WWV Phase Stability Analysis Suite

User Guide

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Contents

1 Overview

This guide covers the WWV phase stability analysis tools for assessing ionospheric phase variations using time signal recordings from KiwiSDR receivers. The analysis is analogous to adaptive optics for astronomy—measuring phase distortions on pilot signals to enable real-time correction.

1.1 Available Programs

Program	Purpose
`wwv_phase_analysis_final.py`	Single-file phase stability analysis with structure function
`wwv_triplet_analysis.py`	Multi-frequency synchronous recording analysis
`wwv_geographic_correlation.py`	Two-site spatial correlation analysis

Table 1: Phase analysis programs

1.2 Scientific Background

WWV (NIST, Fort Collins, CO) broadcasts precise carriers at 2.5, 5, 10, 15, 20, and 25 MHz. By recording these signals via KiwiSDR and analyzing the carrier phase, we can characterize ionospheric phase stability.

The key metric is the **phase structure function**:

$$D(\tau) = \langle[\phi(t+\tau) - \phi(t)]^2\rangle \tag{1}$$

This measures how much the phase varies over time lag τ. For adaptive ionospheric correction to be feasible, the RMS phase variation at the round-trip timescale ($\sim$20 ms for a 2000 km path) should be less than $\sim$0.5 radians.

1.3 Installation

```
# Required dependencies
pip install numpy scipy matplotlib
```

2 Single-File Analysis: wwv_phase_analysis_final.py

2.1 Purpose

Analyzes a single KiwiSDR IQ recording to extract carrier phase stability metrics, detect signal fades, and compute the phase structure function.

2.2 Command Line Usage

```
# Analyze most recent .wav file in current directory
python3 wwv_phase_analysis_final.py

# Analyze specific file
python3 wwv_phase_analysis_final.py recording.wav
```

```
# Batch analyze all files matching pattern
python3 wwv_phase_analysis_final.py --batch "*.wav"

# Analyze only 25 MHz recordings
python3 wwv_phase_analysis_final.py --batch "*freq25000*"

# Skip plot generation (faster, console output only)
python3 wwv_phase_analysis_final.py recording.wav --no-plot
```

2.3 Command Line Arguments

Argument	Description	Default
`filename`	WAV file to analyze (positional)	Most recent
`--batch PATTERN`	Batch analyze files matching glob pattern	None
`--no-plot`	Skip plot generation	False

Table 2: wwv_phase_analysis_final.py arguments

2.4 Input File Format

The program expects stereo WAV files with:

- Channel 1: In-phase (I) samples
- Channel 2: Quadrature (Q) samples
- Sample rate: Typically 12–20 kHz
- Carrier offset: ∼2 kHz from nominal frequency (to create beat signal)

Filename convention extracts frequency from pattern `freq{kHz}`, e.g., `freq25000` = 25 MHz.

2.5 Console Output

```
======================================================================
WWV PHASE STABILITY ANALYSIS
======================================================================
File: 20260106.1828...freq25000.20000.triplet.wav
Frequency: 25.0 MHz
Sample rate: 20000 Hz (dt = 0.050 ms)
Duration: 88.3 s (after 2.0s trim)
Carrier offset: -1699.95 Hz
Valid samples: 75.0%
Phase splices applied: 17
600 Hz tones detected: NO

Phase Structure Function D(tau):
  tau (ms) D(tau) rad^2 RMS rad RMS deg
------------------------------------------
     1.0 0.0048 0.0691 3.96
```

```
    2.0 0.0058 0.0759 4.35
   ...
   20.0 0.0090 0.0946 5.42 <-- 20ms
  ...
 1000.0 1.7548 1.3247 75.90

*** RMS phase @ 20ms: 0.0946 rad (5.4 deg) ***
    Assessment: GOOD - suitable for adaptive correction
```

2.6 Output Metrics Explained

Metric	Description
Carrier offset	Detected beat frequency (Hz) from FFT peak
Valid samples	Percentage of samples above fade threshold
Phase splices	Number of phase discontinuities removed at fade boundaries
600 Hz tones	Whether WWV's ±600 Hz audio tones were detected
$D(\tau)$	Phase structure function at various time lags
RMS @ 20ms	Critical metric for adaptive correction feasibility

Table 3: Output metrics from single-file analysis

2.7 Assessment Criteria

RMS @ 20ms	Assessment	Interpretation
< 0.5 rad	GOOD	Suitable for adaptive correction
$0.5 - 1.0$ rad	MARGINAL	Correction may be possible
> 1.0 rad	POOR	Adaptive correction difficult

Table 4: Phase stability assessment thresholds

2.8 Output Plot

The analysis generates a 4-panel diagnostic plot (Figure 1):

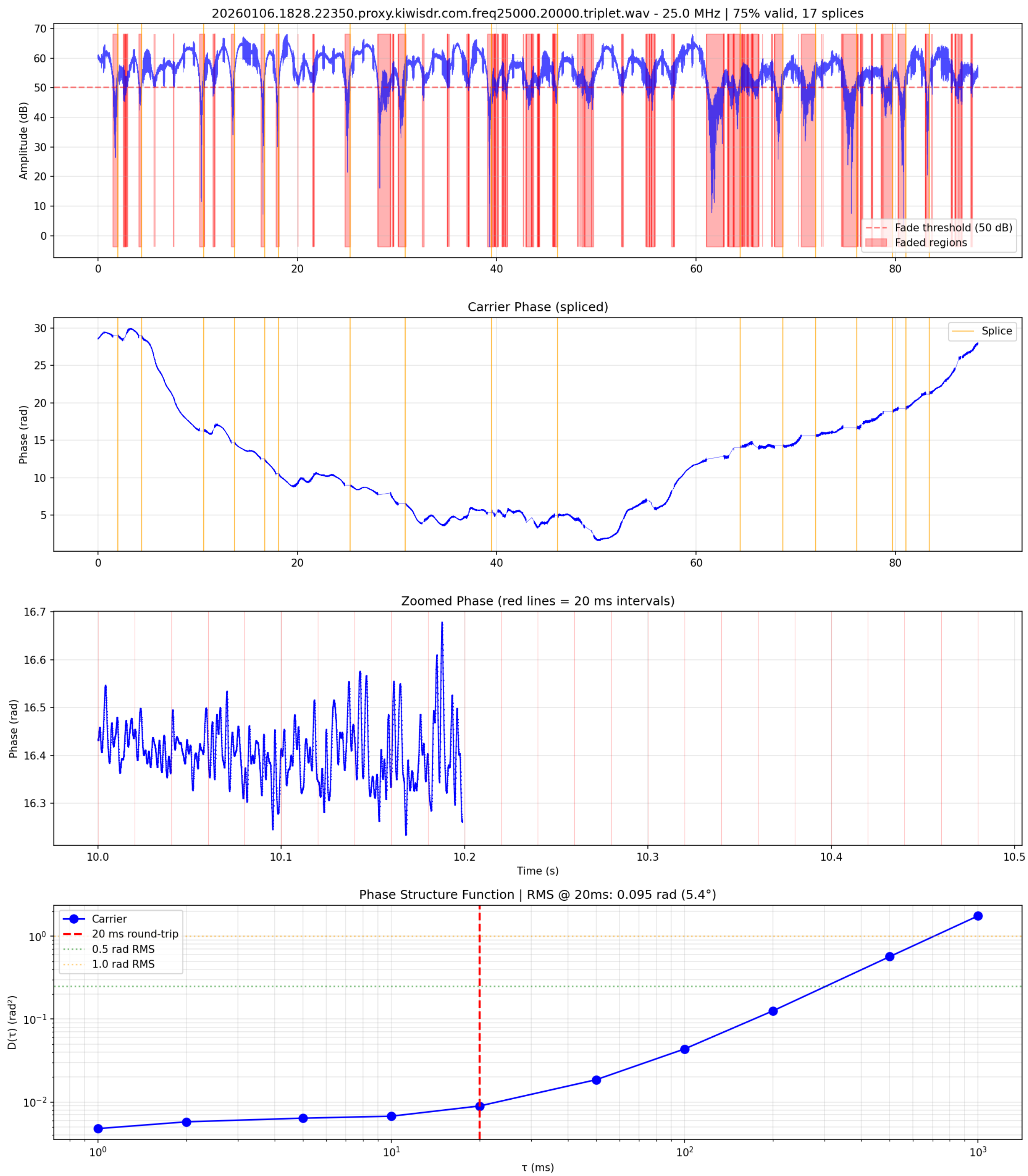

Figure 1: Single-file phase analysis output. **Panel 1** (top): Signal amplitude in dB with fade threshold (dashed red) and faded regions (red shading). **Panel 2**: Unwrapped carrier phase with splice points marked (orange lines). **Panel 3**: Zoomed phase showing 20 ms intervals (red vertical lines). **Panel 4** (bottom): Phase structure function $D(\tau)$ on log-log axes with 20 ms round-trip marker and assessment thresholds.

2.9 Configuration Parameters

Internal parameters (edit source to modify):

Parameter	Default	Description
`T_TRIM_START`	2.0 s	Initial seconds to discard (transients)
`SNR_THRESHOLD_DB`	12.0 dB	Below 90th percentile = fade
`CARRIER_FILTER_BW`	500 Hz	Bandpass filter width for carrier
`PHASE_JUMP_THRESHOLD`	1.5 rad	Jumps exceeding this are spliced
`TAU_ROUNDTRIP`	0.020 s	Critical timescale for assessment

Table 5: Configurable analysis parameters

3 Multi-Frequency Analysis: wwv_triplet_analysis.py

3.1 Purpose

Analyzes synchronously-recorded WWV signals at multiple frequencies to study:

1. Individual carrier phase stability at each frequency
2. Cross-frequency fade correlation (simultaneous vs. independent fading)
3. Cross-frequency amplitude correlation
4. Dispersion analysis via 600 Hz tone separation

3.2 Command Line Usage

```
# Analyze triplet by timestamp
python3 wwv_triplet_analysis.py 20260106.1828

# Analyze most recent triplet
python3 wwv_triplet_analysis.py

# Batch analyze all triplets from a date
python3 wwv_triplet_analysis.py --batch 20260101

# Skip plot generation
python3 wwv_triplet_analysis.py 20260106.1828 --no-plot
```

3.3 Command Line Arguments

Argument	Description	Default
`timestamp`	Triplet timestamp (e.g., 20260101.1044)	Most recent
`--batch DATE`	Analyze all triplets from date (YYYYMMDD)	None
`--no-plot`	Skip plot generation	False

Table 6: wwv_triplet_analysis.py arguments

3.4 Triplet File Convention

Files sharing the same timestamp but different frequencies form a triplet:

```
20260106.1828.22350.proxy.kiwisdr.com.freq7850.20000.triplet.wav
20260106.1828.22350.proxy.kiwisdr.com.freq20000.20000.triplet.wav
20260106.1828.22350.proxy.kiwisdr.com.freq25000.20000.triplet.wav
```

The program groups files by timestamp and station ID automatically.

3.5 Console Output

```
======================================================================
TRIPLET ANALYSIS: 20260106.1828 (Station 22350)
Frequencies: [7.85, 20.0, 25.0] MHz
======================================================================

Analyzing 7.85 MHz...
  7.85 MHz: 73% valid, RMS@20ms=0.155 rad (8.9 deg)

Analyzing 20.0 MHz...
  20.0 MHz: 64% valid, RMS@20ms=0.317 rad (18.2 deg)

Analyzing 25.0 MHz...
  25.0 MHz: 75% valid, RMS@20ms=0.095 rad (5.4 deg)

------------------------------------------------------
CROSS-FREQUENCY CORRELATION ANALYSIS
------------------------------------------------------

  7.85 MHz vs 20.0 MHz:
    Amplitude correlation: r=0.152 at lag=4611.6 ms
    Fade fractions: 7.85MHz=27.5%, 20.0MHz=36.4%
    Simultaneous fade: 10.6%
    P(fade@20.0|fade@7.85): 38.5%

  7.85 MHz vs 25.0 MHz:
    Amplitude correlation: r=0.144 at lag=3942.1 ms
    ...
```

3.6 Cross-Frequency Metrics

Metric	Description
Amplitude correlation	Pearson r between amplitude time series
Peak lag	Time offset of maximum cross-correlation
Fade fraction	Percentage of time each frequency is faded
Simultaneous fade	Percentage of time both frequencies faded together
$P(\text{fade}_B \vert \text{fade}_A)$	Conditional probability of B fading given A is faded

Table 7: Cross-frequency correlation metrics

3.7 Output Plots

The triplet analysis generates 5 diagnostic plots:

3.7.1 Amplitude Analysis

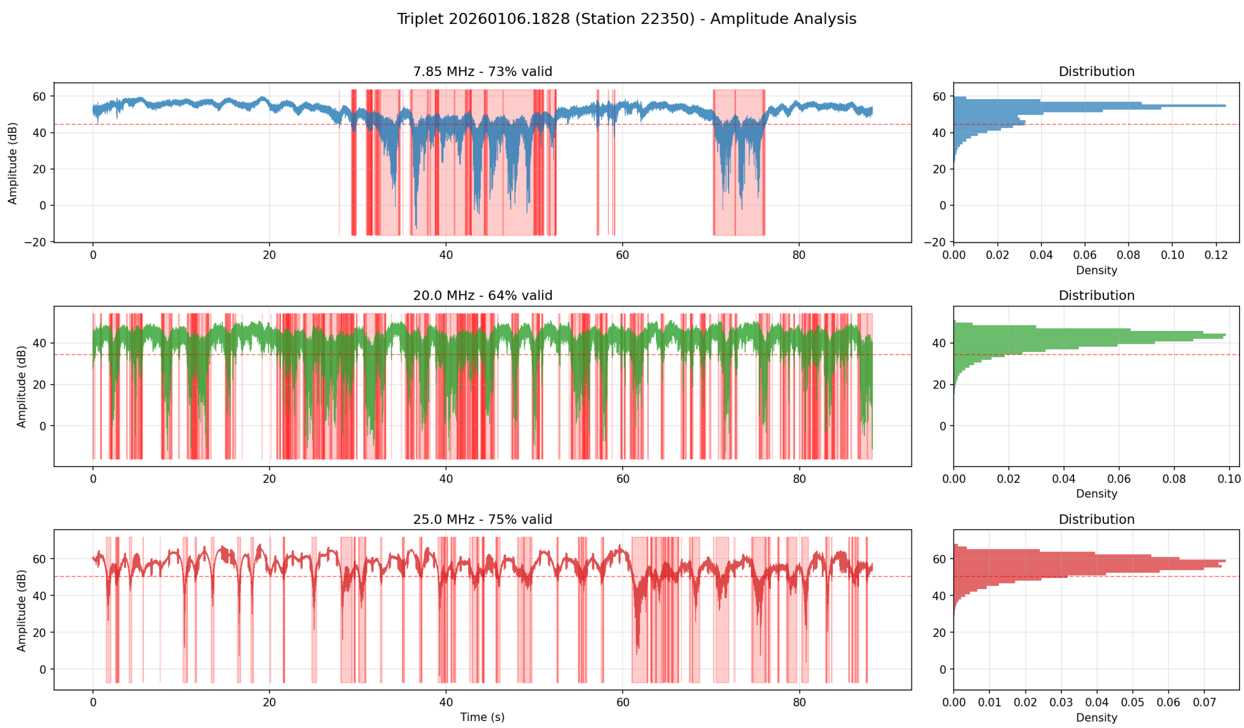

Figure 2: Triplet amplitude analysis. Left column: Time series of signal amplitude (dB) for each frequency with fade regions marked in red. Right column: Amplitude distribution histograms showing the fade threshold.

3.7.2 Phase Analysis

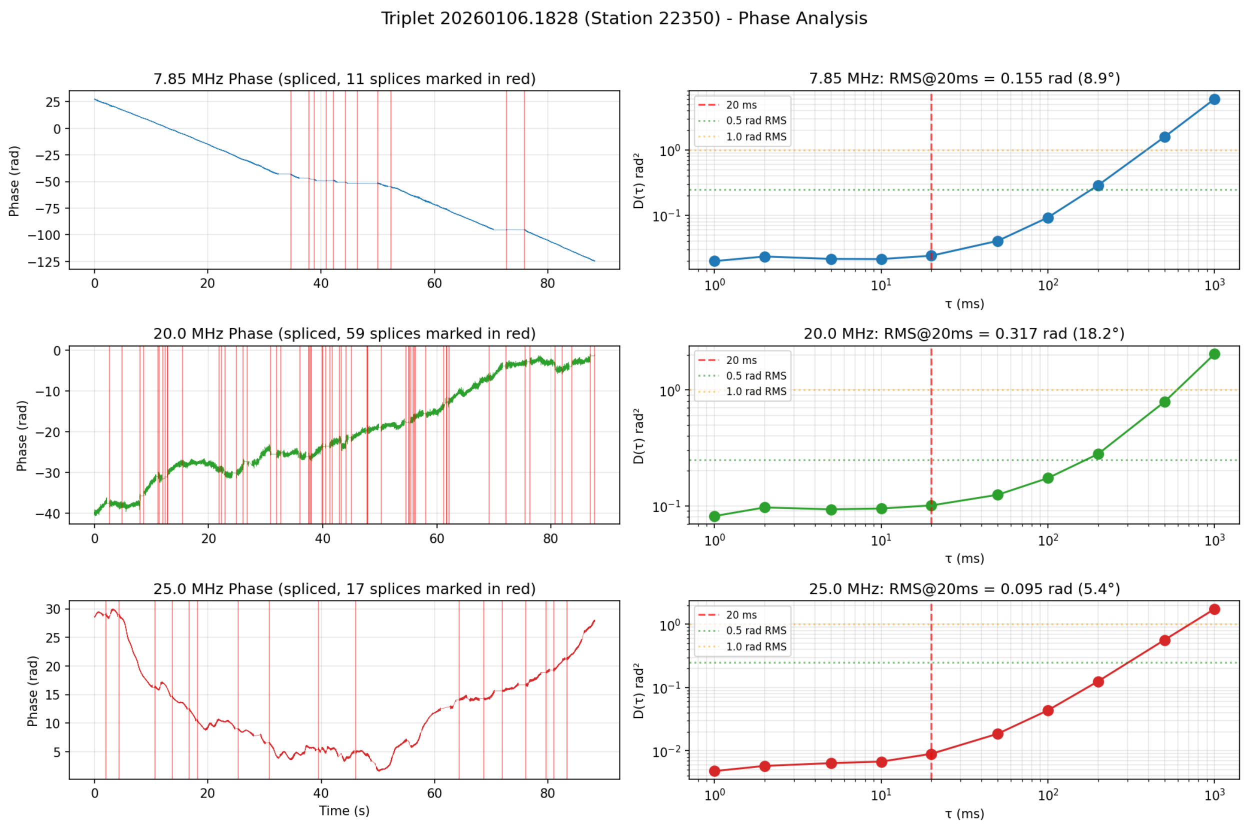

Figure 3: Triplet phase analysis. Left column: Unwrapped phase time series with splice points marked. Right column: Phase structure function $D(\tau)$ for each frequency with 20 ms marker and assessment thresholds.

3.7.3 Fade Analysis

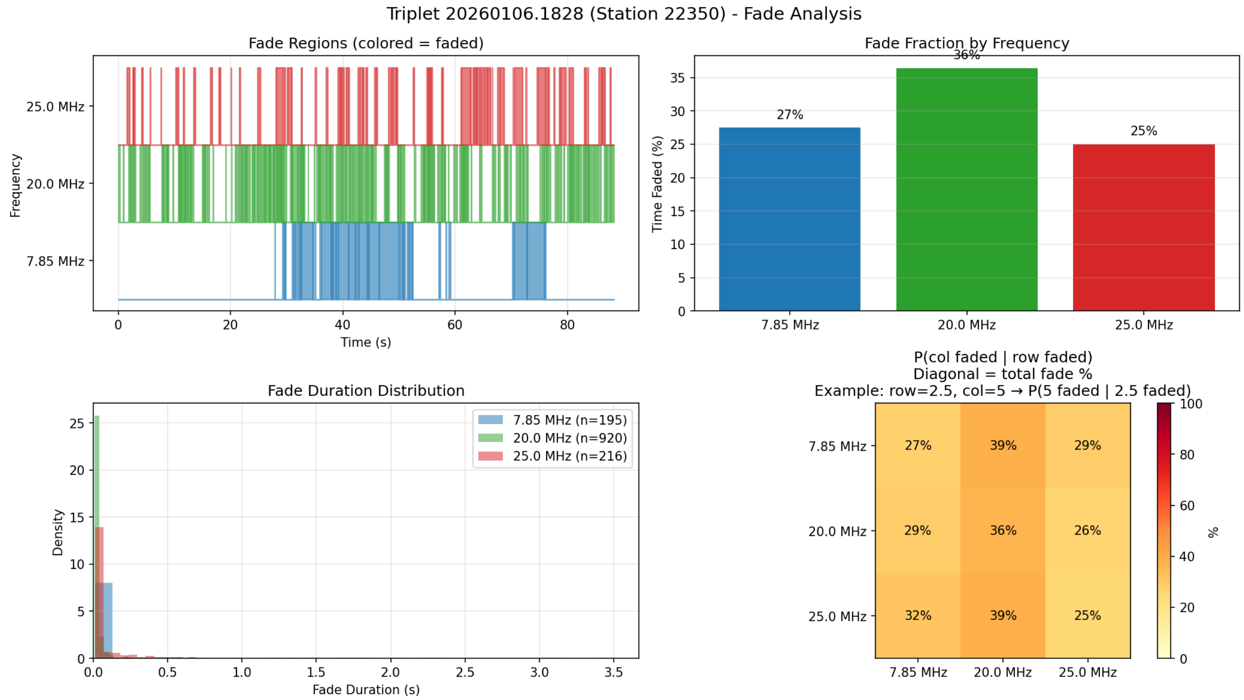

Figure 4: Cross-frequency fade analysis. **Top left**: Fade timeline showing when each frequency is faded (colored bars). **Top right**: Total fade fraction by frequency. **Bottom left**: Fade duration histogram. **Bottom right**: Conditional fade probability matrix—$P(\text{col}|\text{row})$ shows probability column frequency is faded given row frequency is faded.

3.7.4 Cross-Frequency Scatter

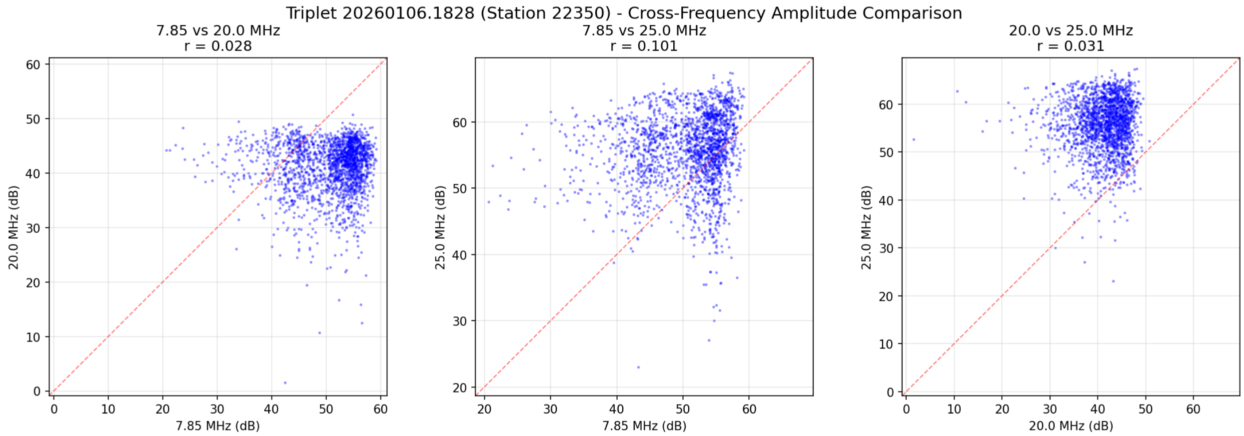

Figure 5: Cross-frequency amplitude scatter plots. Each panel shows amplitude correlation between two frequencies with Pearson correlation coefficient r. Low correlation ($r < 0.3$) indicates independent fading mechanisms at different frequencies.

4 Geographic Correlation: wwv_geographic_correlation.py

4.1 Purpose

Compares phase stability and fading behavior between two geographically separated receivers observing the same WWV frequency simultaneously. This reveals the **spatial coherence scale** of ionospheric disturbances—critical for understanding whether adaptive correction at one site would benefit nearby sites.

Current configuration: Cambridge, MA and Sudbury, MA receivers ($\sim$32 km baseline).

4.2 Command Line Usage

```
# Analyze all available receiver pairs
python3 wwv_geographic_correlation.py

# Analyze specific timestamp
python3 wwv_geographic_correlation.py 20260101.1148

# Analyze all pairs from specific date
python3 wwv_geographic_correlation.py --date 20260101

# List available receiver pairs
python3 wwv_geographic_correlation.py --list

# Skip plot generation
python3 wwv_geographic_correlation.py 20260101.1148 --no-plot
```

4.3 Command Line Arguments

Argument	Description	Default
`timestamp`	Specific timestamp (e.g., 20260101.1148)	All pairs
`--date DATE`	Analyze all pairs from date (YYYYMMDD)	None
`--list`	List available receiver pairs	–
`--no-plot`	Skip plot generation	False

Table 8: wwv_geographic_correlation.py arguments

4.4 Data Requirements

Files with same timestamp but different receiver IDs form a pair:

```
20260101.1148.22350.proxy.kiwisdr.com.freq5000.20000.wav # Cambridge
20260101.1148.22463.proxy.kiwisdr.com.freq5000.20000.wav # Sudbury
```

4.5 Console Output

```
======================================================================
GEOGRAPHIC CORRELATION ANALYSIS: 20260101.1148
Receivers: ['Sudbury', 'Cambridge']
Baseline: ~32 km
======================================================================
Common frequencies: [2.5, 5.0, 10.0] MHz

  Analyzing 5.0 MHz: Cambridge vs Sudbury
    Cambridge: 94% valid, RMS@20ms=0.080 rad
    Sudbury: 81% valid, RMS@20ms=0.197 rad
    Amplitude correlation: r=0.315 at lag=-3507.8 ms
    Fade correlation: r=0.127, Jaccard=0.099
    Joint valid: 77%
    Phase correlation: r=-0.792
    Phase derivative correlation: r=0.002
```

4.6 Output Metrics

Metric	Description
Amplitude correlation	Pearson r between amplitude time series
Peak lag	Time offset of maximum cross-correlation (ms)
Fade correlation	Correlation of binary fade/no-fade states
Jaccard similarity	$\|A \cap B\|/\|A \cup B\|$ for fade regions
Joint valid	Percentage of time both receivers have valid signal
Phase correlation	Correlation of unwrapped phase (after drift removal)
Phase derivative corr	Correlation of $d\phi/dt$ (fast phase variations)

Table 9: Geographic correlation metrics

4.7 Output Plots

The analysis generates multiple diagnostic plots:

4.7.1 Amplitude Comparison

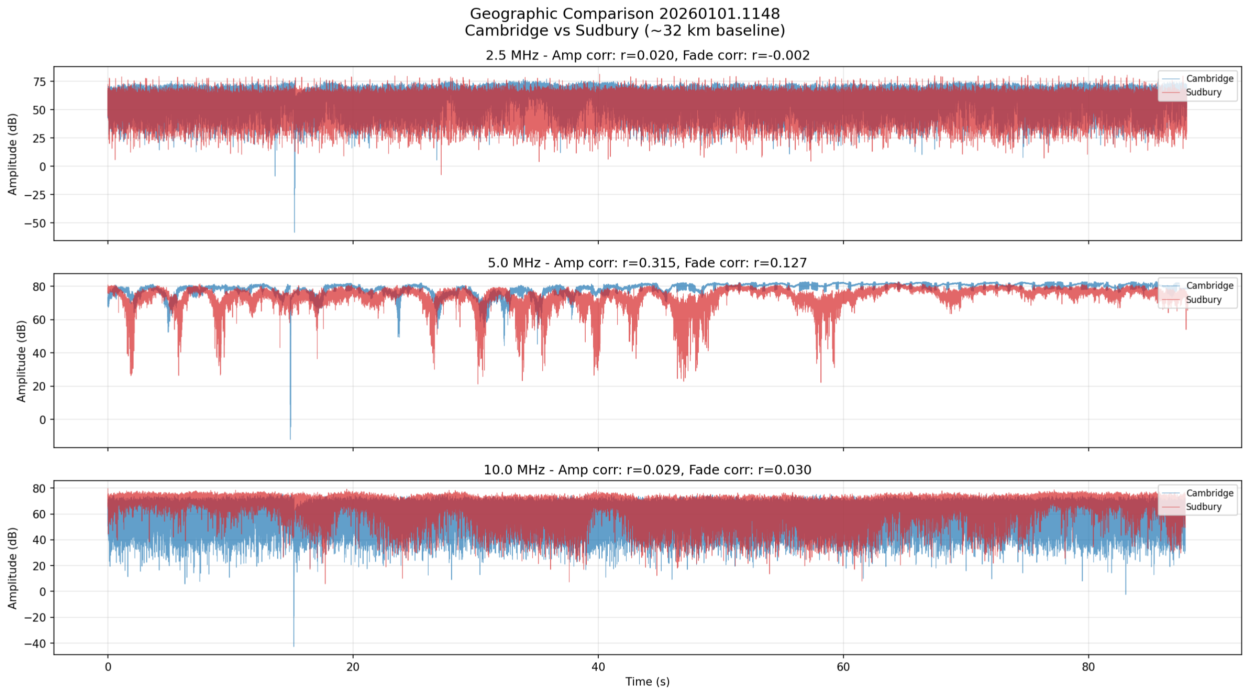

Figure 6: Geographic amplitude comparison. Overlaid time series from Cambridge (blue) and Sudbury (red) receivers at each frequency. Title shows amplitude and fade correlation coefficients. Low correlation ($r < 0.3$) indicates fading is largely independent between the 32 km separated sites.

4.7.2 Fade Correlation

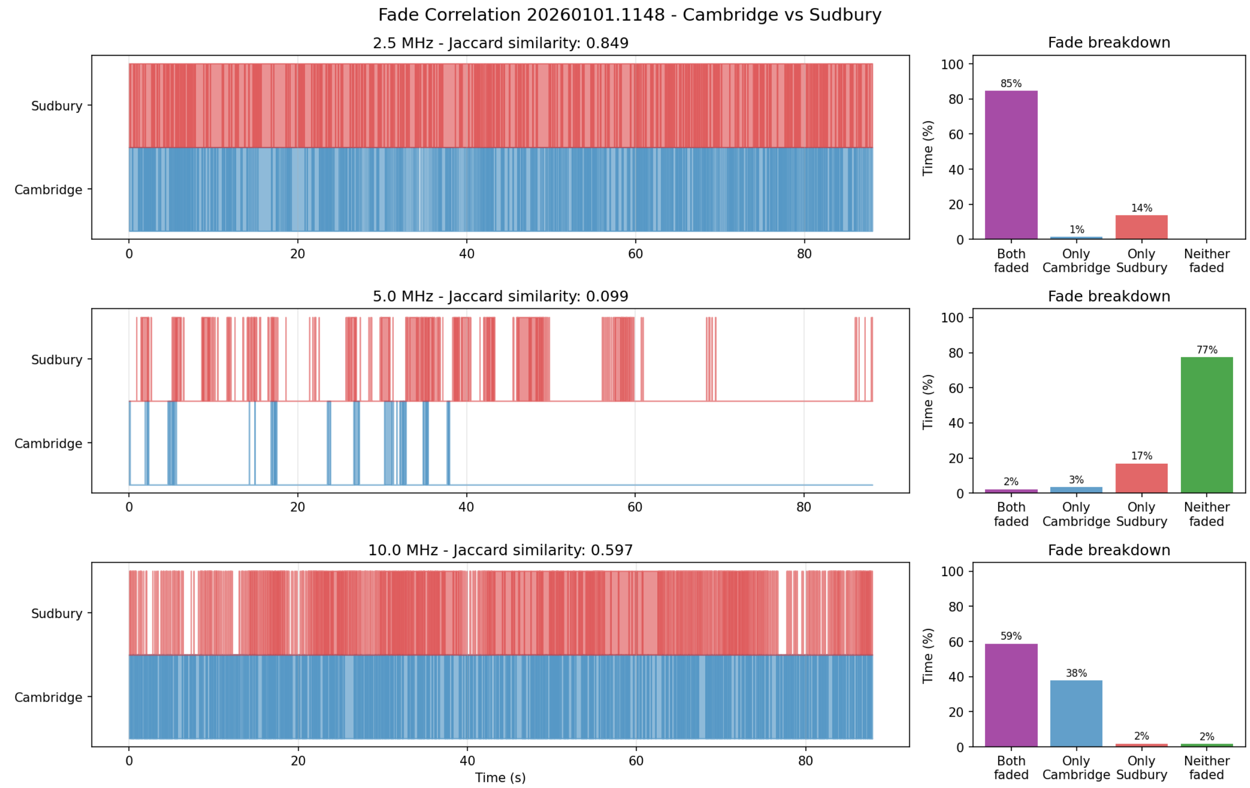

Figure 7: Fade correlation analysis. Left: Timeline showing when each receiver is faded (colored = faded). Right: Breakdown of fade states—"Both faded" indicates correlated fading, while "Only Cambridge/Sudbury" indicates independent fading. Jaccard similarity quantifies fade overlap.

4.7.3 Structure Function Comparison

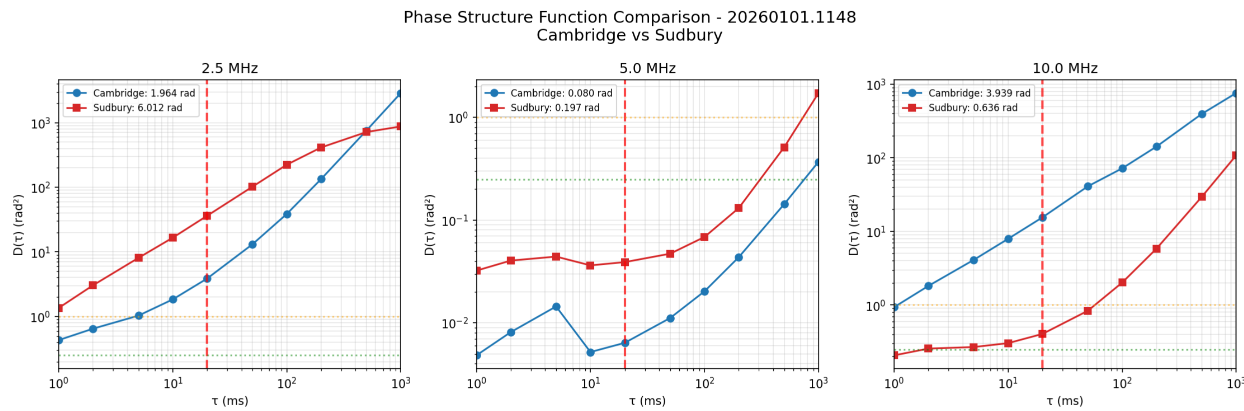

Figure 8: Phase structure function comparison between receivers. Each panel shows $D(\tau)$ for both sites at one frequency. Different structure functions indicate different ionospheric conditions along each propagation path. The 20 ms round-trip marker and assessment thresholds (0.5 rad, 1.0 rad) are shown.

4.8 Interpretation

4.8.1 Spatial Coherence

The key question: Are ionospheric structures large or small compared to the 32 km receiver separation?

- **High correlation** ($r > 0.5$): Large ionospheric structures; correction at one site benefits nearby sites
- **Low correlation** ($r < 0.3$): Small structures or independent paths; each site needs its own correction

4.8.2 Typical Results

At the 32 km baseline:

- Amplitude correlation is often low ($r \approx 0.1$–0.3)
- Fades are largely independent (Jaccard < 0.2 typically)
- This suggests ionospheric coherence scale is smaller than 32 km at HF

5 Data Collection

5.1 Recording Scripts

Several shell scripts automate data collection:

Script	Description
`take3freq5.sh`	Record 3 frequencies simultaneously (triplet)
`takedata3.sh`	Single frequency recording

Table 10: Data collection scripts

5.2 Example: Recording a Triplet

```
# Record 7.85, 20, 25 MHz simultaneously from KiwiSDR
./take3freq5.sh http://22350.proxy.kiwisdr.com:8073
```

This creates three files with matching timestamps for triplet analysis.

5.3 Recording Parameters

Current default settings:

- Duration: 90 seconds
- Sample rate: 20 kHz
- Mode: IQ (complex samples)
- Frequency offset: +2 kHz from nominal (for beat detection)
- AGC gain: Fixed at 50 dB

6 Interpreting Results

6.1 Phase Structure Function

The structure function $D(\tau)$ typically shows:

- **Short lags ($\tau < 10$ ms)**: Dominated by receiver noise, relatively flat
- **Medium lags (10–100 ms)**: Ionospheric scintillation regime, increasing
- **Long lags ($\tau > 100$ ms)**: Large-scale TEC variations, steep increase

The critical value is at $\tau = 20$ ms (round-trip time for $\sim$2000 km path).

6.2 Frequency Dependence

Ionospheric phase effects scale as $1/f^2$, so:

- Lower frequencies (5–10 MHz): More Faraday rotation, more phase variation
- Higher frequencies (20–25 MHz): Less ionospheric effect, better stability

Typical results show 25 MHz has $\sim$2–4$\times$ lower RMS phase than 10 MHz.

6.3 Day vs Night

- **Daytime**: Higher electron density, more D-layer absorption at low frequencies, generally more stable phase
- **Nighttime**: Lower electron density but more irregularities, increased scintillation, more fading

6.4 Cross-Frequency Correlation

Low amplitude correlation ($r < 0.3$) between frequencies indicates:

- Independent propagation paths (different reflection heights)
- Frequency-selective fading (interference between O/X modes)
- Potential for frequency diversity to improve reliability

7 Troubleshooting

7.1 "No carrier found" or Wrong Frequency

- Ensure recording has sufficient SNR
- Check that carrier offset is within ±5 kHz of baseband
- Verify file is stereo IQ format

7.2 100% Faded

- Signal too weak—try different KiwiSDR or time
- AGC may have been varying—use fixed gain recordings
- Frequency may be above MUF (not propagating)

7.3 Excessive Phase Splices

Many splices (>50) indicate heavy fading conditions:

- Consider analyzing a different time period
- Results may still be valid if valid sample percentage is reasonable (>50%)

7.4 No Triplet Files Found

- Ensure files share exact same timestamp (YYYYMMDD.HHMM)
- Check that files contain "triplet" in filename
- Verify frequency pattern `freq{kHz}` is present

8 References

1. NIST WWV/WWVH broadcast information: `https://www.nist.gov/pml/time-and-frequency-division/time-distribution/radio-station-wwv`
2. KiwiSDR project: `http://kiwisdr.com/`
3. Ionospheric scintillation theory: Yeh & Liu, "Radio wave scintillations in the ionosphere," Proc. IEEE, 1982

A Example Output: Summary Report from Geo analysis

```
# WWV Geographic Correlation Analysis
# Timestamp: 20260101.1148
# Receiver 1: Cambridge
# Receiver 2: Sudbury
# Baseline: ~32 km
# Analysis date: 20260101
# Filter bandwidth: 500.0 Hz
# SNR threshold: 12.0 dB
#
# SUMMARY BY FREQUENCY
Freq_MHz        RX1_pct_valid        RX1_RMS_20ms_rad        RX1_n_fades        RX1_fade_rate_per_min        RX2_pct_valid
2.5        13.9        1.9645        1296        882.04        1.7        6.0118        479        326.56        0.0205
5.0        94.4        0.0799        67        45.64        80.9        0.1974        389        264.60        0.3151        0.
10.0        3.4        3.9385        789        538.68        39.4        0.6358        1352        921.73        0.0293

# STRUCTURE FUNCTION D(tau)
# tau_ms = time lag in milliseconds
# D_tau = phase structure function in rad^2
# RMS = sqrt(D_tau) in radians
tau_ms        2.5MHz_Cambridge_D_tau        2.5MHz_Cambridge_RMS        2.5MHz_Sudbury_D_tau        2.5MHz_Sudbury_RMS        5
1.0        0.430716        0.656290        1.355163        1.164115        0.004819        0.069418        0.032188        0.17
2.0        0.647212        0.804495        3.038724        1.743194        0.008108        0.090045        0.040334        0.20
5.0        1.030120        1.014948        8.063970        2.839713        0.014421        0.120086        0.044113        0.21
10.0        1.836788        1.355281        16.560835        4.069501        0.005191        0.072051        0.036224        0.
20.0        3.859141        1.964470        36.142263        6.011844        0.006384        0.079903        0.038960        0.
50.0        13.104374        3.619996        101.955815        10.097317        0.011133        0.105511        0.047066
100.0        38.591522        6.212208        223.619293        14.953906        0.020237        0.142259        0.068420
200.0        133.803394        11.567342        413.027474        20.323077        0.043577        0.208750        0.131031
500.0        756.651184        27.507293        716.193435        26.761791        0.142868        0.377978        0.511649
1000.0        2875.257718        53.621430        873.896069        29.561733        0.369261        0.607668        1.725007

# DETAILED FADE STATISTICS
Freq_MHz        Receiver        Amp_mean_dB        Amp_std_dB        Amp_min_dB        Amp_max_dB        Threshold_dB        Fa
2.5        Cambridge        63.43        5.70        -58.46        77.09        57.60        86.11        1296        882.04
2.5        Sudbury        57.88        5.97        -7.55        81.35        52.46        98.32        479        326.56
5.0        Cambridge        78.72        3.36        -12.19        83.02        69.66        5.64        67        45.64
5.0        Sudbury        74.37        4.56        21.19        82.73        66.82        19.14        389        264.60
10.0        Cambridge        62.49        5.68        -42.83        75.54        56.66        96.61        789        538.68
10.0        Sudbury        67.82        5.16        5.83        79.65        61.25        60.55        1352        921.73

# AMPLITUDE PERCENTILES (dB)
Freq_MHz        Receiver        P1        P5        P10        P25        P50        P75        P90        P95        P99
2.5        Cambridge        45.77        52.92        56.07        60.50        64.40        67.43        69.60        70.72
2.5        Sudbury        39.96        47.07        50.25        54.69        58.64        61.86        64.46        65.96
5.0        Cambridge        67.12        72.15        74.73        77.61        79.57        80.95        81.66        81.96
5.0        Sudbury        58.33        65.43        68.57        72.48        75.43        77.55        78.82        79.40
10.0        Cambridge        44.74        52.03        55.20        59.59        63.43        66.46        68.66        69.80
10.0        Sudbury        50.96        57.98        61.08        65.31        68.85        71.47        73.25        74.12
```