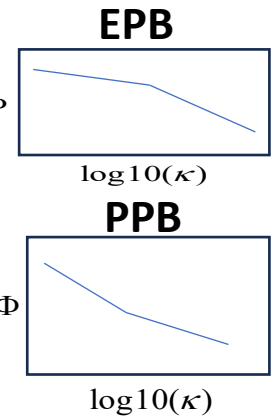
# Extreme Equatorial Scintillation Structure Variation

by
Charles L. Rino, Charles S. Carrano, Tatsuhiro Yokoyama, Dmytro Vasylyev,
Luca Spogli , and Yu Morton

## BACKGROUND

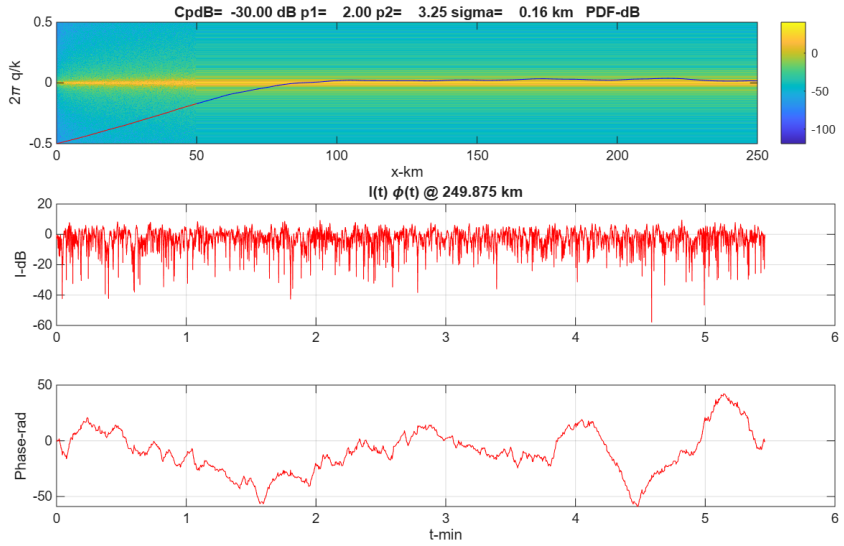
- **The onset and evolution of equatorial plasms bubbles (EPBs) is captured by physics-based high-resolution simulations.**
  - **Analyses of simulated EPB and measured C/NOFS intermediate-scale structure support a two-component inverse power-law spectral density function (SDF) with the larger-scale index smaller than the smaller-scale index.**
  - **Although the expected GNSS structure is found with scintillation diagnostics, it coexists with single-power law and enhanced large-scale structure, denoted PPB.**
  - **Recent back-propagation structure diagnostics confirm that the measured EPB and PPB structure is consistent with propagation predictions, indicating that EPB structure is more varied and may have multiple sources.**




This poster reviews scintillation diagnostics supporting multiple instability mechanisms as an extension of *Extreme scintillation structure diagnostics, JATP*
https://doi.org/10.1016/j.jastp.2026.106805

# Definitive diagnostic measurements require a unification of Propagation theory, Stochastic Processes, and Plasma Physics

## Propagation Theory




Upper frames show power spectral density (PSD) of evolving complex field with S4 overlaid (red MPS, blue free-space. Lower frames are intensity and phase at observation point.
UPPER =>EPB LOWER=PPB

## Stochastic Processes

### SDF

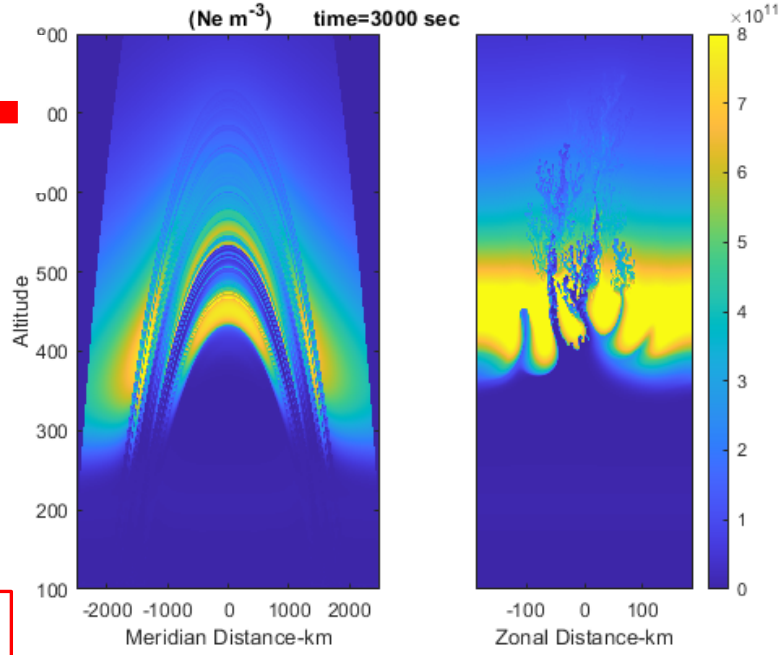
$$\Phi_{\Delta N}(K_y) = C_p \begin{cases} K_y^{-p_1} & K_y < K_0 \\ \left(K_0^{p_2-p_1}\right) K_y^{-p_2} & K_y > K_0 \end{cases}$$

### Universal Strength Param

$$U = C_P \begin{cases} \rho_F^{p_1-1} & \text{for } \mu_0 \le 1 \\ \rho_F^{p_2-1} \mu_0^{p_1-p_2} & \text{for } \mu_0 \le 1 \end{cases}$$

- **4 Structure parameters and the Fresnel scale connect EPB structure and propagation diagnostics**
- **The standard $S4$, $\sigma_\phi$, and ROTI diagnostic are inadequate**

## Plasma Physics

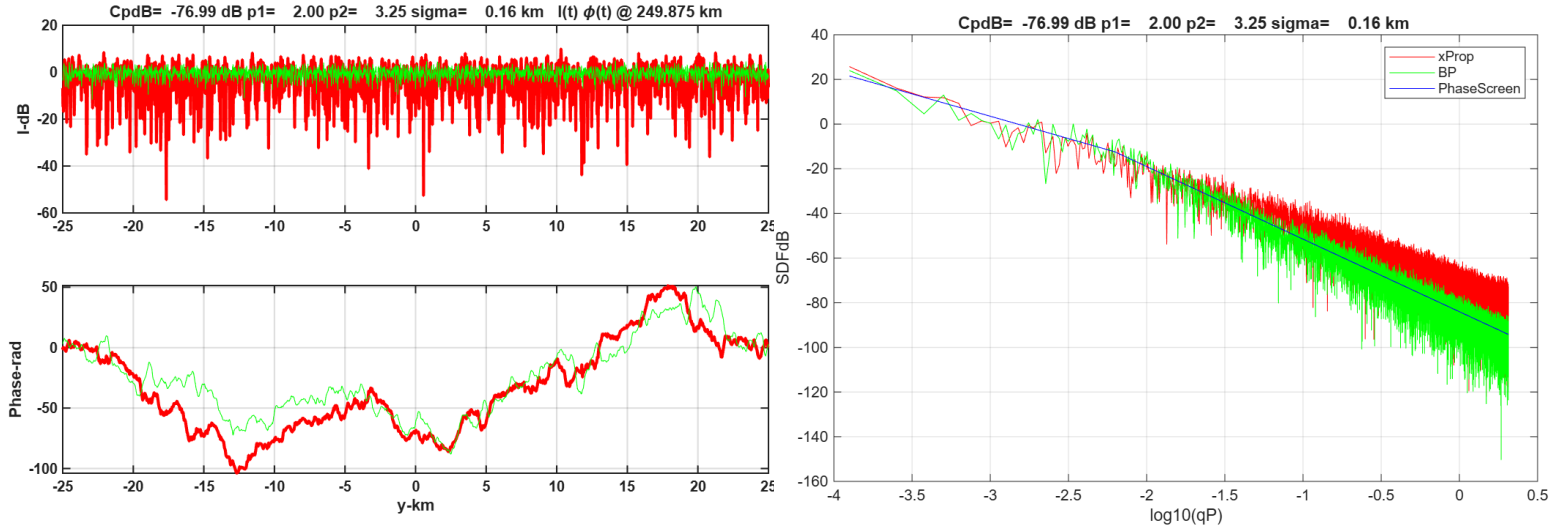



Left and right frames show, respectively, meridian and equatorial plane slices of 3D physics-based simulations of developed EPB structure

# Simulations Validate Structure Diagnostics

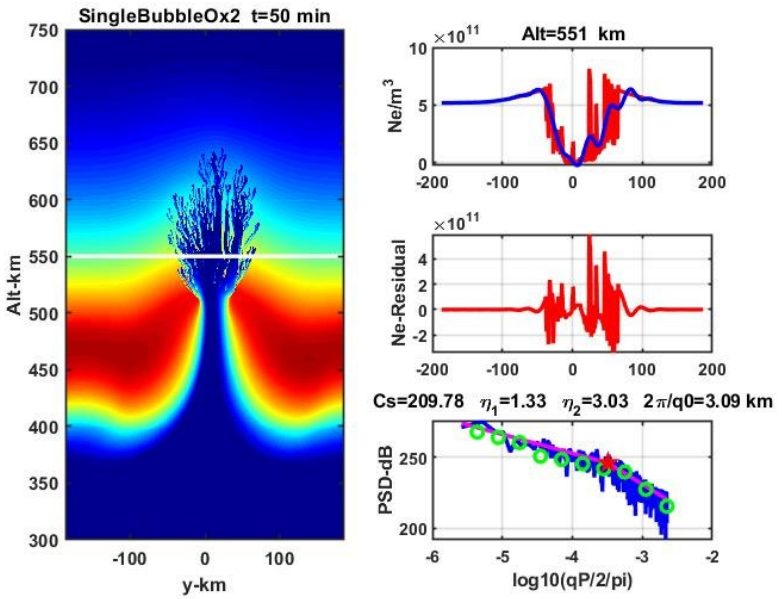
- **High resolution physics-based simulations provide structure realizations for the dominant instability associated with equatorial plasma bubbles. Developed structure is referred to as EPB.**
- **Multiple-Phase-Screen (MPS) simulations of propagation through structured ionospheric regions captures the full range of scintillation phenomena at frequencies above HF.**
- **Under ideal conditions ionospheric structure measure by one-dimensional scans can be related to time-series generated by propagation paths traversing disturbed regions.**

Diagnostic measurements applied to MPS simulations




Left frames show intensity & phase realizations.
Right frame shows measured phase SDFs

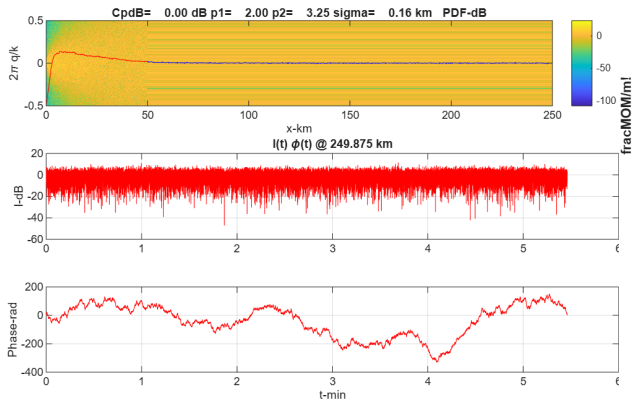
Diagnostic measurements applied to structure simulations

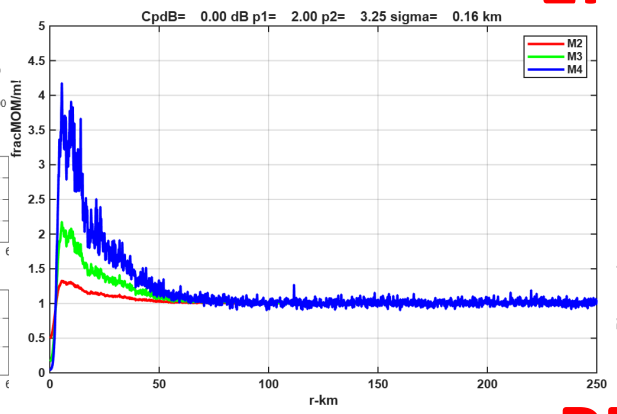


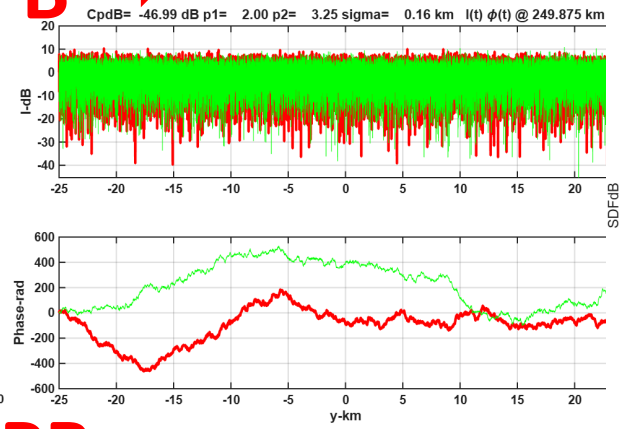

Rino *et al. Progress in Earth and Planetary Science* (2018) 5:83
https://doi.org/10.1186/s40645-018-0243-0

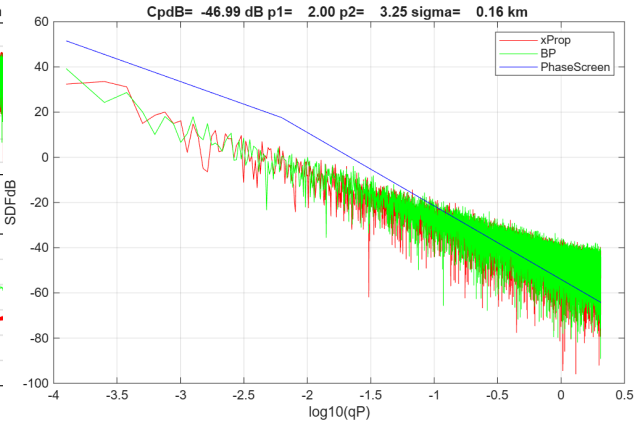
# MPS BP Extreme EPB & PPB Scintillation Examples

## ← EPB →

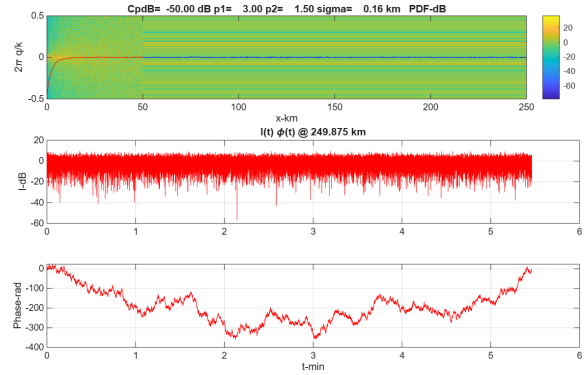


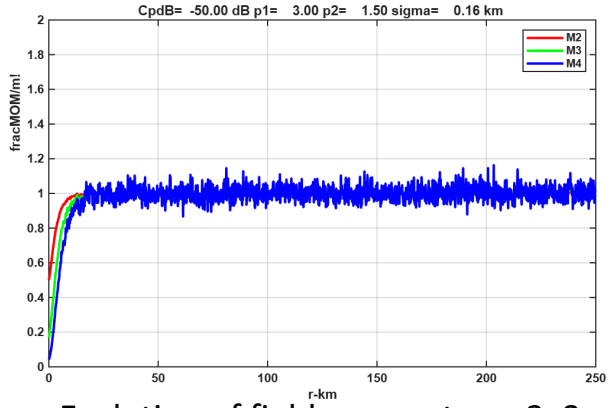



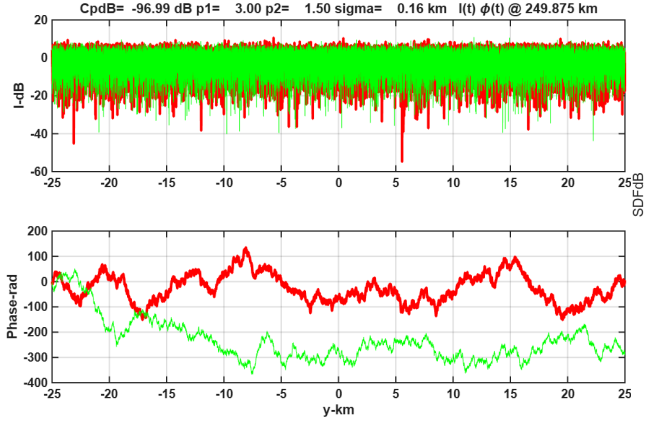



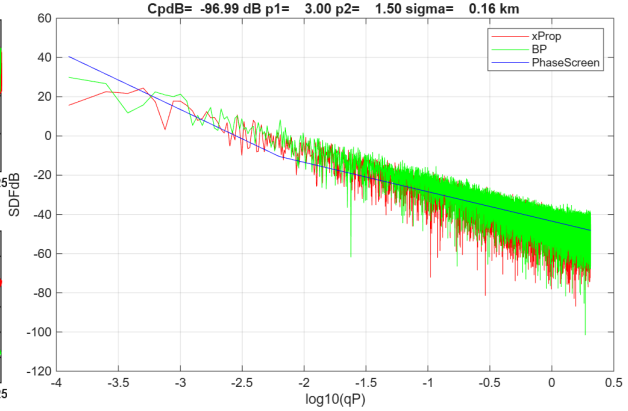




## ← PPB →




Upper frames show power spectral density (PSD) of evolving complex fields with S4 overlaid (red MPS, blue free-space). Lower frames show intensity and phase at observation point.

Evolution of field moments m=2, 3, and 4 normalized to exponential value m! Free propagation shows exponential (speckle) limit irrespective of initiating structure. (NOTE: Using the measure moments provides a good fit to alpha-mu distribution. )

Upper frames show observation intensity (red) with BP overlaid. Lower frames show phase (red) with extracted BP phase green. (NOTE: Different realization from PSD)

- Measured and theoretical phase SDFs.
  - Measured SDFs capture the large-scale index
  - Two-component identification marginal

# GPS/GNSS Diagnostic Measurement Summary

- j.jastp.2026.106805 describes BP/IP processing and data sets.
- Structure categories:
  - PPB (blue) => $p_1 - p_2 > 1$
  - EPB (red) => $p_2 - p_1 > 0.5$ and not PPB (Include $p_1 \approx p_2$ )
- EPB evolution and decay properly includes $p_1 \approx p_2$ ( Revised 2026 )
- PPB with $p_1 > 2$ implies an enhanced population of large-scale structure (green line)

**Segment Structure Summary**

Hong Kong 1159 segs

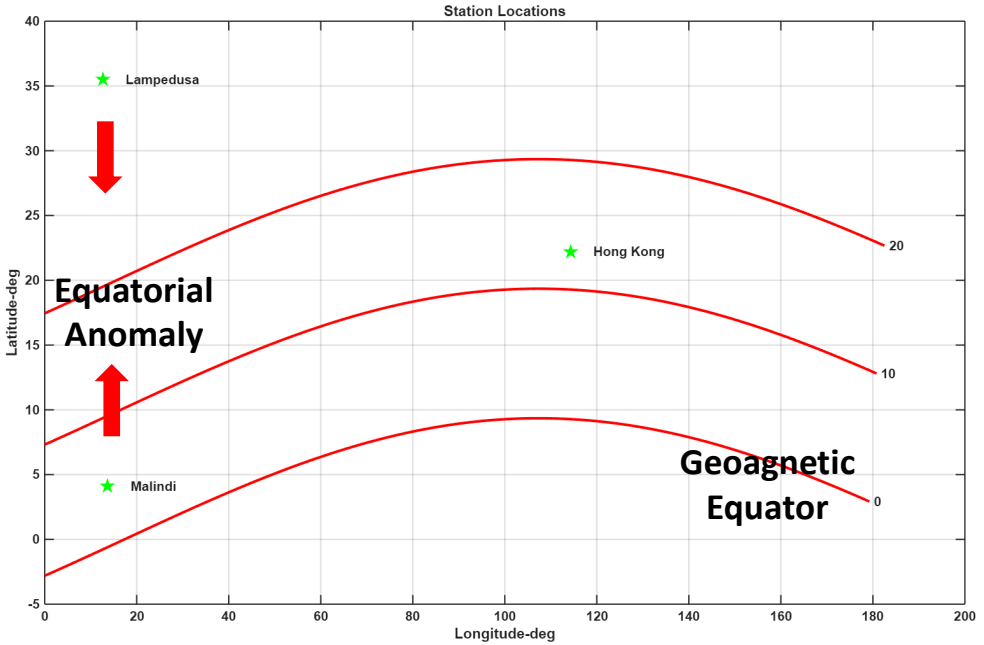
| | EPB | PPB |
|---|---|---|
| BP_OK=722 | 488 | 234 |

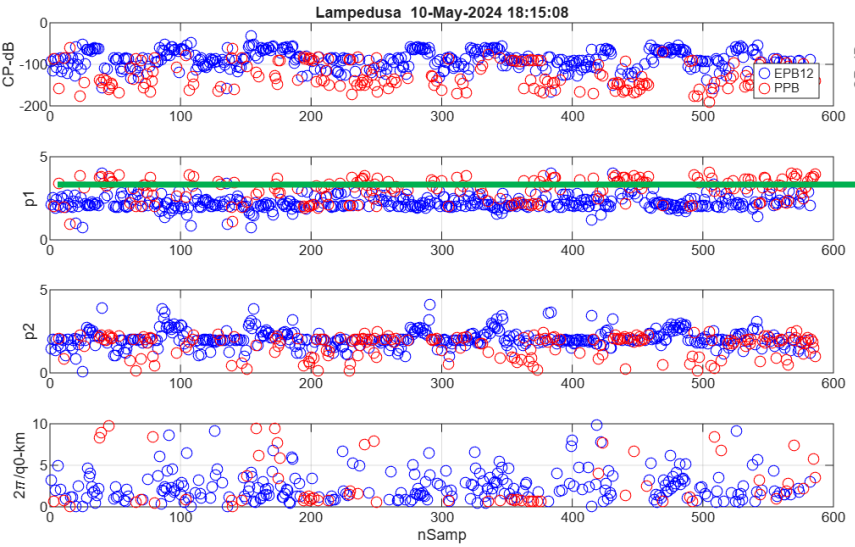
Lampedusa 586 segs

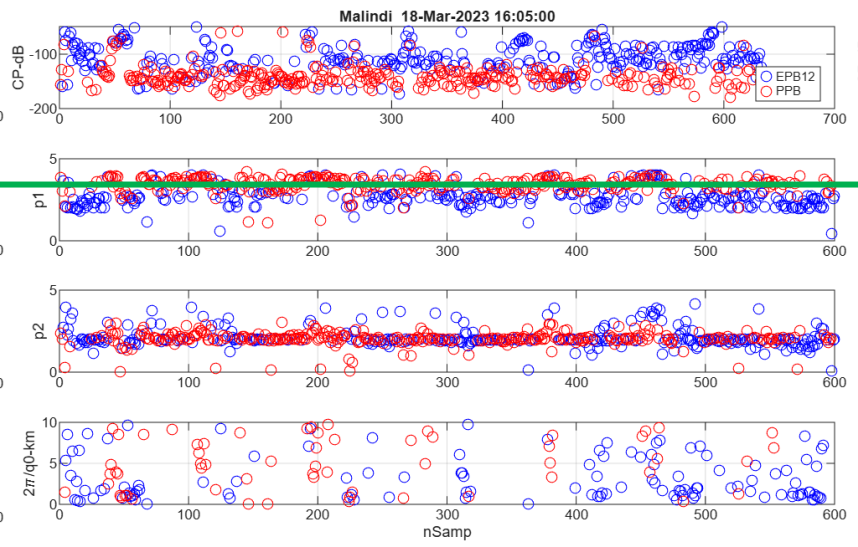
| | EPB | PPB |
|---|---|---|
| BP_OK= 324 | 215 | 109 |

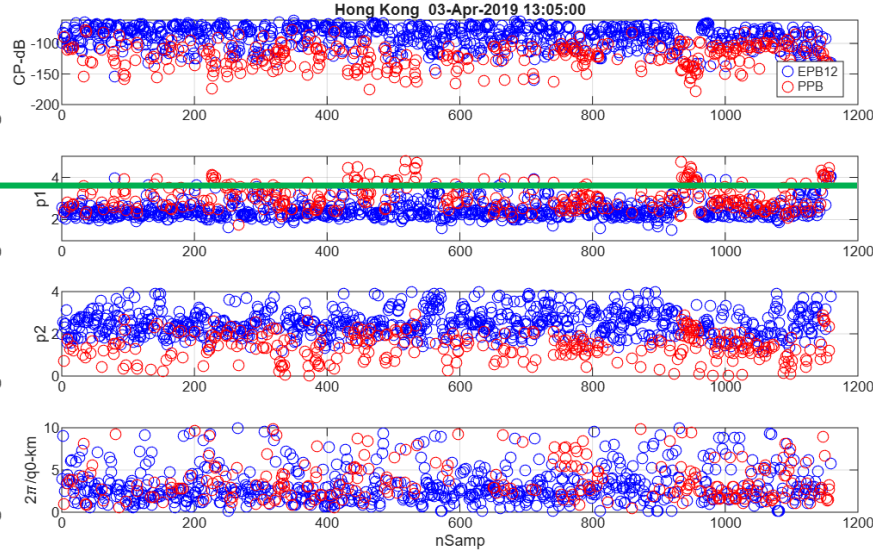
Malindi 646 segs

| | EPB | PPB |
|---|---|---|
| BP_OK= 390 | 197 | 193 |



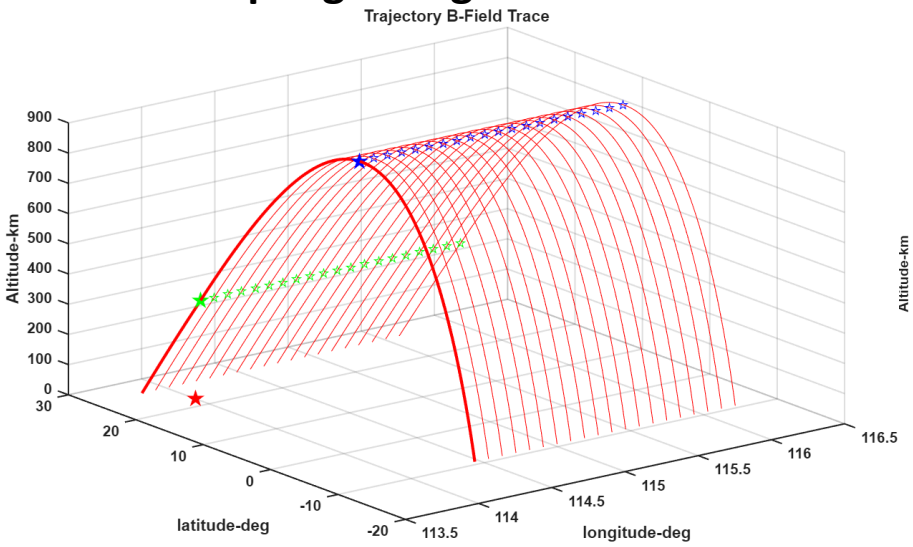



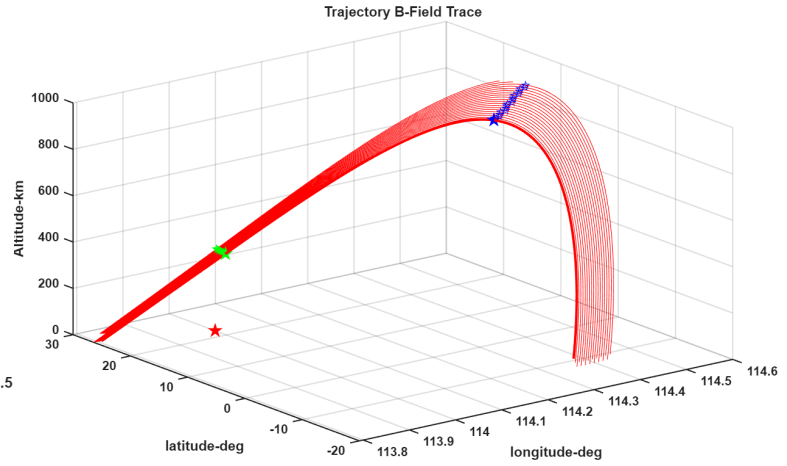



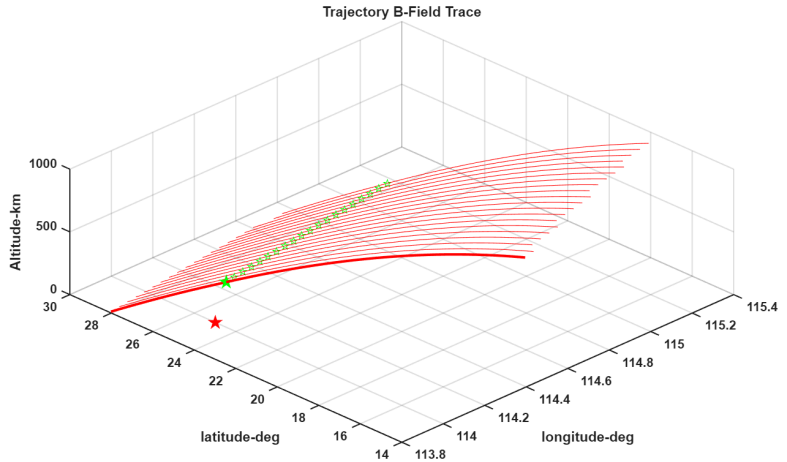



# Interpretation

- **Each BP_OK segment *locates a region* of enhanced structure characterized by SDF parameters**
  $C_P$, $p_1$, $p_2$, and $q_0$ $(\sigma_0 = 2\pi / q_0)$
  - **The SDF parameters can be used to generate an MPS statistically equivalent realization of the complex field. The satellite/station locations and an effective scan velocity estimate the spatial scale range.**
  - **Two structure categories have been identified: EPB with structure consistent with simulations and C/NOFS measurements; and PPB with enhanced large-scale structure associated with instability mechanisms distinctly different from successive bifurcation, which generates smaller scale structure.**
- **EPB structure initiated by perturbations on the bottom side of a rising F-layer involve striations subtending entire field lines. To explore the geometric dependence magnetic field lines are traced form the estimated penetration points of the identified for each processed segment. Examples for constant altitude trajectories are shown below.**
- **A sampling of segment details follow on the next two vu graphs.**

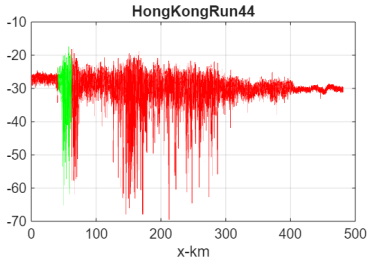


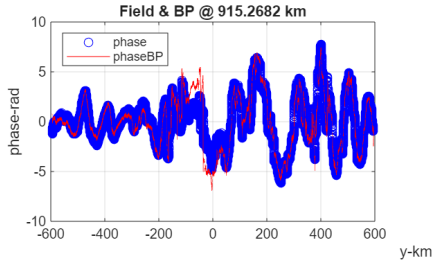



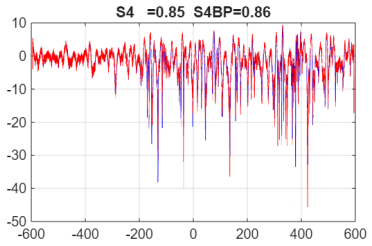



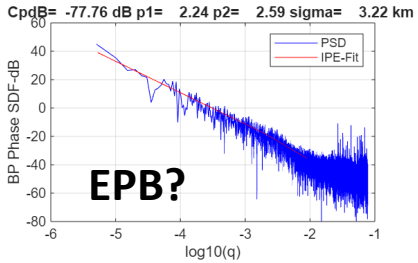
# Cross Field EPB Intercept Trajectory

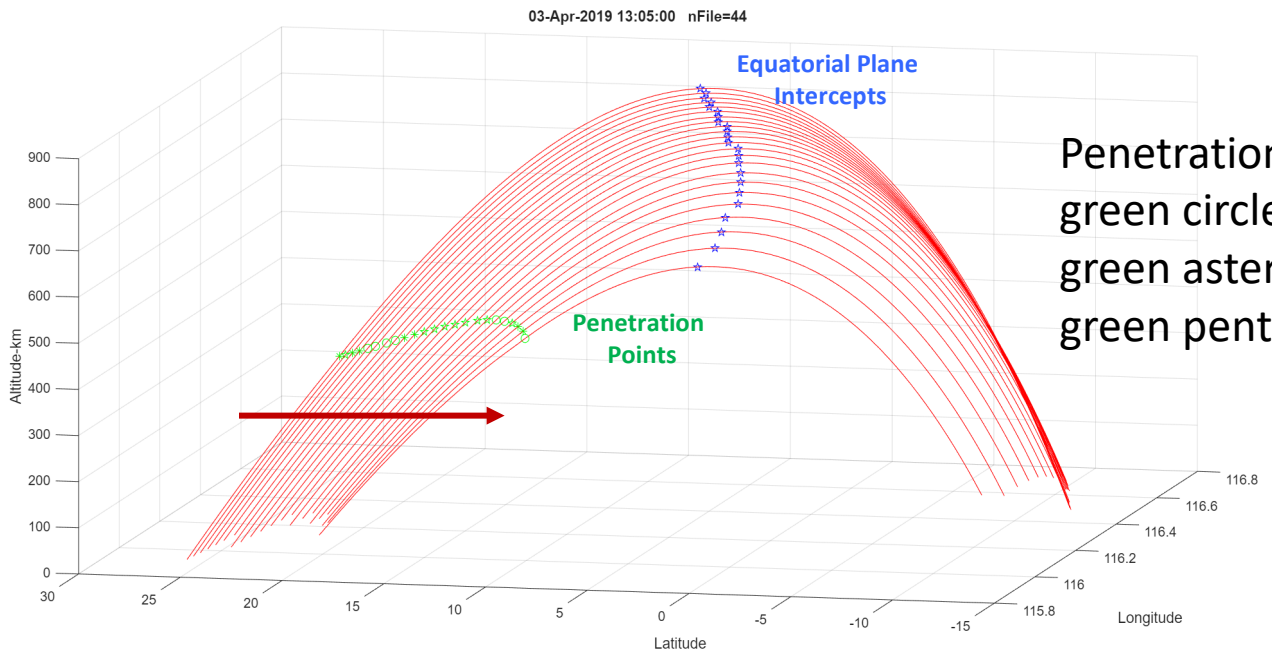
## Segment detail examples



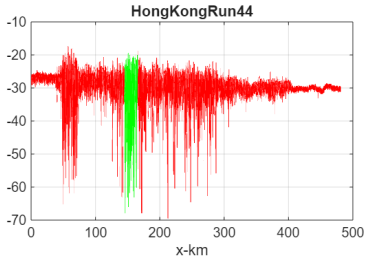



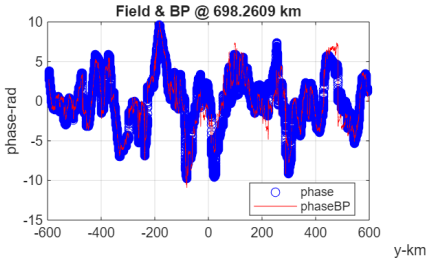



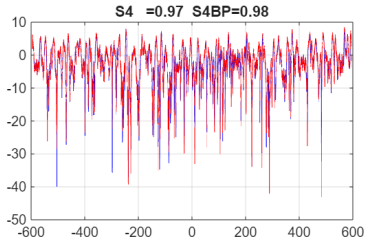



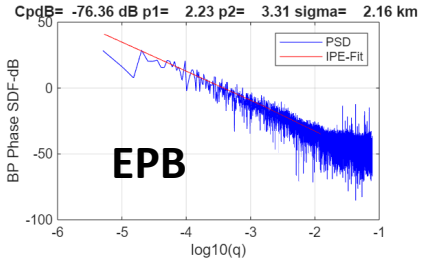



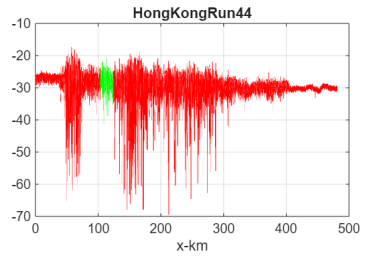

Penetration point code:
green circle =>PPB,
green asterisk=> P12
green pentagram =>EPB

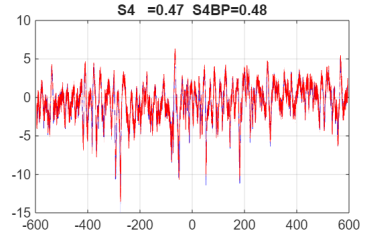


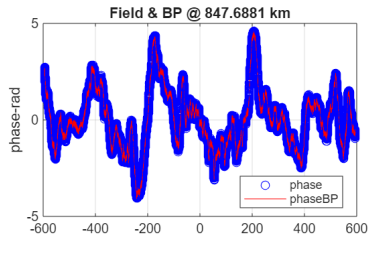



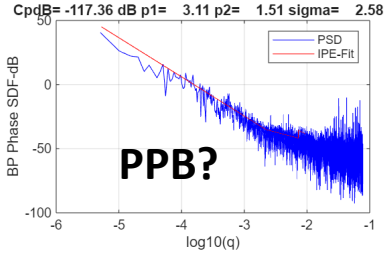



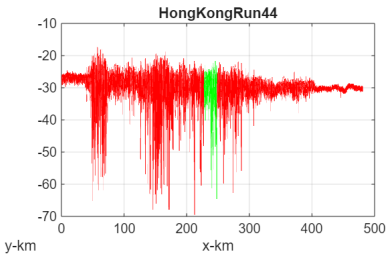



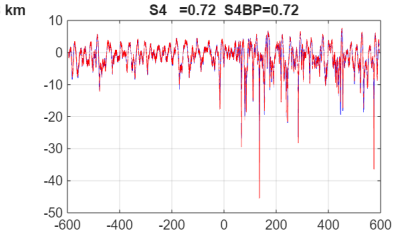



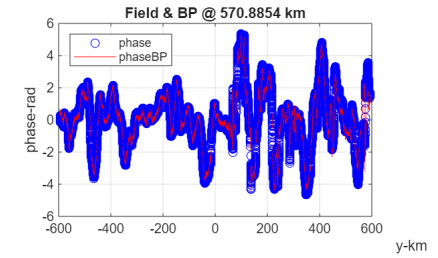



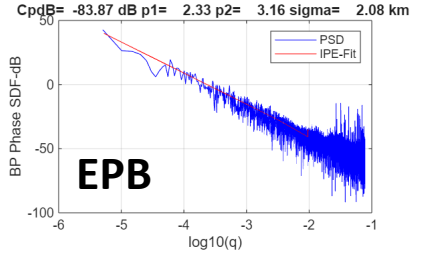



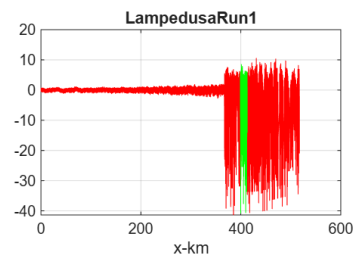



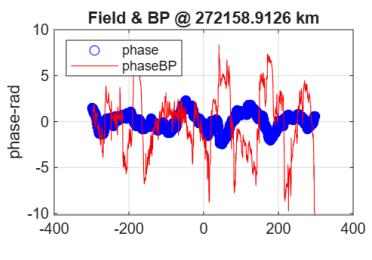



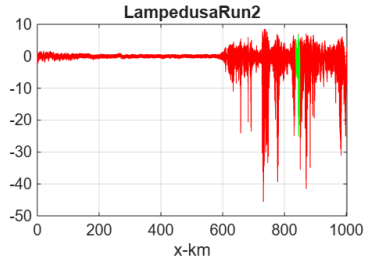



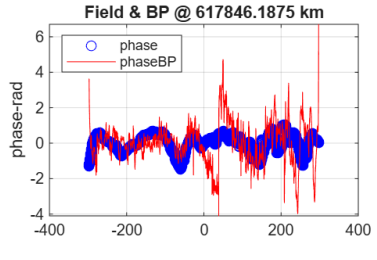



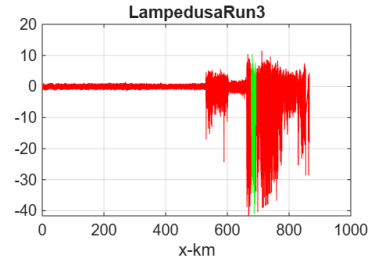
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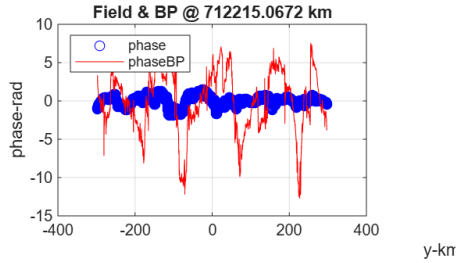


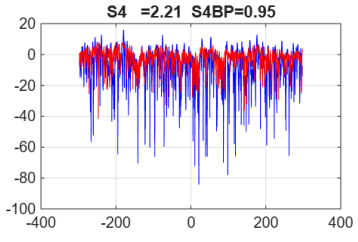



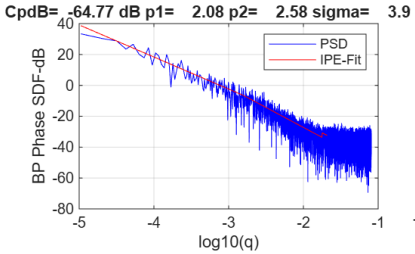



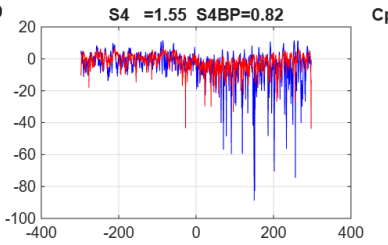



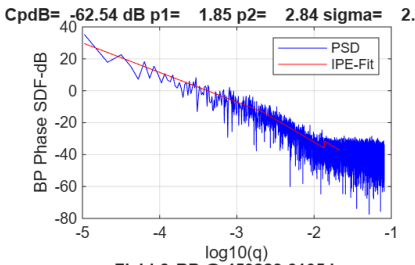



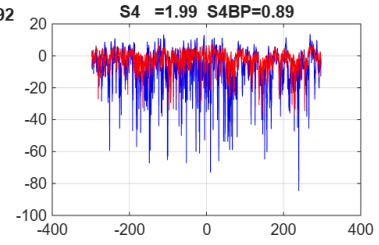



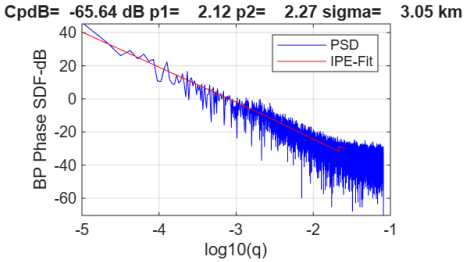



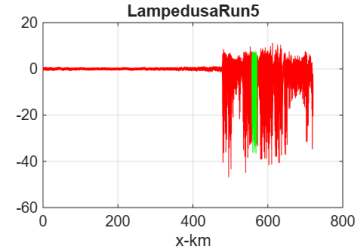



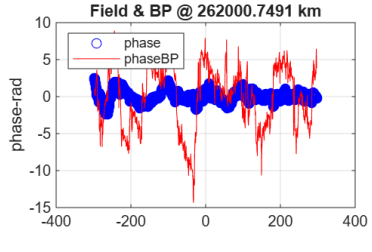



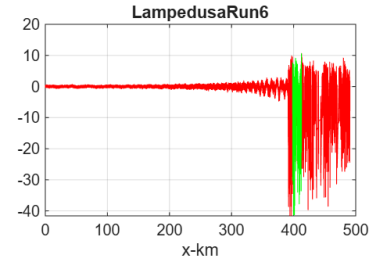



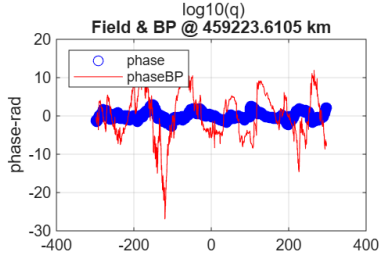



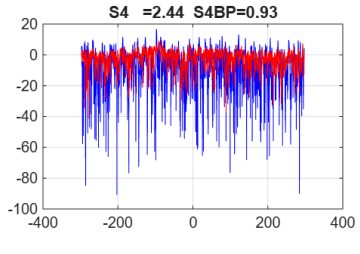



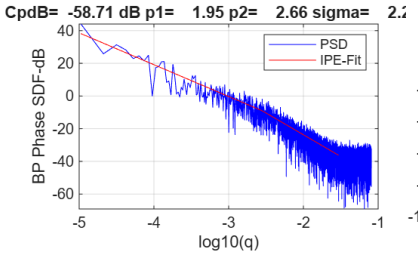



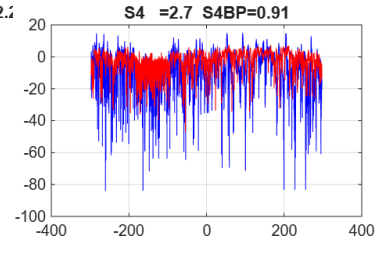



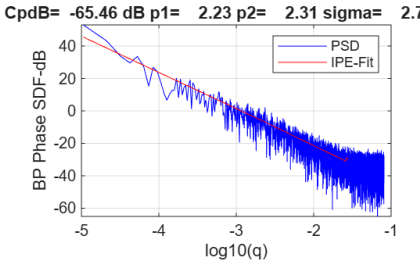



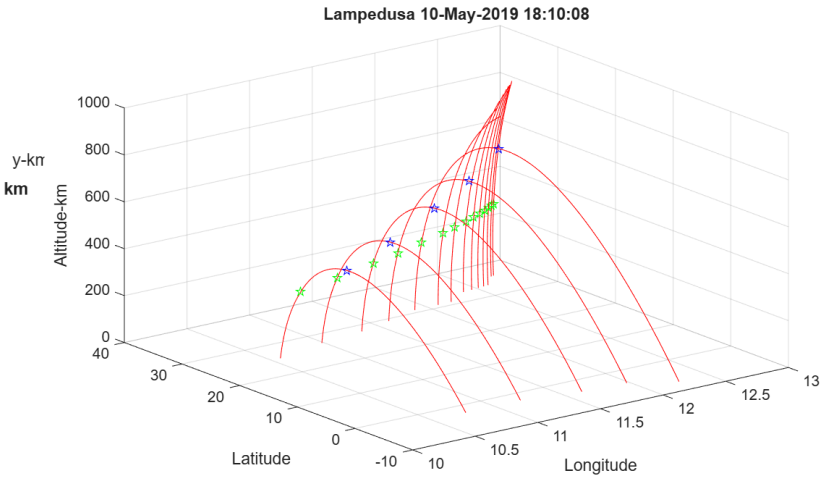



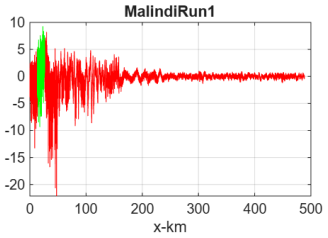



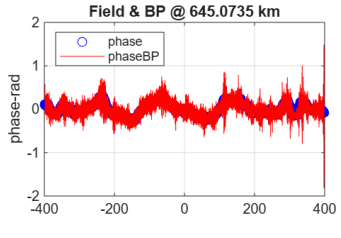



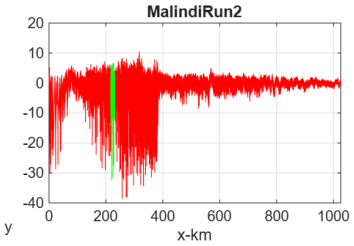



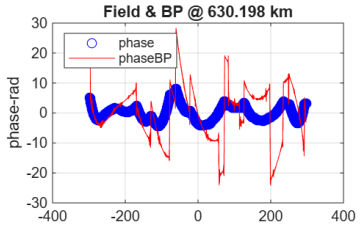



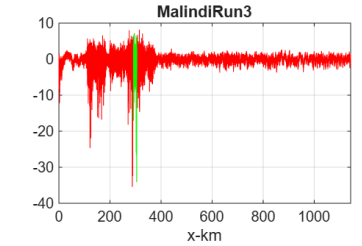
# Extreme Scintillation Examples Malindi

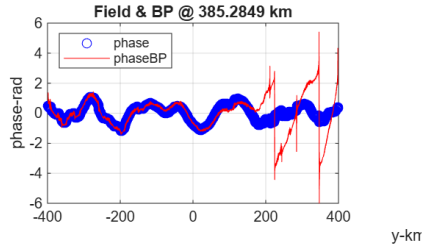


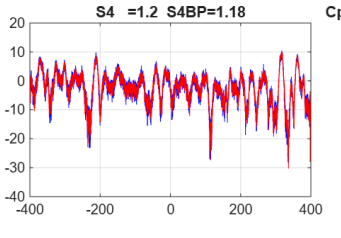



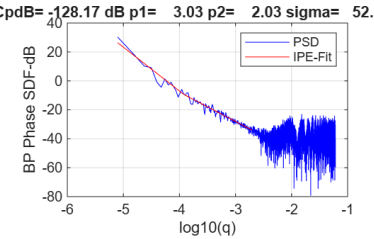



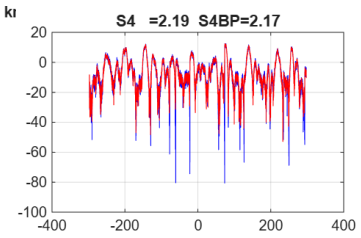



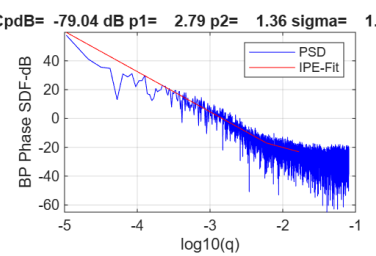



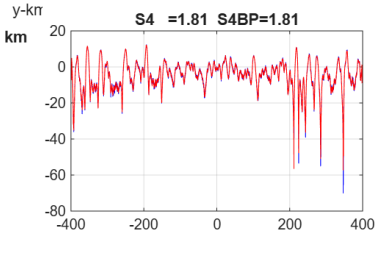



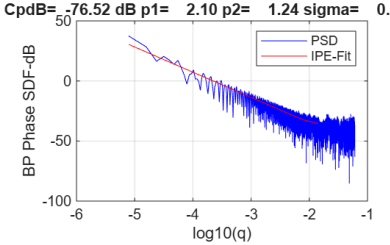



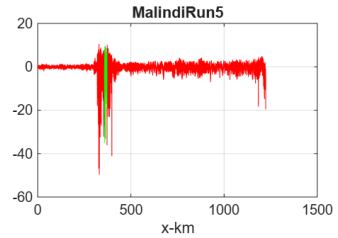



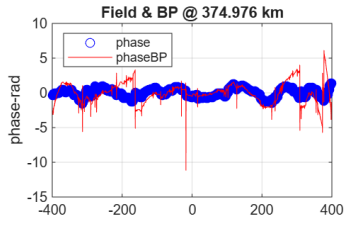



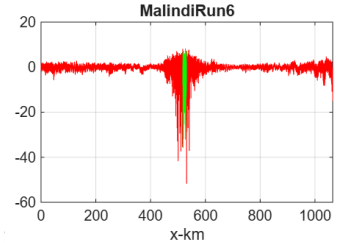



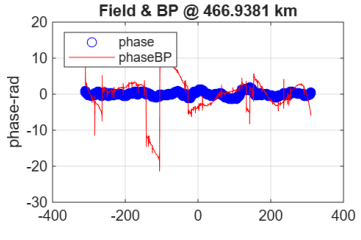



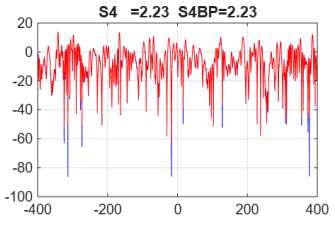



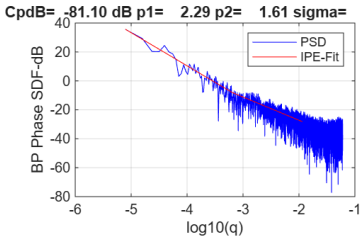



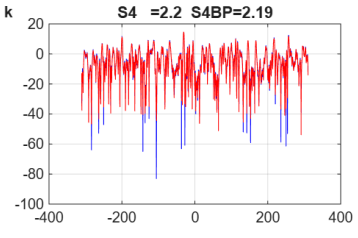



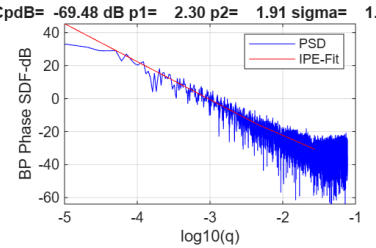



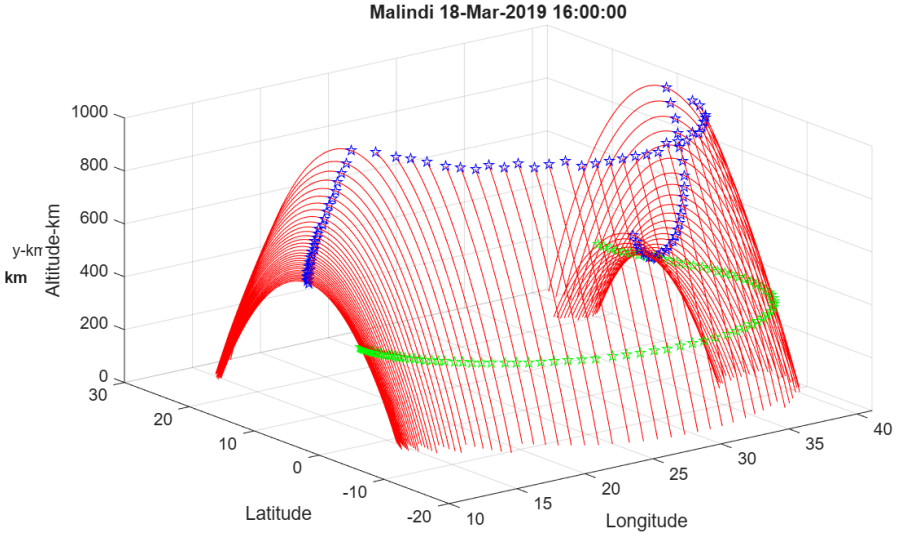



# Conclusions & Path Forward

- **In our 2026 paper three structure categories were identified: EPB, PPB, & P12**
  - **Whereas IPE correctly identifies power-law structure, reconstructed BP phase is affected by diffraction. Our more recent analysis show that diffraction often misidentifies two-component structure as a single power law.**
  - **Our more recent studies also show that BP applied to extreme scintillation does discriminate between enhanced (prominent large-scale structure)**
  - **This led us to reclassify the previous P12 (~single power law) segments as EPB.**
- **Regarding interpretation, with accommodation of geometry EPB and PPB segments reflect electron density structure in the intercepted region. A distinction can be made between expected convective instability structure and pronounced large scale structure possibly associated with a shear instability causing an upward structure cascade or a direct signature of TIDs**
- **Path Forward**
  1. **Implement the modest increase sampling and computation required for routine GNSS structure analysis to supersede the standard** $S4$, $\sigma_\phi$, and ROTI **summary parameters**
  2. **Develop quantitative relations between plasma instability parameters and inverse-power-law parameters to connect scintillation diagnostics directly to the underlying physics**