propagating through the medium as illustrated in **Fig. 1**. Therefore, phase instability is measured via the interferometer, which receives two spatially separated versions of the same signal and calculates the observed differential phase.

Table 1. *Site Test Interferometer system specifications.*

Sampling Rate	3.64 MHz
Integration Time	144 ms
Downconversion	2-step down to 455 kHz
Time Series Output Rate	1 Hz
Noise Floor	< 1.8° RMS

The general system specifications of the STI design, detailed in **[3]**, are shown in **Table 1**. The STIs sample at a rate of 3.64 MHz with a 144 ms integration time after downconverting the signal in two steps to 455 kHz. The time series output data is stored at 1 Hz. In laboratory testing, the noise floor of this implementation was observed to be less than 1.8° RMS (0.24 ps).

Table 2. *Site parameters of the three STI locations.*

		Goldstone	White Sands	Guam
	Installation Date	May 2007	Feb. 2009	May 2010
Site	*Latitude*	35.2477° N	32.5423° N	13.5868° N
	Longitude	116.7915° W	106.6139° W	144.8409° E
	Altitude	3408 ft	4821 ft	425 ft
Baseline	*Bearing*	90°	180°	170°
	Length	256 m	208 m	600 m
Satellite	*Name*	ANIK F2	ANIK F2	UFO 8
	Orbital Longitude	111.1°	111.1°	171°
	Elevation	48.6°	51.8°	37.3°
	Azimuth	170.2°	188.3°	256.4°
	Beacon Freq.	20.2 GHz	20.2 GHz	20.7 GHz
	Polarization	Linear V	Linear V	Circular RH
Antenna	*Diameter*	1.2 m	1.2 m	1.2 m
	Gain	41 dBi	41 dBi	41 dBi
LNB	*Noise Figure*	2.0 dB	1.5 dB	3.0 dB
	Gain	30 dB	30 dB	25 dB

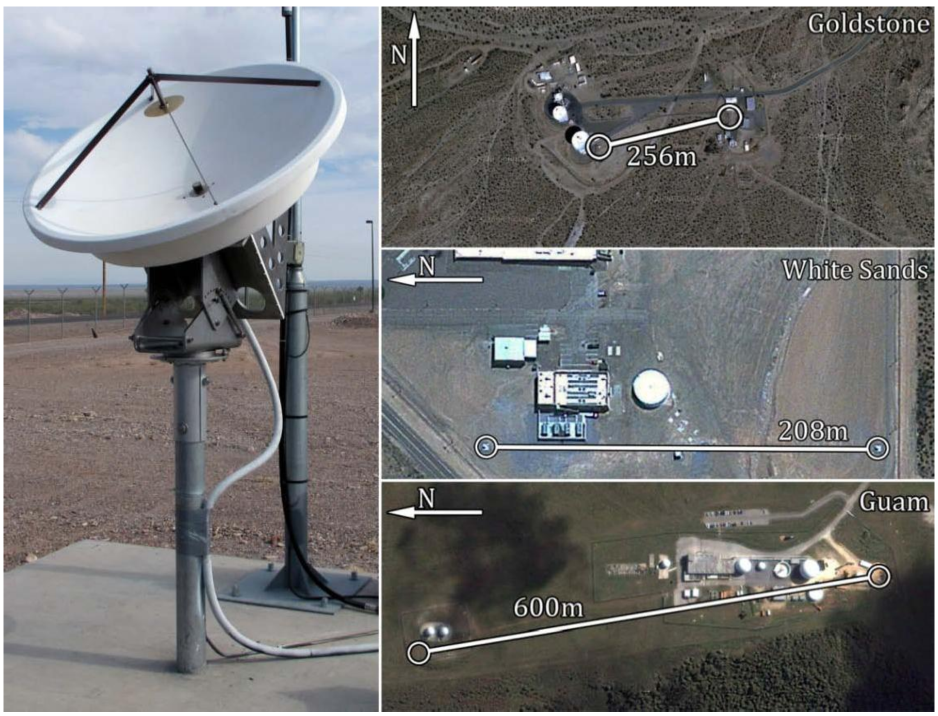

Fig. 2. *On the left, the south antenna at White Sands is presented as an example of the STI terminal design. On the right, aerial views of the STIs at each of the three sites indicate their baselines and orientations.*

The specifications of all three STI locations and their associated satellites are presented in **Table 2**, and the sites themselves are shown in **Fig. 2**. The interferometer deployed to Goldstone (installed May 2007) sits at an elevation of 3408 feet above sea level on an east-west baseline of 256 meters. The STI at White Sands (installed February 2009) is located at an elevation of 4821 feet above sea level with a north-south baseline of 208 meters. Both interferometers observe the 20.2 GHz beacon signal from the geostationary Anik F2 satellite. The third interferometer, in Guam (installed May 2010), is located at 425 feet above sea level on a north-south baseline of 600 meters. This station receives the UFO-8 beacon signal at 20.7 GHz.

At all locations, the carrier-to-noise-density ratio (C/N_0) was measured to be approximately 80 dB-Hz. The performance of each instrument was evaluated in the laboratory environment (no atmospheric contributions) and consistently showed a root-mean-square (RMS) time delay fluctuation of 0.21 picoseconds (1.5 degrees) over a 600 second integration period.

III. Data Processing

Before any statistical analysis can begin, the phase fluctuations induced by the atmosphere must be isolated from systemic effects (e.g. satellite motion, thermal drift). This calibration procedure, as validated in **[4]**, is summarized below.

From the raw collected data, the processing begins by finding the differential phase (or correlation phase) curve, which is calculated by subtracting the phases of each of the interferometer's two elements. The results of this calculation performed on one day of data from Guam are shown in **Fig. 3 (top left)**. This indicates the difference in phase between the two antennas, which would be negligible in the ideal case of zero atmospheric distortion. As a relative phase value, the correlation phase is bounded between ±180°. To obtain a continuous phase curve, the data is unwrapped to observe the continuous phase fluctuation throughout the entire day, as in **Fig. 3 (bottom left).**

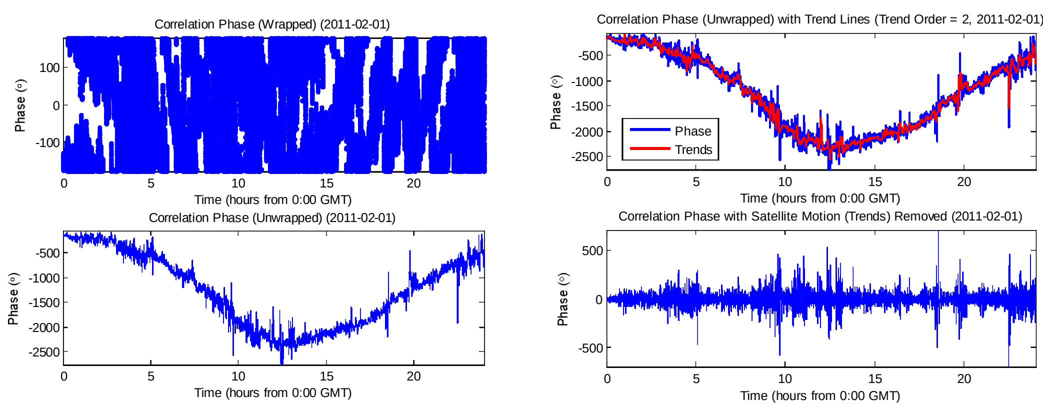

Fig. 3. *To process the data, the correlation phase is unwrapped (left), and slow-varying trends are removed (right).*

The distinct sinusoidal pattern in the unwrapped phase is not due to the atmospheric effects, but rather is induced by diurnal motion of the satellite. To remove this effect (as well as any other slow varying trends in the data, such as thermal effects) a form of high pass filtering is implemented by fitting 2^{nd} order polynomial trends to the data in ten minute blocks and subtracting these trends from the data. This leaves only the short timescale variations as presented in **Fig. 3 (bottom right)**.

At this point, the slow varying effects induced by the system have been removed, leaving only the effects of interest: the shorter timescale distortions introduced by the atmospheric effects.

IV. Statistical Results

Before comparing results across the three sites, the values must be normalized with respect to elevation angle (a signal received at a lower elevation angle will traverse a longer path through the troposphere and scale the measurements accordingly). The STIs at Goldstone and White Sands are pointed to Anik F2 at an elevation of 48.6° and 51.8° respectively, while the STI at Guam observes UFO-8 at 37.3°. To normalize the phase values to zenith, the following conversion is used:

$$\sigma_{zenith} = \frac{1}{\sec(90° - \theta)} \sigma_\theta$$

where σ_θ is the measurement at the original elevation angle θ, and σ_{zenith} is the measurement referenced to zenith (90°). To further convert this phase instability in degrees to a time delay in picoseconds, the following equation is used:

$$\Delta t = \frac{\sigma}{360° * f}$$

where σ is the phase delay in degrees, and f is the frequency of the signal.

With the data normalized, **Fig. 4** shows spectrogram representations of the phase instability for one year (2011) at each site. For Goldstone and White Sands, the scale runs from 0° RMS to 48° RMS (0 to 6.60 ps), while the Guam scale has been increased to 0° to 96° RMS (0 to 12.88 ps) to avoid saturation.

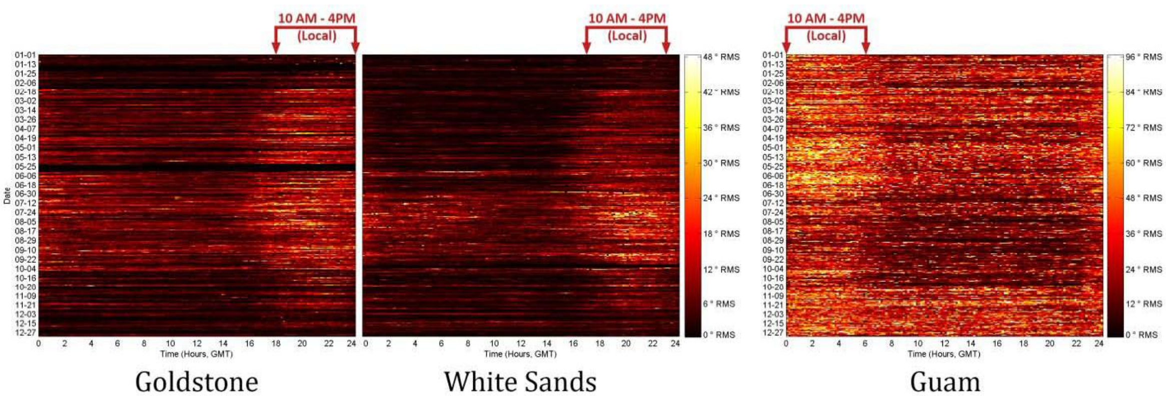

Fig. 4. *Spectrograms of the phase instability at all three sites highlight the increase in phase instability during the daylight hours as well as exhibiting seasonal variations and the stark contrast between the tropical and desert climates.*

The time axis of all three spectrograms is in hours GMT, so the local time has been noted above the plots. Goldstone is on Pacific Time (GMT -8), White Sands is Mountain Time (GMT -7), and Guam is in the Chamorro Time Zone (GMT +10). At all three sites, the period of most intensity in phase fluctuations was observed approximately between 10AM and 4PM local time, year round. Seasonally, Goldstone and White Sands were the worst during the summer months, June through September, while Guam was the worst from December through May, corresponding with the region's dryer season.

Fig. 5 presents the cumulative distribution functions (CDFs) of the phase data, by year, at each site since the installation of the Guam terminal in 2010. The 2010 plot thus represents 8 months from May through December, while the 2011 plot covers a full calendar year, and the 2012 plot covers the currently available data from January through June.

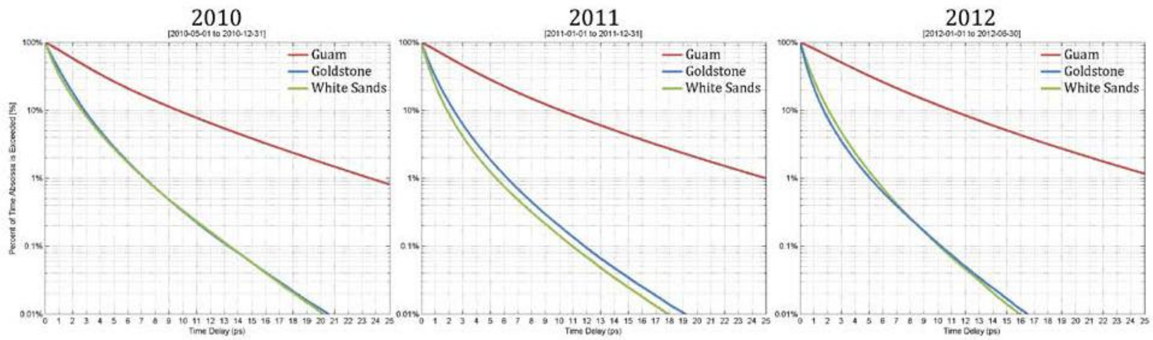

Fig. 5. *The cumulative distribution functions (CDFs) of phase instability at each site, by year, from the installation of the Guam terminal in May 2010 through June 2012. The 2011 plot represents a full calendar year, while 2010 and 2012 comprise 8 and 6 months, respectively.*

In **Fig. 6**, the full year of data from 2011 is taken from each site and broken down into monthly CDFs. As observed in **Fig. 4**, Goldstone and White Sands both exhibit the lowest phase instability in the winter months. Though Guam offers a worse phase performance overall, as compared to Goldstone and White Sands, it is more consistent throughout the year as compared to the other two.

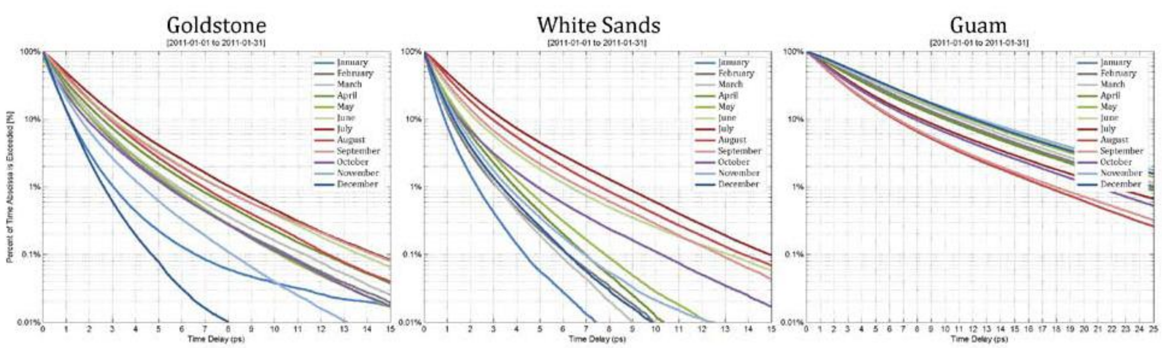

Fig. 6. *The CDFs of phase instability at each site in 2011, plotted by month to characterize seasonal variations.*

Goldstone's best month in 2011 was December, with 1.17 ps in the 90^{th} percentile, as compared to its worst month, July, with 3.36 ps at 90%. The best month in White Sands was January, with 0.89 ps, and the worst month was also July, with 3.41 ps. Guam's best month was August at 6.36 ps, and its worst was January at 10.31 ps.

V. Conclusion and Future Work

The most noticeable trend in the phase fluctuations at all three sites is that they are significantly more intense during the daylight hours as compared to the night hours, as should be expected with the sun heating the atmosphere and increasing turbulence. Phase instability also tends to be the worst during the summer months and best during winter months, with the exception of Guam, which does not experience the same temperate climate seasons as the other two sites and instead saw its worst phase instability during its dry season.

A statistically meaningful comparison between these sites is not possible with only two common years of data collection between the three of them, but these preliminary results indicate that the Goldstone and White Sands sites have very similar atmospheric phase stability (time delay) characteristics, while the results from Guam were worse by a factor of five. A more comprehensive comparison can be performed within the next few years, when more years of simultaneous data have been collected.

References

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