An Inter-Comparison of Two Independent Site Test Interferometers Located in Goldstone, California: Initial Study Results

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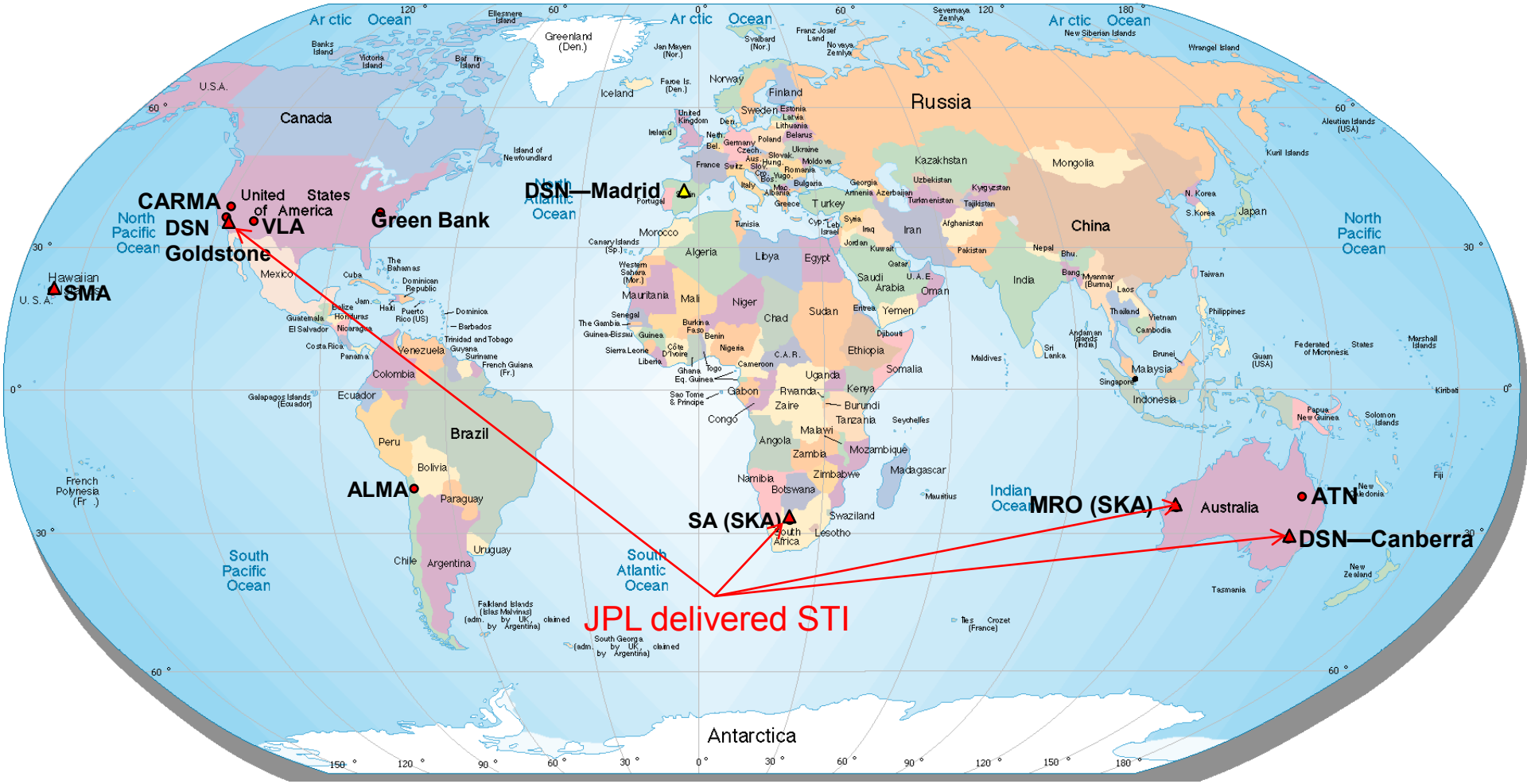
Scope

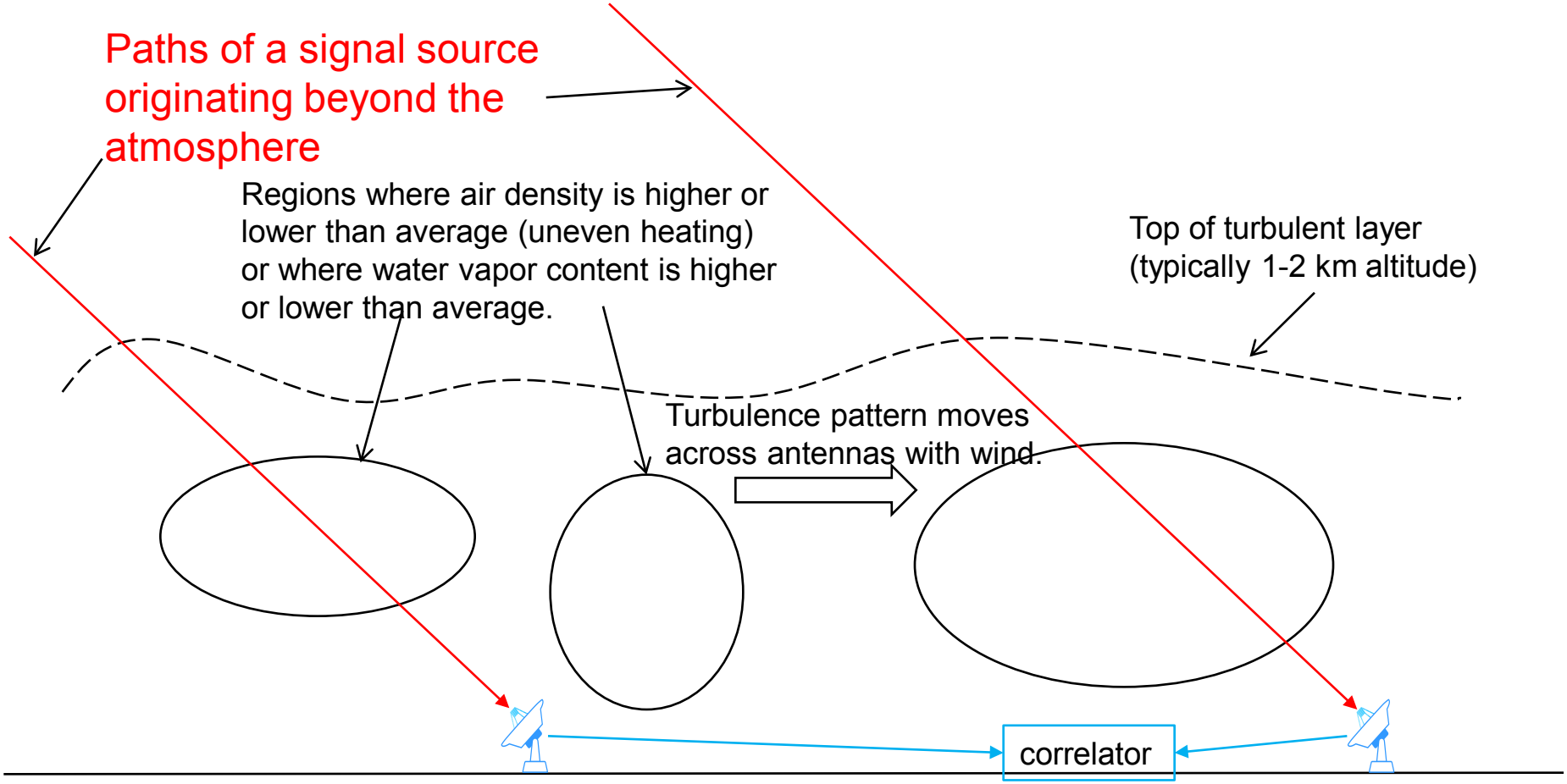
- **Background:** The DSN of the future will incorporate both uplink and downlink arraying. An important component of understanding the performance of arraying is the understanding of tropospheric propagation. The classical way of achieving this understanding is to use STIs.
- **Benefit to DSN**: The prediction of arraying loss magnitude and its dynamics
  - **Downlink Arrays** typically correct for the anomalies caused by tropospheric turbulence. However, the turbulence dynamics influence the design of the control loop. The characterization of a site by a STI will provide 1) information on the suitability of the site for arraying and 2) information for suitable design of the control loop.
  - **Uplink arrays** typically do not correct for turbulence effects, however, site characterization will allow the designer of the communications link to provide adequate margin to meet system requirements.
- **DSN Infusion:** A new DSN Telecommunications Link Design Handbook module will provide measured phase delay statistics, the corresponding array loss statistics, and the procedure to calculate loss for a given array.
- **This study:** Results of an inter-comparison of two independent STIs operating at Goldstone, California.
- **NASA SCaN Activity:** NASA STI activity is a collaborative effort between JPL and GRC

Definition of arraying loss for this paper**:** The difference between received signal power or transmitted EIRP without and with the atmospheric turbulence

The Global View

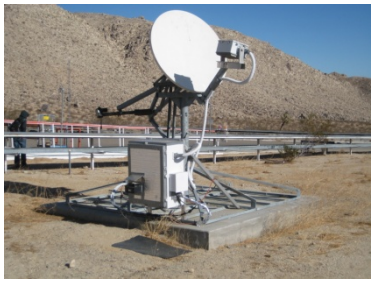


Theoretical Background



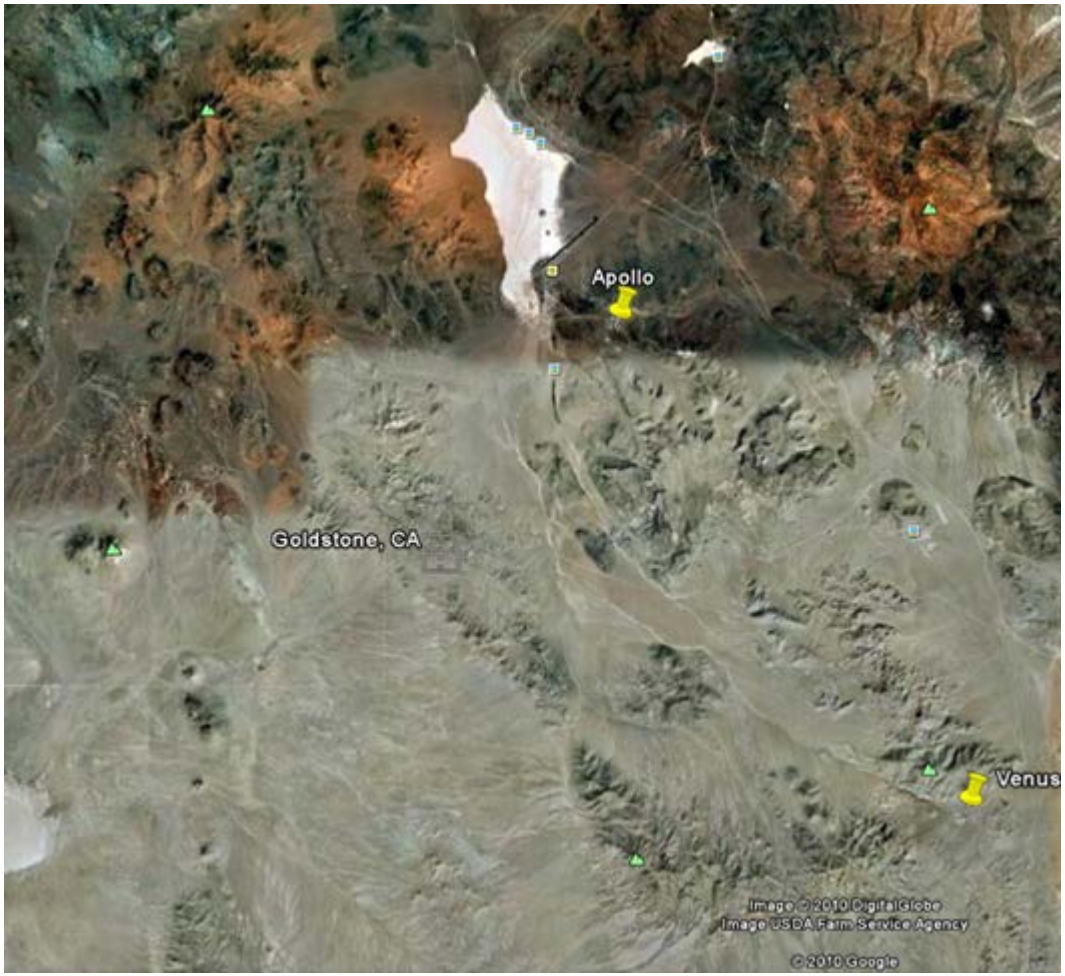
Goldstone STIs

- Venus STI (delivered by GRC, 2007)
  - Beacon – phase difference estimated in post-processing
  - Initiated data acquisition in May 2007
  - Altitude 1070.4 m
  - Baseline distance 256 m
  - ANIK F2 geostationary satellite
    - Frequency 20.199 GHz
    - Elevation Angle 48.5°



- Apollo STI (delivered by JPL, 2010)
  - Has three elements operating as of Nov 2011
  - Wideband - Equal arm white noise interferometer
  - Initiated data acquisition in September 2010
  - Altitude 951.5 m
  - East-West baseline distance 190 m
  - CIEL 2 geostationary satellite
    - Frequency 12.45 GHz
    - Elevation angle 47.0°

Goldstone STIs

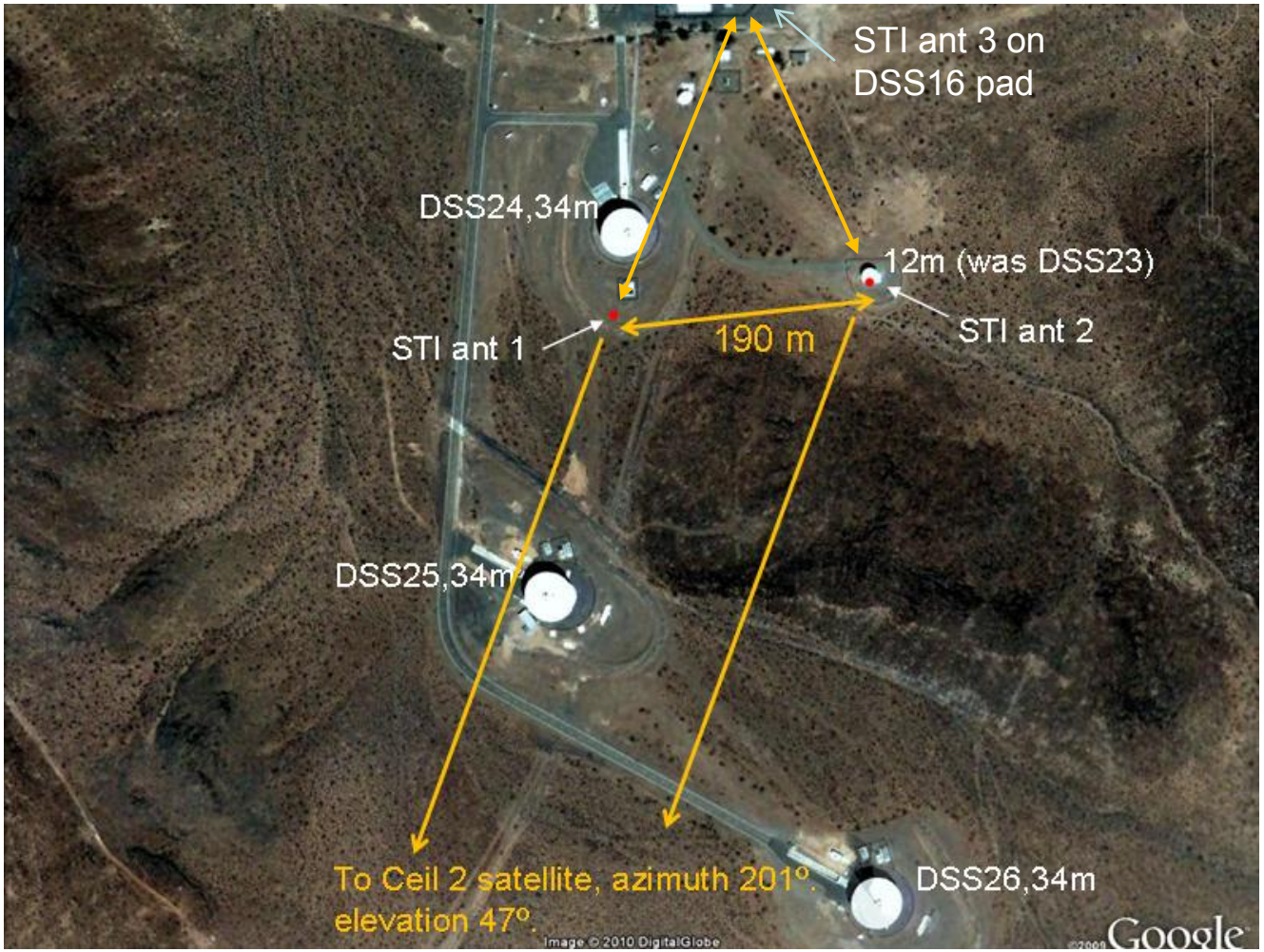


Venus and Apollo STIs are 12.5 km apart with Apollo located at a heading of 324 deg with respect to Venus

- Venus STI is a 256 m EW baseline
- Apollo STI is a 191 m EW baseline

Image credit: Google Maps

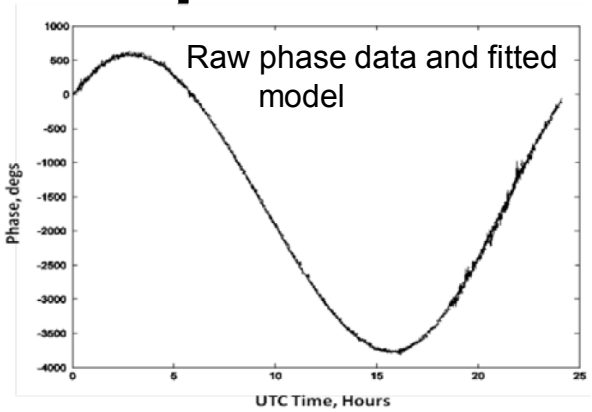
Apollo STI
(NASA JPL Equipment)

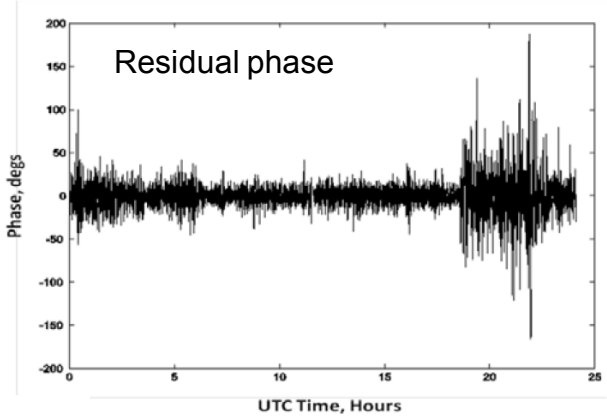


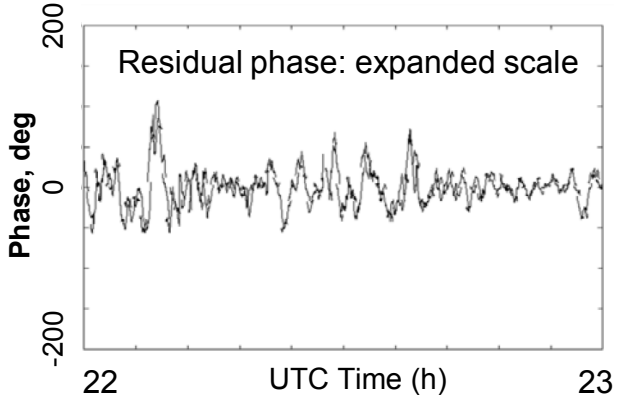
Venus STI
(NASA GRC Equipment)

STI Data Examples

- Phase samples for the Venus STI are recorded at 1-sec time resolution and for the Apollo STI are recorded at 0.1-sec time resolution.
  - Differential or correlated phase between elements is unwrapped, and slow variations are removed during post-processing
  - High-frequency thermal noise can be measured using a zero-baseline test, or “inferred” by inspecting all bins from all data sets for minimum STI phase fluctuation
- Variations due to satellite motion and instrumental drift are removed
- The standard deviation of the residual STI phase variations is estimated over a data interval of 10 minutes
  - This interval is selected as it is long compared to typical wind crossing time of the STI baseline and short compared to typical instrumental drift and satellite motion effects

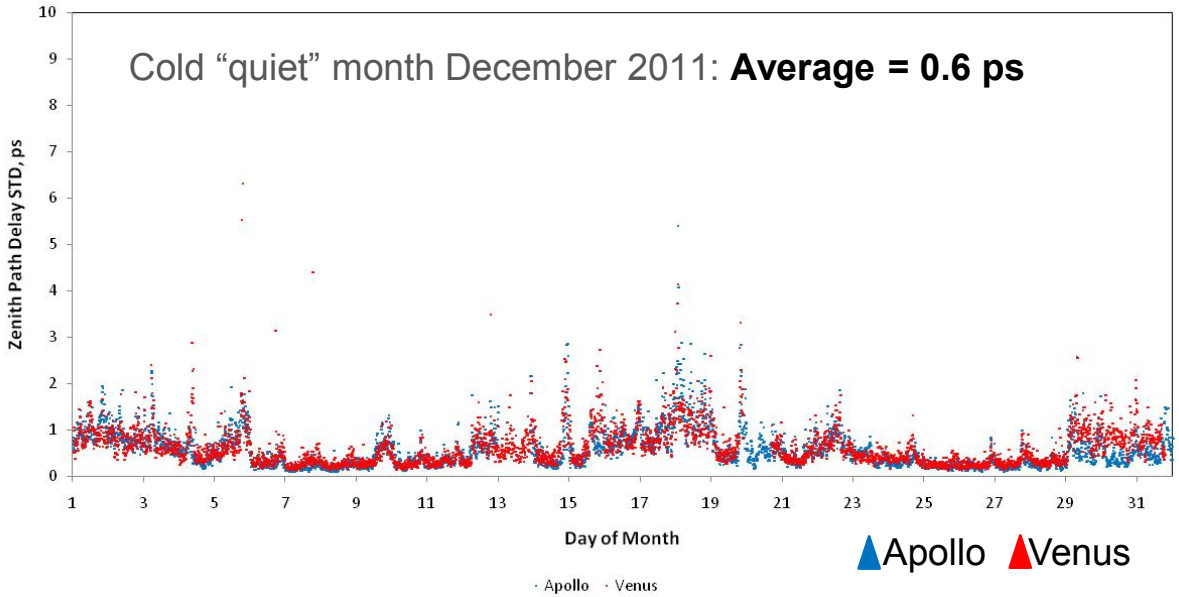


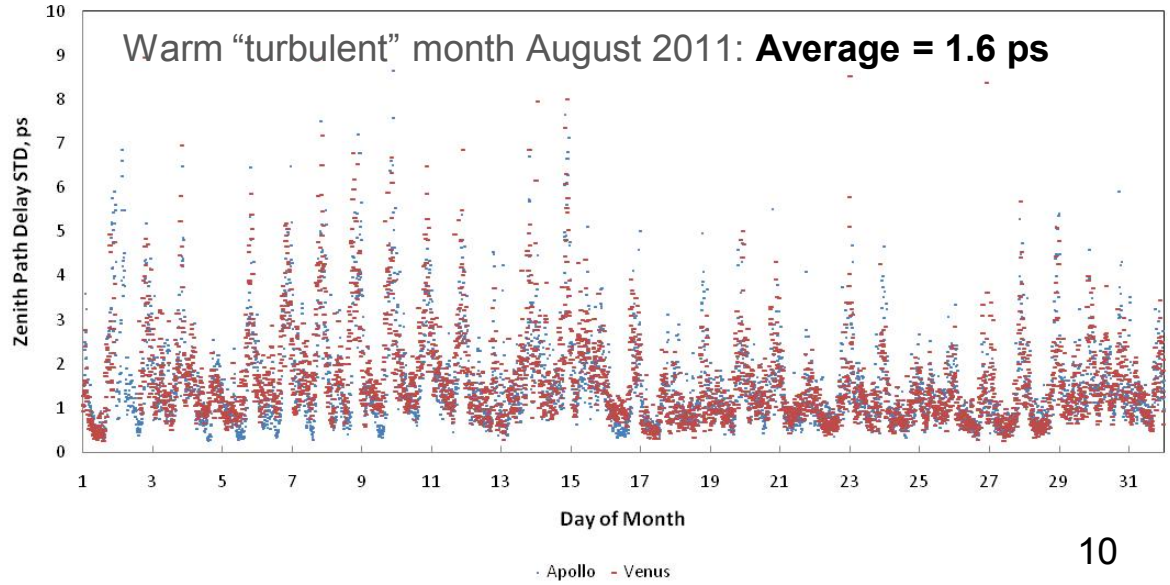




Measure of Turbulence-Induced delay differential (Goldstone)

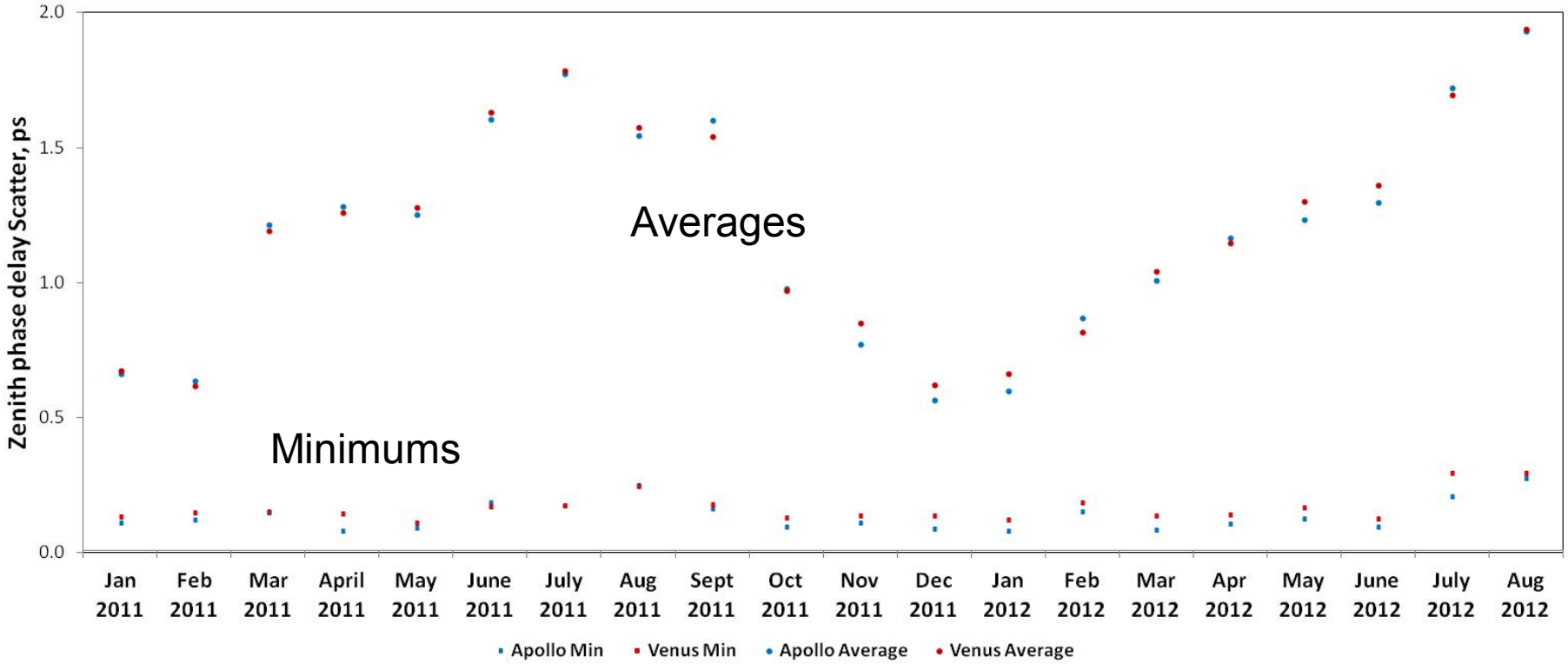
- Data are scaled to zenith delay fluctuations from measured satellite-elevation phase fluctuations $\tau = \phi/f$
- Results were scaled to the same baseline length
  - **Venus STI element spacing = 256 m**
  - **Apollo STI element spacing = 191 m**
  - $\sigma_{Apollo} = \sigma_{Venus} \ (r_{Apollo} / r_{Venus})^{\beta/2}$
    β is an exponent from turbulence theory
- Adjustment for difference in heights above mean sea level has been applied
- These latter adjustments were applied to the Venus STI data to refer it to Apollo conditions



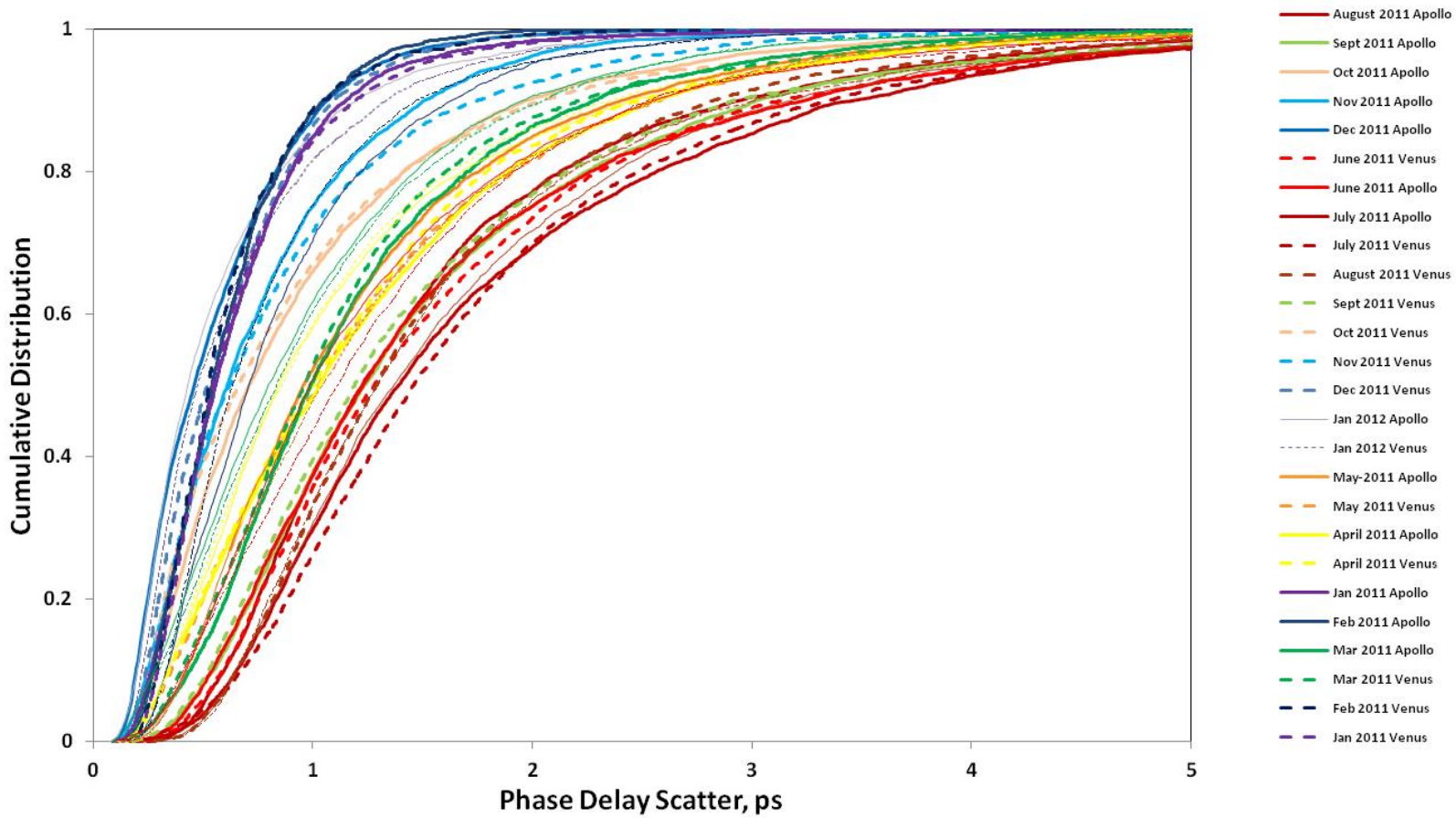


Apollo/Venus East-West Baseline Inter-comparison Monthly Statistics

- Statistics from more recent data have been included
- Average values clearly follow annual trend
- Minimum values representative of “noise floor”
- Very good statistical agreement achieved between Apollo (blue) and Venus (red) data

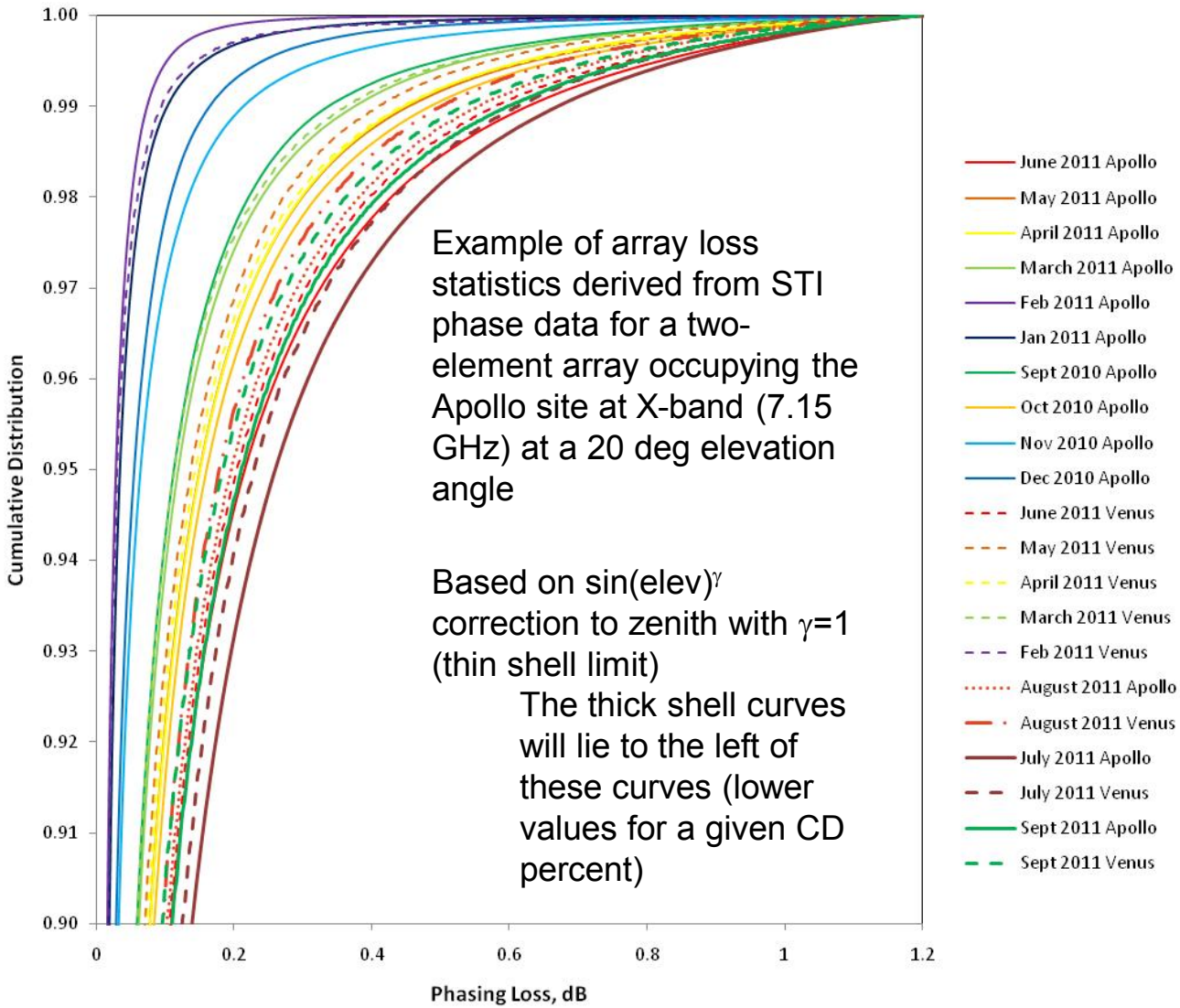


Cumulative Distribution of Zenith Phase Delay Scatter Goldstone East-West Baselines



- Apollo STI CD's are solid curves. Venus STI CD's are dashed curves
- Summer month curves shown in reddish colors, winter month curves in bluish colors and intermediate (spring/autumn) months in greenish/yellowish colors.
- Assumes thick layer model elevation angle corrections.

Goldstone 2-element Array Power Loss, dB, due to Phase error caused by the atmosphere



Example of array loss statistics derived from STI phase data for a two-element array occupying the Apollo site at X-band (7.15 GHz) at a 20 deg elevation angle

Based on $\sin(\text{elev})^{\gamma}$ correction to zenith with $\gamma=1$ (thin shell limit)

The thick shell curves will lie to the left of these curves (lower values for a given CD percent)

Use of STI Data in Telecom Link Budgets

- Conversion of 2 or 3 element STI phase delay statistics to array loss.
- Tables with monthly values of zenith phase delay at particular percentages for each DSN site (such as the 90% values shown on slide 14)
  - Sub-tables for daytime and nighttime.
- The module would describe the approach to convert the zenith delay scatter (STD) statistics to array loss (dB) for a particular link configuration at a given cumulative distribution (e.g., 90%)
  - Conversion from zenith delay STD to line-of-sight delay STD at elevation angle of the link
  - Conversion of line-of-sight delay STD to phase fluctuation STD using the frequency of the link
  - Conversion of the phase fluctuation STD (referenced to STI baseline length) to that for each of the element separations of the link array
  - The handling of other corrections in the algorithm (such as instrumental noise of the particular array)
  - Combining of the phase fluctuation STD for each pair of elements to yield array loss in dB
- Nominal values of array loss for an established DSN array, e.g., the 34-m BWG subnet at Apollo at X-band, similar to the curves on slide 14.
  - Example of phasing loss curves for Apollo 34-m subnet shown in http://tmo.jpl.nasa.gov/progress_report/42-175/175G.pdf

Summary and Future Activities

Two-element array loss in dB (90% availability), 20° elevation angle, and 191-m baseline for Goldstone, based on data collected between Jan 2011 and Jan 2012

Referenced to 7.1 GHz X-band

Elevation Angle Model	Apollo Average	Venus Average	Apollo Min	Venus Min	Apollo Max	Venus Max
Thick Shell	0.03	0.03	0.006	0.006	0.08	0.06
Thin Shell	0.06	0.06	0.014	0.016	0.14	0.12

Referenced to 34.5 GHz Ka-band

Elevation Angle Model	Apollo Average	Venus Average	Apollo Min	Venus Min	Apollo Max	Venus Max
Thick Shell	0.61	0.62	0.160	0.159	1.43	1.36
Thin Shell	1.19	1.22	0.335	0.340	2.32	2.27

Future Efforts

- Prepare array-loss module for DSN Telecommunications Link Design Handbook
- Report on detailed behavior of statistics with month, season, year, day-night, hourly, etc.
- Report on 3-element measurements.
- Install 3-element STI in Madrid (equipment has been built; one of the elements has been funded by GRC, planned to occur in FY13)
- Possible collaboration with atmospheric physics personnel on Goldstone atmospheric properties (e.g., boundary layer height)