IONOSPHERIC SCINTILLATION IMPACT ON THE PERFORMANCE OF COMMUNICATION SATELLITES

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Sapporo, Japan,
23 August 2023

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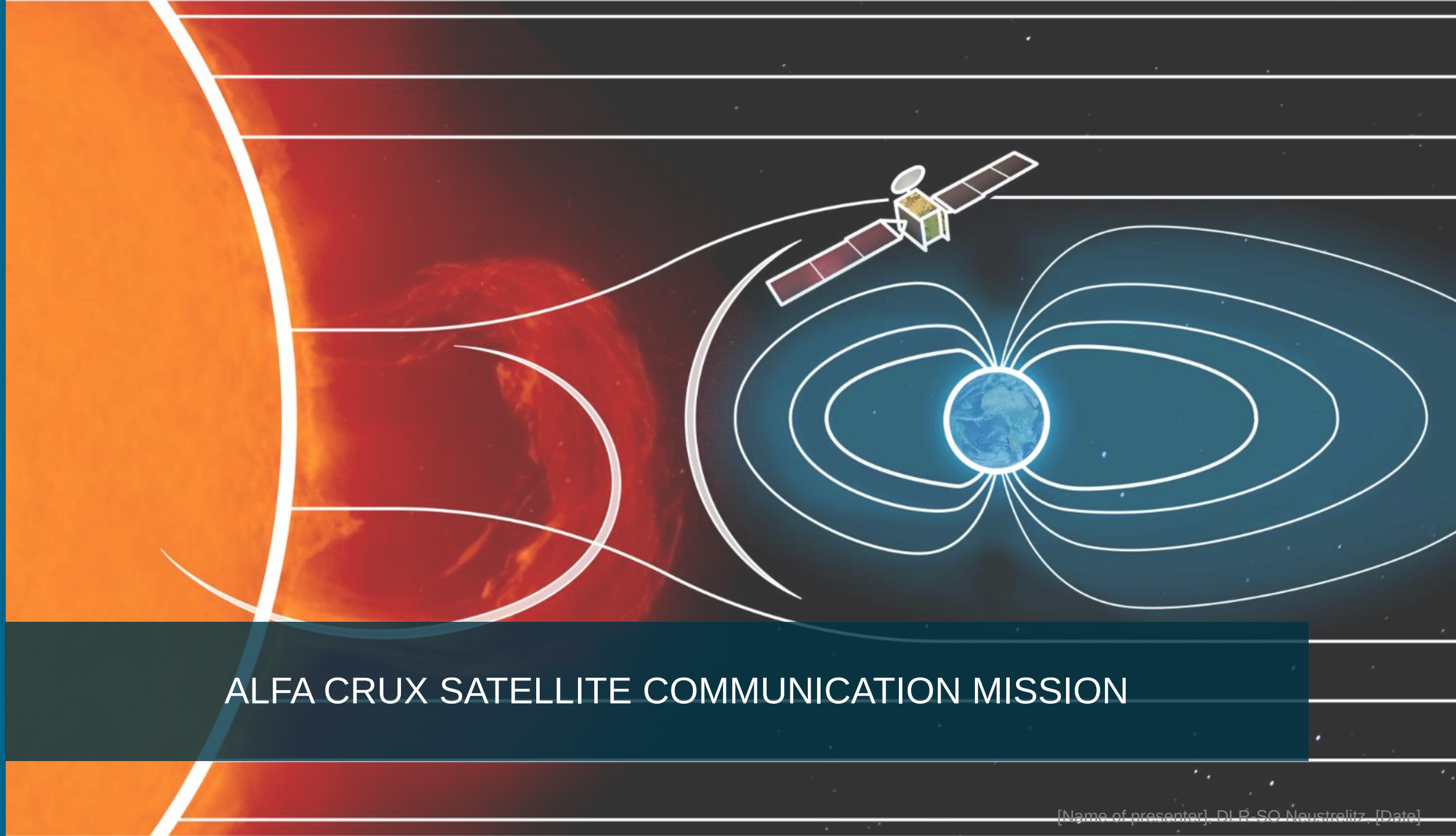


ALFA CRUX SATELLITE COMMUNICATION MISSION

[Name of presenter], DLR-SO Neustrelitz, [Date]

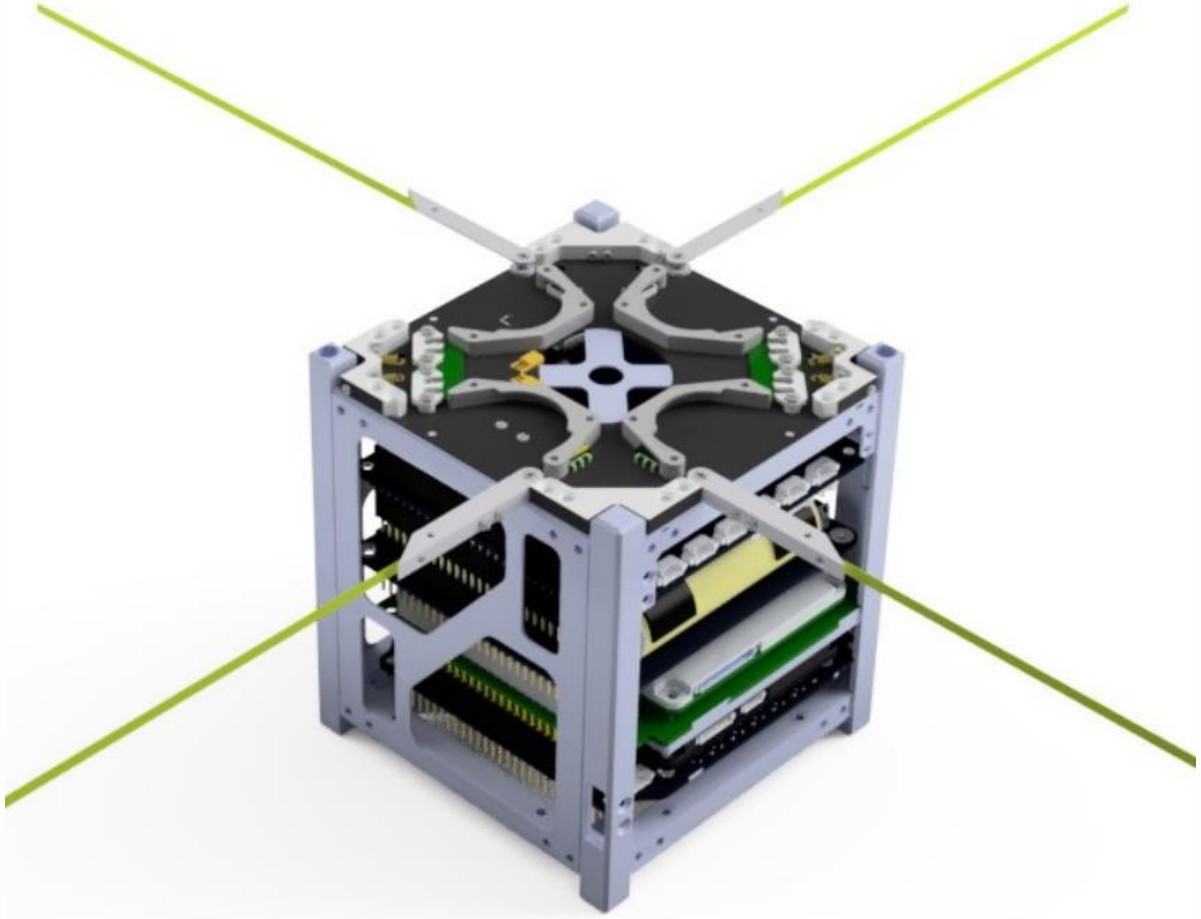
Mission concept

- AlfaCrux is an amateur radio and educational mission operating over Brazil.

- Part of the mission are scientific experiments related to the impact of space weather in the communication channel.

- The mission implements a low-rate, bidirectional, short-message-based store-and-forward communication system.
  - Communication with weather stations in remote areas
  - Environmental sensors
  - Communication in areas affected by disasters

R. A. Borges et al., Appl.Sci. 12, 9764 (2022)



AlfaCrux CAD isometric view

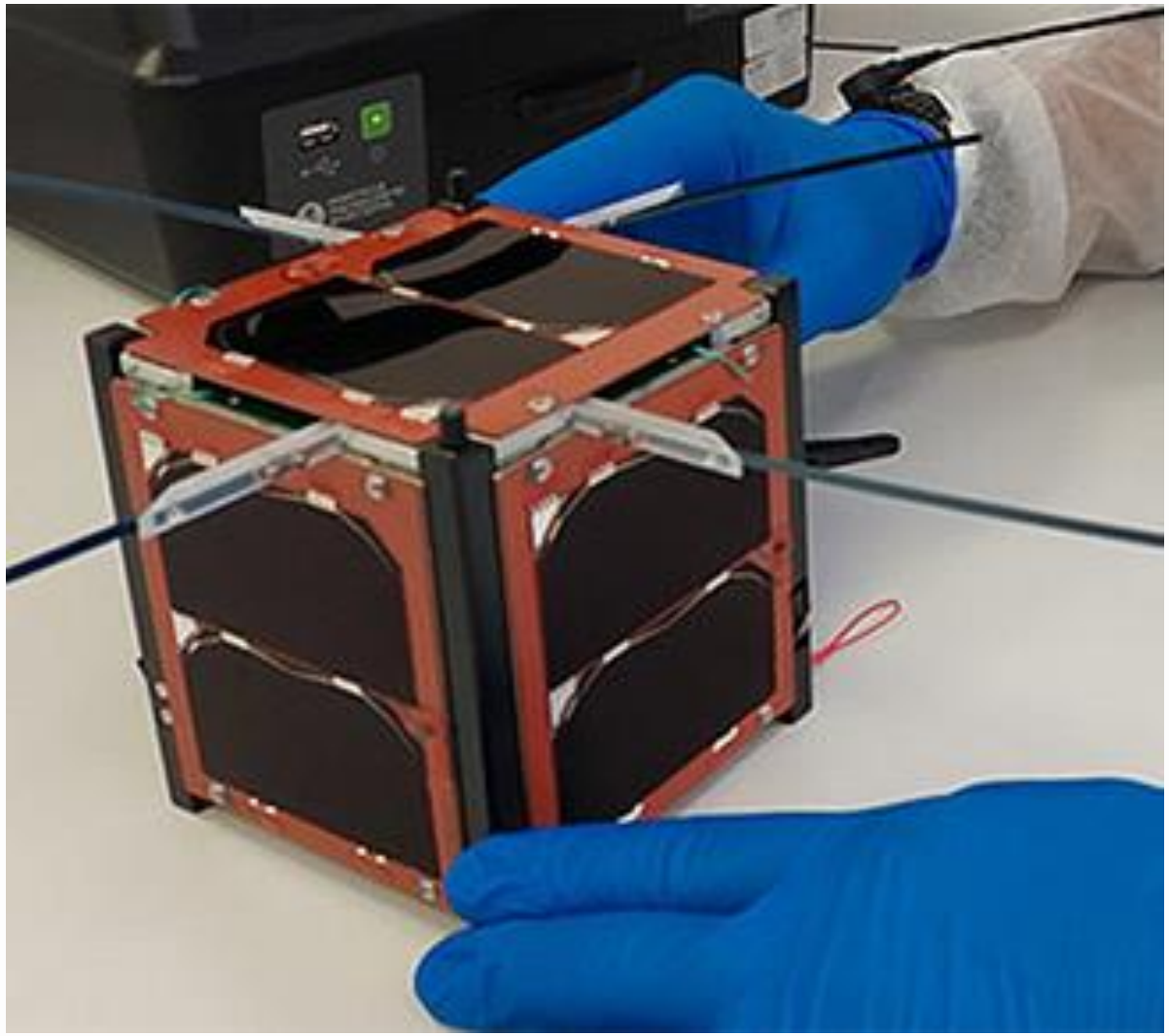
MDPI, Appl. Sci.

Mission concept

- AlfaCrux Cube Sat parameters:
  - Dimensions: 10x10x10 cm
  - Mass: 1 kg
  - Payload: TOTEM-SDF @ UHF 437 MHz
  - Telemetry: UHF 435-438 MHz

- Orbit parameters:
  - Launch: 1 April 2022
  - Period: 94.64 min
  - Inclination: 97.39°
  - Apogee: 508 km
  - Perigee: 494 km

R. A. Borges et al., Appl.Sci. 12, 9764 (2022)



AlfaCrux, University of Brasilia

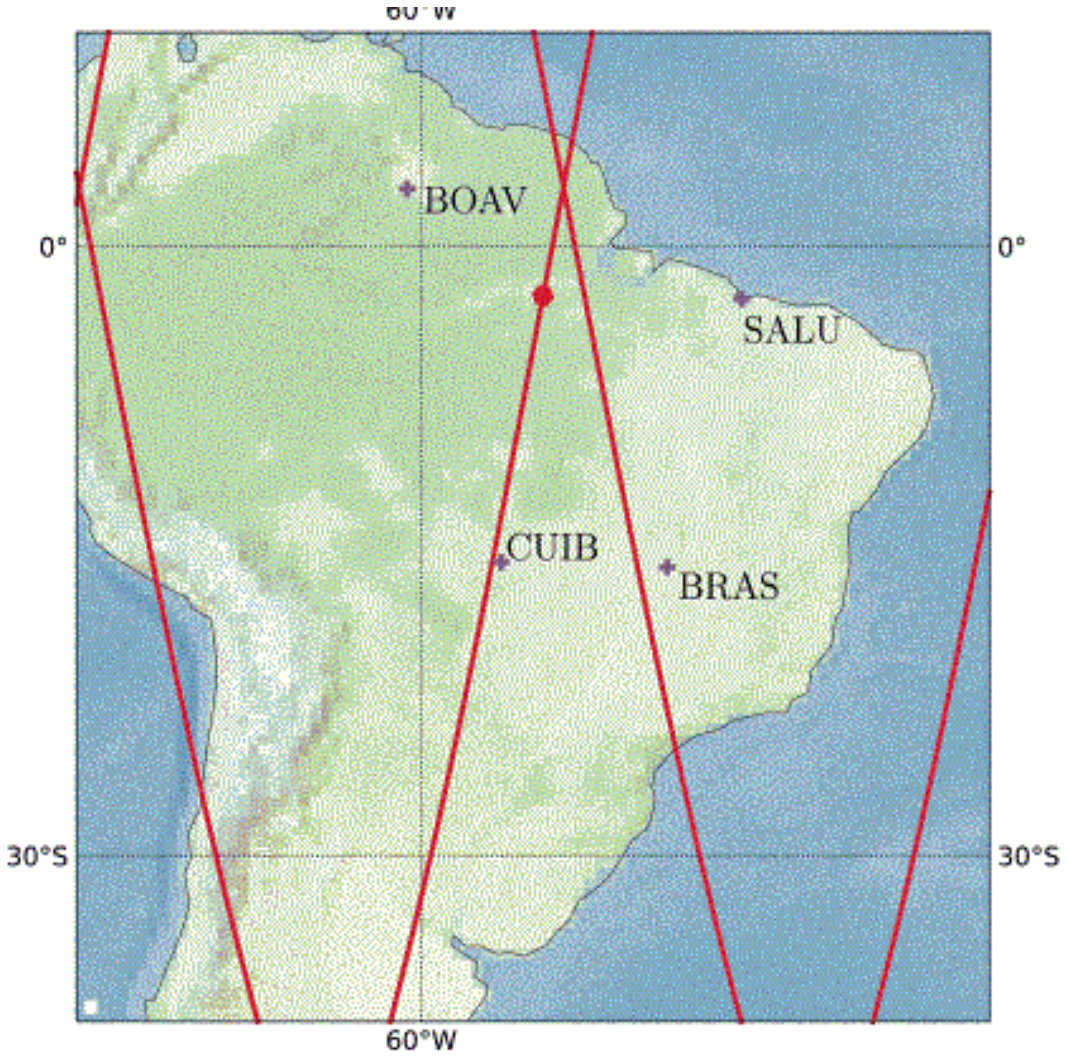
space.skyrocket.de

Accounting of space weather in planning of the mission

- Simulation of sample satellite trajectory (whole day picture):
  - Epoch: 17241.99979167
  - Inclination: 97.39°
  - RAAN: 153.1430°
  - Eccentricity: 0.0003134
  - Argument of perigee: 220.5360°
  - Mean anomaly: 108.0034°
  - Mean motion: 15.13104507 (revolutions per day)

- Sample stations:
  - BOAV (Boa Vista, $2^{\circ}\ 50'N,\ 60^{\circ}\ 42'W$)
  - BRAS (Brasilia, $15^{\circ}\ 47'S,\ 47^{\circ}\ 52'W$)
  - CUIB (Cuiaba, $15^{\circ}\ 33'S,\ 56^{\circ}\ 04'W$)
  - SALU (São Luis, $2^{\circ}\ 35'S,\ 44^{\circ}\ 12'W$)

A. Aferreira et al., IEEE Access. 10, 65744 (2022)



IEEE Access

AlfaCrux: sample trajectories and position of selected stations

Link Budget

- Link budget is estimated by comparing the power given to the transmitter to the power available at the receiver.

$$P_r = P_t \frac{G_t G_r}{L_{t+r}}$$

  - Receiver-transmitter loss L_{t+r} consists of:
    - Free-space loss $L_{free} = (4\pi\, R/\lambda)^2$ [dB]
    - Tropospheric loss
    - Polarization loss (Faraday rotation)
    - Miscelaneous losses
    - Ionospheric scintillation $L_{scint} = 19.44\, S_4^{1.26}$ [dB] (empirical relation)
  - Slant range R depends on elevation angle.

- Reliability of communication is characterized by the energy-bit, E_b, to noise spectral density, N_0,

$$\frac{E_b}{N_0} = P_t \frac{G_t G_r}{L_{t+r}\, k_B T\, R_b}$$

A. Ferreira et al., IEEE Access. 10, 65744 (2022)

Ionospheric Propagation Data and Prediction Methods Required for the Design of Satellite Networks and Systems, (2019)

Parameter	**Value**
Frequency	437 MHz
Data rate (R_b)	9600 bps
Cubesat antenna gain (G_t)	0.0 dBi
Ground station antenna gain (G_r)	14.95 dBi
Transmitted power (P_t)	1 W (0 dbW)
Free-space loss	144.43 dB
Tropospheric loss	3.3 dB
Polarization loss	1.04 dB
Noise temperature (T)	500 K
E_b/N_o	27.95 dB
Required E_b/N_o	8.4 dB
Margin	**19.56 dB**

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Parameters of the link budget calculations for elevation angle of 30° for downlink.

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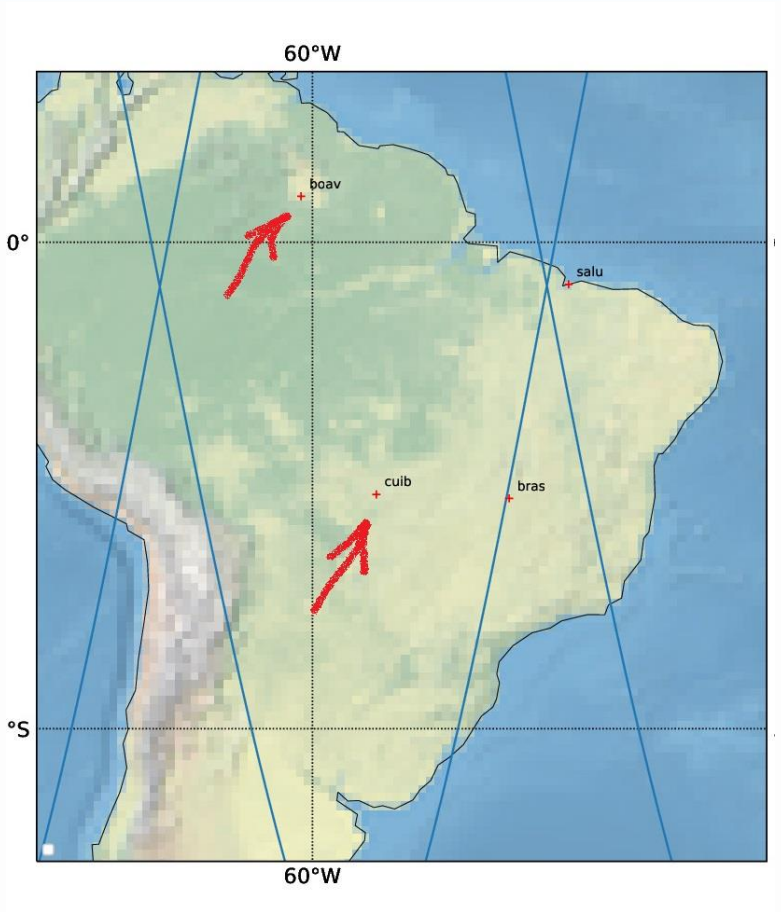

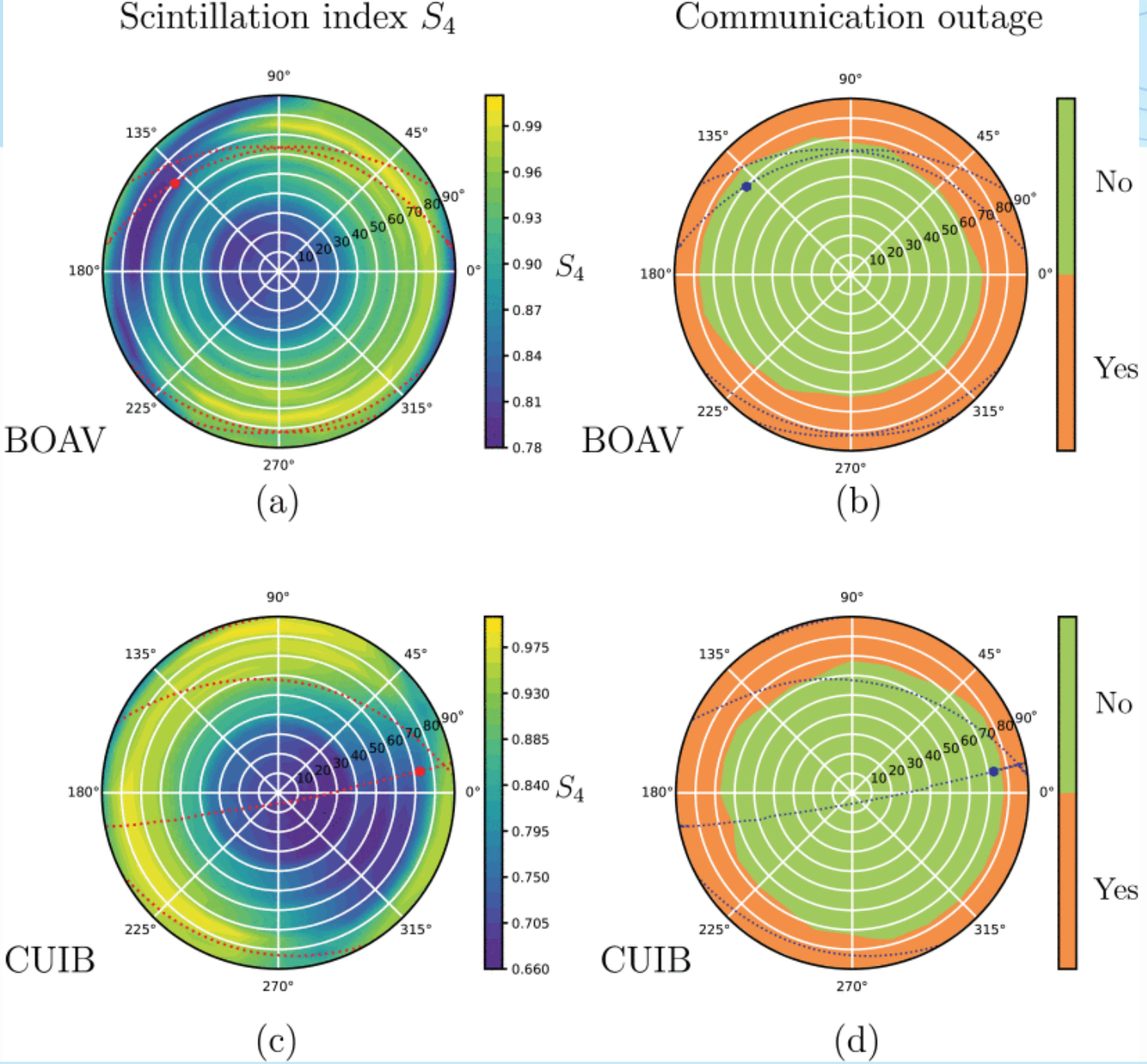

Scintillation S4 indices (a), (c) and the associuated communication outage maps (b), (d) mapped to the sky plots for 7th September 2017 at 01:30 UT.

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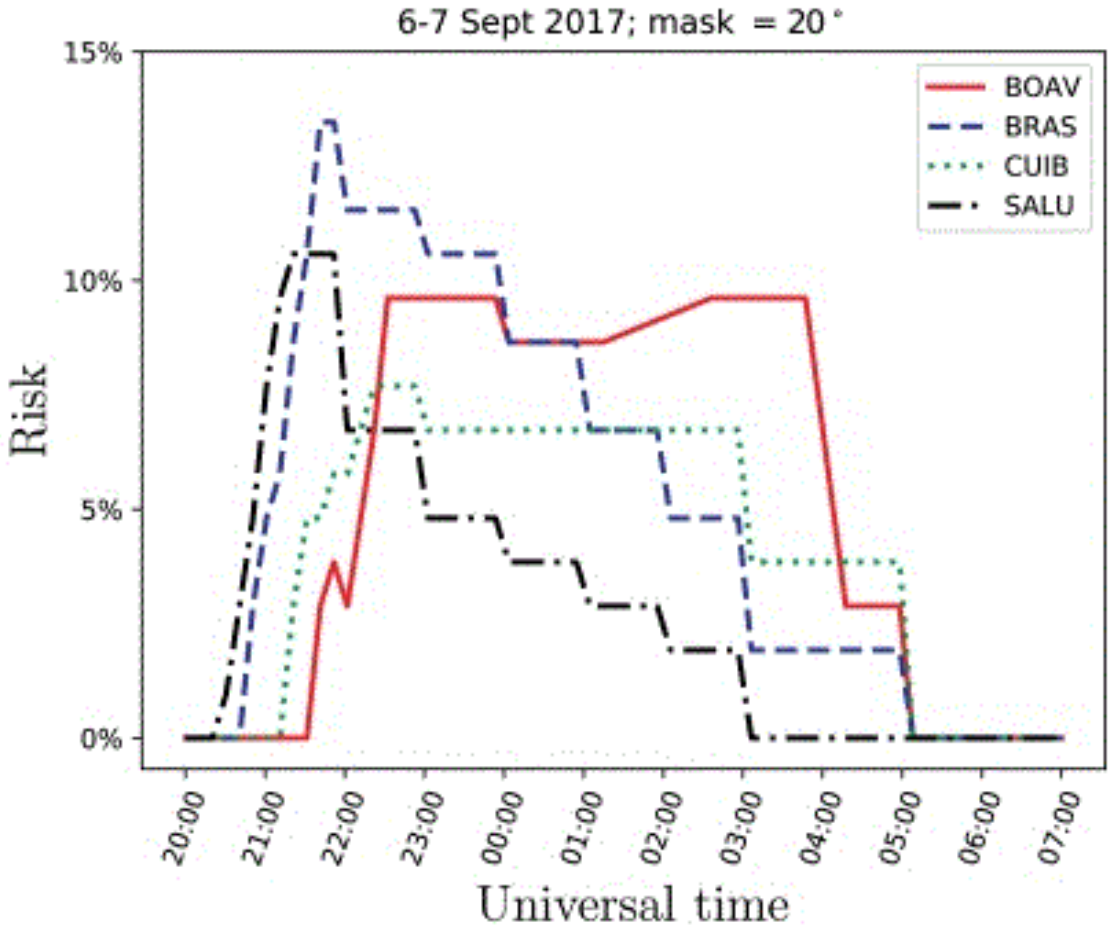
Risk analysis

- We use the risk analysis from decision theory (Oppe, 1988 ; Koulouri et al, 2020).
- Risk → expected loss incurred to an activity.
- Esential for the estimation of risk are:
  - Features that describe the condition in which the activity is performed (e.g. S4 level);
  - Frequency of occurrence of such features;
  - Estimates of how harmful the condition is to the successful outcome of the activity

- Feature: $z = |I - \langle I \rangle| / \langle I \rangle$
- Loss: $l(z; z_{thr}) = \begin{cases} 0, & if\ z < z_{thr} \\ 1, & otherwise \end{cases}$
- Risk: $r(z_{thr}) = \langle l(z; z_{thr}) \rangle$

S. Oppe, Ergonomics, 31, 435 (1988), A. Koulouri et al., J. Geodesy. 94, 1, (2020)



Risk of communication outage due to scintillation for the AlfaCrux mission.

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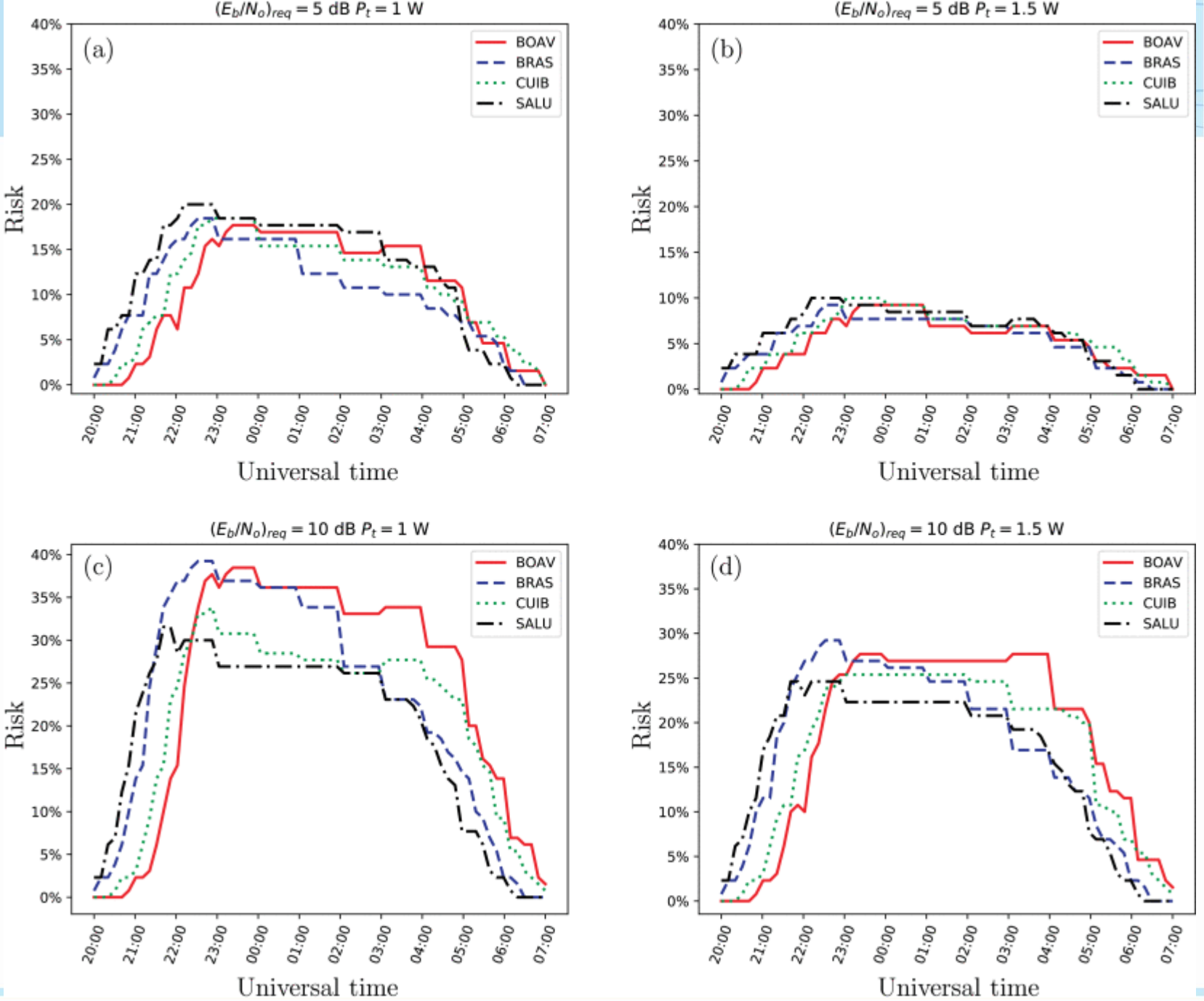
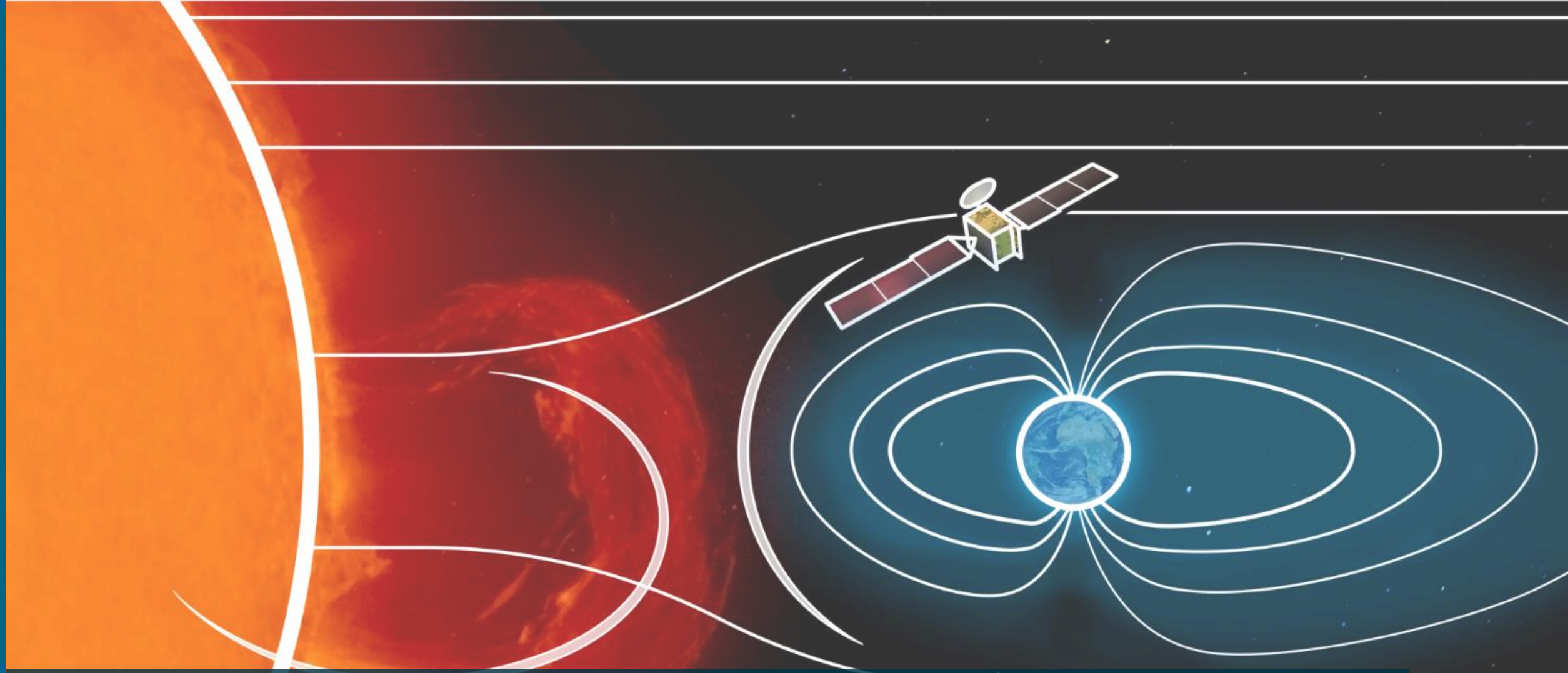
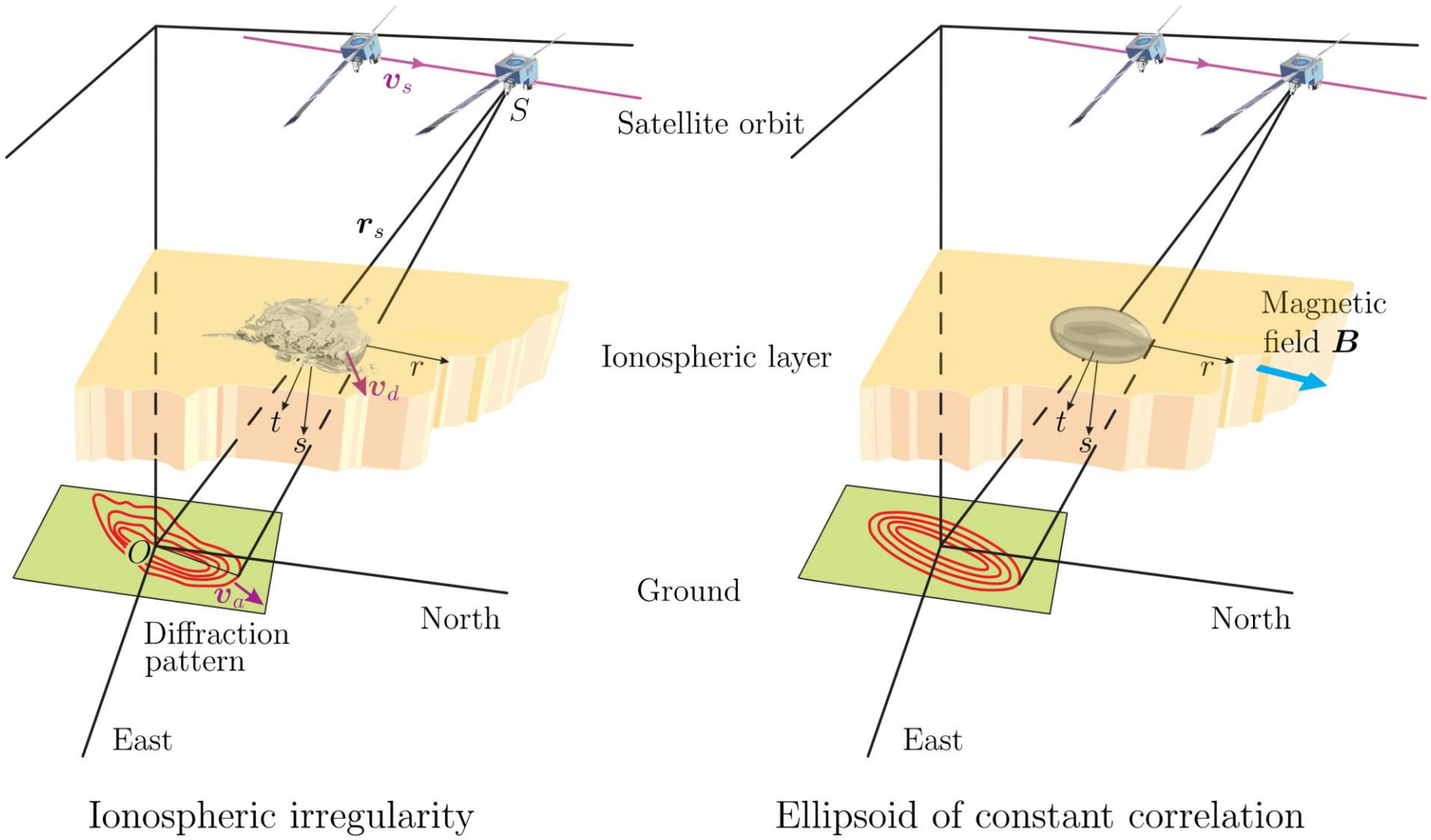


Evolution in time of the communication risk estimates for various values of the required threshold ratio $(E_b/N_o)_{req}$ and the power of the transmitter antenna. The calculations are performed for the night from 6th to 7th of September 2017 using the solar radio flux daytime value of 140 sfu



EFFECT OF SCINTILLATION ANISOTROPY

Anisotropy of ionospheric irregularities



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Simplified model of the field-aligned scintillation-associated irregularities is given by the ellipsoidal correlation surface for electron density fluctuations.

Anisotropy of ionospheric irregularities

- Ionospheric irregularities are predominantly field-aligned. They are usually elongated in the direction of magnetic field B.

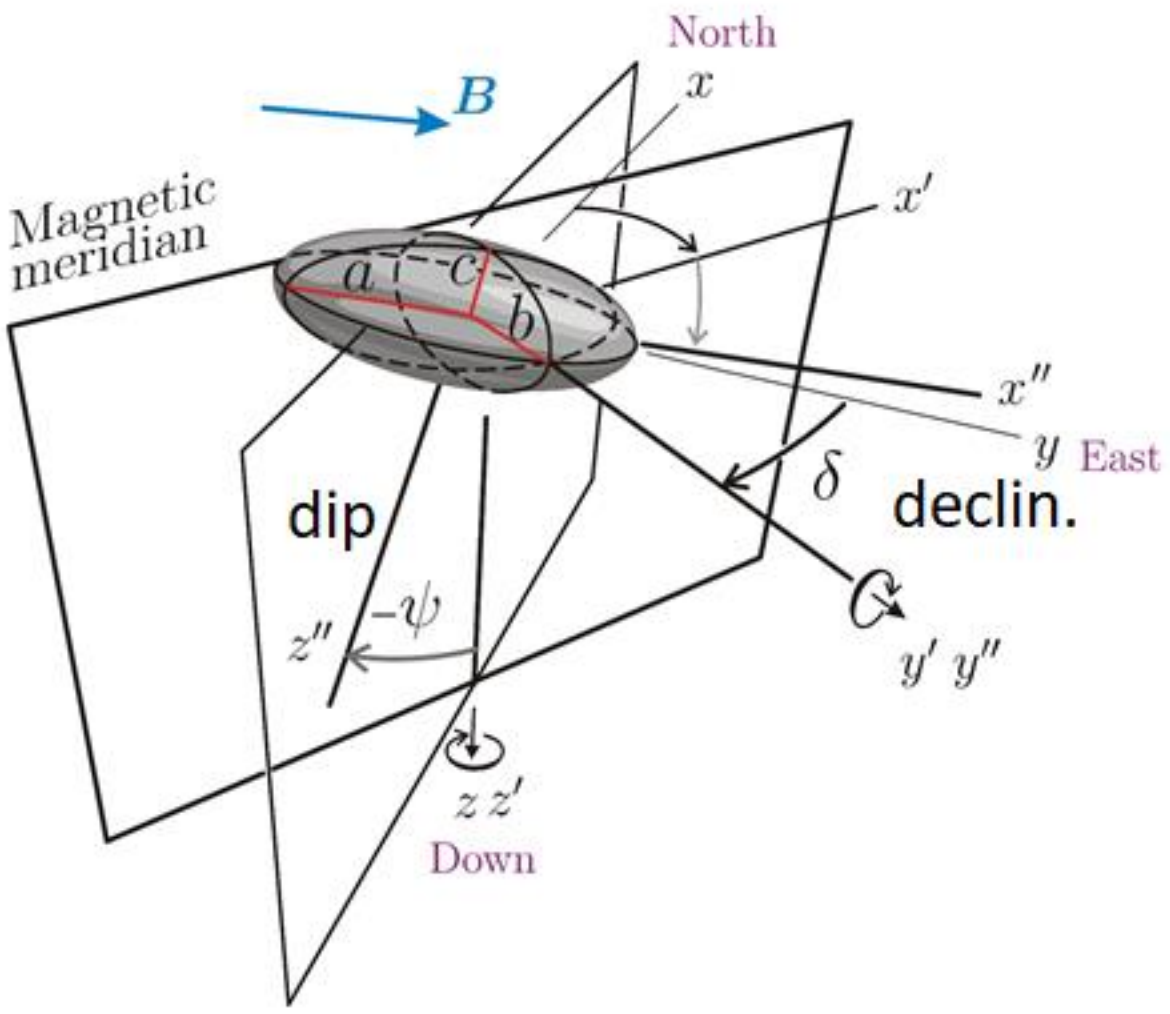
- Signal disturbances are maximized if the propagation path that crosses the irregularity coincides with the major semi-axis of correlation ellipsoid.

- This is the so-called geometric enhancement of scintillation

C. Rino, Radio Sci. 14, 1135 (1979)

D. Vasylyev, Y. Beniguel, V. Wilken, M. Kriegel, J. Berdermann. JSWSC, 22, 12 (2022).

D. Vasylyev, et al. „Anisotropic scintillation indices for weak scattering regime“ (submitted to Adv. Space Res.)



JSWSC

Position of correlation ellipsoid relative to the local coordinate system of the observer. The tilt angle is set to zero.

Geometric enhancement of scintillation

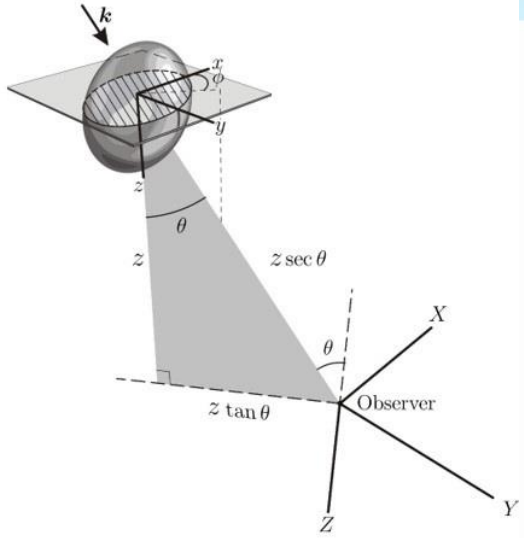
Flat-Earth approximation

$$S_4^2 = 8\pi k^2 z \sec\theta\, C_s Z^{\frac{p}{2}} \frac{\sqrt{\pi}}{p} \frac{\Gamma\left(1-\frac{p}{4}\right)}{\Gamma\left(\frac{1}{2}-\frac{p}{4}\right)} \mathcal{J},$$

$$\mathcal{J} = 2\pi\alpha\beta\, r_0^{p+2} \left[\frac{1}{\sqrt{\mathcal{A}\mathcal{C}-\mathcal{B}^2}}\right]^{1+\frac{p}{2}} P_{\frac{p}{2}}\left(\sec\theta \frac{\mathcal{A}+\mathcal{C}-\mathcal{A}a_1^2-2\mathcal{B}a_1a_2-\mathcal{C}a_2^2}{2\sqrt{\mathcal{A}\mathcal{C}-\mathcal{B}^2}}\right)$$

$$C_s = \frac{\langle\delta n^2\rangle}{\pi^{3/2}} \frac{\Gamma\left(\frac{p+2}{2}\right)}{\Gamma\left(\frac{p-1}{2}\right)} \kappa_0^{p-1}, \qquad Z = \frac{z}{2k}\sec\theta,$$

$$a_1 = \sin\theta\cos\phi, \quad a_2 = \sin\theta\sin\phi$$



C. Rino, Radio Sci. 14, 1135 (1979)

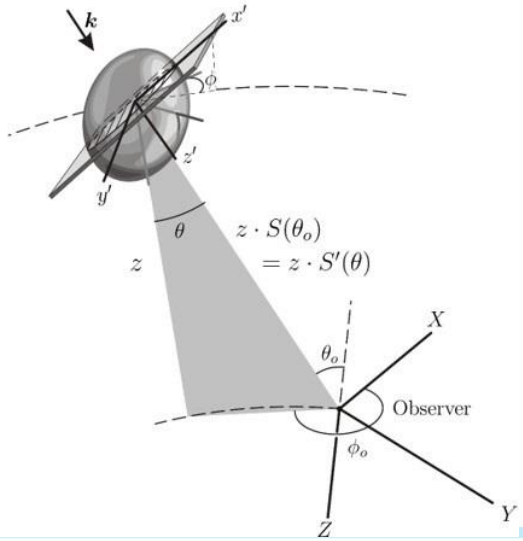
Spherical-Earth approximation

$$S_4^2 = 8\pi k^2 z S'(\theta)\, C_s Z'^{\frac{p}{2}} \frac{\sqrt{\pi}}{p} \frac{\Gamma\left(1-\frac{p}{4}\right)}{\Gamma\left(\frac{1}{2}-\frac{p}{4}\right)} \mathcal{J}',$$

$$\mathcal{J}' = 2\pi\alpha\beta\, r_0^{p+2} \left[\frac{1}{\sqrt{\mathcal{A}'\mathcal{C}'-\mathcal{B}'^2}}\right]^{1+\frac{p}{2}} P_{\frac{p}{2}}\left(\frac{\mathcal{A}'+\mathcal{C}'}{2\sqrt{\mathcal{A}'\mathcal{C}'-\mathcal{B}'^2}}\right)$$

$$Z' = \frac{z}{2k} S'(\theta), \qquad S'(\theta) = (1+\xi)\cos\theta - \sqrt{(1+\xi)^2\cos^2\theta - 1 - 2\xi},$$

$$\theta \in [0, \theta_{max}], \qquad \theta_m = \arccos\left[\sqrt{1+2\xi}/(1+\xi)\right], \qquad \xi = R_\oplus / z_{irreg}$$



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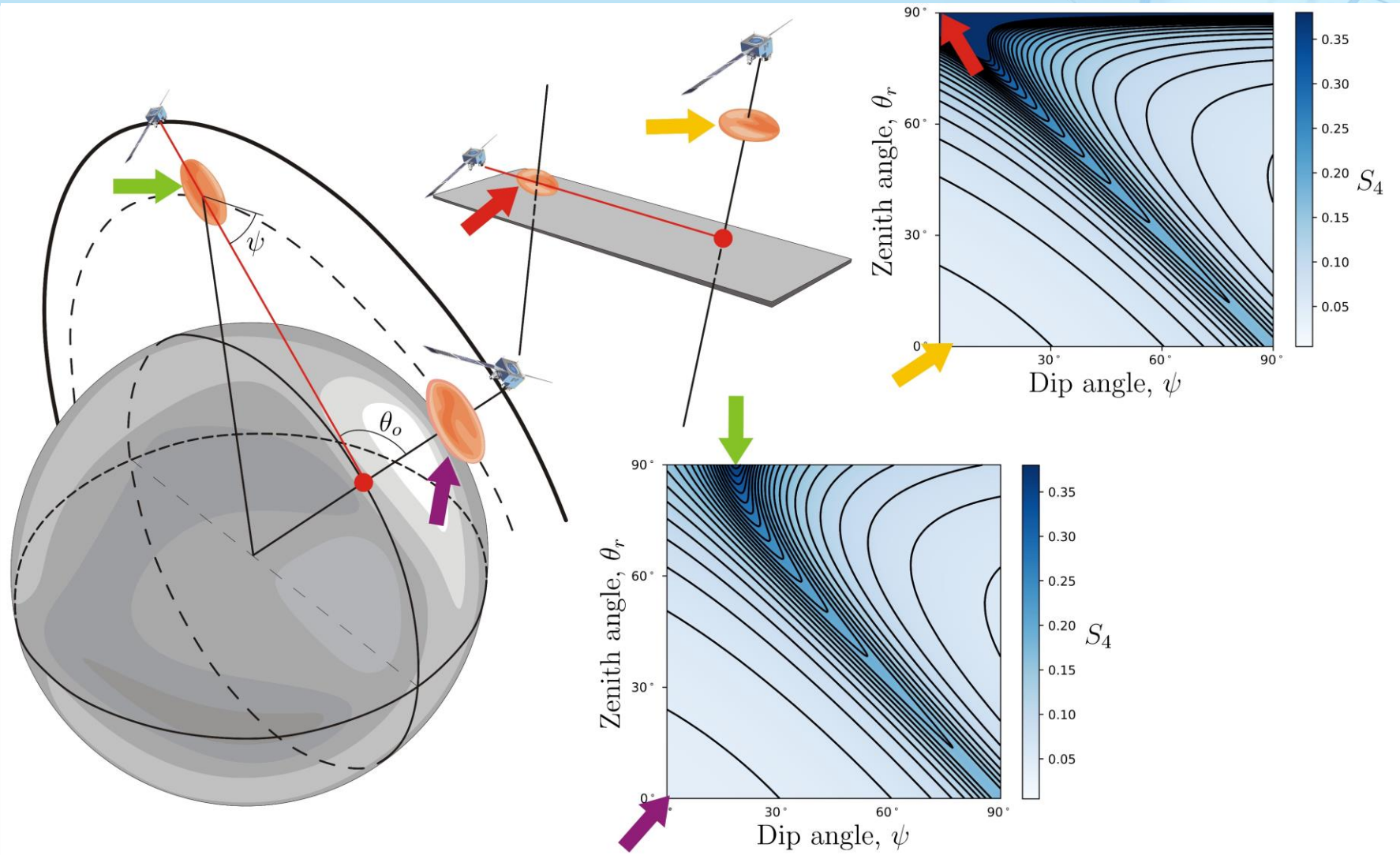
D. Vasylyev et al., JSWSC, 22,12 (2022)

Geometric enhancement of scintillation



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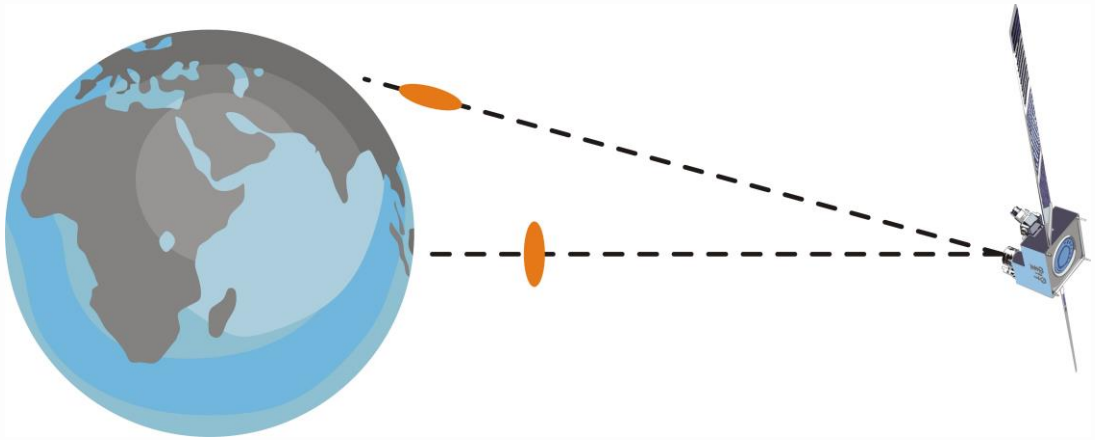
Comparison of scintillation indices obtained within the flat-geometry (Rino'79) and the spherical-geometry (Vasylyev'22) approximations.

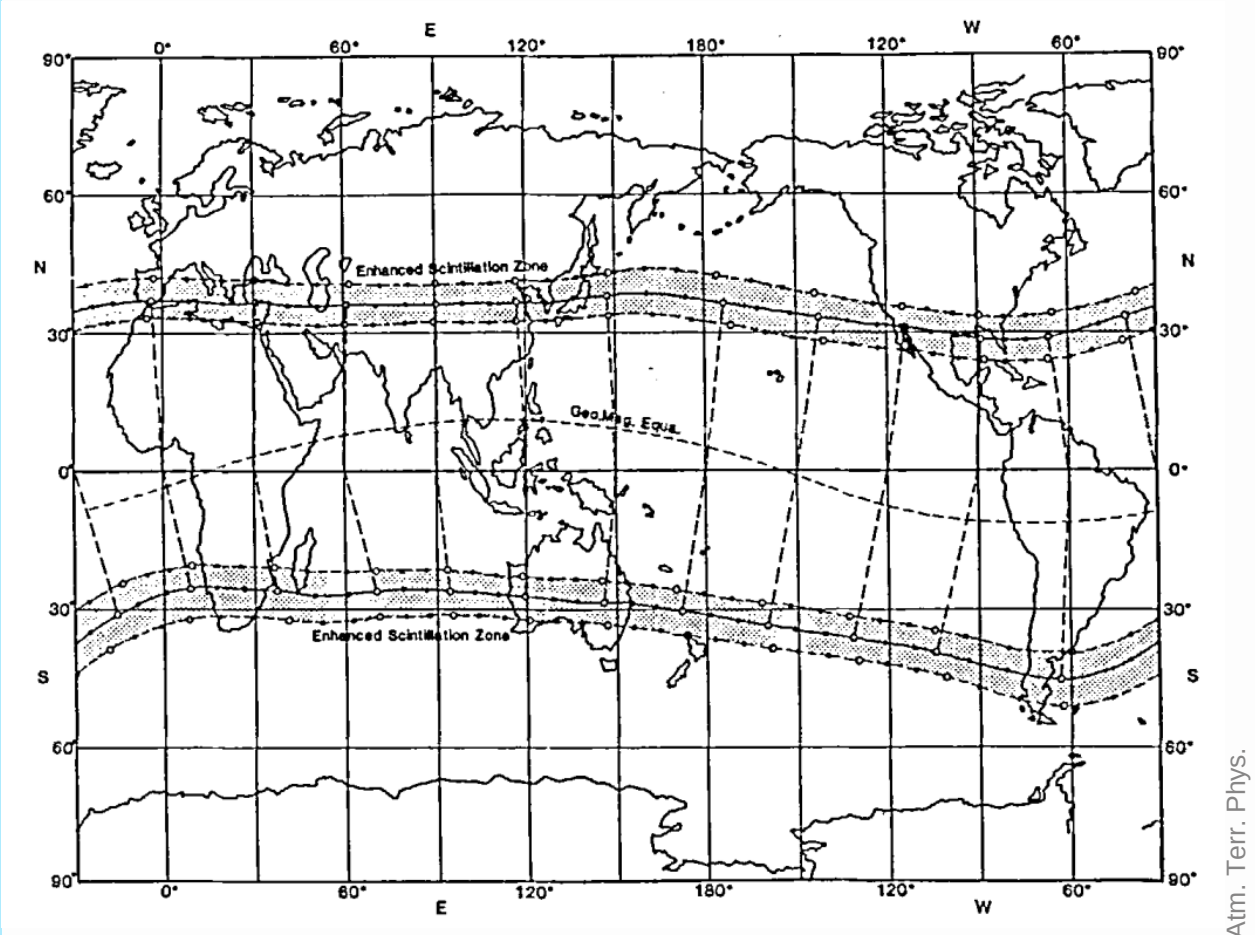
Geometric enhancement of scintillation

- Anomalous high scintillation in VHF signals from ETS-II satellite detected in the region of Japan in nighttime.

- Explained by the geometric enhancement effect



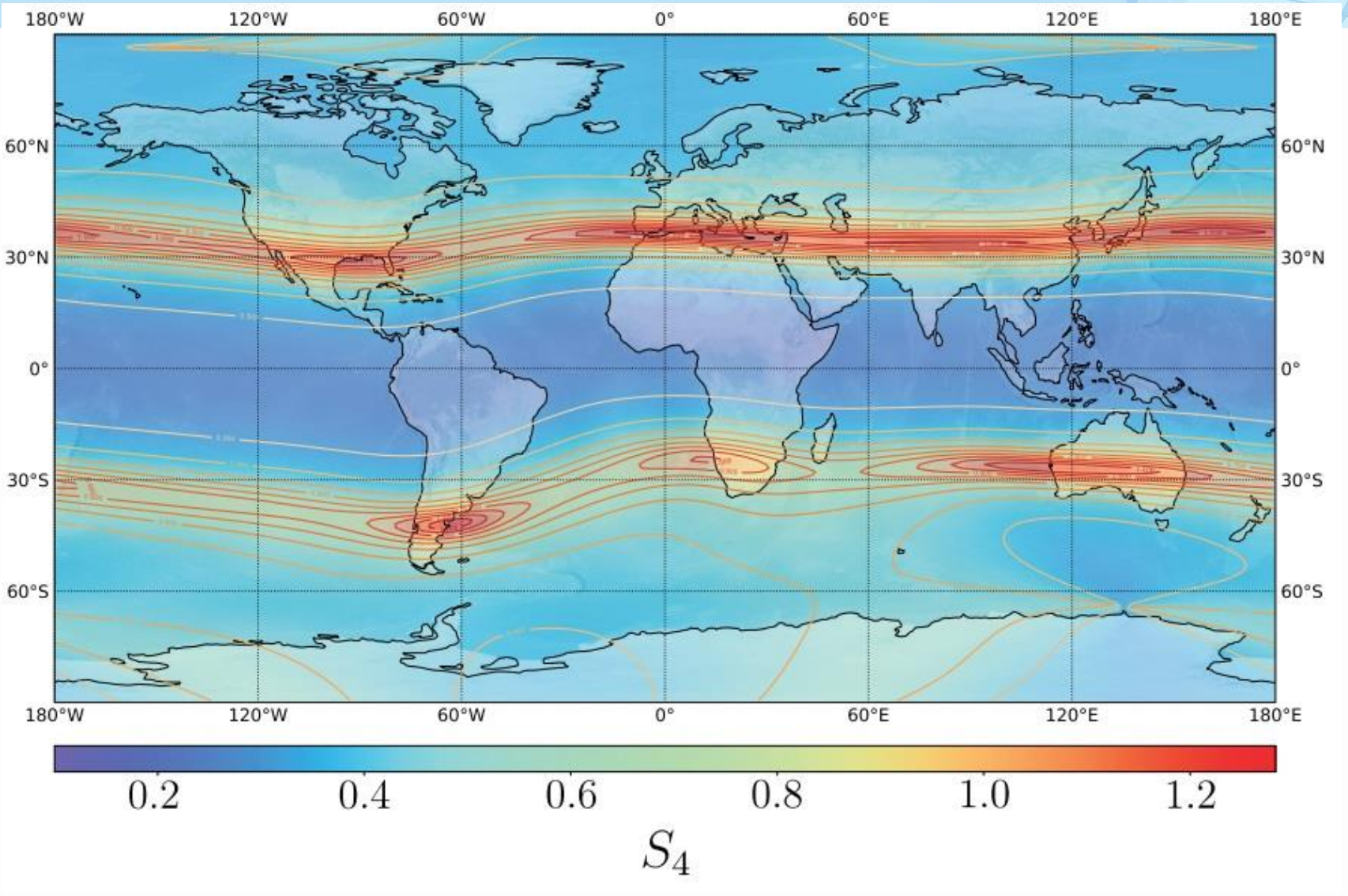
K. Sinno and H. Minakoshi, J. Atm. Terr. Phys. 45, 563 (1983)



J. Atm. Terr. Phys.

Zones of enhanced scintillation due to field-aligned irregularities for a geostationary satellite over the equator

Geometric enhancement of scintillation



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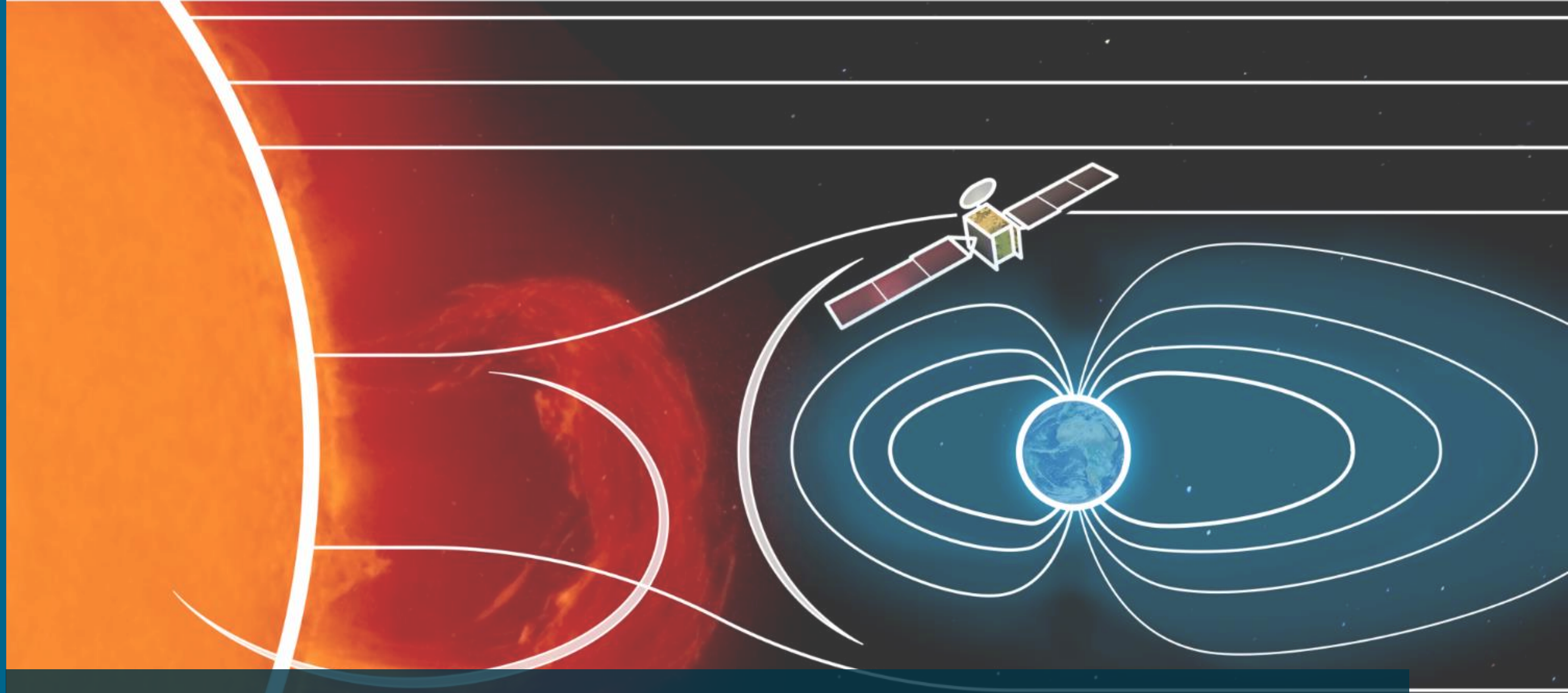
Geometric enhancement of scintillation for a VHF signal from a geostationary satellite over the equator. The irregularity strength parameter is set to constant.



REFRACTIVE SCINTILLATION

Refractive scintillation

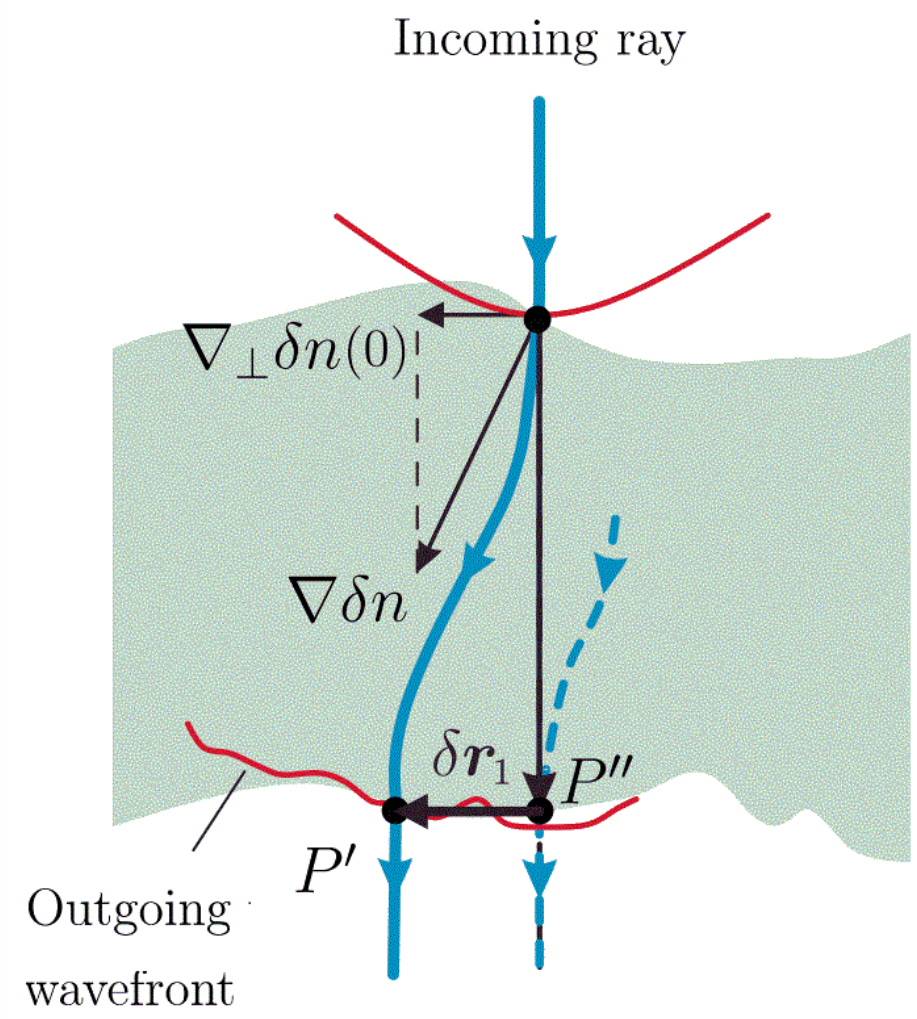
- Multiple studies reveal good correlation of scintillation indices and other indices based on spatial/temporal gradients of electron density or TEC (e.g. ROTI, RODI, AATR, GIX, etc.)

- This correlation can be explained by refractive scattering on large-scale inhomogeneities.

- The signal ray attains random deflection from its original direction, while the outgoing wavefront gains additional distortions like tilt.

- Examples: phase scintillation at high latitudes; phase and amplitude scintillation due to EPBs,etc.

- Affected: GNSS, communication, and microwave remote sensing systems.



Propagation of the signal ray in irregularly inhomogeneous medium. On the top interface the ray is being randomly deflected. The strength of deflection is proportional to spatial gradient of the refractive index.

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Refractive scintillation

- For simulation of refractive scintillation the electron density gradient (NEGIX) obtained from SWARM measurements is used.

- NEGIX is obtained from in-situ electron density measurements at A and C satellites as

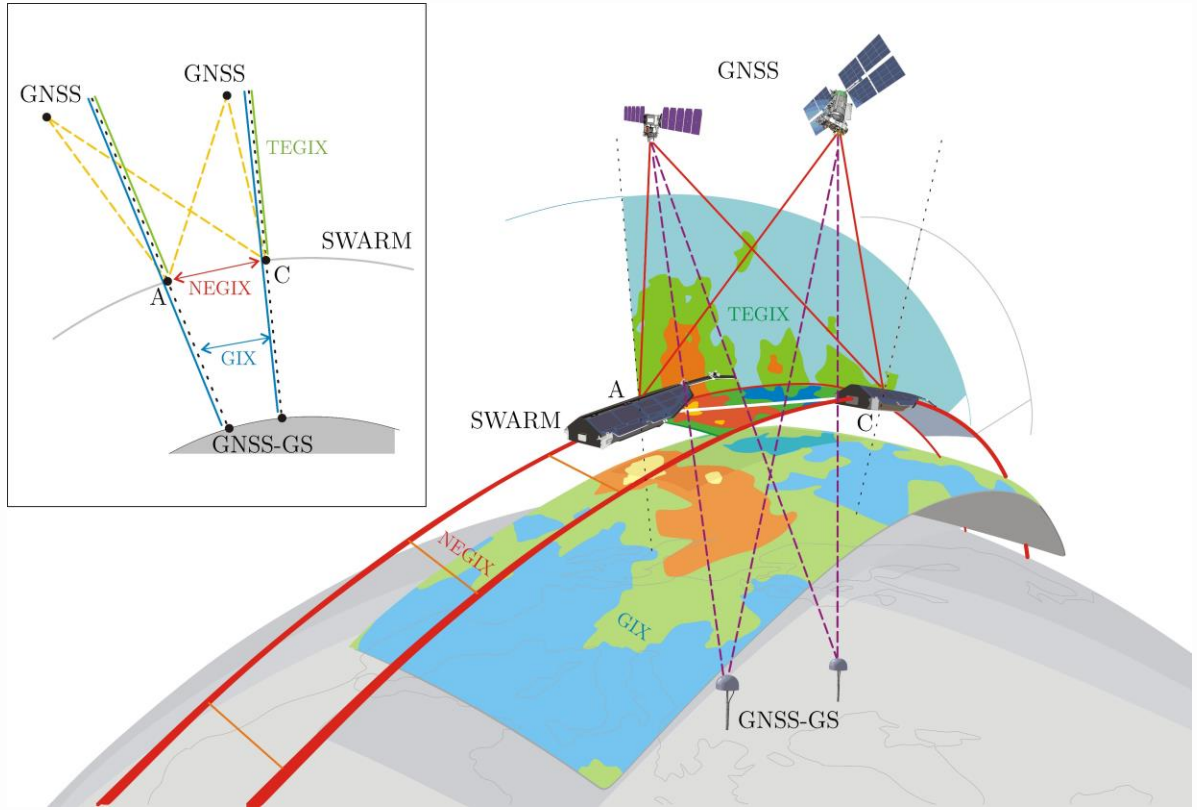
$$\vec{\nabla}_{\perp} Ne_{AC} = (Ne_A - Ne_C)/\Delta\vec{s}_{AC}$$

- Strength of wavefront distortion due to refractive scattering is measured in terms of TEC gradients $\vec{\nabla}_{\perp} N_{TEC}$.

- Radiowave propagation is simulated using the split-step approach and the modified random phase screen method, where the random phase contains the term proportional to

$$\vec{\nabla}_{\perp} N_{TEC} \cdot \vec{\nabla}_{\perp} Ne_{AC}$$

Monitoring of Ionospheric GRAdients at SWARM (MIGRAS)



Example of two new data products from SWARM satellite mission defined within the MIGRAS project.

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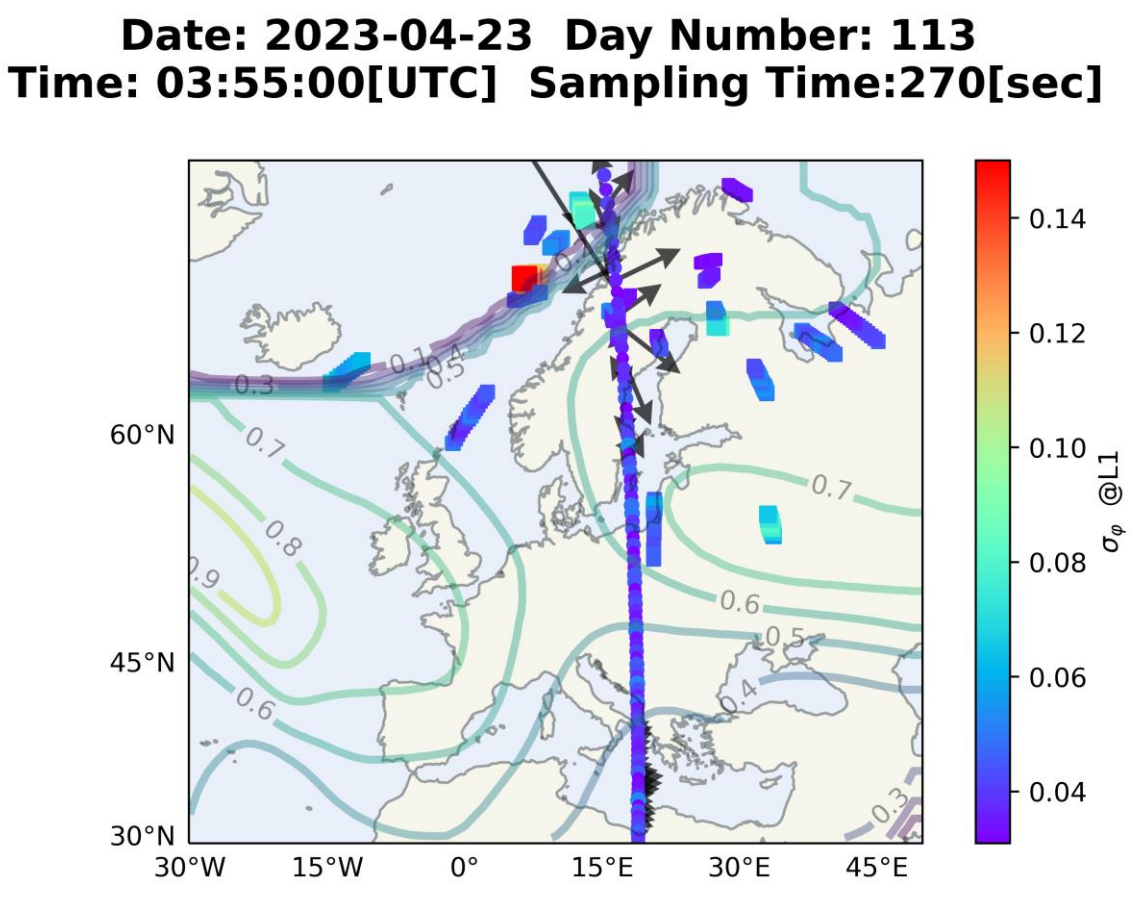
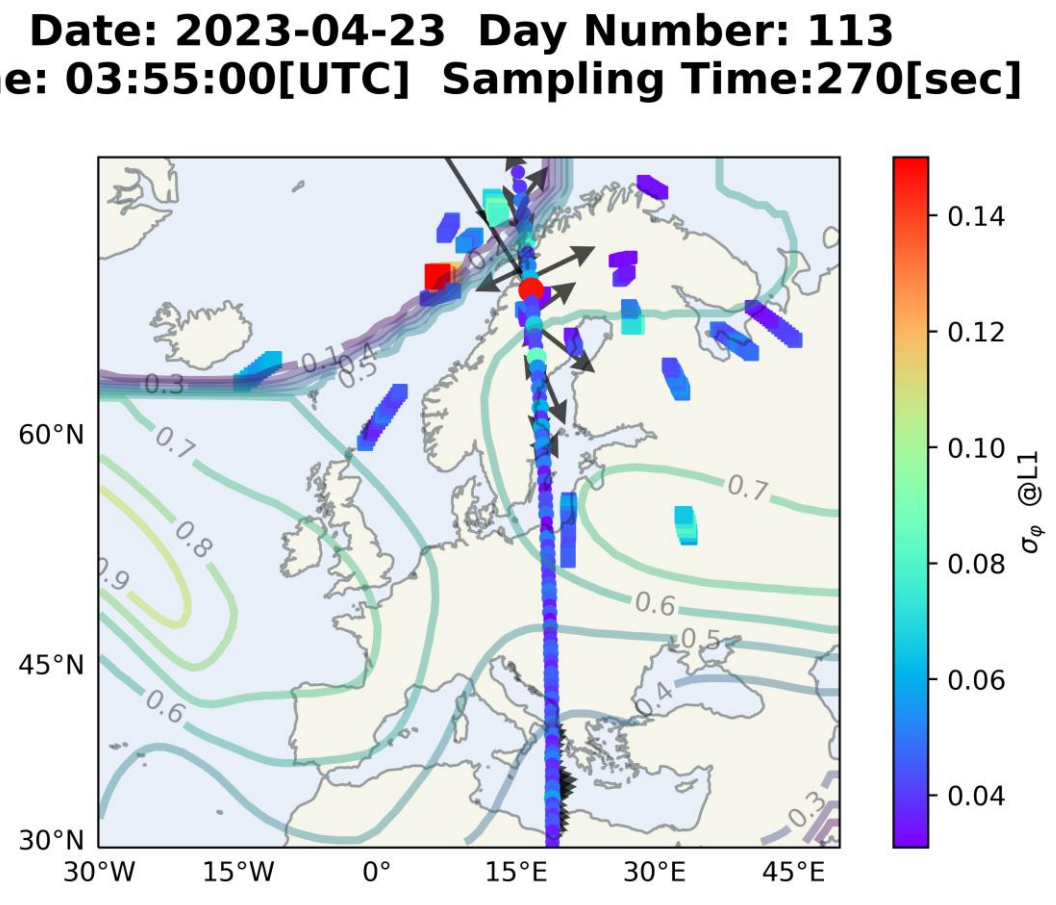
Refractive scintillation and phase gradient screen simulation

Conventional phase screen method
(scintillation along the track)



Gradient phase screen simulation
(scintillation along the track)



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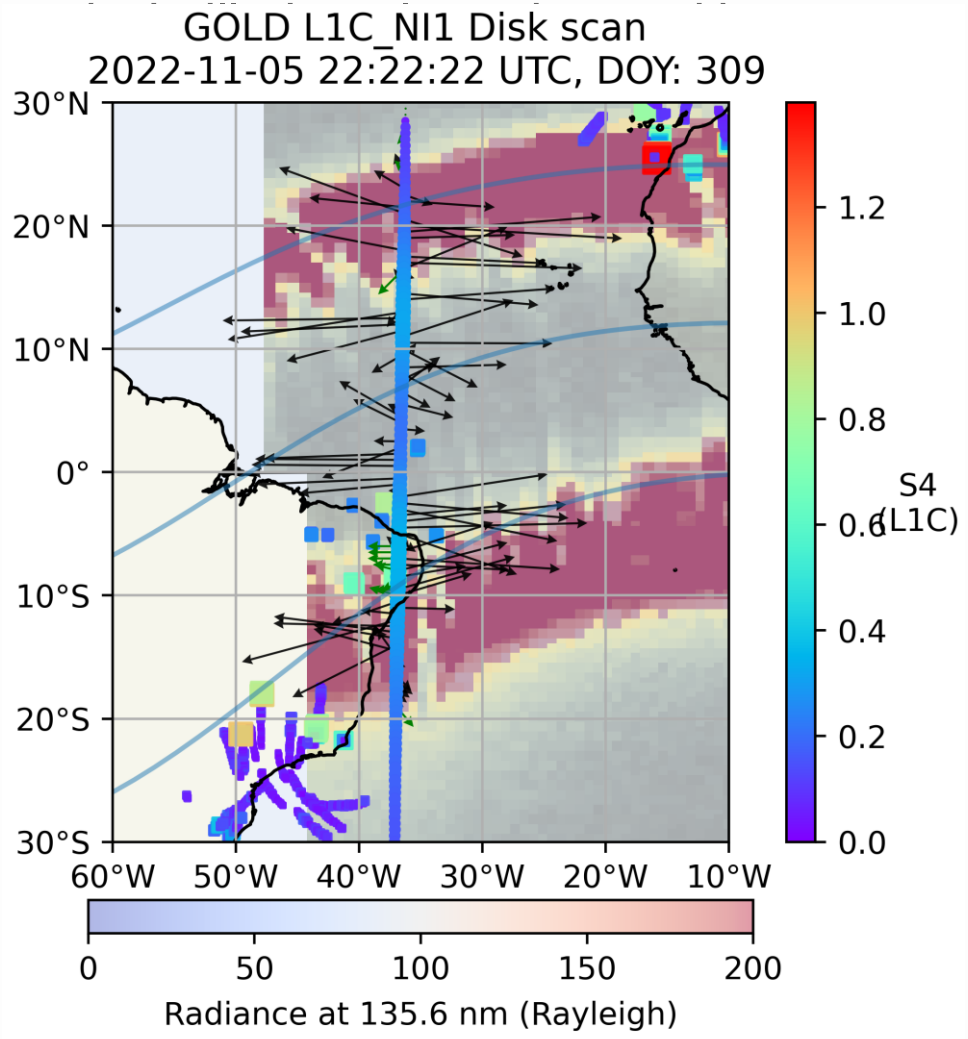

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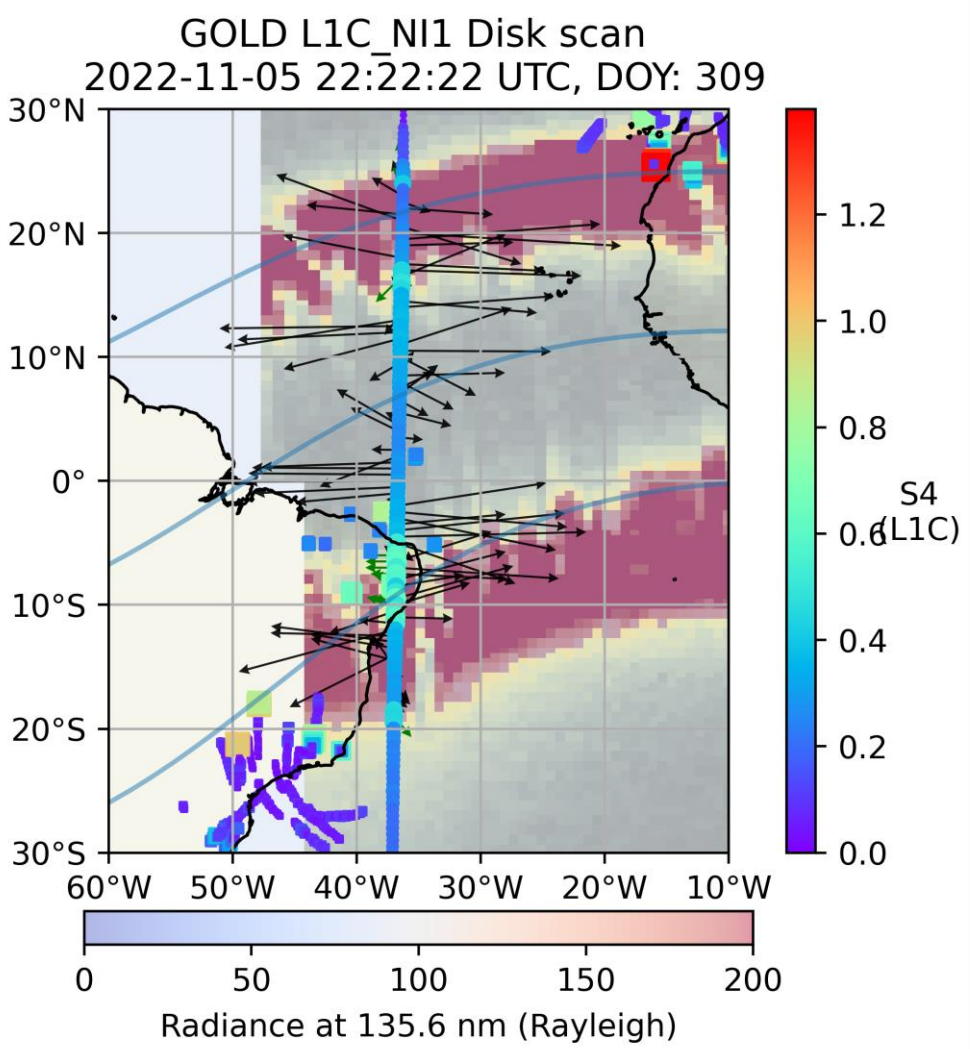

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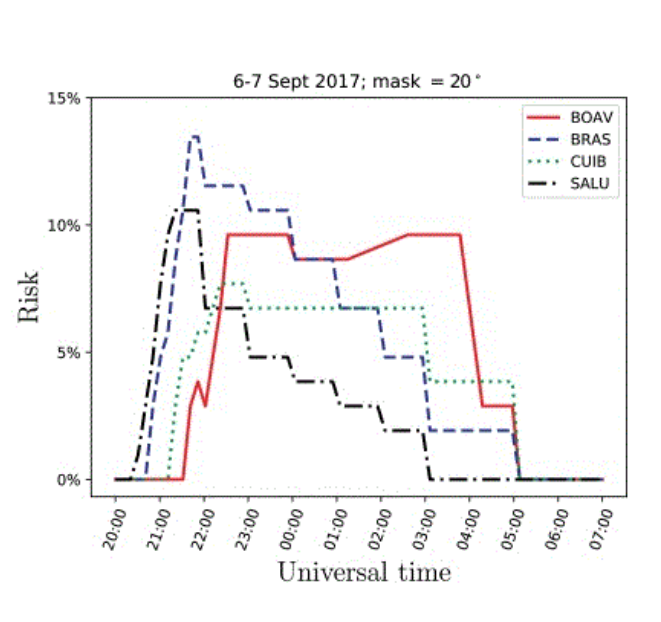
Conclusions

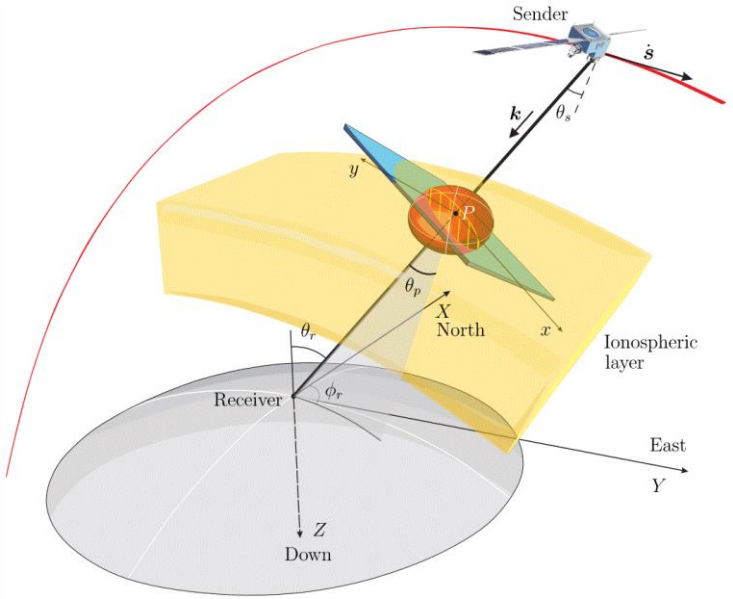
CubSat mission planning

- Scintillation affect link loss budget.
- Loss estimation can be used for the definition of optimal mask angle
- Risk analysis helps to optimize the mission design.



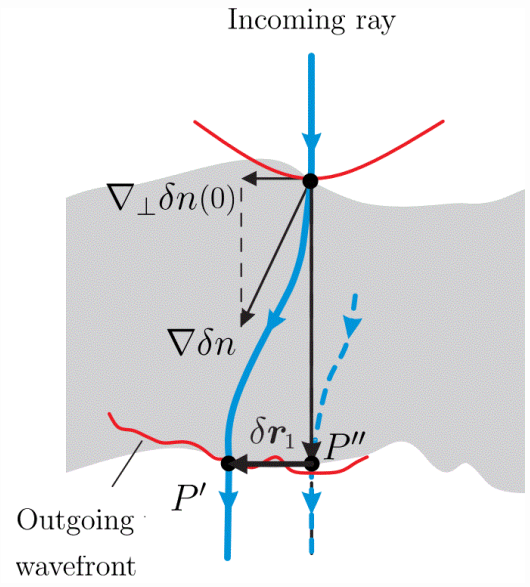
Anisotropic scintillation

- Ionospheric scintillation aremainly anisotropic
- The associated signal distortions depend on relative position of scintillation-associated irregularities and the communication link



Refraction on gradients

- Large-scale irregularities contribute to refractive scattering
- The associated change in signal phase is related to the gradients of electron density. This contribution is not negligible in regions with large gradients



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