Risk Awareness for Equatorial Plasma Bubbles and Scintillations

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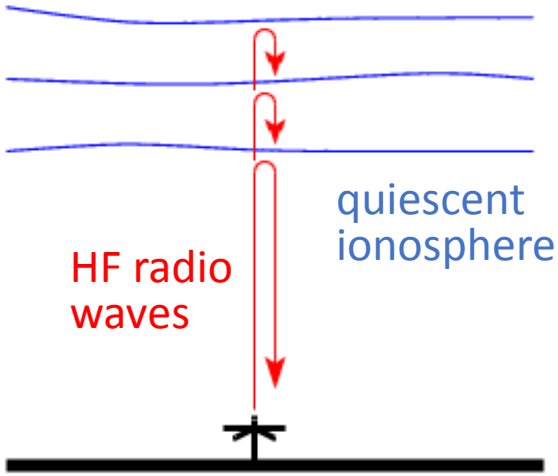
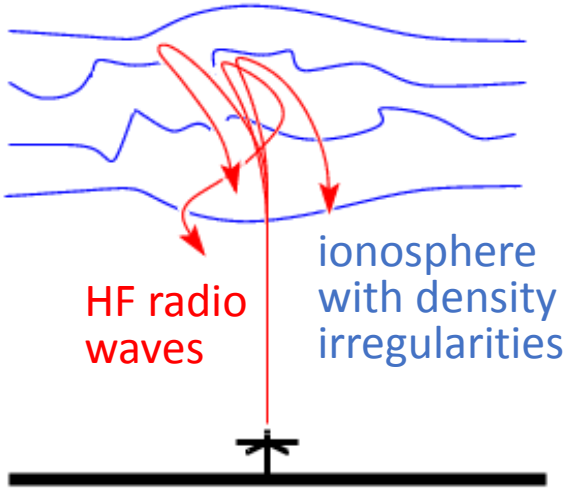
Regional Workshop on GNSS and Space Weather
Rabat, Morocco, 9-13 May 2022

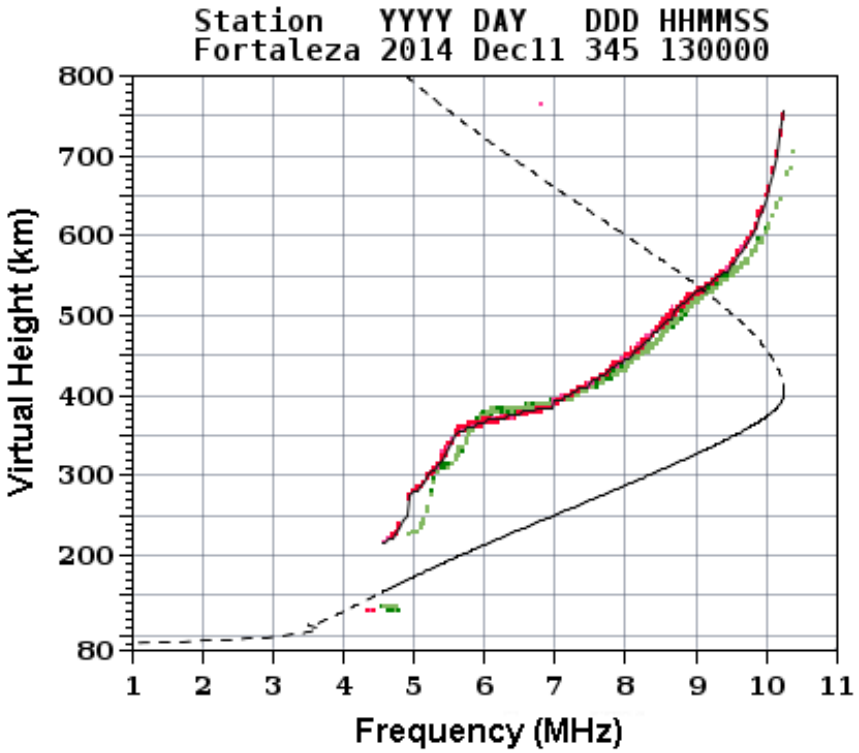
Outline of Presentation

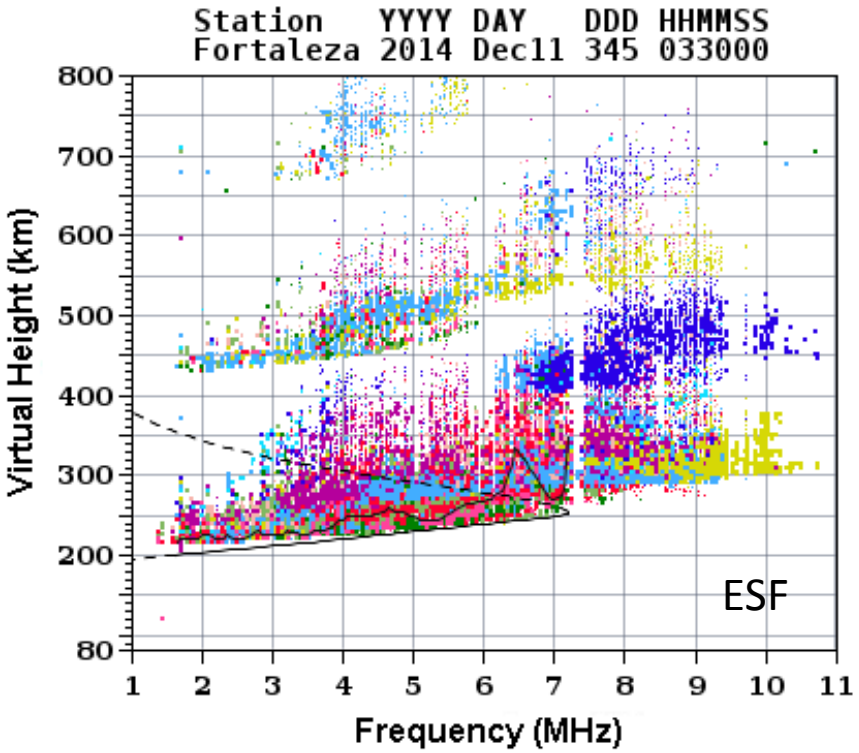
- Same or different: equatorial spread-F (ESF), equatorial plasma bubbles (EPBs), and scintillations
- Technological implications of ESF/EPB/scintillations
- A basic review on the fundamentals of EPBs
- Geometrical morphology of EPBs in more details
- Factors that influence EPB occurrence (long-term & short-term)
- Viewing ESF, EPB, and scintillations as part of space situational awareness (SSA) in order to better appreciate the risk
- Resource for familiarizing ourselves with the EPB and scintillation occurrence climatology – to be better at evaluating the risk
- Practical demonstration of *EPB Climatology Tool*
- Summary and conclusions

ESF/EPB/Scintillations: Basic Phenomenology

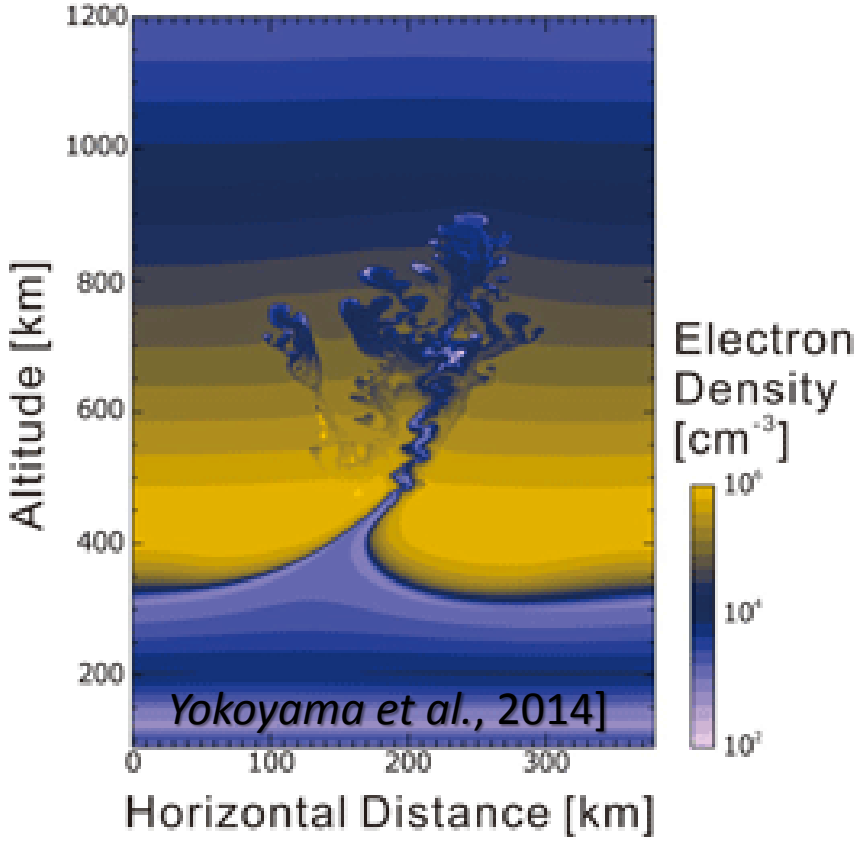


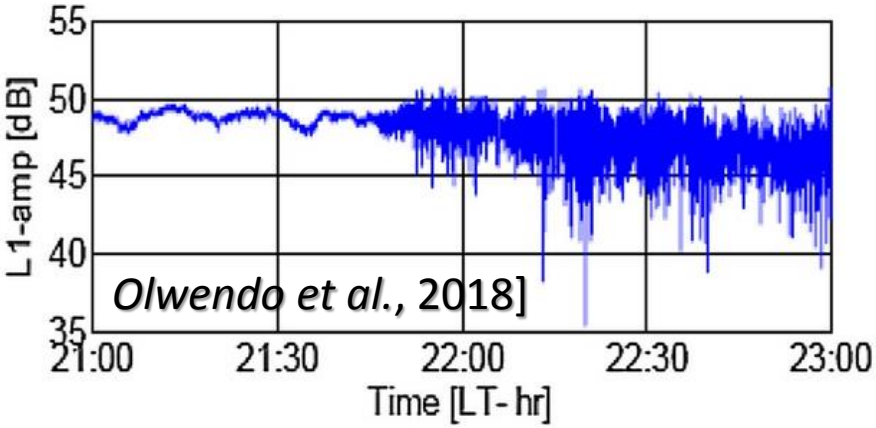


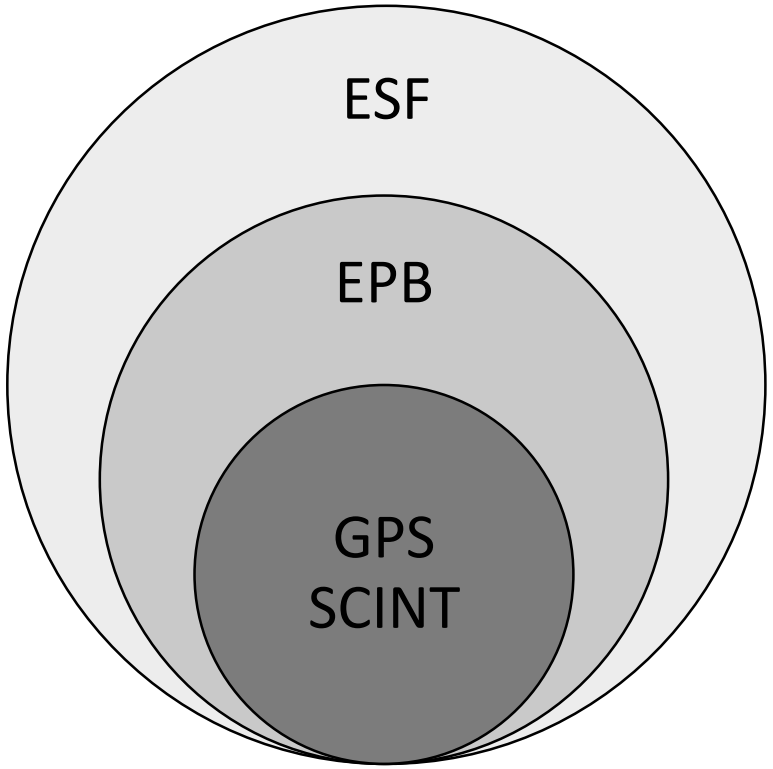




ESF/EPB/Scintillations: Phenomenology (cont.)



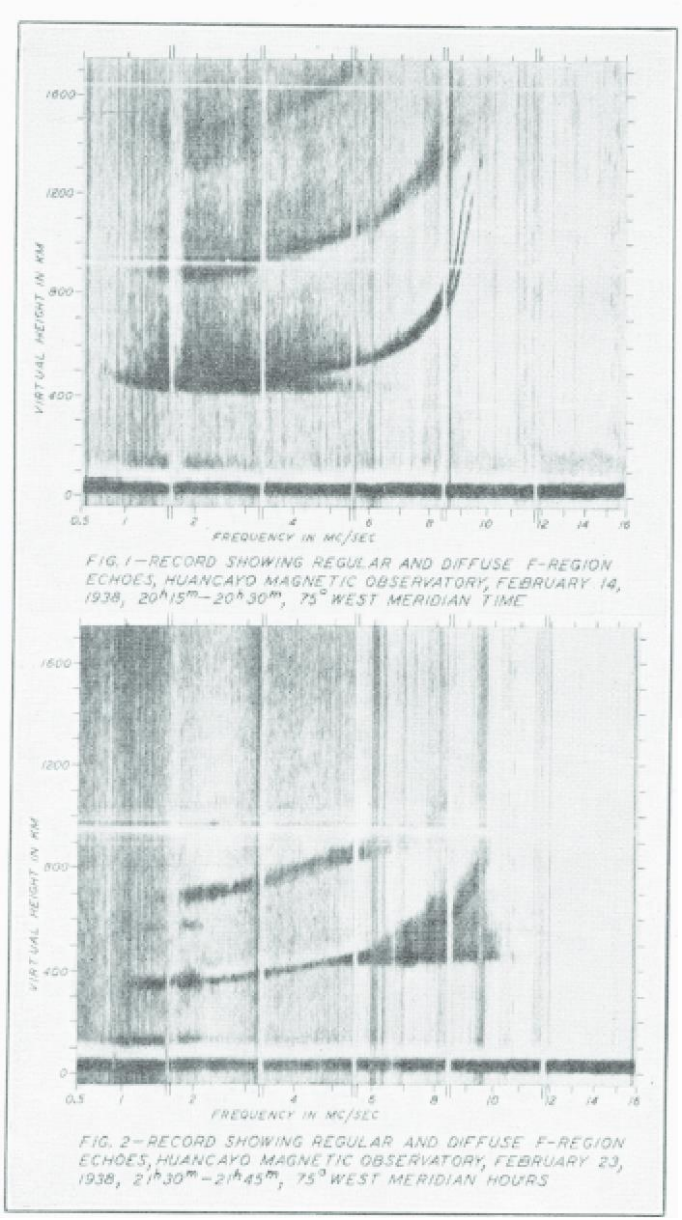




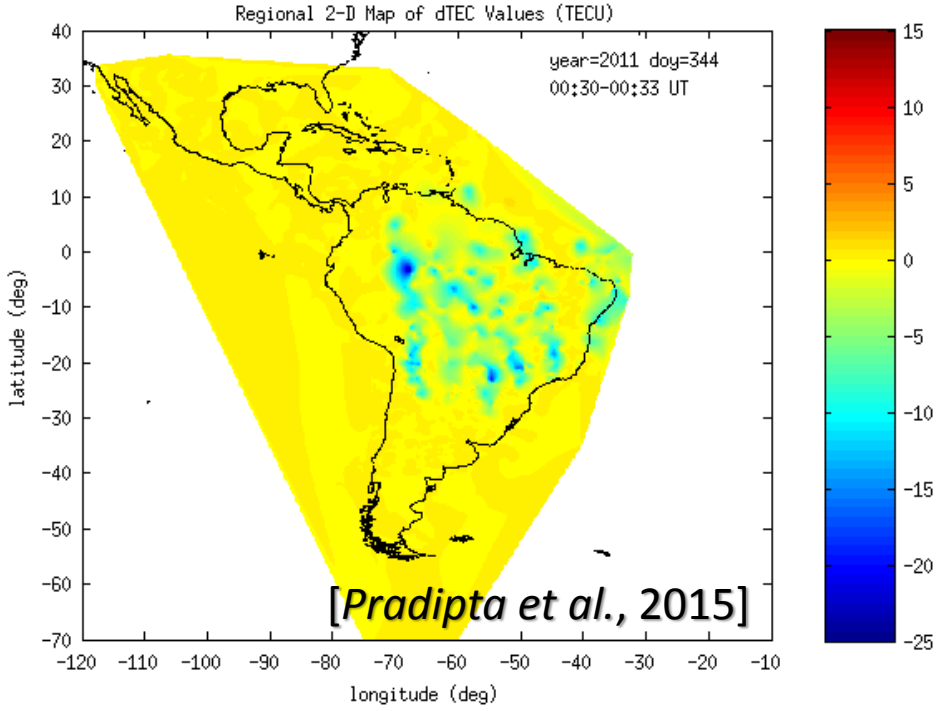
In terms of a Venn diagram, we may denote
GPS SCINT < EPB < ESF

On the aggregate, a rough prevalence ratio is
ESF : EPB = 100 : 78
EPB : GPS SCINT = 100 : 66

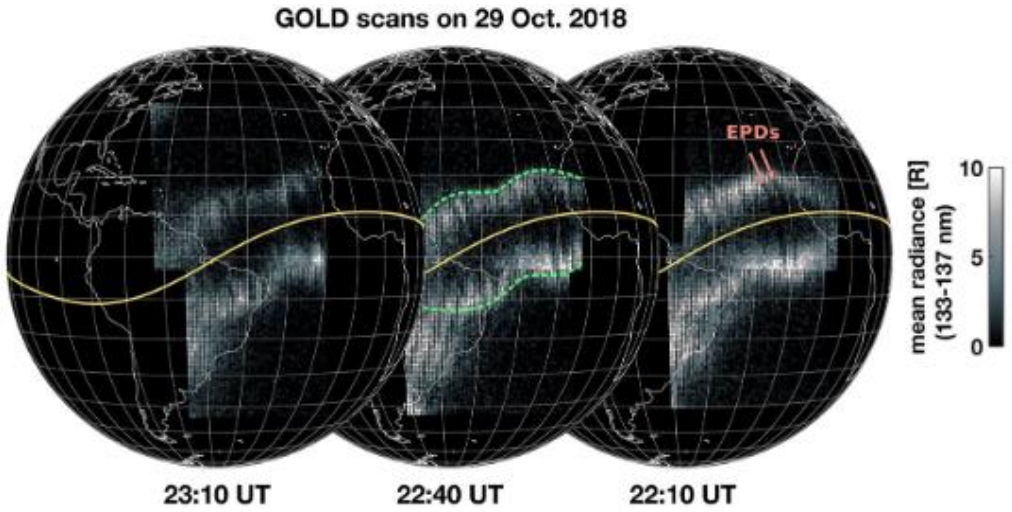
ESF/EPB/Scintillations: Phenomenology (cont.)



[*Booker and Wells*, 1938]



[*Pradipta et al.*, 2015]



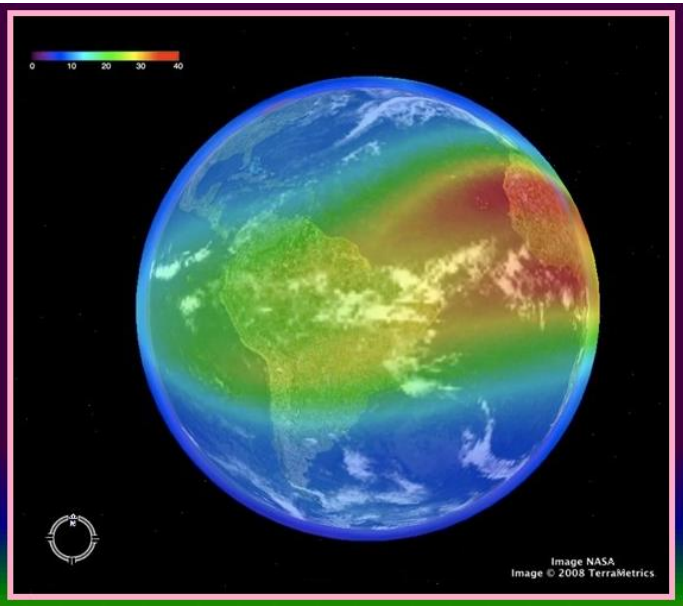
[*Rodríguez-Zuluaga et al.*, 2021]

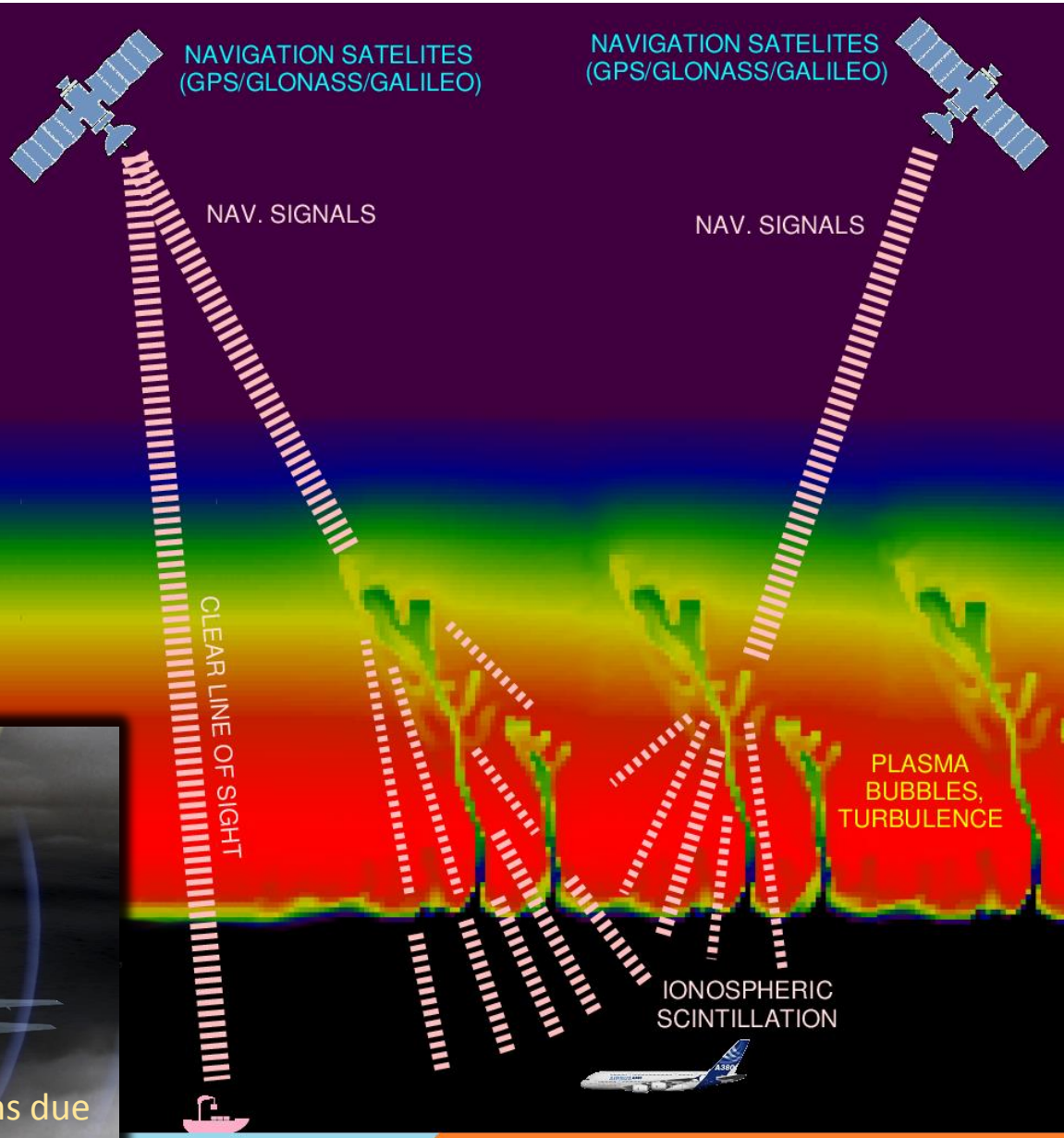
ESF/EPB/Scintillations: Phenomenology (cont.)

Red airglow bands in the clear dark sky over the ESO Paranal Observatory (24.62°S 70.4°W) in the Atacama Desert, Chile, with some green airglow near the horizon and the Milky Way in the background. Images by *Yuri Beletsky* (@YBeletsky).

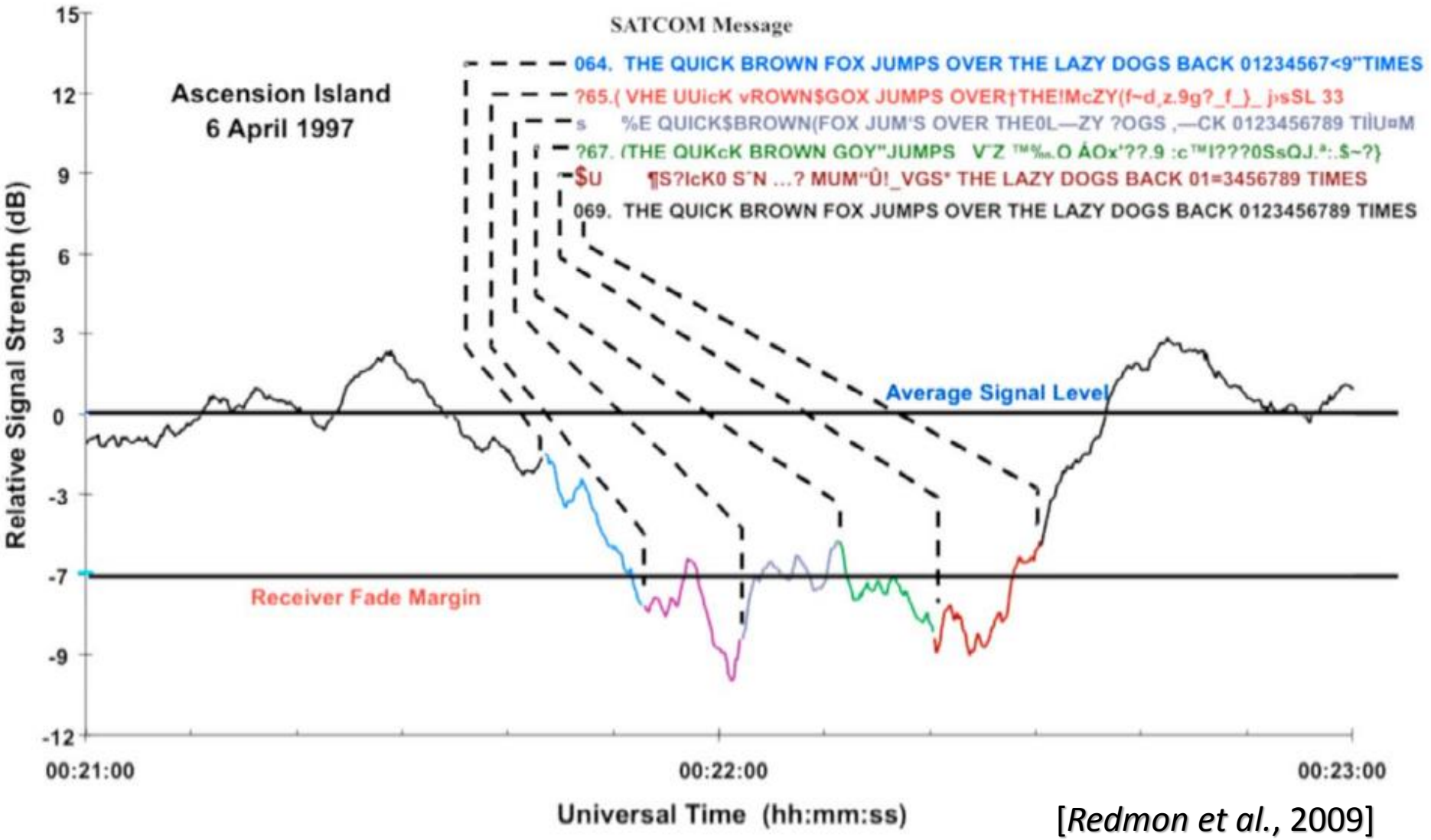
https://www.atoptics.co.uk/fza67.htm

Threats Posed by EPB on Modern Technology





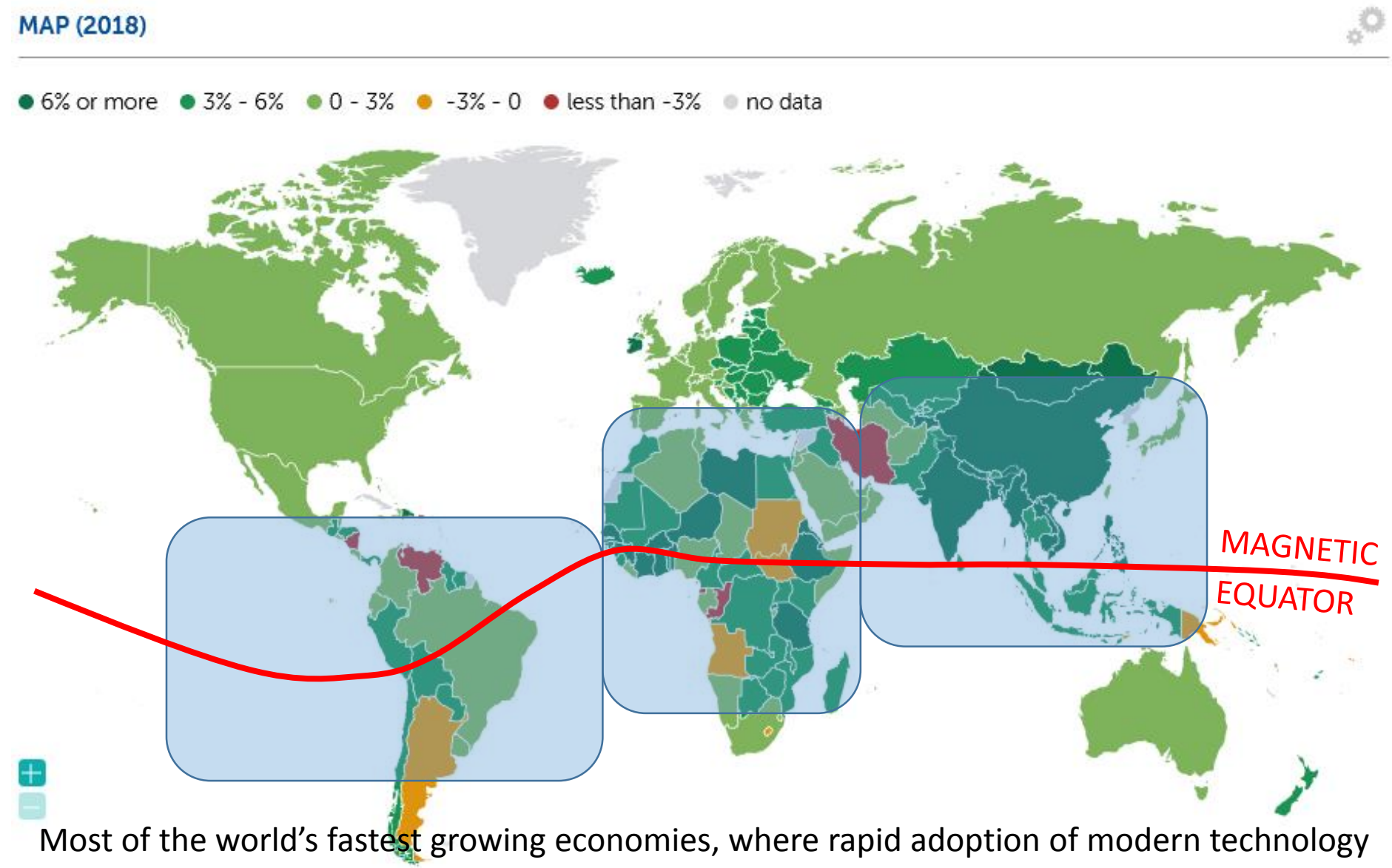
Threats Posed by EPB on Modern Tech (cont.)



[*Redmon et al.*, 2009]

If signal strength is attenuated below the receiver's fade margin, communications messages are compromised. During periods of scintillation, received messages may become garbled.

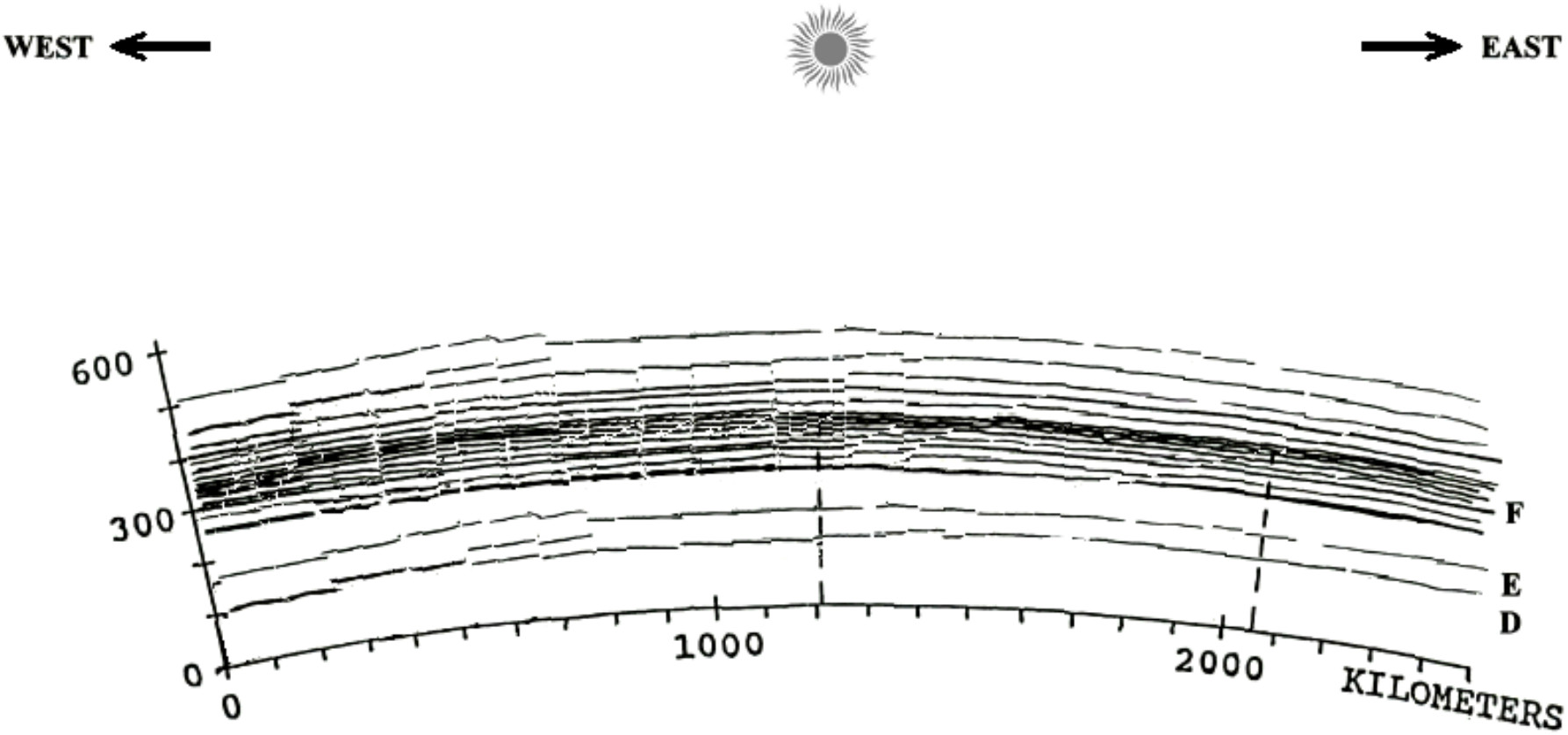
A Wider Public Discourse on EPBs is Needed



Most of the world's fastest growing economies, where rapid adoption of modern technology is currently happening in the general population, are located in (or near) the low-latitudes.

https://www.imf.org/external/datamapper/NGDP_RPCH@WEO/OEMDC/ADVEC/WEOWORLD

Equatorial Plasma Bubbles: Basic Primer

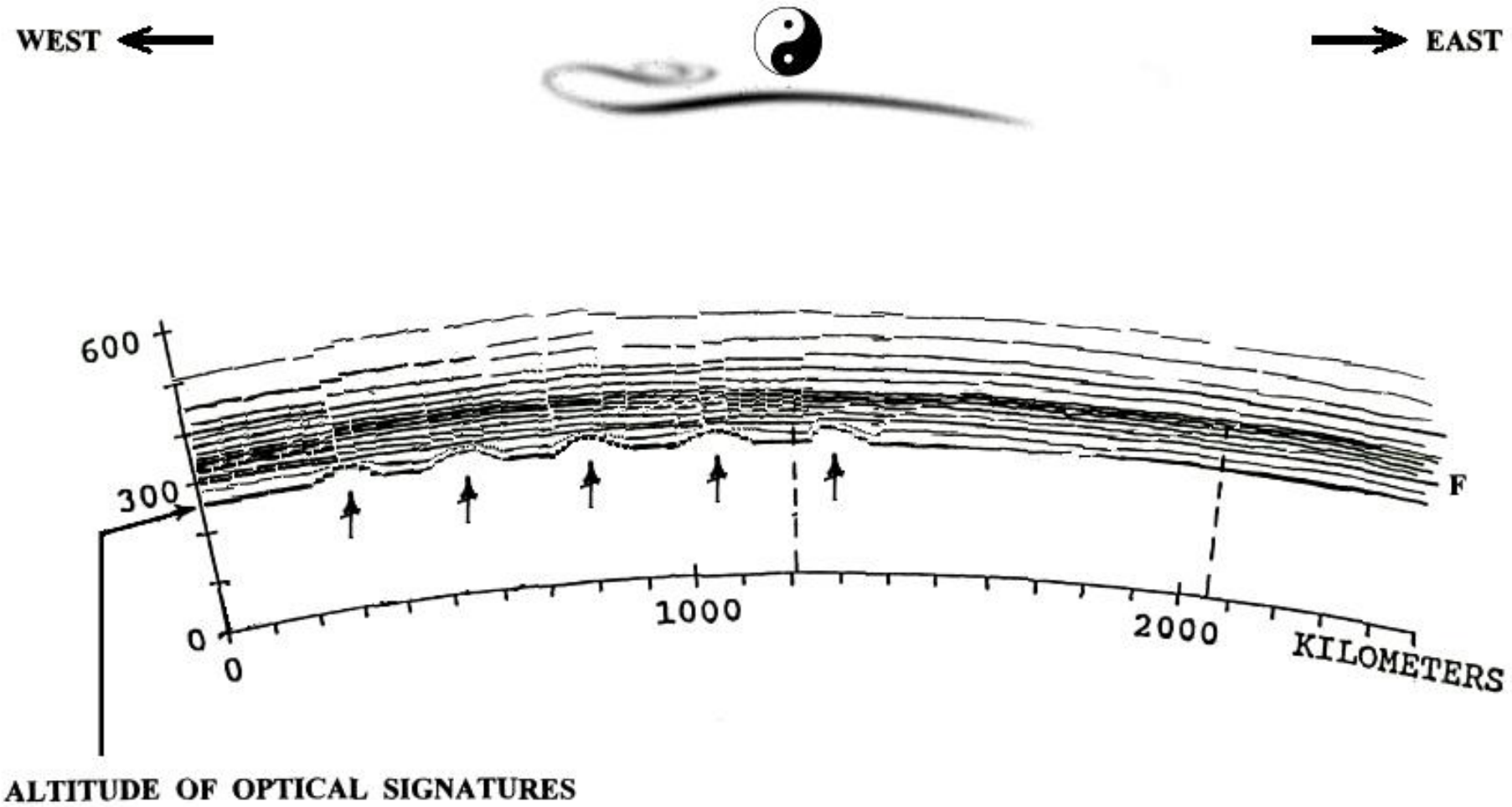


Daytime ionosphere: comprised of D-, E-, and F-regions at different altitude range.

The isodensity contours of these daytime ionospheric layers are generally stable from large-scale instabilities or turbulence.

Hence, trans-ionospheric radio propagation (e.g. for GNSS or SATCOM) during daylight hours usually experiences no significant interruption (except from D-region absorption).

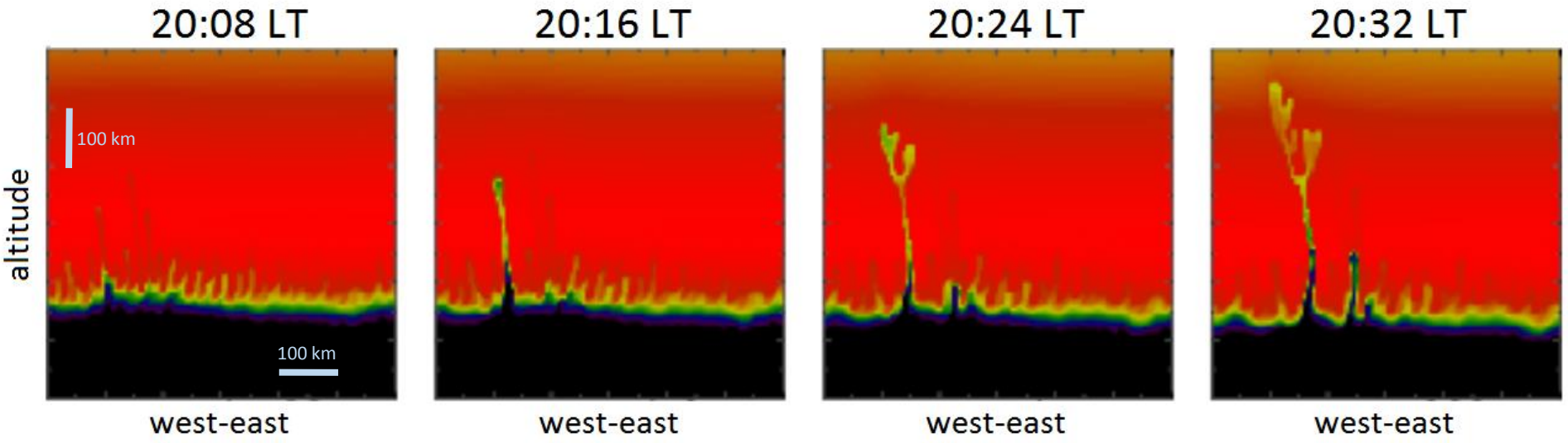
Equatorial Plasma Bubbles: Basic Primer (cont.)

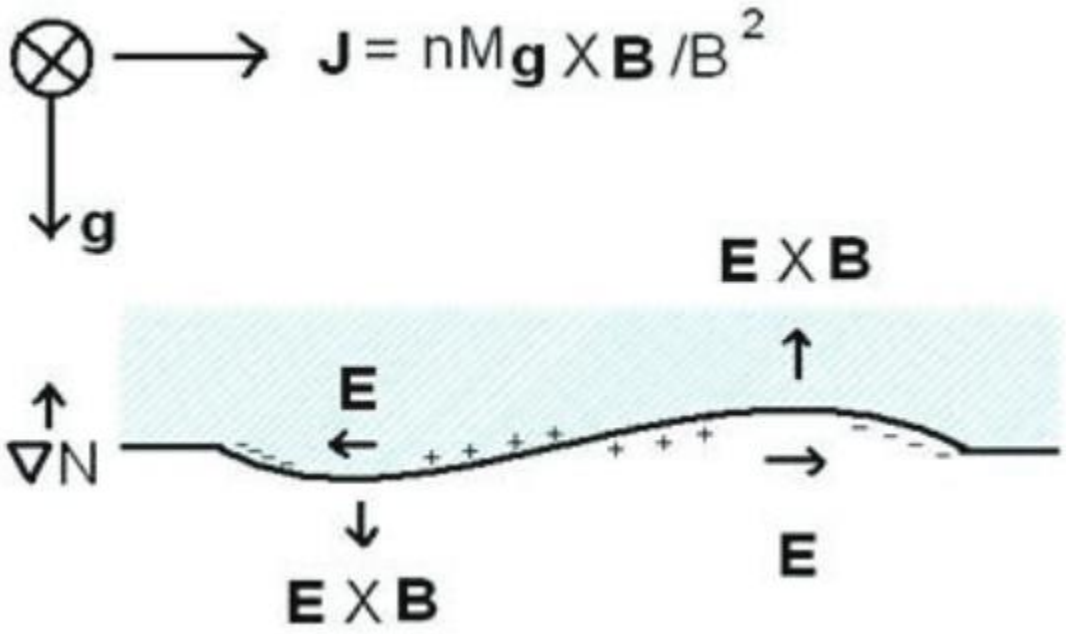


During sunset/dusk hours, the bottomside of equatorial ionosphere starts to become unstable from sharp vertical gradient (due to the disappearance of D- and E-regions).

Some uplift or undulations in the isodensity contours may appear in the bottomside ionosphere (which could grow into large-scale turbulence).

Equatorial Plasma Bubbles: Basic Primer (cont.)



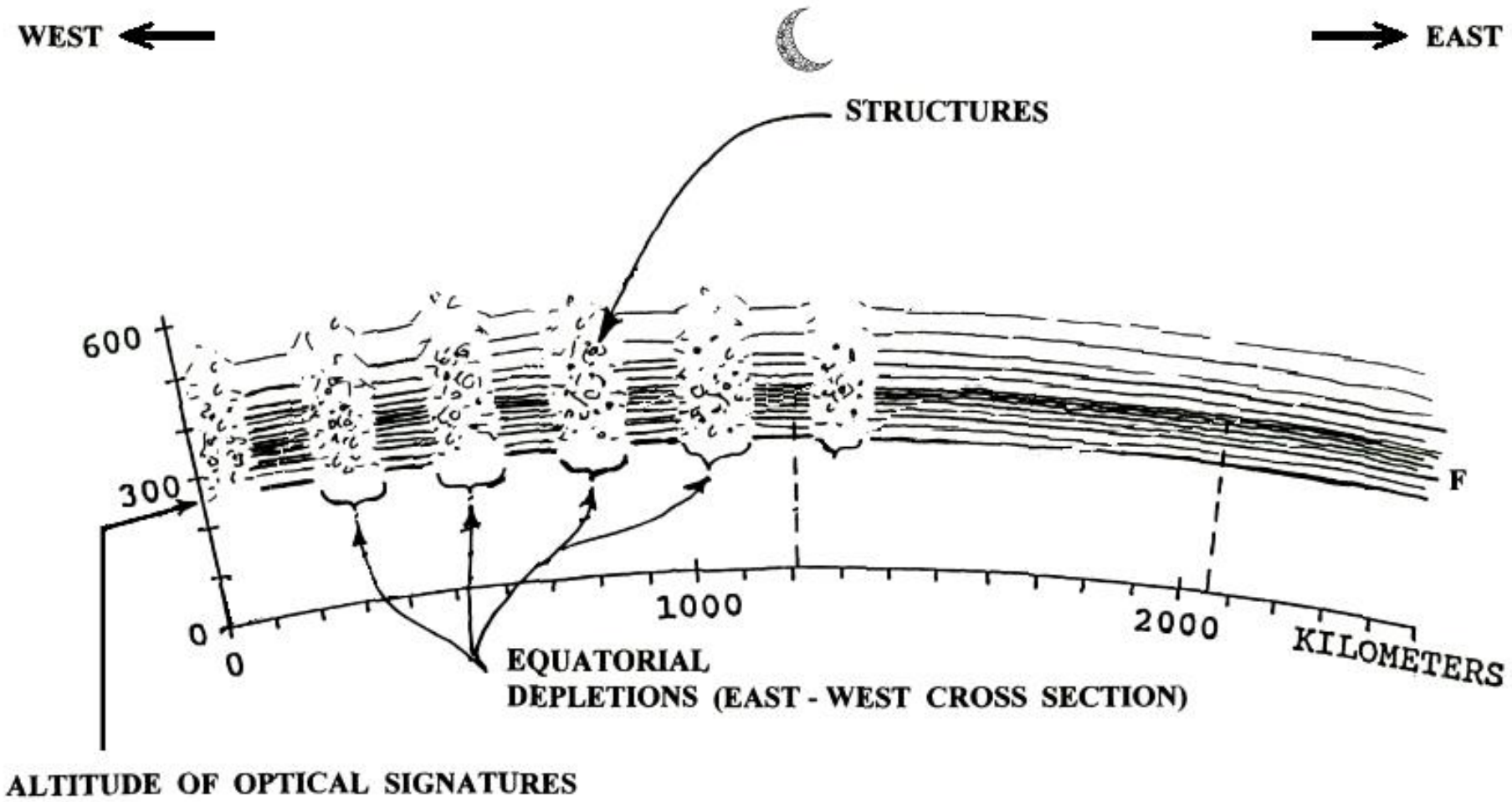


Rayleigh-Taylor instability leads to a growth of the bottomside ionospheric irregularities into full-size plumes

Top: PBMOD numerical simulation of Rayleigh-Taylor instability in a model ionosphere (credit: *John Retterer* - BC)

Left: Rayleigh-Taylor instability diagram (credit: *Archana Bhattacharyya* - IIG)

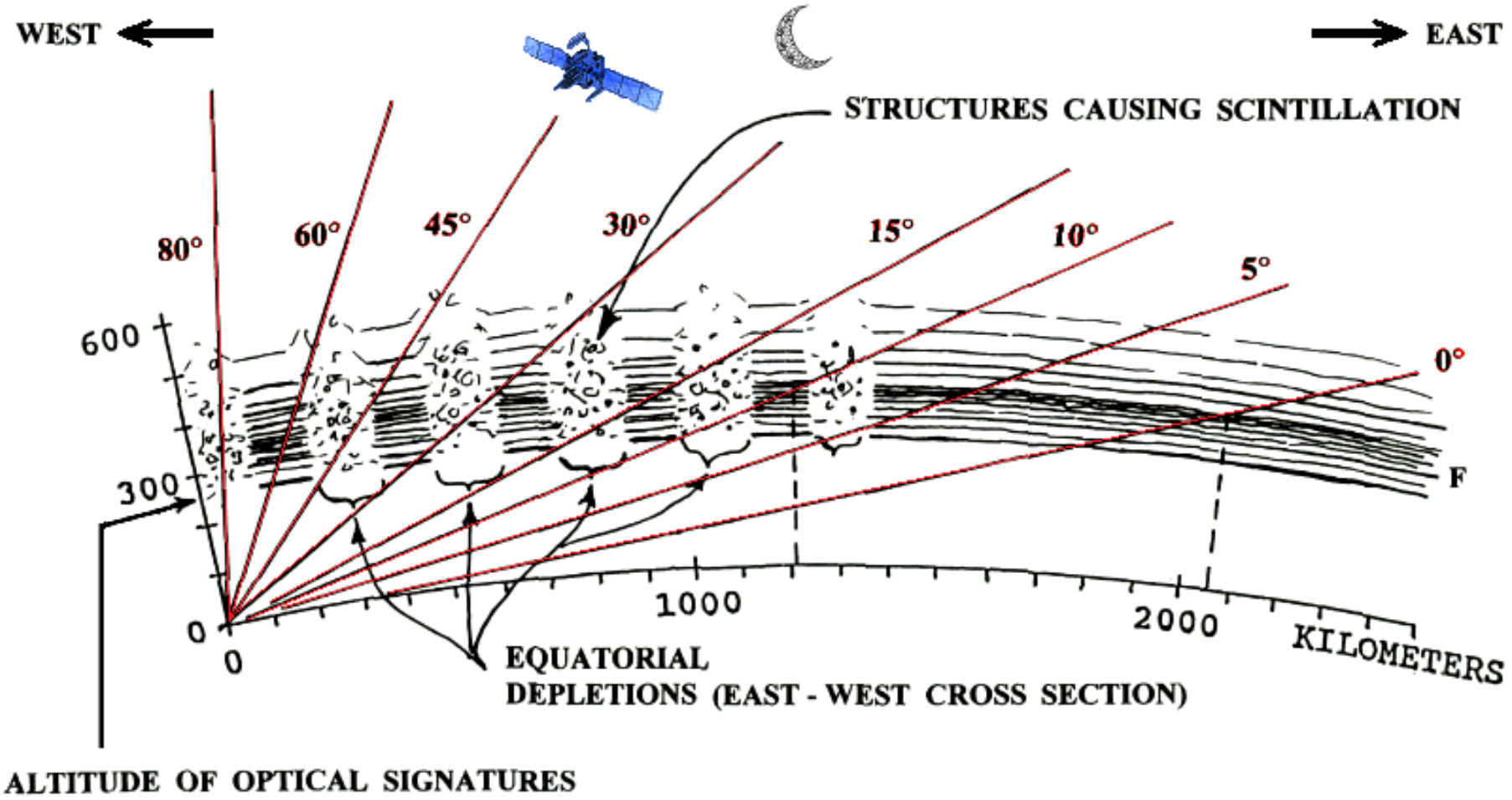
Equatorial Plasma Bubbles: Basic Primer (cont.)



If the Rayleigh-Taylor instability is sufficient to make the seed perturbations grow in amplitudes, we may have full-size EPB plumes that extend vertically to topside.

Fully developed EPB structures in the nighttime low-latitude ionosphere also have turbulent structures/eddies within the large-scale ionospheric density depletions.

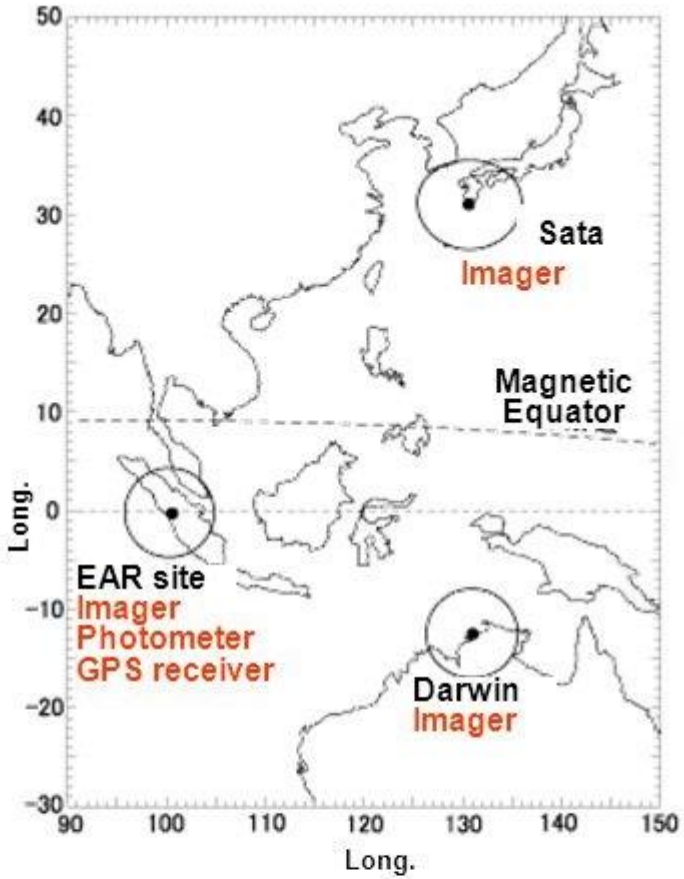
Equatorial Plasma Bubbles: Basic Primer (cont.)

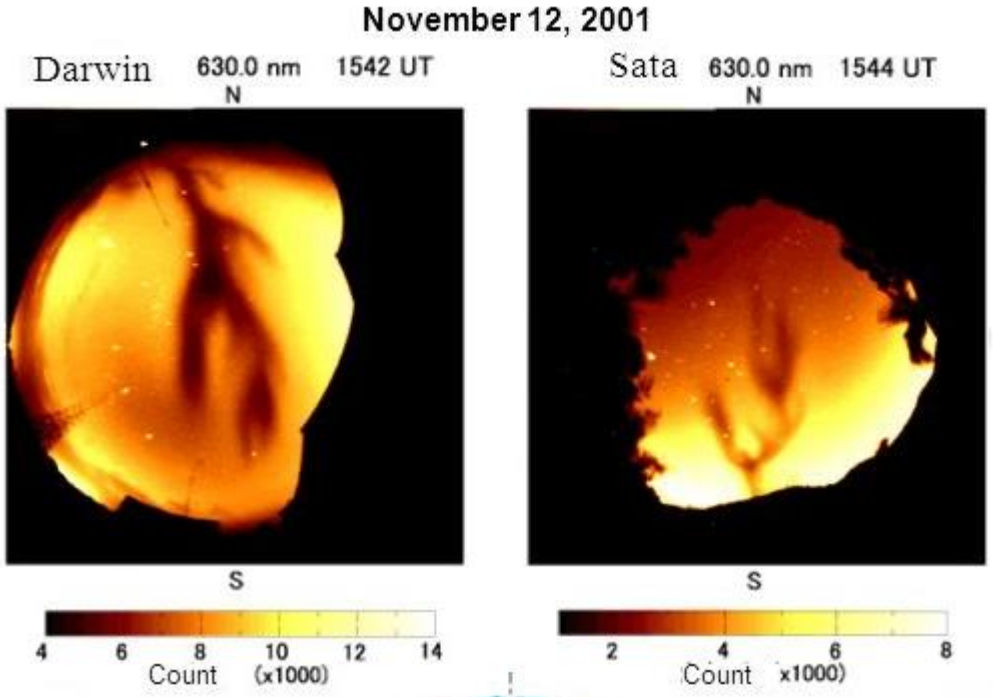


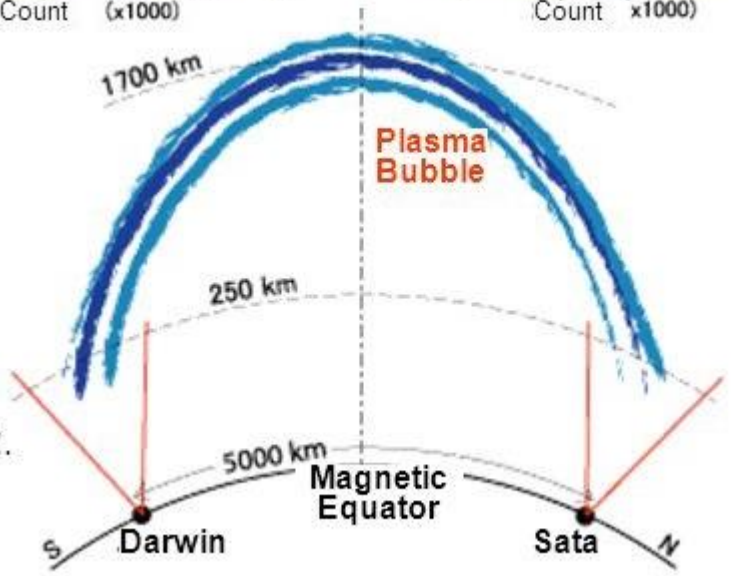
The turbulent structures/eddies that exist within the EPB depletions are capable of causing scintillations in GNSS an SATCOM radio signals.

This may pose serious problems since modern technology (and the digital economy) are more heavily reliant on space-based satellite infrastructure.

Geometrical Morphology of EPBs in 3-D Space



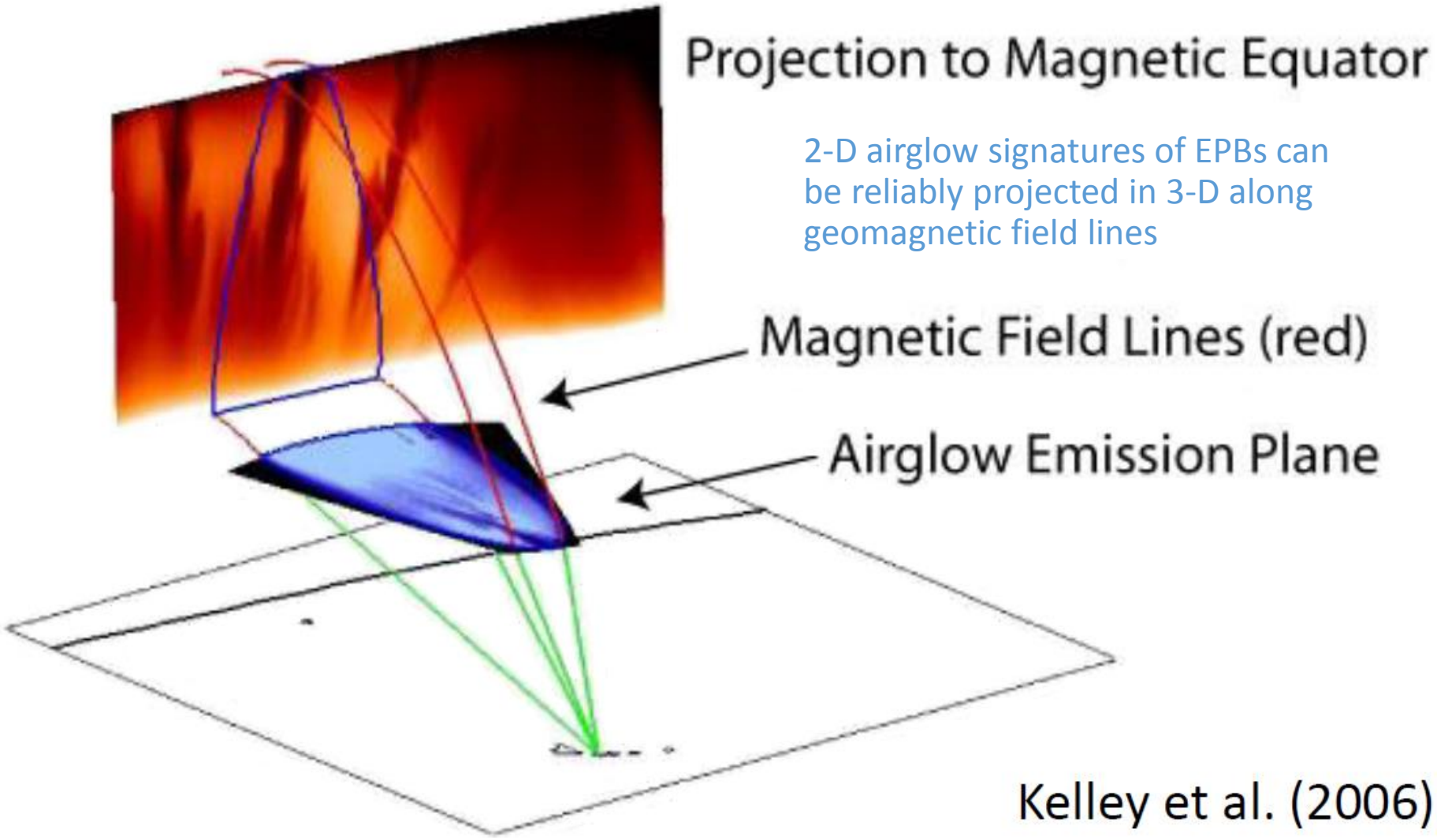




Observation by Prof. Ogawa group
STE Lab., Nagoya Univ.

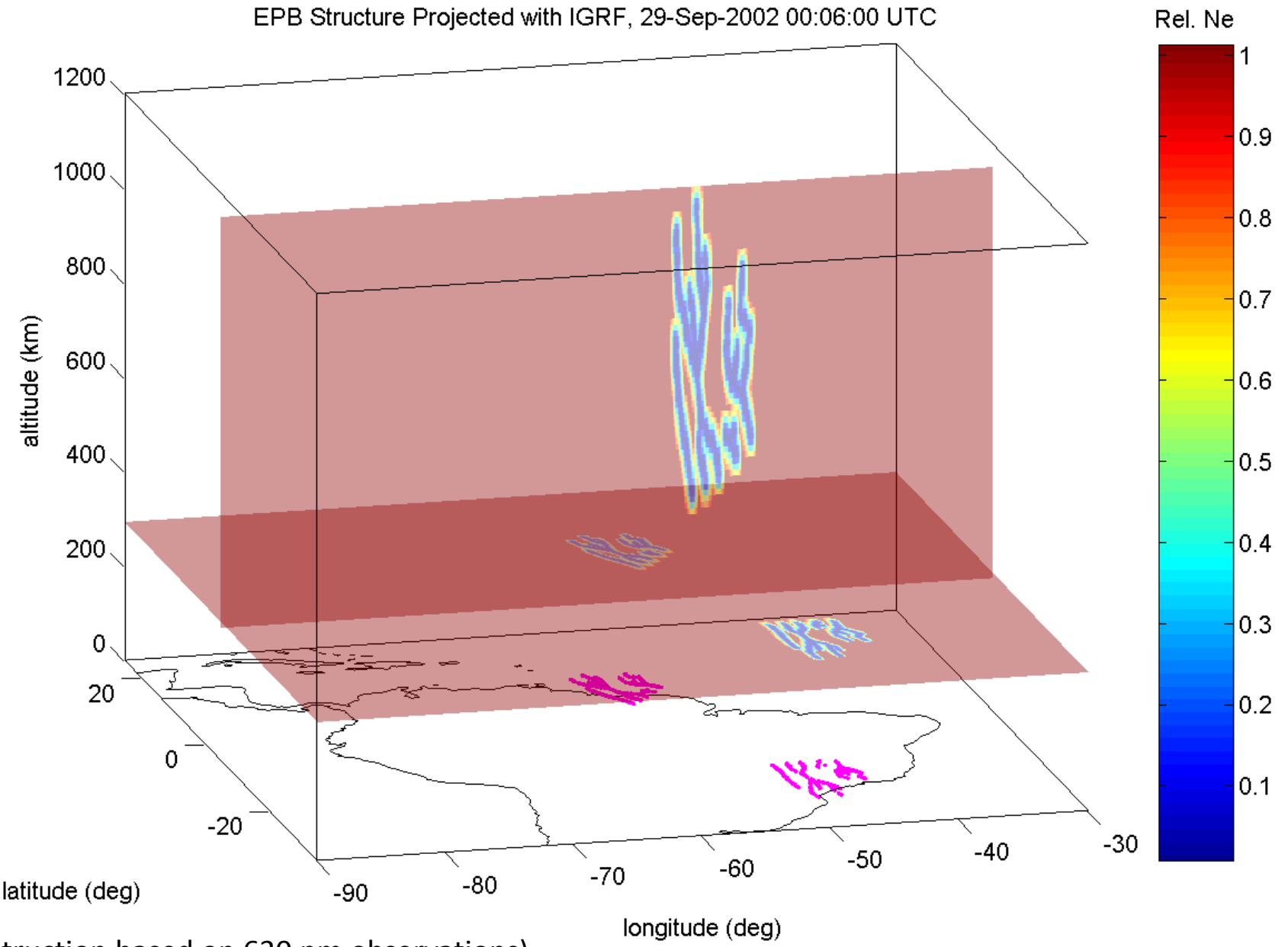
Otsuka, Y., K. Shiokawa, T. Ogawa, and P. Wilkinson, *Geophys. Res. Lett.*, 29(15), 10.1029/2002GL015347, 2002.
Shiokawa, K., Y. Otsuka, T. Ogawa, and P. Wilkinson, *Ann. Geophysicae*, 2004.

Geometrical Morphology of EPBs (continued)



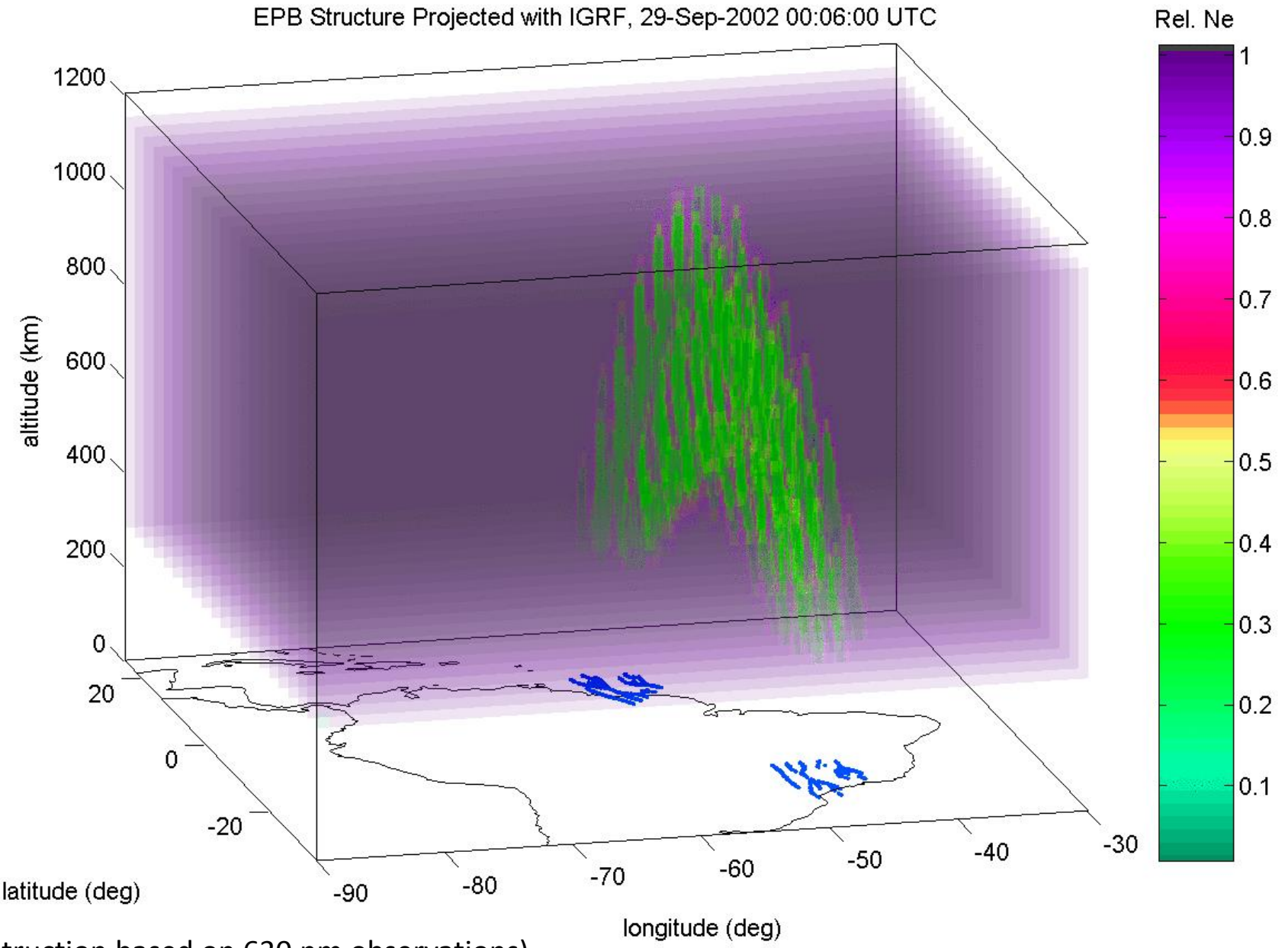
For IGRF tools, see e.g. <https://www.mathworks.com/matlabcentral/fileexchange/34388>

Geometrical Morphology of EPBs (continued)



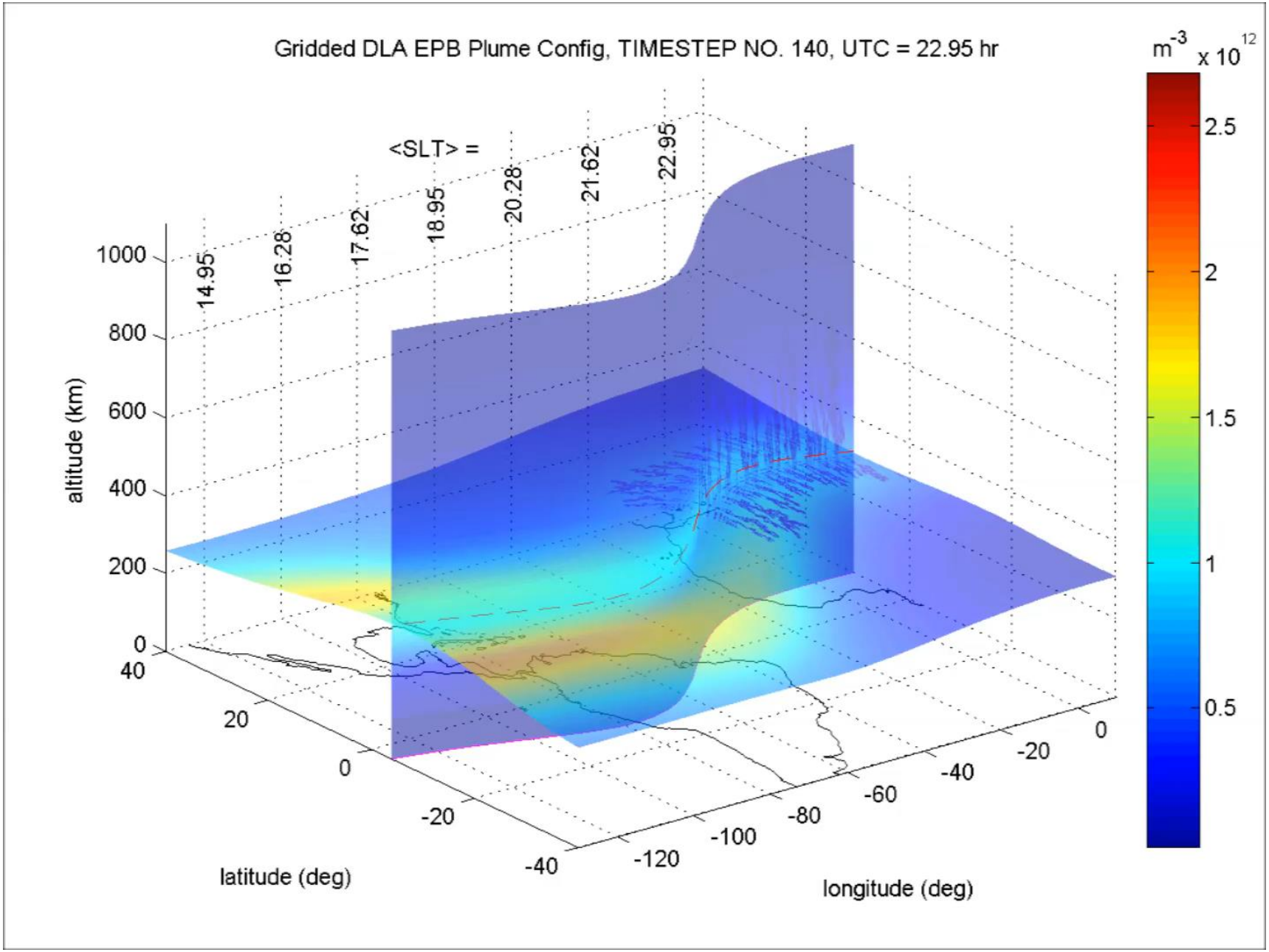
(Reconstruction based on 630 nm observations)

Geometrical Morphology of EPBs (continued)

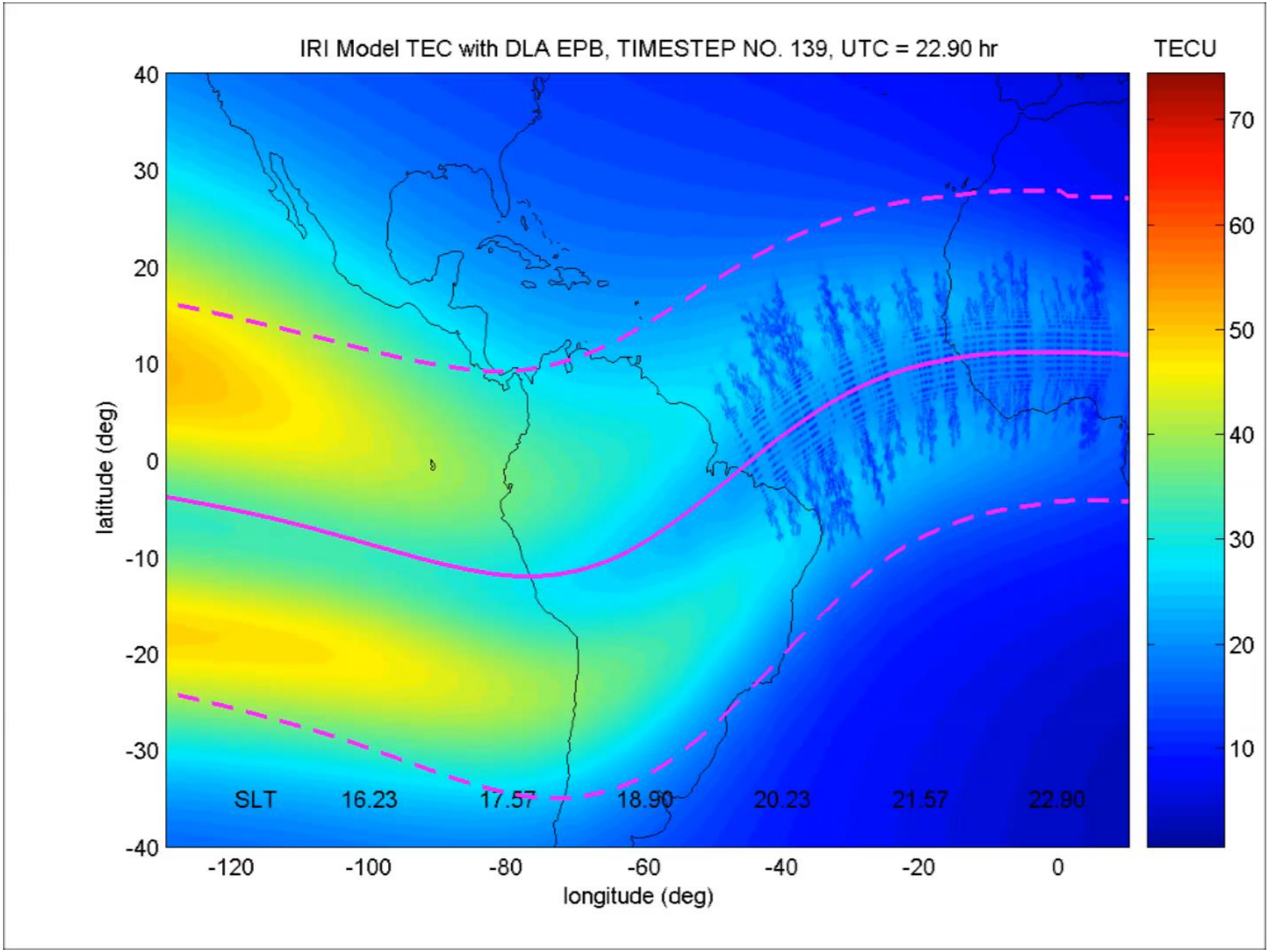


(Reconstruction based on 630 nm observations)

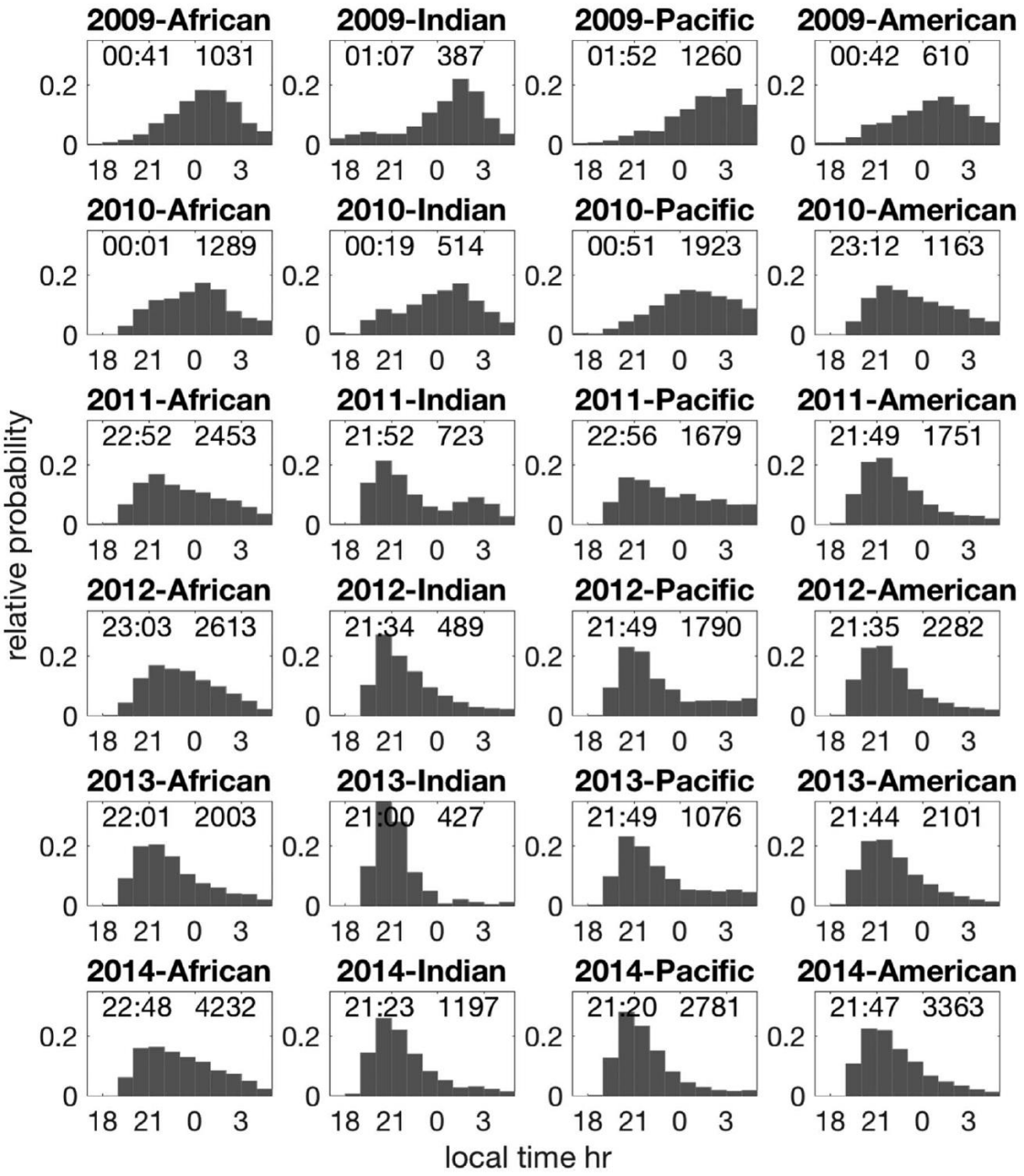
Geometrical Morphology of EPBs (continued)



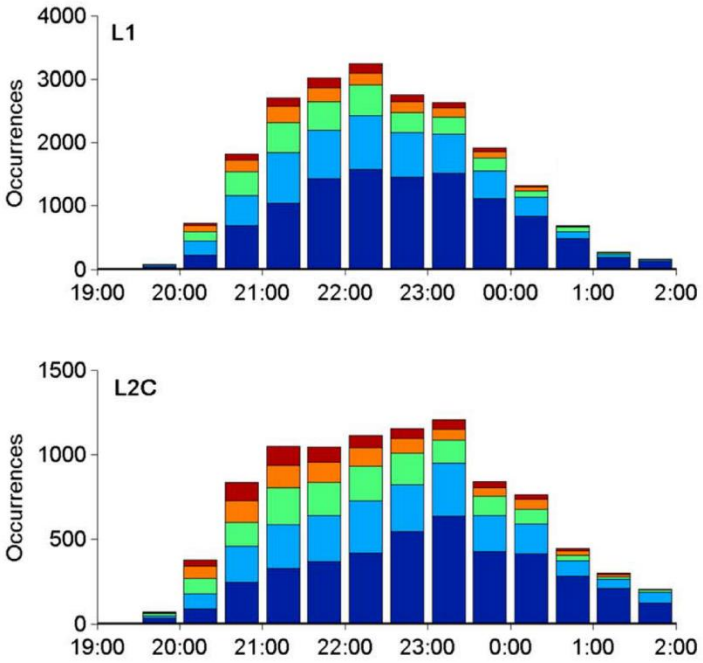
Geometrical Morphology of EPBs (continued)



Local Time Dependence of EPB Occurrence



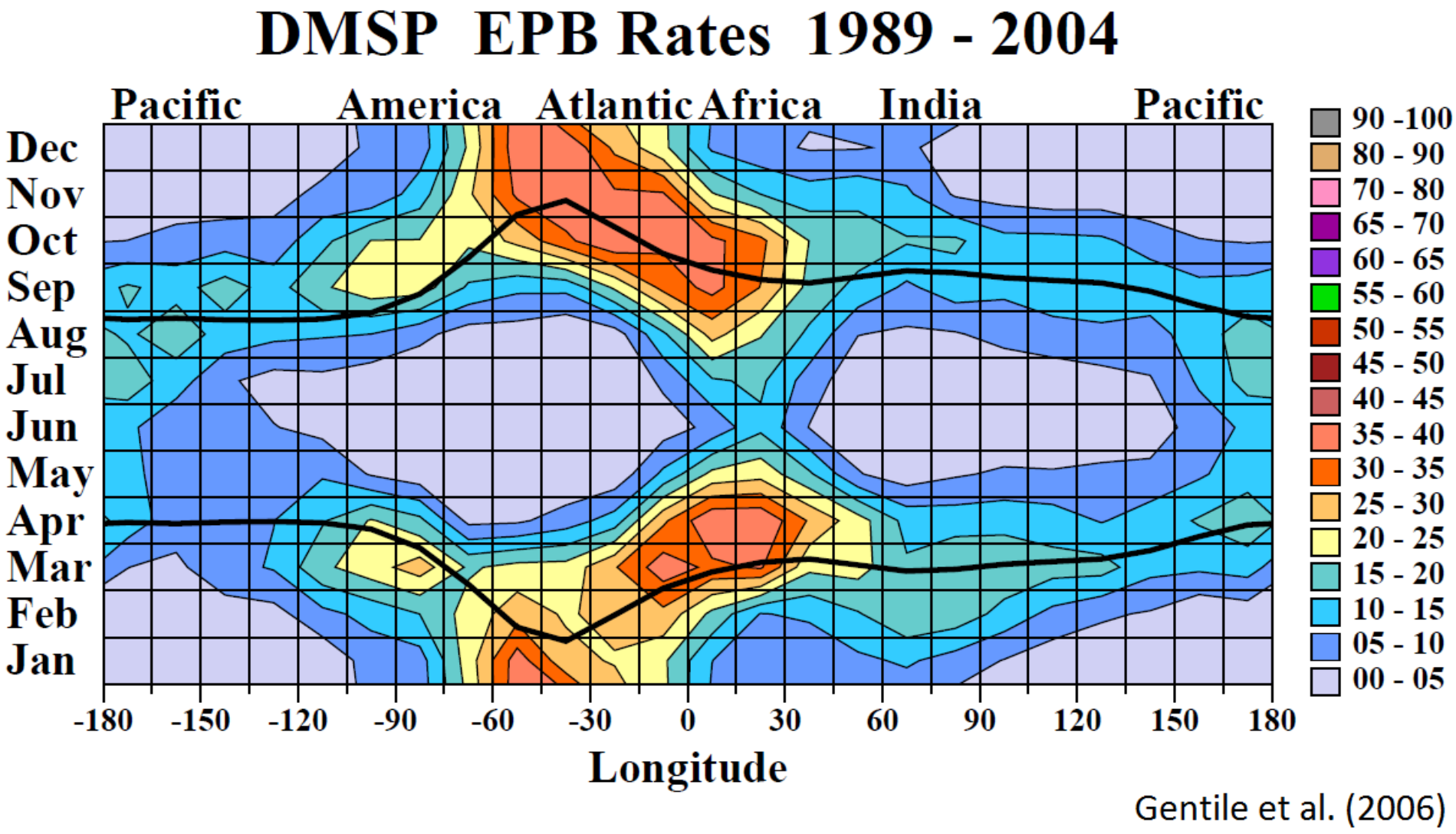
EPB and GPS L-band scintillation onset time at approximately 8pm. GPS L-band scintillations usually last until around midnight. EPBs may persist for some time longer.



[*Moraes et al.*, 2017]

[*Smith and Heelis*, 2017]

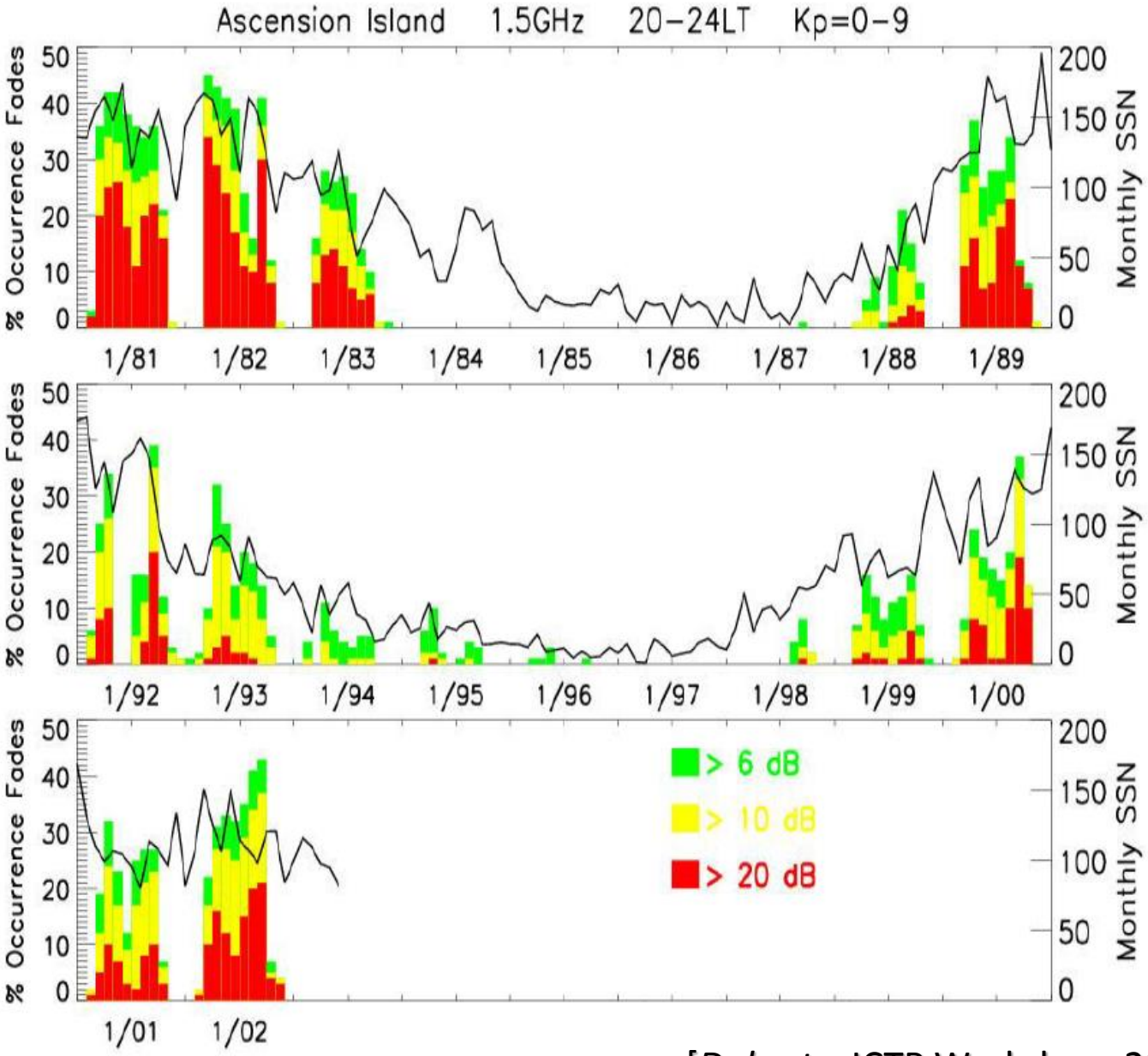
Longitude and Seasonal Dependence of EPBs



Gentile et al. (2006)

On a given calendar date, EPB occurrence rate is maximized over longitude sector(s) where the dusk terminator and the local magnetic meridian are aligned.

Solar Cycle Dep. of EPB-associated Scintillations



[*Doherty*, ICTP Workshop, 2010]

Effects of Geomag. Storms on EPB Occurrence

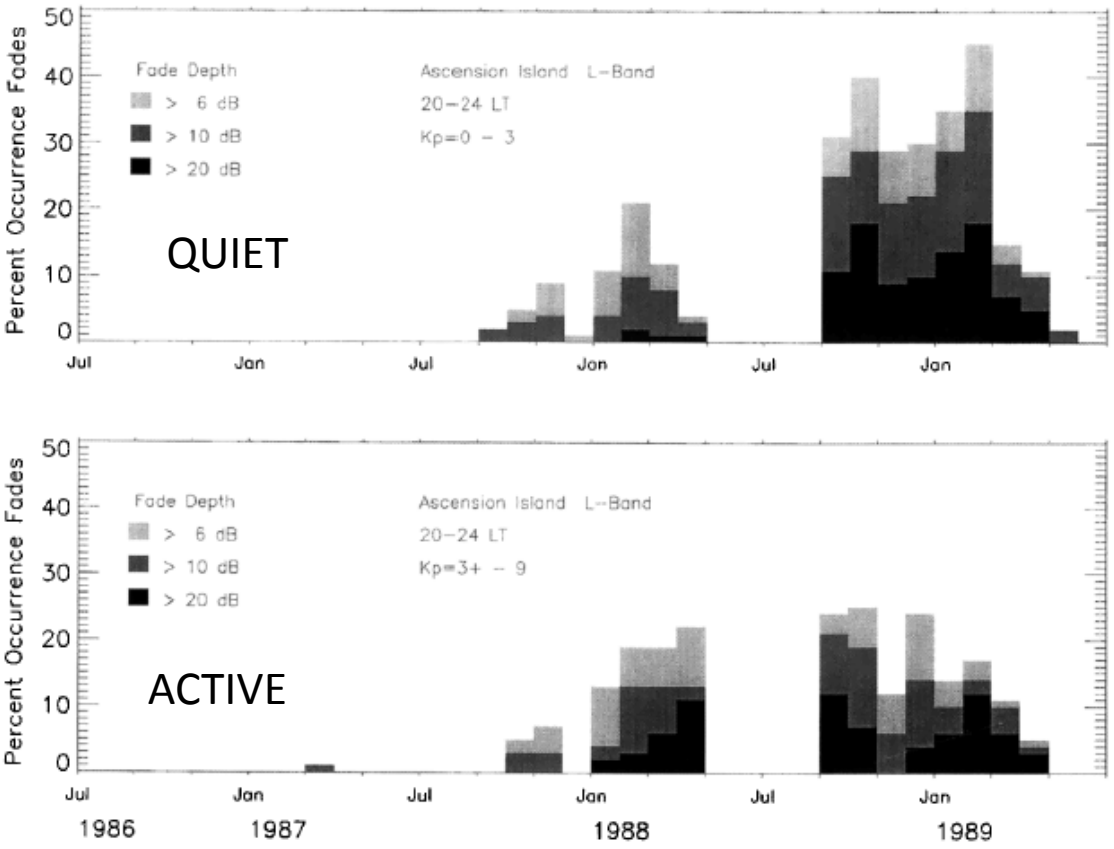
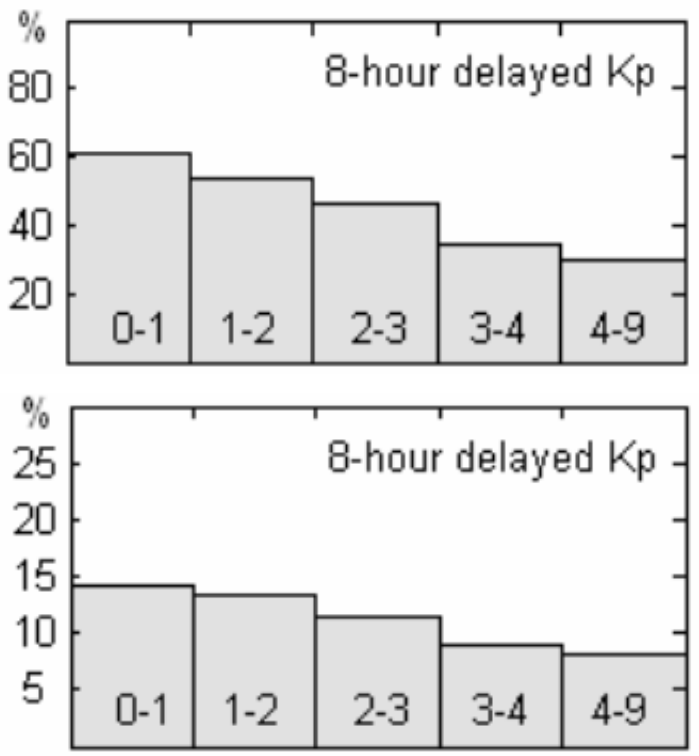


Figure 3. The occurrence statistics of L-band scintillation at Ascension Island during magnetically quiet (Kp = 0–3) and active (Kp = 3^+–9) conditions.

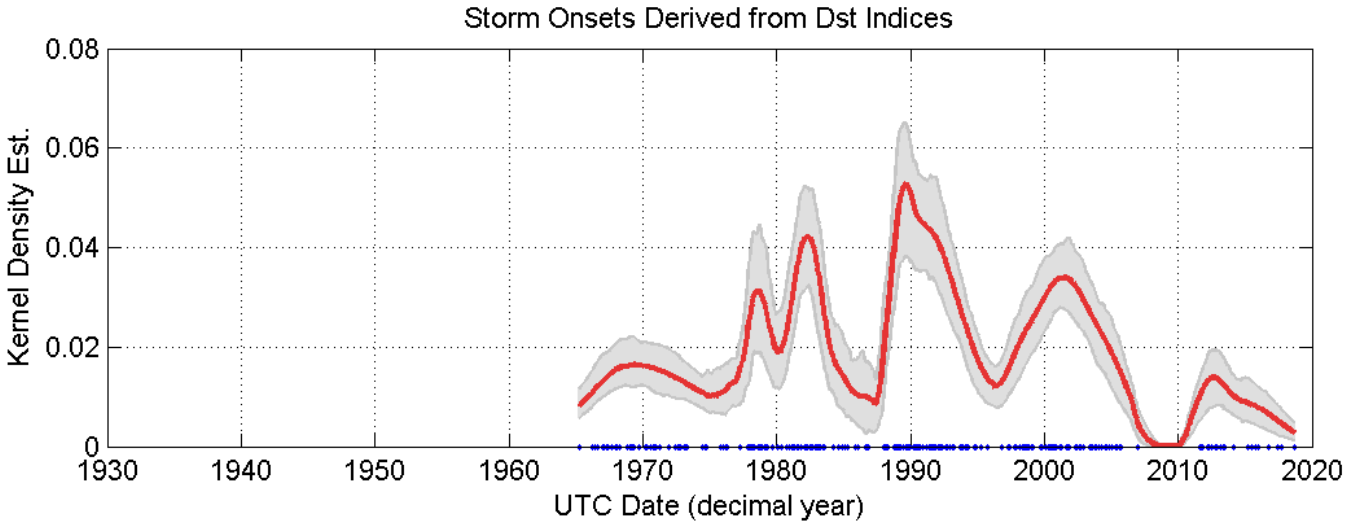
Groves et al. [1997]

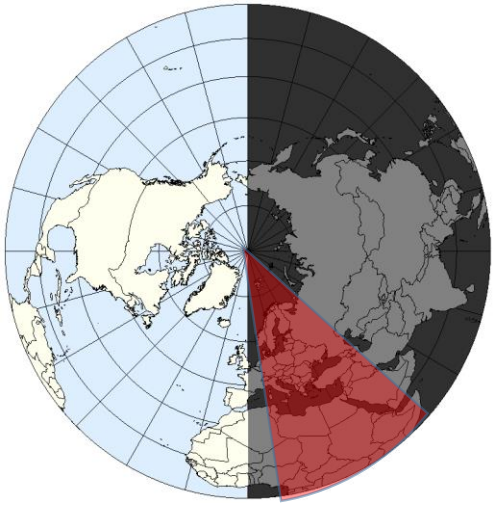


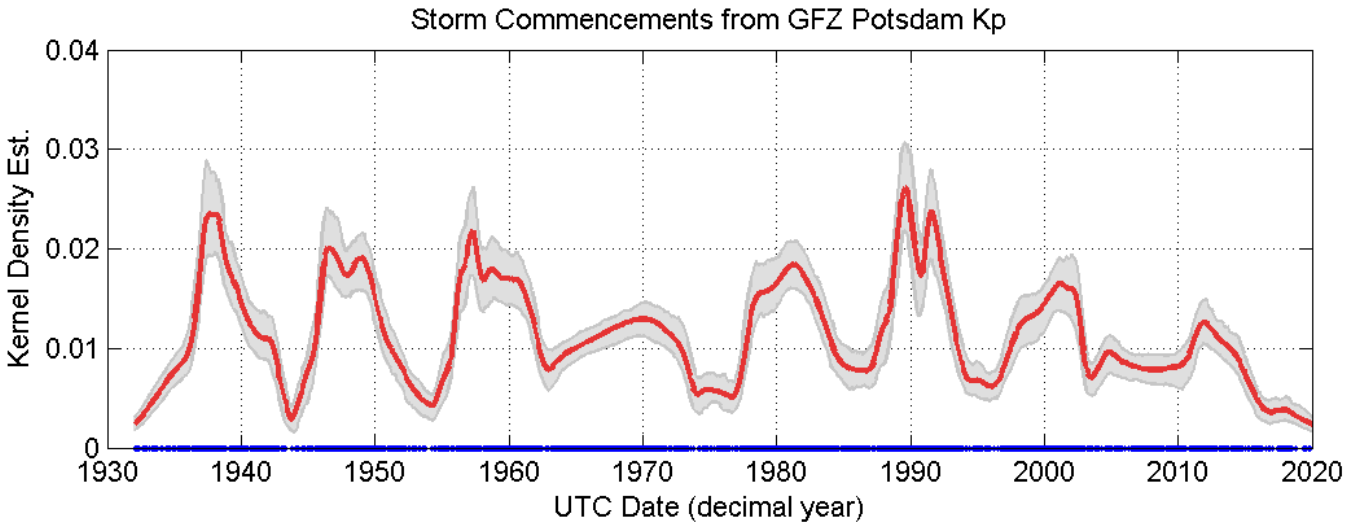
Li et al. [2009]

On the average, a moderate increase in geomagnetic activity (Kp = 0 to 4) tends to suppress EPB occurrence. However, during geomagnetic storms (Kp > 4), situation may become highly uncertain (suppression or intensification are possible).

Geomagnetic Storm Onset Time is a Key Aspect



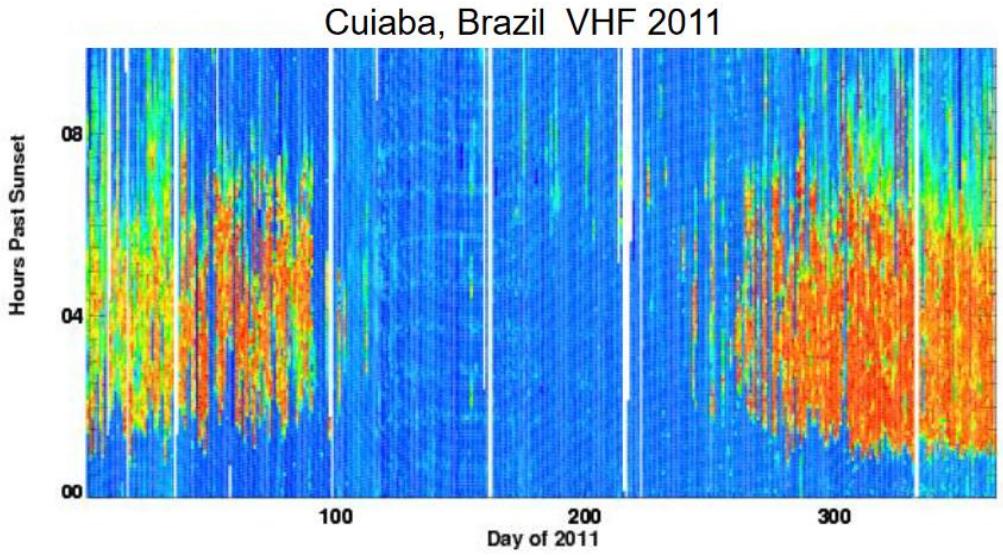


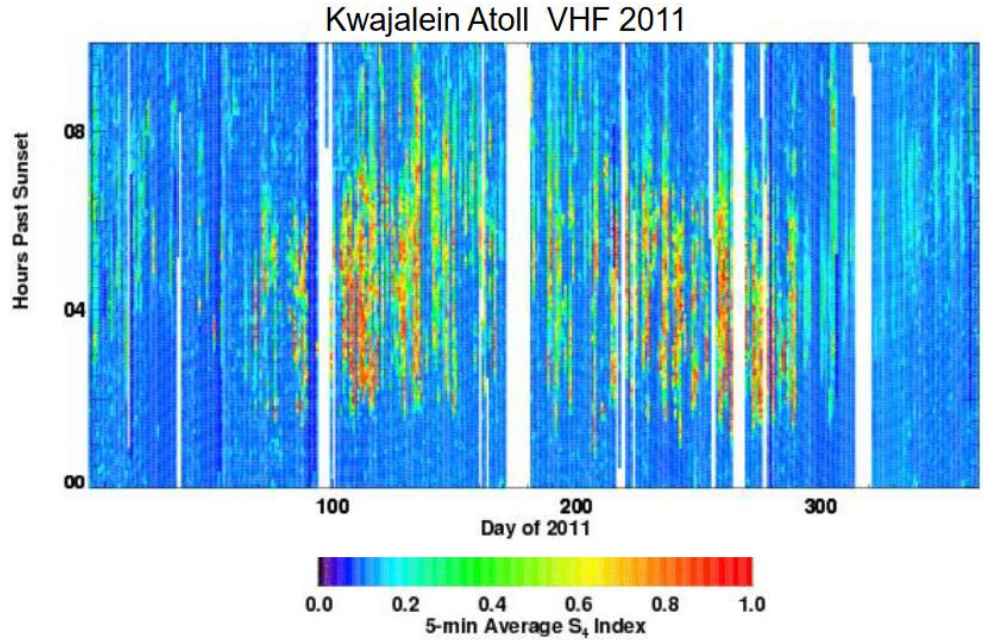


7–9 pm SLT window for an enhancement of EPB by PPEF during the main phase of geomagnetic storms

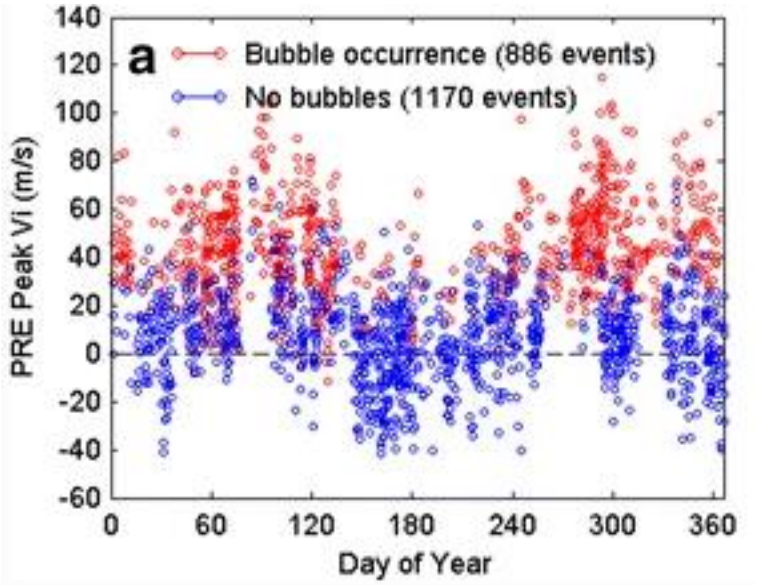
The use of Kp and Dst indices may not necessarily yield identical characterization of geomagnetic storms. Sometimes we need to pay attention to both indices.

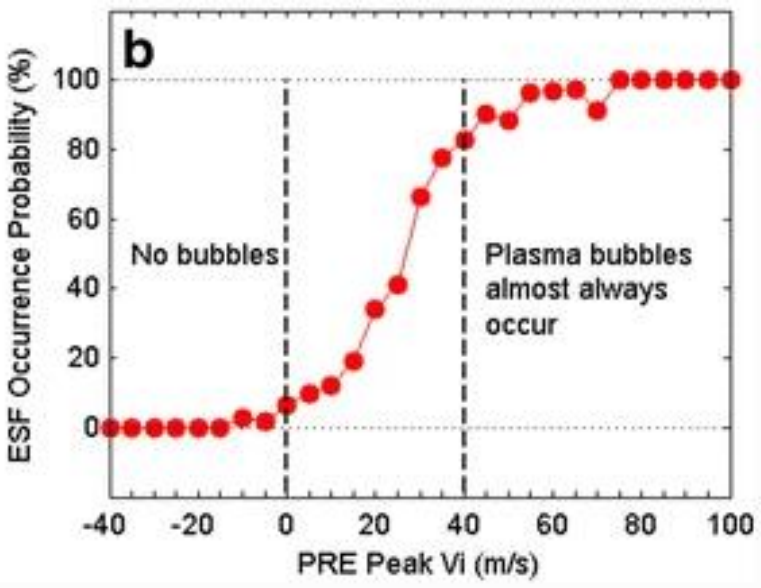
The Day-to-day Variability of EPB Occurrence





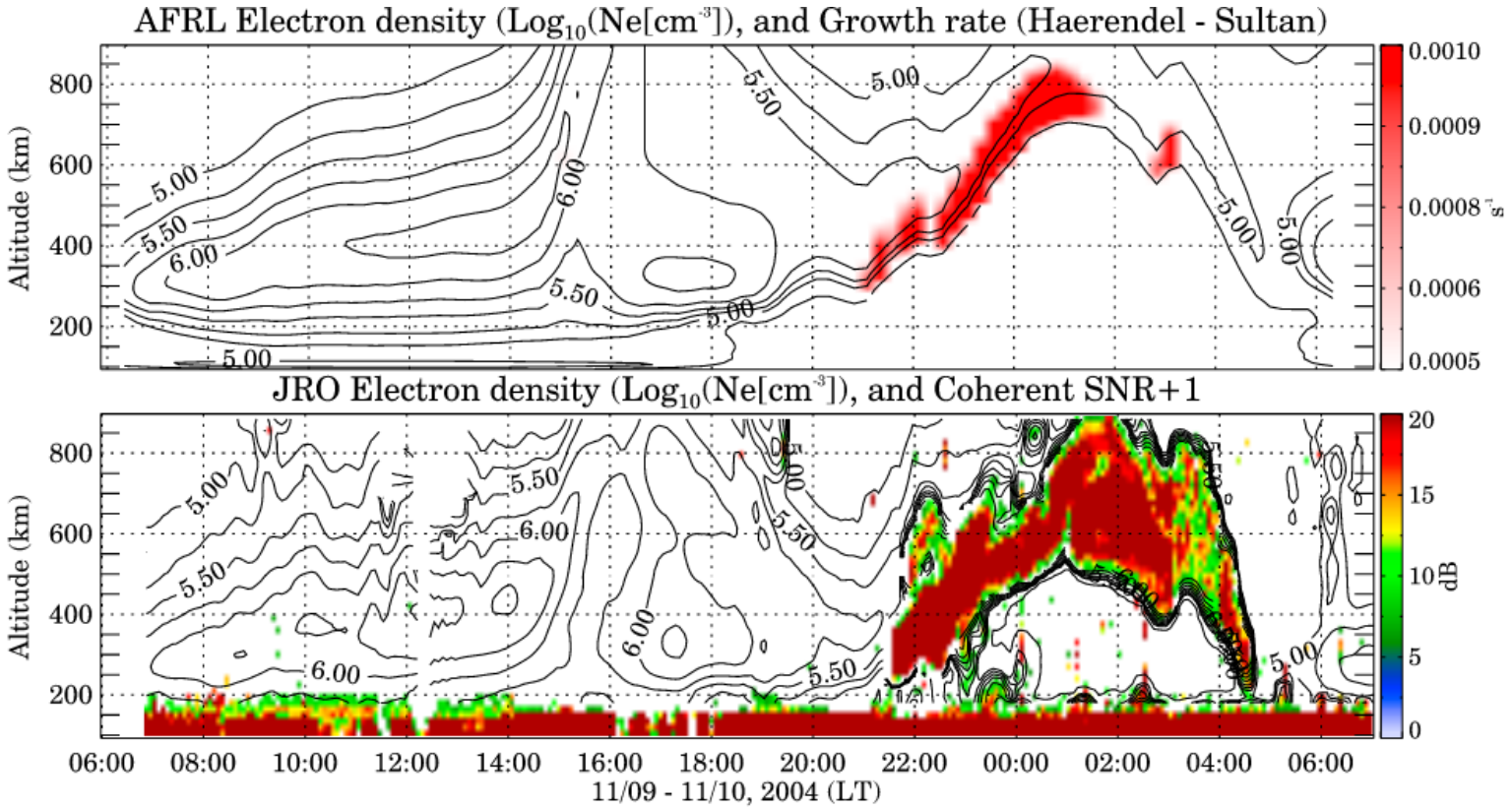
[*Groves and Carrano*, UNOOSA-Fiji, 2019]





[*Huang and Hairston*, 2015]

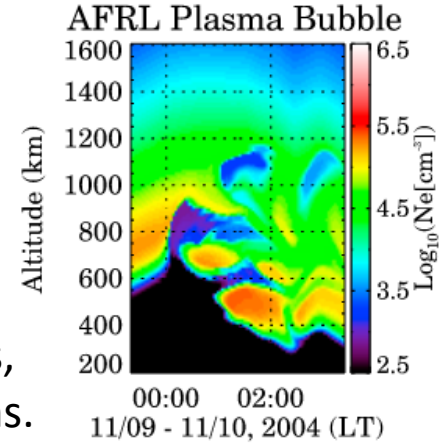
Many Different Factors Influence EPB Growth



Rayleigh-Taylor instability growth rate:

$$\gamma = \frac{\Sigma_P^F}{\Sigma_P^E + \Sigma_P^F}\left(V_p - U_L^P - \frac{g_e}{\nu_{\text{eff}}^F}\right)K^F - R_T$$

We must pay attention to quantities that affect various terms in the instability growth rate. Plus, we must also pay attention to seed perturbations.



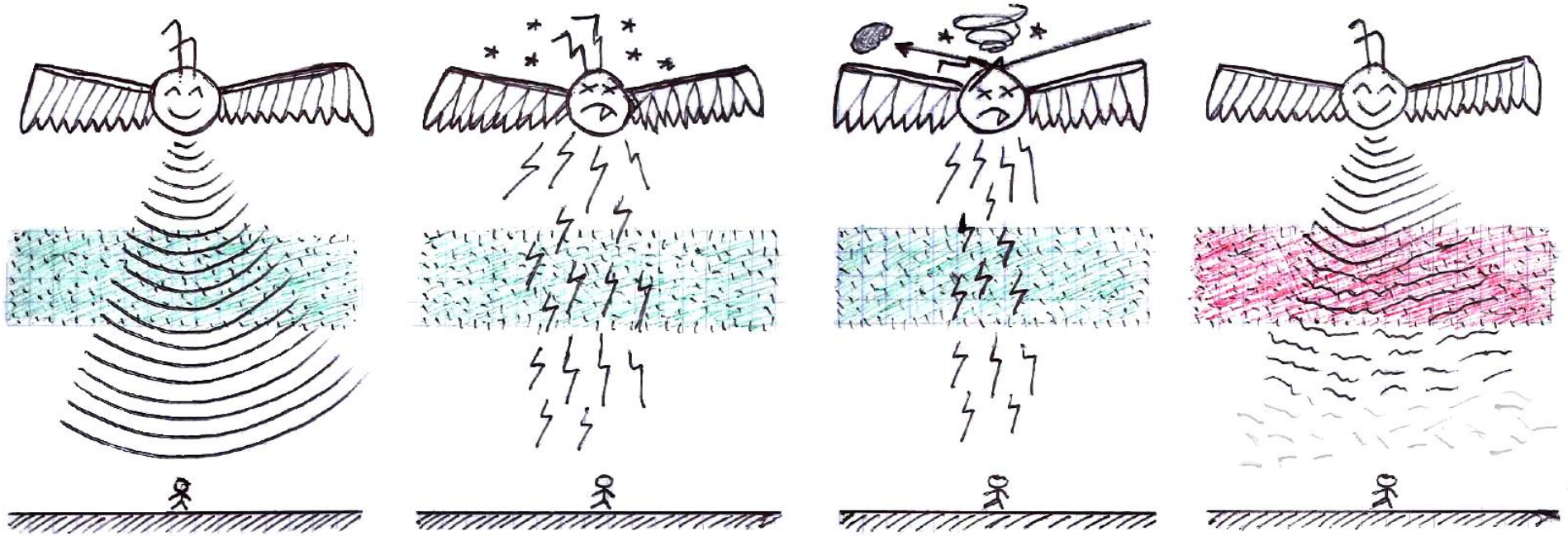
Day-to-day variability of ESF/EPB is still an active research area. Predictive models are really important, yet EPB climatology will remain relevant.

Concept of Space Situational Awareness (SSA)

Image: *Lockheed Martin* (iSpace & Space Fence programs)

SSA may be a useful concept to borrow for the context of risk/hazard due to EPBs.

Space Situational Awareness (SSA) and ESF/EPB



No harm to satellite; normal operation.
[SSA: things are fine]

Damages to satellite due to adverse space weather condition.
[SSA: this is not OK]

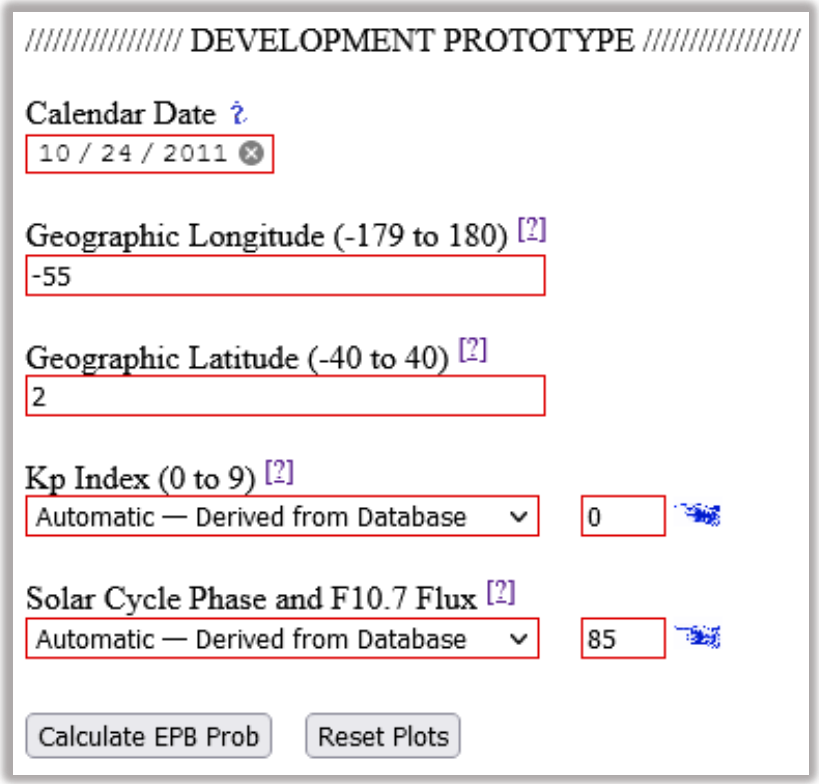
Satellite collided with other space objects.
[SSA: this is not OK]

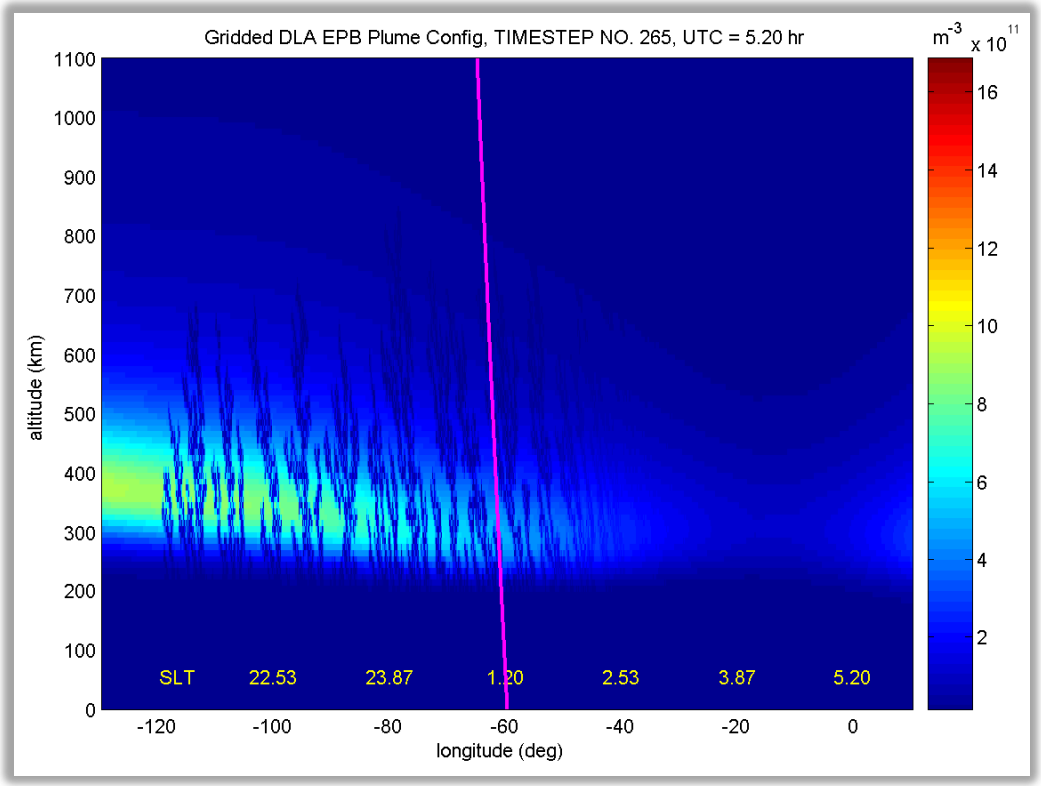
No harm to satellite; but there are EPBs and scintillations.
[SSA: is this fine?]

Traditionally, Space Situational Awareness (SSA) refers to the capability of detecting and tracking man-made and natural threats, predicting and assessing the risks, and enabling the implementation of mitigation measures aimed at protecting space and ground assets [*PwC France*]. *EPBs may compel us to broaden the definition of SSA.*

https://www.pwc.fr/en/industrie/secteur-spatial/space-situational-awareness.html

Facilitating Distrib. of EPB-related Knowledge

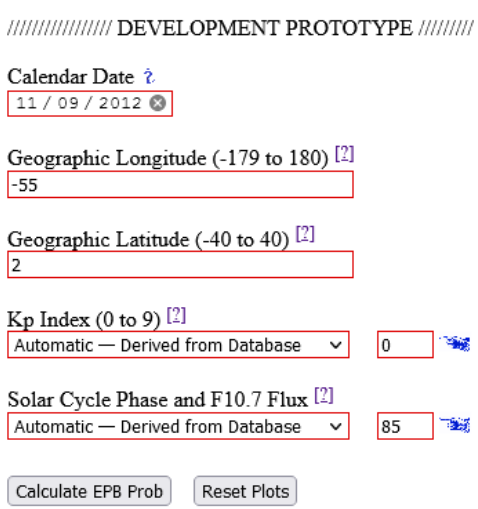


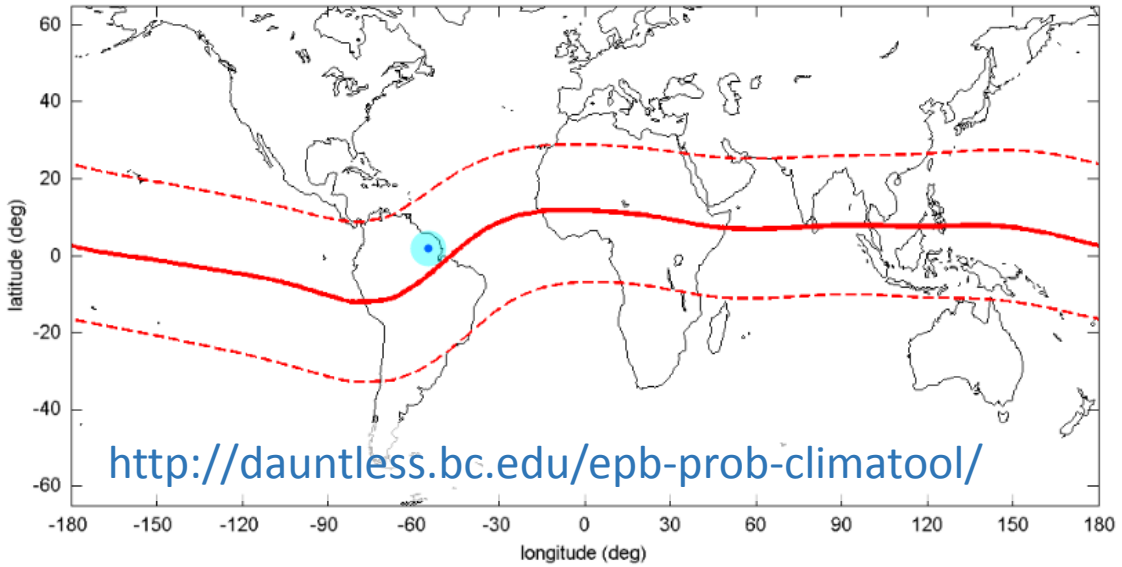


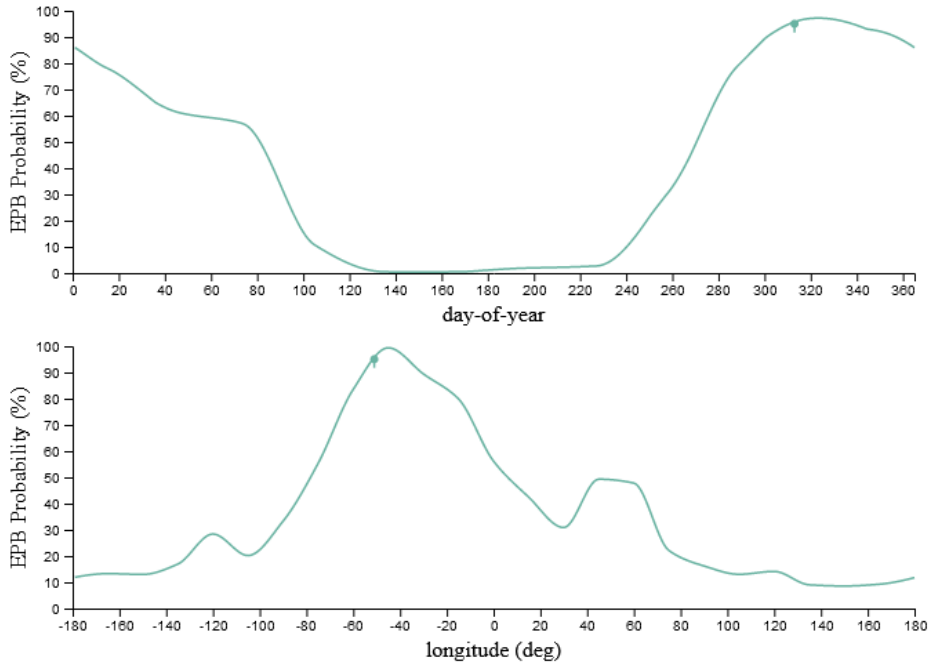
The climatology of EPB is well-documented in scientific literature, but it tends to stay as expert knowledge. More accessible tools for familiarizing oneself with EPB phenomenology is desirable, since it may become necessary even in management and policy. Here we discuss a potentially useful resource [*Pradipta et al.*, 2021].

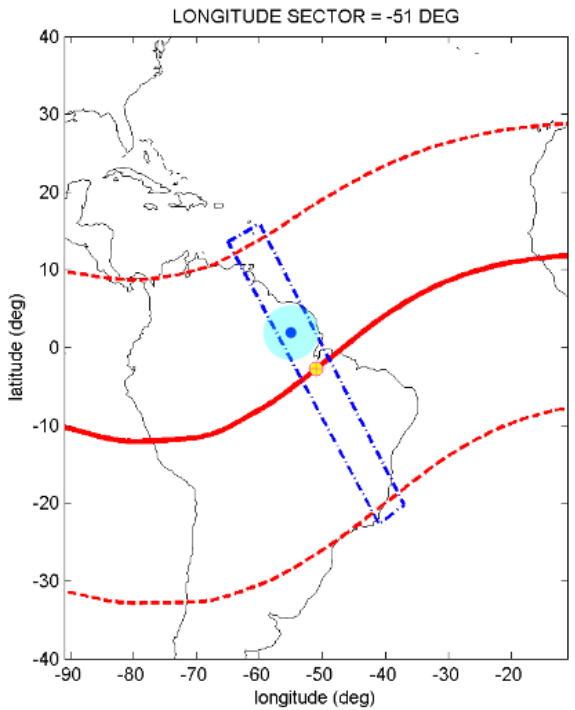
- EPB & scintillation climatology tool – basic system description
- EPB & scintillation climatology tool – demonstration/practice

Making Basic EPB Climatology More Accessible

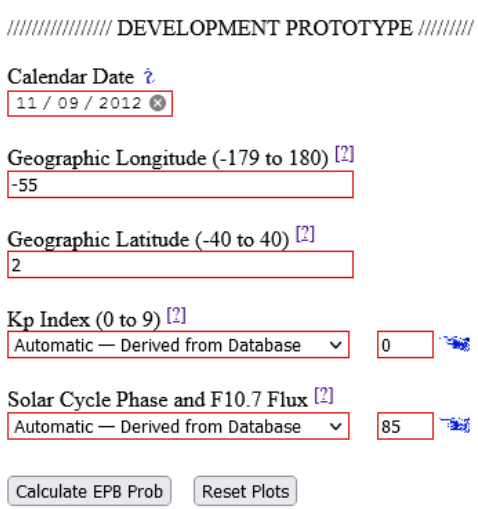


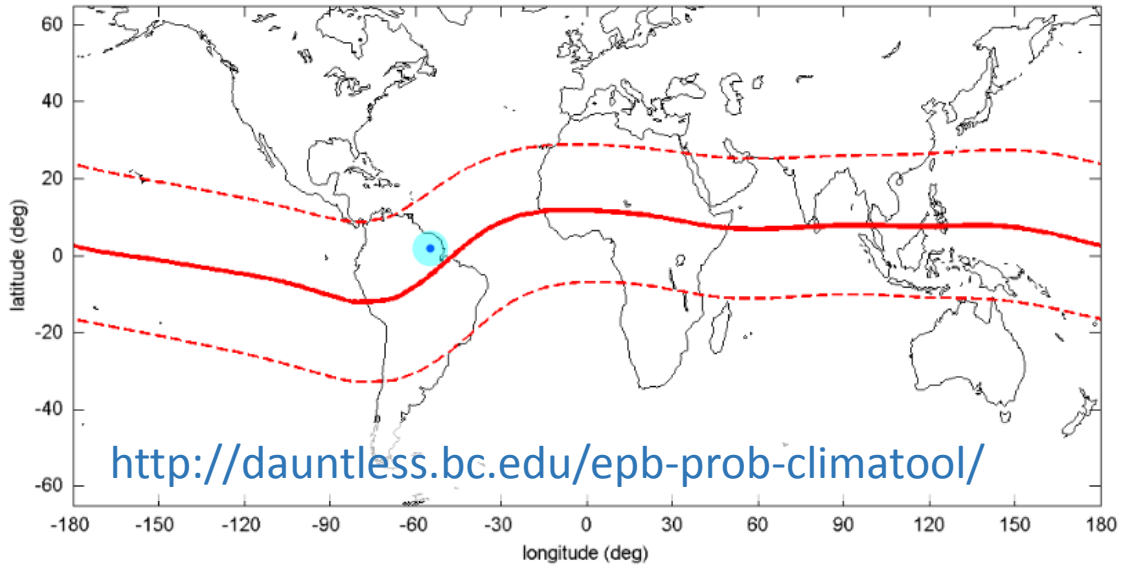


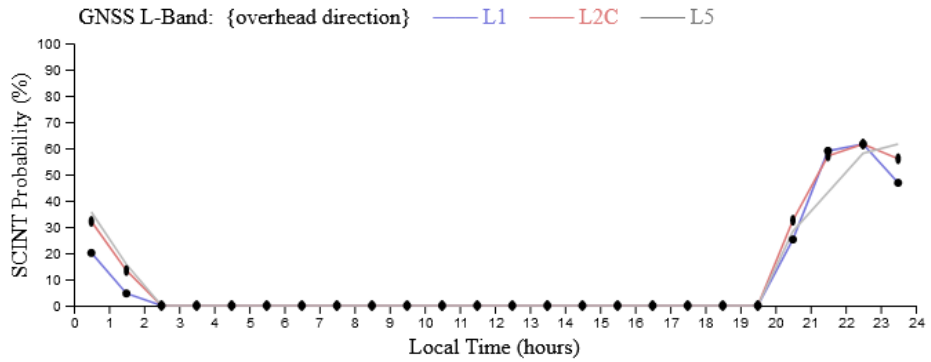


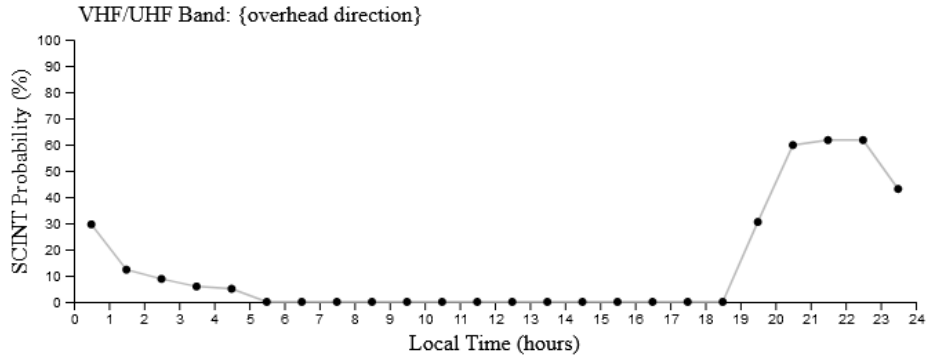


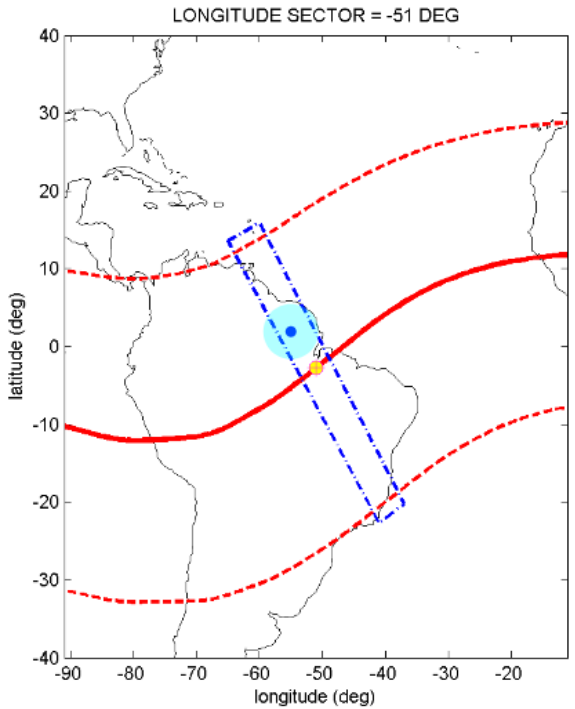
Making Basic EPB Climatology More Accessible



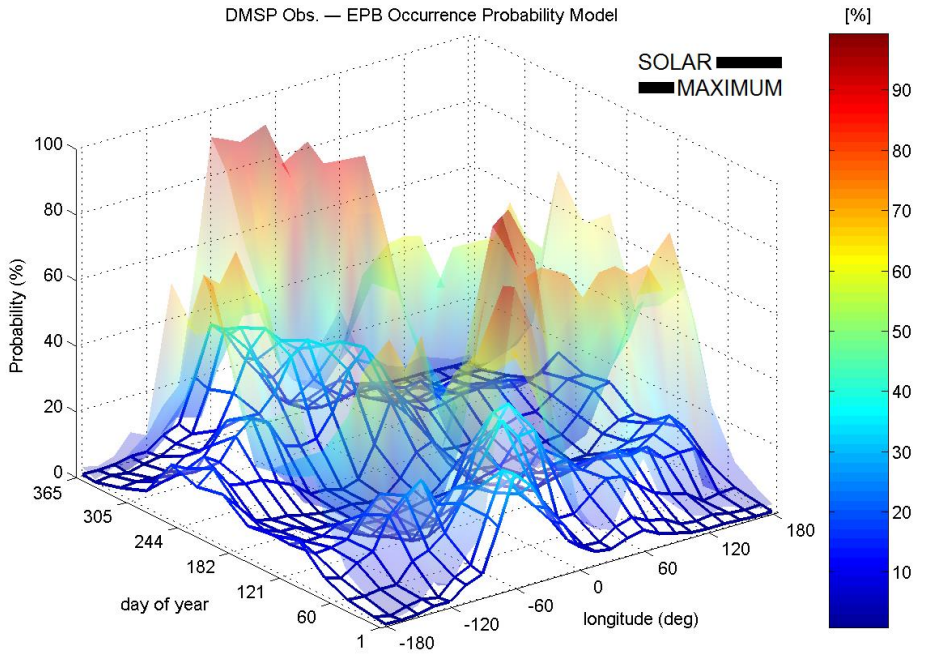


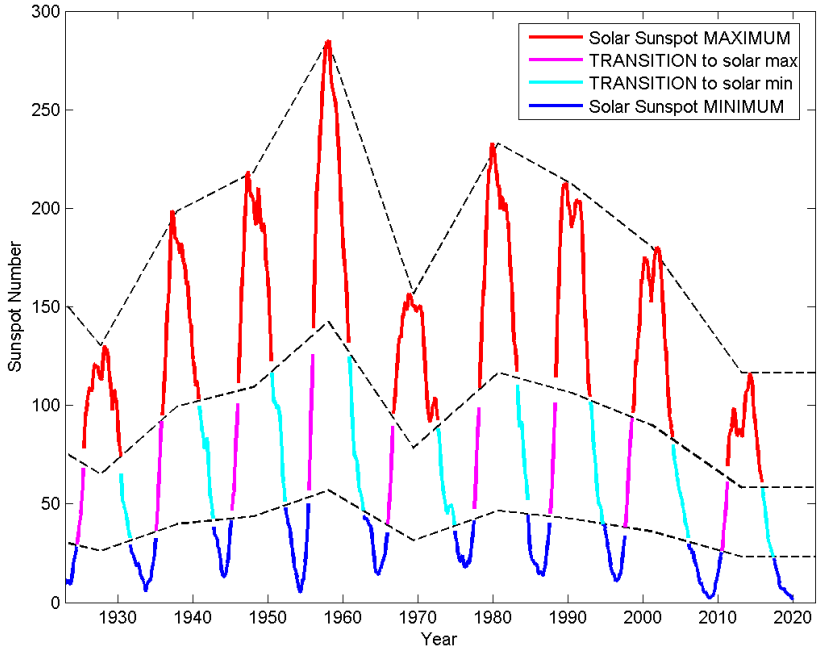


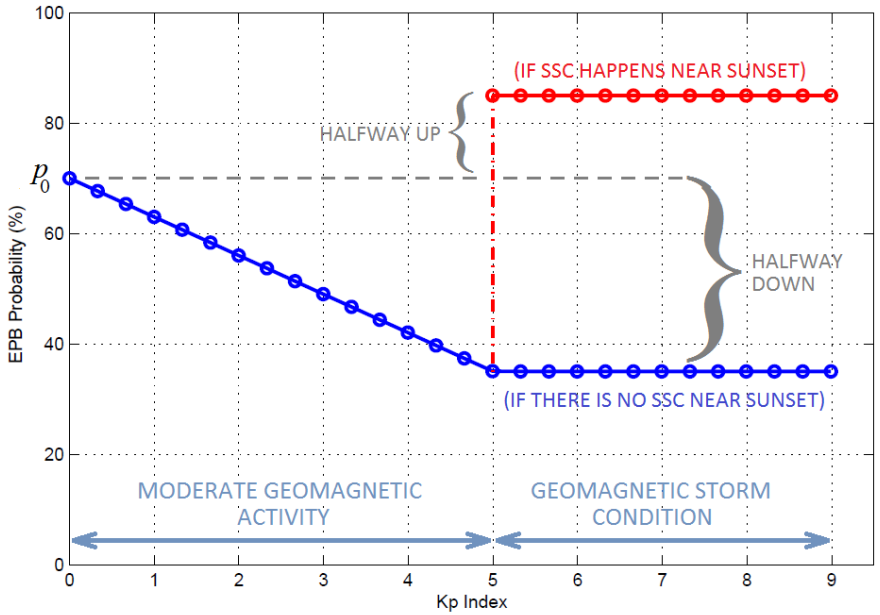


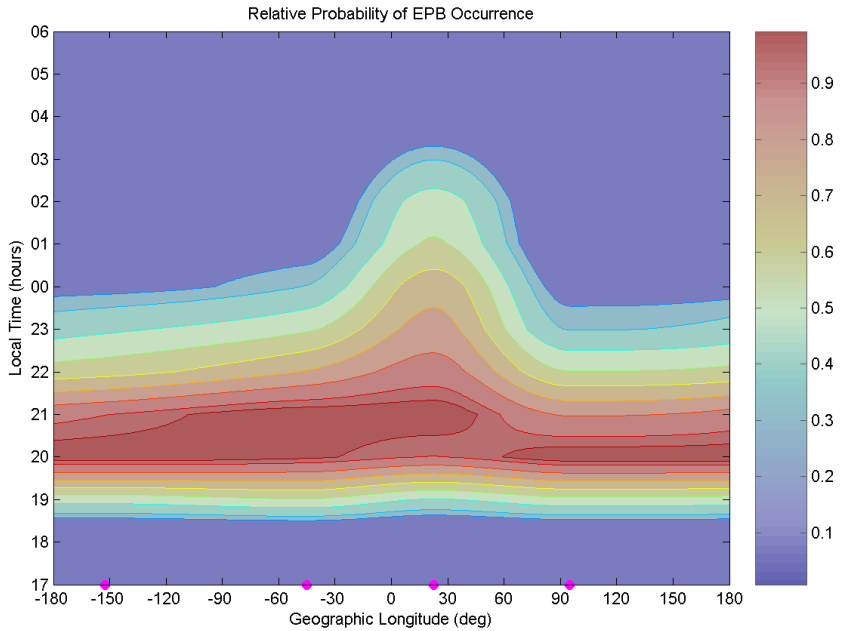


Elements of the EPB & Scintillation Climo Tool

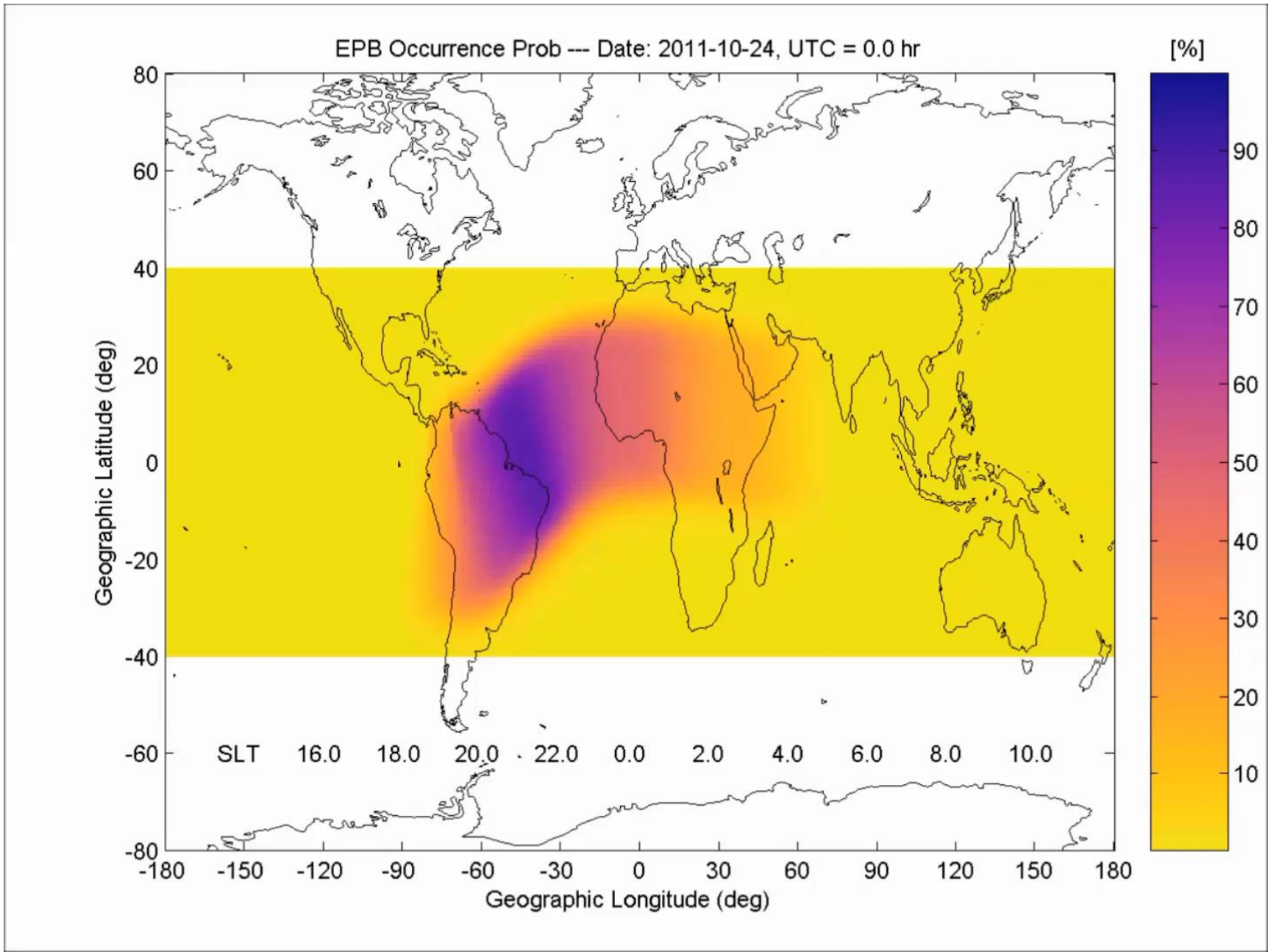








Projected EPB Probability (24 Oct 2011 storm)



Now is Time for Some Demo and Practice!

Web version of the *EPB Climatology Tool* (development prototype) can be accessed online via the URL: http://dauntless.bc.edu/epb-prob-climatool/

The *EPB Climatology Tool* primarily uses Kp index as measure of geomagnetic activity and geomagnetic storm condition.

Where to obtain the latest/nowcast values of Kp index:
NOAA SWPC: https://www.swpc.noaa.gov/ >> PRODUCTS and DATA >> OBSERVATIONS >> Planetary K Index
GFZ Potsdam: https://isdc.gfz-potsdam.de/kp-index/

Where to obtain forecast/projection of Kp index:
NOAA SWPC https://www.swpc.noaa.gov/ >> PRODUCTS and DATA >> FORECASTS >> 3-Day Geomagnetic Forecast
NOAA SWPC https://www.swpc.noaa.gov/ >> PRODUCTS and DATA >> FORECASTS >> 27-Day Outlook of 10.7 cm Radio Flux and Geomagnetic Indices

More complete archive of Kp index (1932 – present):
https://www.gfz-potsdam.de/en/kp-index/

Summary and Conclusion

- In addition to scientific research, there is also a need for serious public discourse on ESF/EPB/scintillations and their potential risk/hazard to modern technology
- In addition to advanced theory and models, more accessible tools to familiarize ourselves with EPB occurrence pattern may also help to facilitate this discourse
- A potential resource is *EPB Climatology Tool* that codified some of the empirical knowledge (on EPB & low-latitude ionosphere) which had existed in literature
- Two versions of the EPB climatology tool have been constructed: one in MATLAB and another in HTML/Javascript
- Web version of the EPB climatology tool can be accessed online via the URL http://dauntless.bc.edu/epb_prob_climatool/
- Further model validation tests and eventual MATLAB code distributions are currently being planned

Thank you for your attention!
Questions?