Chris and Claude's Crude Multihop HF Propagation Simulator

User Guide

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Contents

1 Overview

The HF propagation modeling code `multihop.py` is a full-polarization HF ionospheric propagation simulator that models radio wave propagation through the Earth's ionosphere. It calculates ray paths, Faraday rotation, polarization states, path losses, and O/X mode separation for single-hop and multi-hop skywave paths.

The program was generated over a two-day period with multiple iterations between C. Stubbs and the Claude Code command line interface, running on a Mac laptop. Version details are shown in Table 1.

Field	**Value**
Version	2.0.76
Session ID	9b16310f-4494-453e-aaf9-f0e4e7dfbdb5
cwd	/Users/christopherstubbs/Desktop/projects/ionosphere/kiwiclient
Auth token	none
API key	/login managed key
Organization	Chris's Individual Org
Model	opus (claude-opus-4-5-20251101)

Table 1: Claude Code version information.

1.1 Key Features

- **N-hop propagation**: Simulates 1, 2, 3, or more ionospheric reflections with ground bounces
- **O/X mode ray tracing**: Separate ray paths for ordinary (O) and extraordinary (X) magnetoionic modes
- **Faraday rotation**: Full calculation of polarization rotation through the ionosphere
- **Polarization analysis**: Complete Stokes parameter output and polarization ellipse visualization
- **Space weather integration**: Auto-fetches F10.7 solar flux and geomagnetic indices from NOAA
- **MUF calculation**: Maximum Usable Frequency based on path geometry and ionospheric conditions
- **D-layer absorption**: Frequency-dependent daytime absorption modeling
- **Preset paths**: Built-in WWV transmitter paths for common research scenarios

2 Installation

2.1 Requirements

```
# Required
pip install numpy matplotlib
```

```
# Optional (for space weather auto-fetch)
pip install requests
```

3 Command Line Arguments

3.1 Path Specification

Argument	Description	Default
`--path`	Preset path: `wwv-cambridge` or `wwv-owens`	None
`--tx-lat`	Transmitter latitude (degrees N)	40.68 (WWV)
`--tx-lon`	Transmitter longitude (degrees E, negative for W)	-105.04 (WWV)
`--tx-alt`	Transmitter altitude (meters)	0
`--rx-lat`	Receiver latitude (degrees N)	Required
`--rx-lon`	Receiver longitude (degrees E)	Required
`--rx-alt`	Receiver altitude (meters)	0

Table 2: Path specification arguments

3.2 Preset Paths

Preset	Transmitter	Receiver	Distance
`wwv-cambridge`	WWV Fort Collins, CO	Cambridge, MA	2812 km
`wwv-owens`	WWV Fort Collins, CO	Owens Valley, CA	1206 km

Table 3: Built-in preset paths

3.3 Simulation Parameters

Argument	Description	Default
`--hops`	Number of ionospheric hops (1, 2, 3, ...)	1
`--frequencies`	List of frequencies in MHz	5 10 15 20 25
`--date`	Date/time in ISO format (UTC)	Current time
`--f107`	Override F10.7 solar flux (sfu)	Auto-fetched
`--kp`	Override Kp geomagnetic index	Auto-fetched

Table 4: Simulation parameters

3.4 Output Control

Argument	Description	Default
`--output`	Output file prefix	`hf_prop`
`--no-plots`	Skip generating plot files	False

Table 5: Output control arguments

4 Usage Examples

4.1 Example 1: Basic Single-Hop Simulation

```
python3 multihop.py --path wwv-owens --hops 1 --frequencies 5 10 15 20 25
```

This simulates single-hop propagation from WWV to Owens Valley at the current time.

4.2 Example 2: Multi-Hop Nighttime Simulation

```
python3 multihop.py --path wwv-cambridge --hops 2 \
    --date 2026-01-15T06:00:00 --frequencies 5 10 15
```

This simulates 2-hop nighttime propagation (06:00 UTC) from WWV to Cambridge.

4.3 Example 3: Custom Path with Override

```
python3 multihop.py --tx-lat 45.295 --tx-lon -75.753 \
    --rx-lat 37.234 --rx-lon -118.282 \
    --hops 2 --frequencies 3.33 7.85 14.67 \
    --f107 180 --date 2026-06-21T18:00:00
```

This simulates CHU Ottawa to Owens Valley with manually specified F10.7 flux.

4.4 Example 4: Quick Check (No Plots)

```
python3 multihop.py --path wwv-owens --hops 3 --no-plots
```

Runs simulation and prints results to console without generating plot files.

5 Output Files

When run without `--no-plots`, the simulator generates these files:

File	Description
`hf_prop_summary.txt`	Complete text report with all parameters and results
`hf_prop_overview.png`	4-panel overview: ray paths, electron density, Faraday rotation, path loss
`hf_prop_3d_rays.png`	3D visualization of O/X mode ray splitting and ground reflections
`hf_prop_polarization.png`	Stokes parameters, polarization ellipses, DoLP/-DoCP
`hf_prop_rx_polarization.png`	Detailed receiver polarization state analysis
`hf_prop_ox_modes.png`	O-mode vs X-mode separation in RCP/LCP receiver channels
`hf_prop_ray_details.png`	Detailed ray path profiles and refractive indices

Table 6: Output files generated by the simulator

6 Understanding the Output

6.1 Console Output Table

The main results table shows propagation characteristics for each frequency:

Column	Description
Freq (MHz)	Signal frequency
Reflect (km)	Ionospheric reflection height (varies with frequency)
Loss (dB)	Total path loss (free space + D-layer absorption)
Faraday (deg)	Total Faraday rotation (typically thousands at HF)
N_rot ($\times\pi$)	Number of half-rotations
O-X phase (waves)	Phase difference between O and X modes in wavelengths
AoA Elev (deg)	Angle of arrival elevation at receiver
AoA Az (deg)	Angle of arrival azimuth from North
RCP frac	Fraction of power in RCP receiver channel
LCP frac	Fraction of power in LCP receiver channel
Status	`OK` or `ABOVE_MUF`

Table 7: Console output column definitions

6.2 Status Interpretation

- **OK**: Frequency is below the Maximum Usable Frequency (MUF) and will propagate
- **ABOVE_MUF**: Frequency exceeds MUF; signal penetrates ionosphere instead of reflecting

6.3 O/X Mode Separation

The O/X mode table shows how the two magnetoionic modes map to circular polarization channels:

- **O-mode** (ordinary wave) appears almost entirely in **LCP** (left circular polarization)
- **X-mode** (extraordinary wave) appears almost entirely in **RCP** (right circular polarization)

- Cross-talk is typically $< 0.1\%$ at HF frequencies

7 Output Plots

7.1 Overview Plot

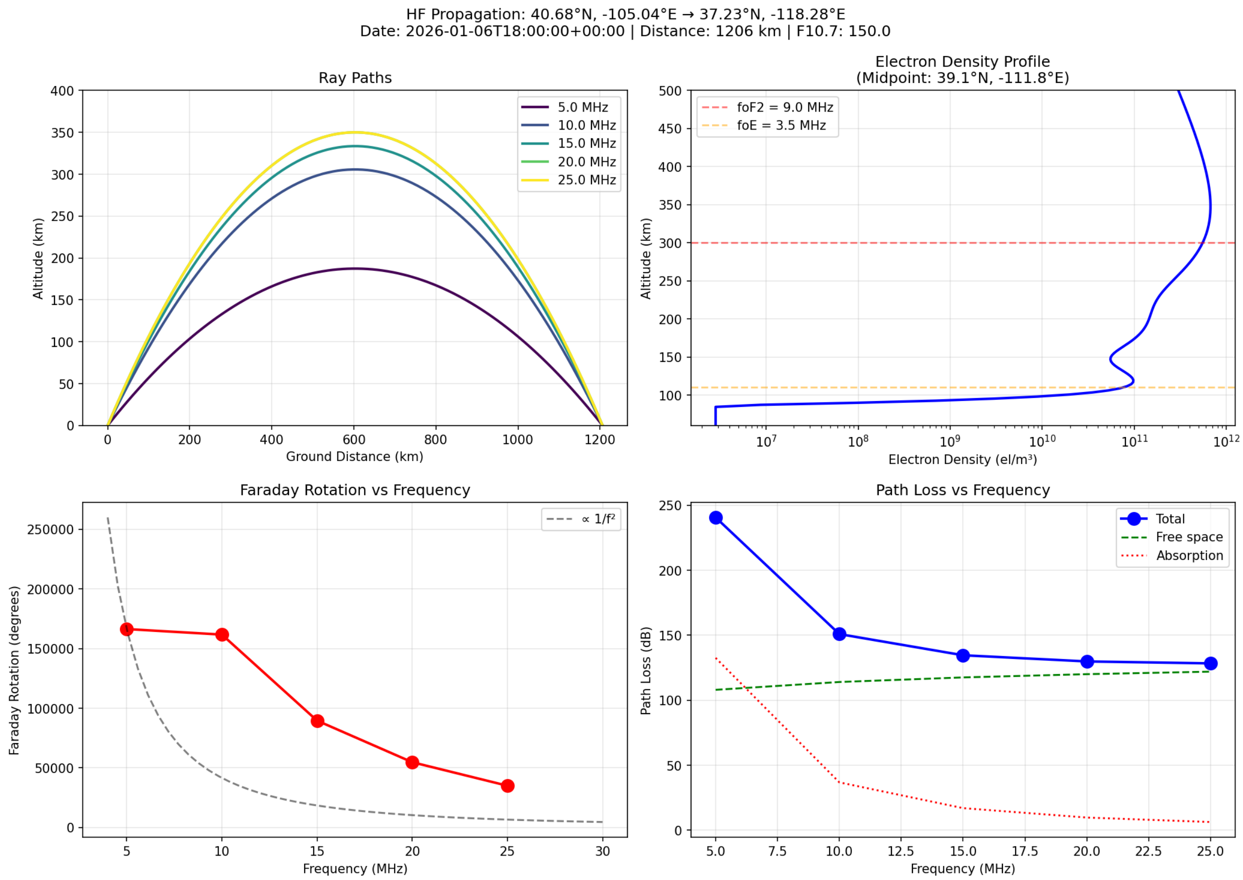

Figure 1: Overview plot showing ray paths (top left), electron density profile (top right), Faraday rotation vs frequency (bottom left), and path loss components (bottom right). The ray paths show different reflection heights for each frequency, with lower frequencies reflecting from the E-layer ($\sim$110 km) and higher frequencies from the F2-layer ($\sim$300 km).

7.2 3D Ray Tracing

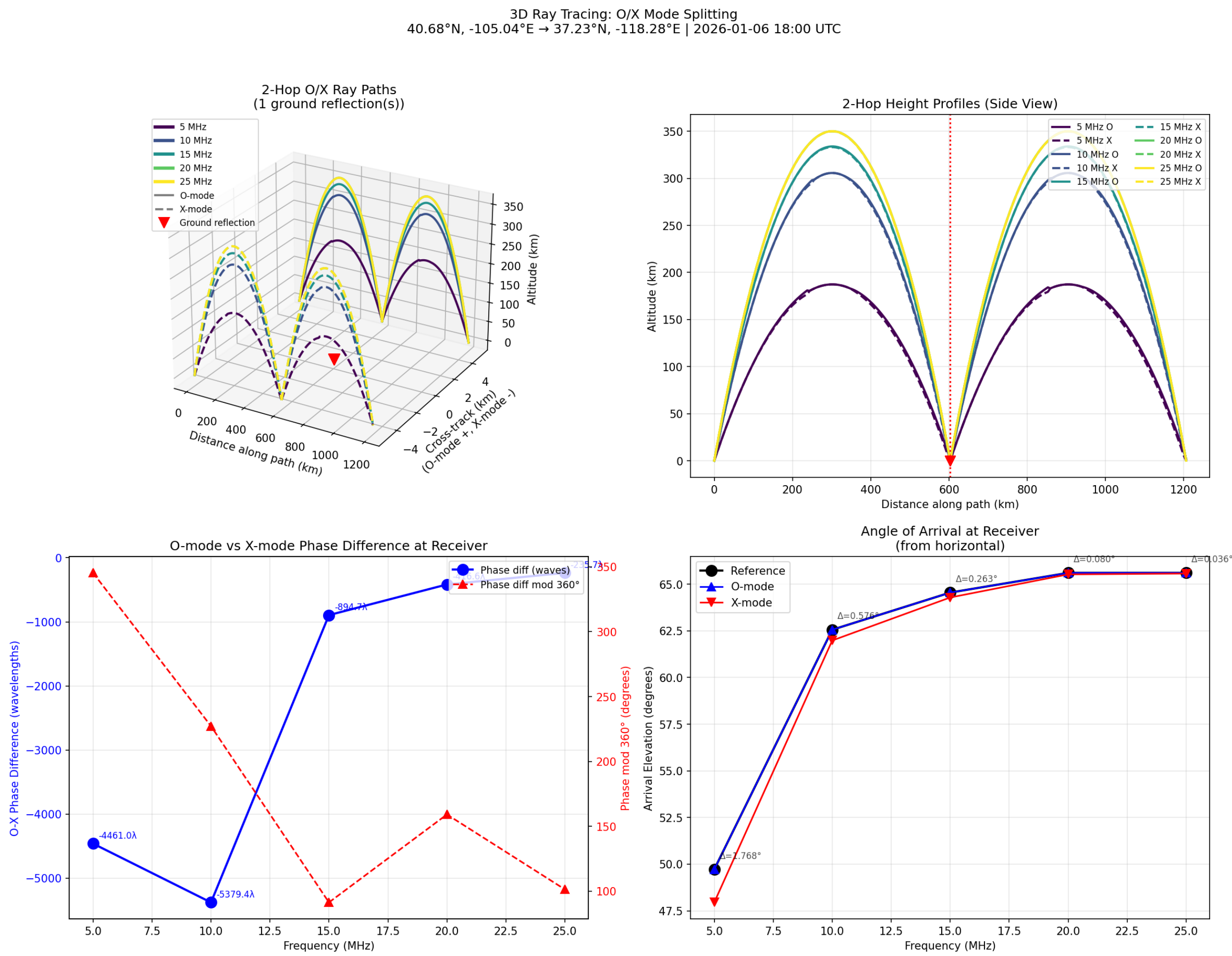

Figure 2: 3D ray tracing visualization showing O/X mode splitting. Top left: 3D view of ray paths with ground reflection points marked. Top right: Side view of 2-hop height profiles. Bottom left: O-X phase difference in wavelengths. Bottom right: Angle of arrival at receiver with O/X splitting annotations.

7.3 Polarization Analysis

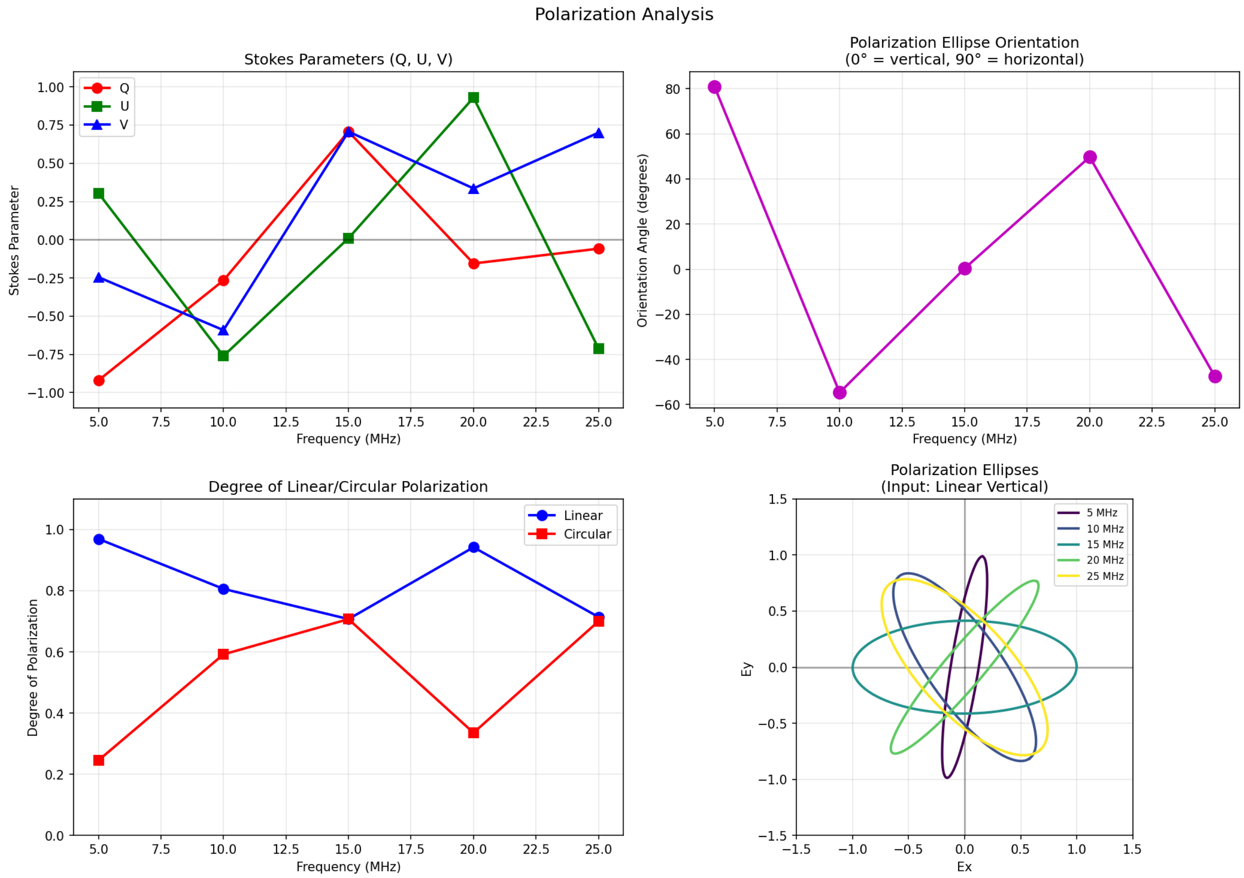

Figure 3: Polarization analysis showing Stokes parameters Q, U, V (top left), polarization ellipse orientation angle (top right), degree of linear/circular polarization (bottom left), and polarization ellipse traces (bottom right) for each frequency.

7.4 O/X Mode Channel Composition

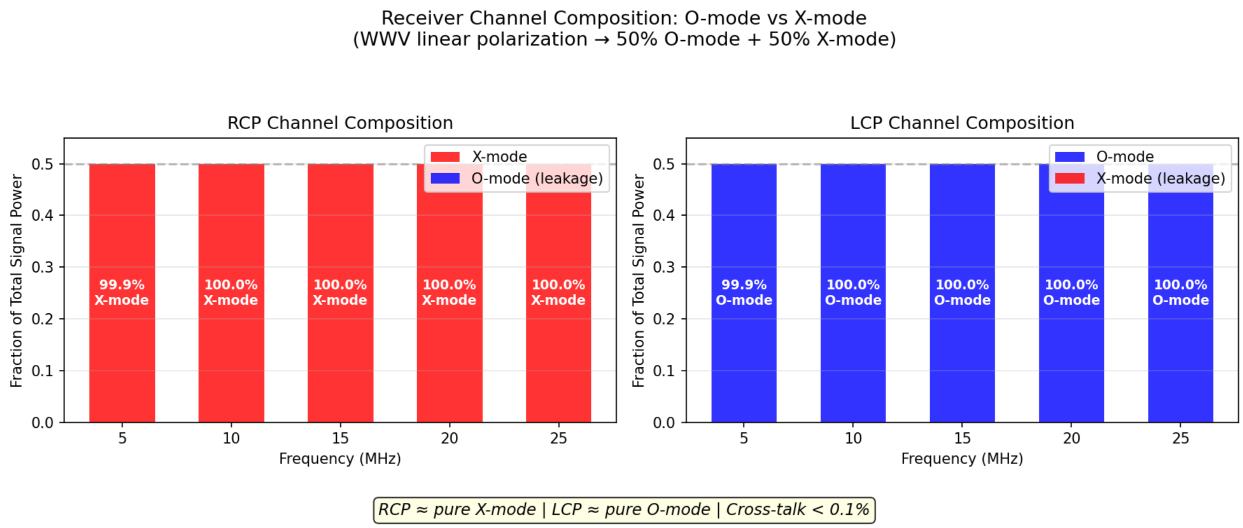

Figure 4: O-mode vs X-mode separation in dual-circular receiver channels. Left: RCP channel receives almost pure X-mode. Right: LCP channel receives almost pure O-mode. Cross-talk is $< 0.1\%$, demonstrating that dual-circular polarization receivers can cleanly separate the two magnetoionic modes.

8 Physics Background

8.1 Maximum Usable Frequency (MUF)

The MUF is given by:

$$\text{MUF} = f_{oF2} \times \sec(\theta) \tag{1}$$

where f_{oF2} is the critical frequency of the F2 layer and θ is the angle of incidence at the ionosphere.

- Shorter paths have steeper incidence angles → **lower MUF**
- Longer paths have shallower angles → **higher MUF**
- More hops means shorter individual hops → **lower MUF**

8.2 Faraday Rotation

The total Faraday rotation is:

$$\Omega = \frac{K}{f^2} \int N_e B_{\|} \, ds \tag{2}$$

where $K \approx 2.365 \times 10^4$ (SI units), N_e is electron density, $B_{\|}$ is the magnetic field component along the ray path, and f is frequency.

At HF frequencies (5–25 MHz), the total rotation is typically hundreds to thousands of complete rotations, making the final polarization angle effectively unpredictable.

8.3 Reflection Height vs Frequency

Frequency Range	Reflection Layer	Height
$< f_{oE}$ ($\sim$3 MHz day)	E-layer	100–120 km
f_{oE} to f_{oF2}	Between E and F2	120–280 km
Near f_{oF2}	F2-layer	280–350 km

Table 8: Reflection height dependence on frequency

8.4 Day vs Night Differences

Parameter	Daytime	Nighttime
f_{oF2}	$\sim$9 MHz	$\sim$5 MHz
f_{oE}	$\sim$3.5 MHz	$\sim$1 MHz
MUF	Higher	Lower
D-layer absorption	Strong at low freq	Negligible
Best frequencies	10–25 MHz	2.5–10 MHz

Table 9: Day vs night ionospheric conditions

8.5 D-Layer Absorption

Daytime D-layer absorption follows approximately:

$$L \propto \frac{\cos^{0.75}(\chi)}{(f + f_L)^2} \tag{3}$$

where χ is the solar zenith angle and $f_L \approx 0.5$ MHz. This causes severe attenuation of low frequencies (<10 MHz) during daytime.

9 Time Signal Station Reference Frequencies

Station	Location	Frequencies (MHz)
WWV	Fort Collins, CO, USA	2.5, 5, 10, 15, 20, 25
WWVH	Kauai, HI, USA	2.5, 5, 10, 15
CHU	Ottawa, Canada	3.330, 7.850, 14.670

Table 10: Time signal station frequencies

10 Troubleshooting

10.1 "Could not fetch space weather"

The simulator tries multiple sources (NOAA SWPC, CelesTrak). If all fail:

- Check internet connectivity

- Use `--f107` and `--kp` to manually specify values
- Default values (F10.7=150, Kp=2) are used as fallback

10.2 High Path Loss Values

Very high losses (>300 dB) typically indicate:

- Low frequency + daytime = extreme D-layer absorption
- Consider nighttime operation for frequencies below 10 MHz

10.3 All Frequencies Show ABOVE_MUF

The MUF is too low for your chosen frequencies:

- Try lower frequencies
- Try fewer hops (increases MUF)
- Try daytime simulation (higher f_{oF2})
- Check if path is too short (short paths have low MUF)

11 Model Limitations

1. **Flat-Earth approximation**: Rays refract from ionosphere and reflect from ground
2. **Chapman layer ionosphere**: No tilts, gradients, or sporadic E
3. **Tilted dipole geomagnetic field**: Approximation (IGRF not implemented)
4. **Simplified D-layer absorption**: ITU-R inspired but not full model
5. **Parabolic ray approximation**: Valid for most HF, less accurate near MUF
6. **Perfect ground reflection**: No ground conductivity effects
7. **No tropospheric effects**: Assumes vacuum below ionosphere
8. **Single-mode propagation**: No mode coupling or conversion

A Example Output: Summary Report

```
================================================================================
HF POLARIZATION PROPAGATION SIMULATION - SUMMARY REPORT
================================================================================

SIMULATION METADATA
----------------------------------------
Report generated: 2026-01-06T17:48:01.617705
Simulator version: 2.0 (with O/X ray tracing)

PATH GEOMETRY
----------------------------------------
Transmitter location:  40.6800°N, -105.0400°E, 0 m
```

```
Receiver location:     37.2339°N, -118.2822°E, 0 m
Midpoint:              39.14°N, -111.82°E
Ground distance:       1206.0 km
Initial bearing:       -104.2°

DATE/TIME
----------------------------------------
Simulation date/time:  2026-01-06T18:00:00+00:00
Solar zenith angle:    65.0° at midpoint
Conditions:            Daytime

SPACE WEATHER
----------------------------------------
F10.7 solar flux:      150.0 sfu
F10.7 81-day avg:      150.0 sfu
Ap index:              10
Kp index:              2.0
Sunspot number:        100

IONOSPHERIC PARAMETERS
----------------------------------------
Critical freq foF2:    8.98 MHz
Critical freq foE:     3.48 MHz
F2 layer peak height:  300 km
F2 layer peak Ne:      1.00e+12 el/m³

GEOMAGNETIC FIELD (at midpoint, 250 km)
----------------------------------------
Total field:           43751 nT
Dip angle:             64.3°
Declination:           0.0°
Model:                 Tilted dipole approximation

====================================================================================================
SIMULATION RESULTS BY FREQUENCY
====================================================================================================

Freq     Reflect    Path       Faraday      N_rot    O-X phase    AoA Elev   Azimuth
(MHz)    Ht (km)    Loss(dB)   (deg)        (×pi)     (waves)      (deg)      (deg)
----------------------------------------------------------------------------------------------------
5.0      187.3      240.7      166401       924      -4461.0      49.7       75.8
10.0     305.7      150.9      161765       899      -5379.4      62.6       75.8
15.0     333.5      134.6      89640        498      -894.7       64.5       75.8
20.0     350.0      129.9      54770        304      -416.6       65.6       75.8
25.0     350.0      128.4      35053        195      -235.7       65.6       75.8

POLARIZATION STATE AT RECEIVER
(Input: Linear Vertical from WWV vertical dipole antenna)
--------------------------------------------------------------------------------
Freq     Orient     Ellipt     DoLP     DoCP     Q          U          V
(MHz)    (deg)      (deg)
--------------------------------------------------------------------------------
5.0      80.8       -7.1       0.969    0.245    -0.920     0.305      -0.245
10.0     -54.6      -18.1      0.806    0.592    -0.266     -0.761     -0.592
15.0     0.4        22.5       0.707    0.707    0.707      0.009      0.707
20.0     49.8       9.8        0.942    0.335    -0.156     0.929      0.335
25.0     -47.4      22.2       0.714    0.700    -0.059     -0.712     0.700

O-MODE AND X-MODE: POWER IN RCP vs LCP CHANNELS
(For a dual-circular polarization receiver)
------------------------------------------------------------------------------------------
Freq     Mode       RCP frac     LCP frac     Dominant   Stokes V     Notes
------------------------------------------------------------------------------------------
5.0      O-mode     0.0005       0.9995       LCP        -0.9990      99.9% in LCP
         X-mode     0.9995       0.0005       RCP        0.9990       99.9% in RCP
10.0     O-mode     0.0001       0.9999       LCP        -0.9997      100.0% in LCP
         X-mode     0.9999       0.0001       RCP        0.9997       100.0% in RCP
15.0     O-mode     0.0000       1.0000       LCP        -0.9999      100.0% in LCP
```

```
         X-mode     1.0000       0.0000       RCP        0.9999       100.0% in RCP
20.0     O-mode     0.0000       1.0000       LCP        -1.0000      100.0% in LCP
         X-mode     1.0000       0.0000       RCP        1.0000       100.0% in RCP
25.0     O-mode     0.0000       1.0000       LCP        -1.0000      100.0% in LCP
         X-mode     1.0000       0.0000       RCP        1.0000       100.0% in RCP

Interpretation for dual-circular receiver:
  - RCP channel primarily sees X-mode
  - LCP channel primarily sees O-mode
  - Small cross-talk due to non-circular characteristic polarizations

================================================================================
NOTES
================================================================================

1. FARADAY ROTATION: At HF frequencies (5-25 MHz), the total Faraday rotation
   is typically many complete rotations (hundreds to thousands of degrees).
   This makes the final polarization angle essentially unpredictable from
   small variations in electron density. This explains polarization fading.

2. O/X MODE SPLITTING: The ordinary (O) and extraordinary (X) waves travel
   along slightly different paths due to their different refractive indices
   in the magnetized ionosphere. The O-wave typically penetrates higher
   before reflecting. The angular splitting at the receiver is typically
   small (<0.1°) but can cause interference when the modes recombine.

3. ANGLE OF ARRIVAL: The elevation angle reported is measured from the
   horizontal at the receiver location. For a single-hop path, this depends
   on the reflection height and path geometry.

4. PROPAGATION MODE: This simulation implements 1-hop (single reflection)
   propagation. For multihop paths at longer distances, run separate
   simulations for each hop or modify the ray tracer.

5. MODEL LIMITATIONS:
   - Chapman layer ionosphere (no tilts, irregularities, or sporadic E)
   - Simplified D-region absorption
   - Parabolic ray approximation (valid for most HF paths)
   - No tropospheric effects
   - Tilted dipole geomagnetic field (unless ppigrf installed)

================================================================================
END OF REPORT
================================================================================
```