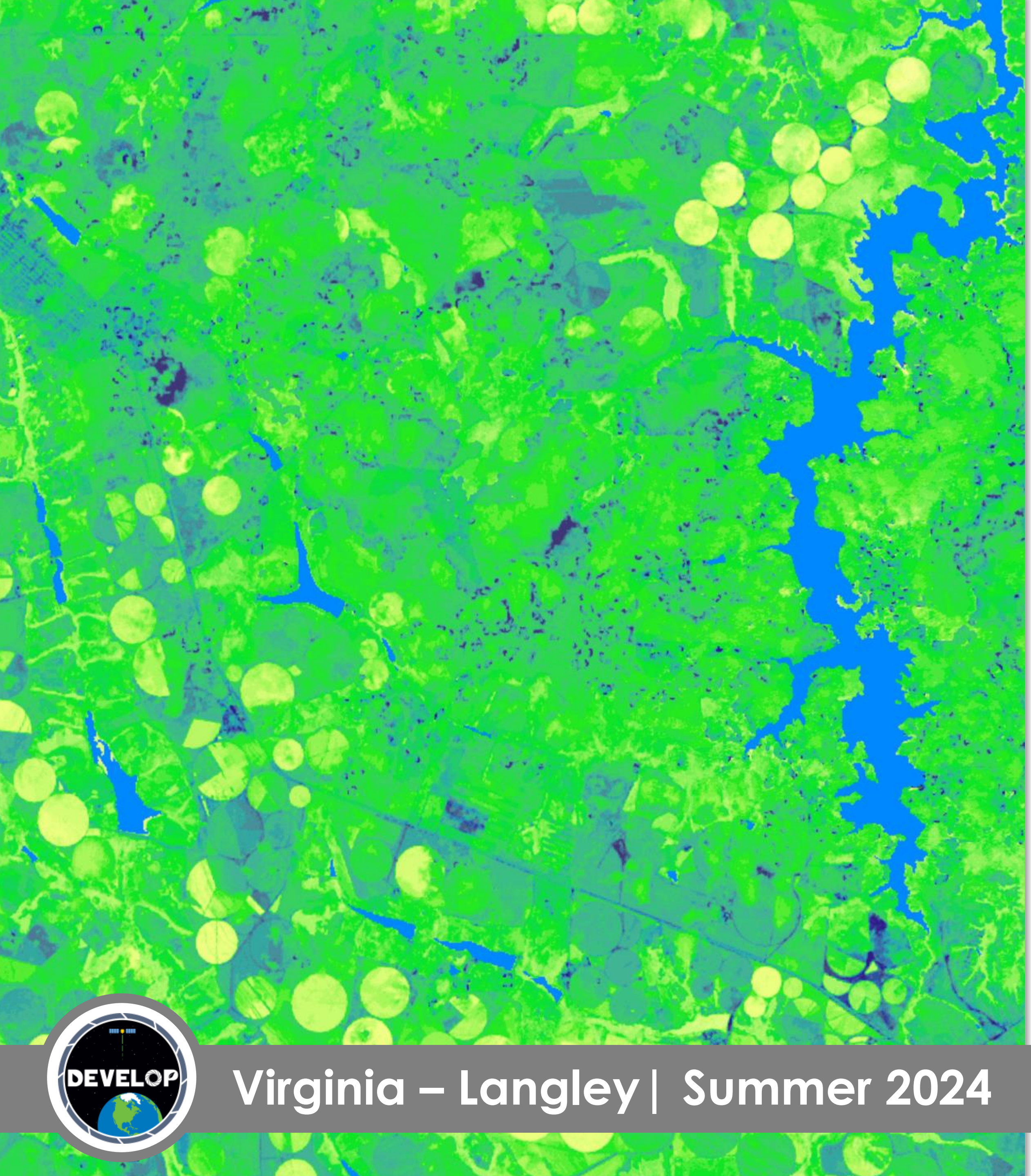


National Aeronautics and
Space Administration

Brazil Space Weather

Assessment of Space Weather Impact on Precision Agriculture Using the Global Navigation Satellite System in Brazilian Farms

Jennifer Hall

Alyson Bergamini

Ann Ehrlich

Melissa Marquez

Virginia – Langley | Summer 2024

GENERAL BACKGROUND

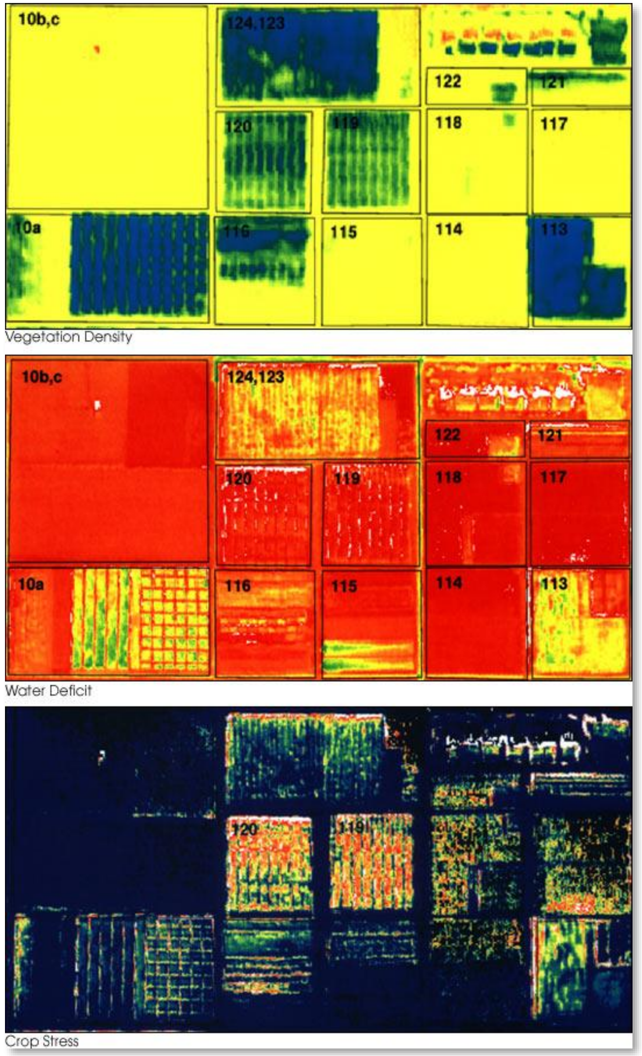


Image credit: Susan Moran, Landsat 7 Team

Precision Agriculture

- Sowing, harvesting, and fertilizer/pesticide application in **precise locations** enabled by **Global Navigation Satellite Systems** (GNSS) **positioning**

Image credit: Lance Cheung

GNSS & ERROR FROM SCINTILLATION

- Location determined by time between receiver and satellite
- Signals travel through **ionosphere** to reach ground receiver
  - Ionosphere:
    layer of **ionized particles/plasma** in Earth's outer atmosphere
- **Scintillations,** or refraction in the signal, lead to **positioning errors** or a **loss of lock**
  - Disrupts GNSS used for aviation, farming, space stations, boats, etc.

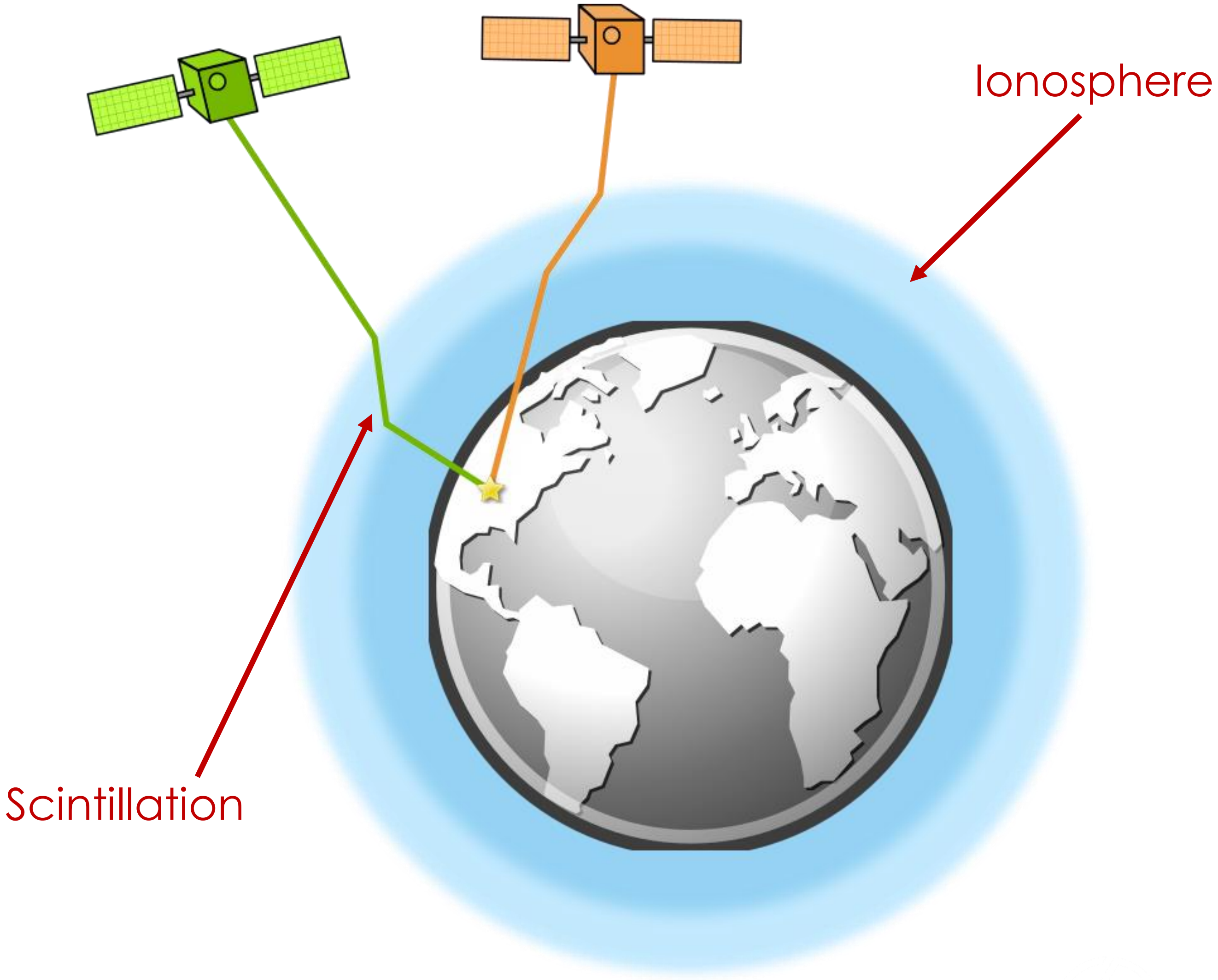


Image credit: tmjbeary

SPACE WEATHER

- **Ionization** of plasma in the ionosphere is related to solar activity, which impacts space weather
  - Follows 11-year solar cycle
  - During solar maximum: increases in solar activity, solar flares, and geomagnetic storms
- **Ionospheric irregularities** concentrate around geomagnetic equator
  - Not aligned with geographic equator

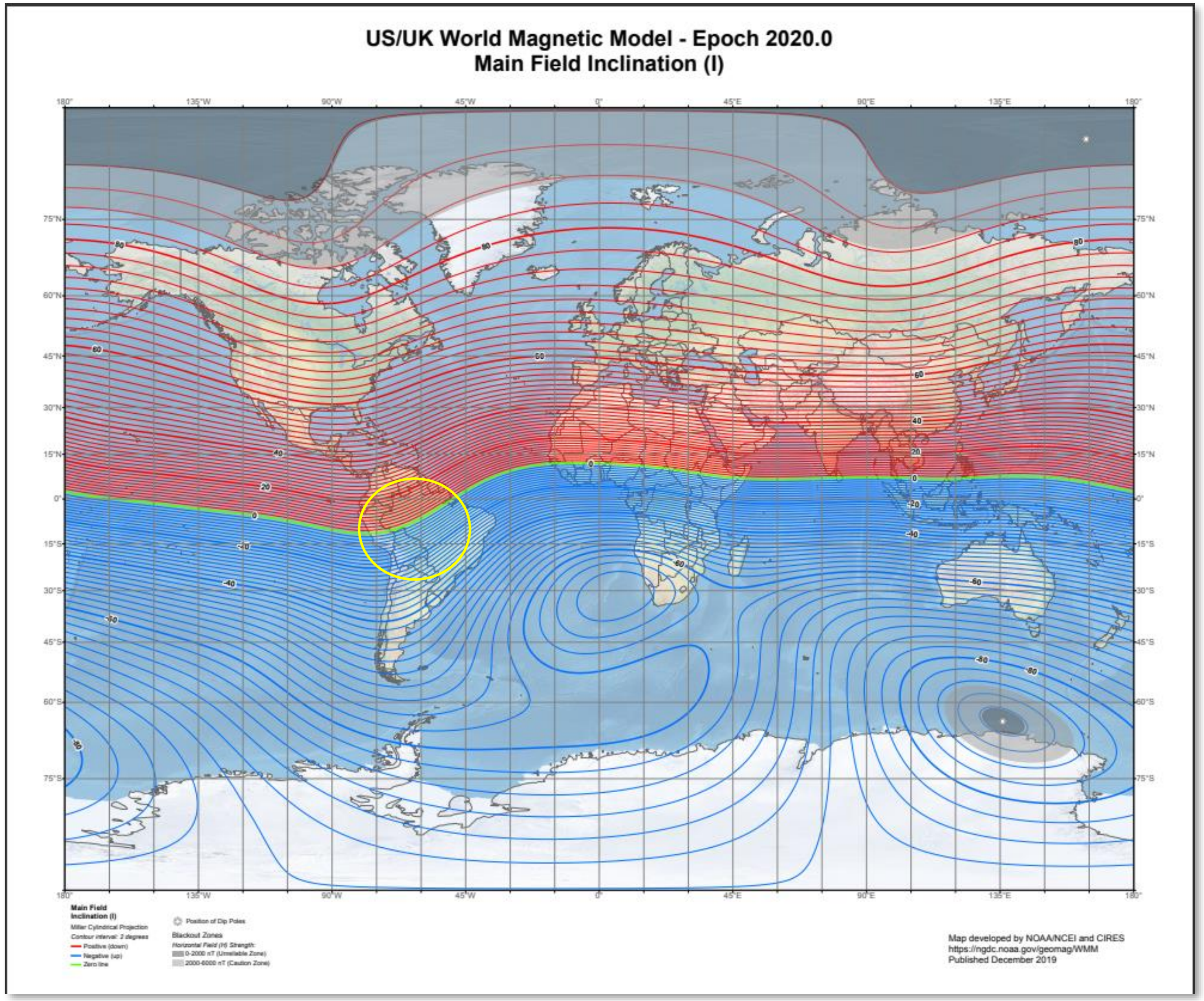


Image Credit: NCEI

EQUATORIAL PLASMA BUBBLES (EPBs)

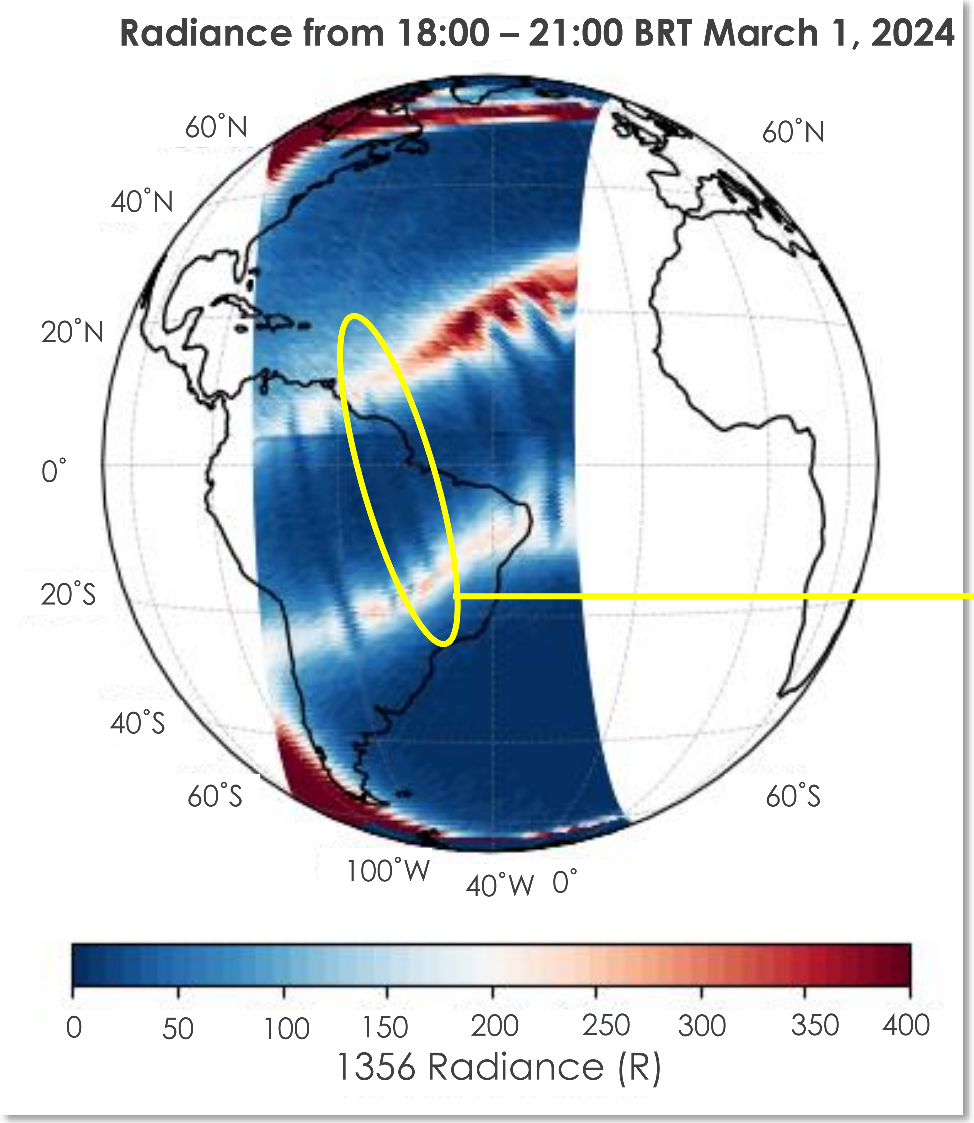


Image Credit: Ann Ehrlich

- Areas of **minimal density** in ionosphere
- Occur at **night**
- Common in **Brazil** during summer (December – March)
- Length: thousands of km
- Width: hundreds of km
- Density depletions along magnetic field lines
- Density changes with bubble movement, causing **scintillations**

Equatorial plasma bubbles: striped pattern of low radiance

COMMUNITY CONCERNS

Farm technology for planting, fertilizing, watering, and harvesting **relies on GNSS**, which is affected by solar activity

Inaccurate **crop yield estimation** impacts the ability to manage resources efficiently

Map distortion hinders farmers' abilities to **identify** and **address locations** requiring attention

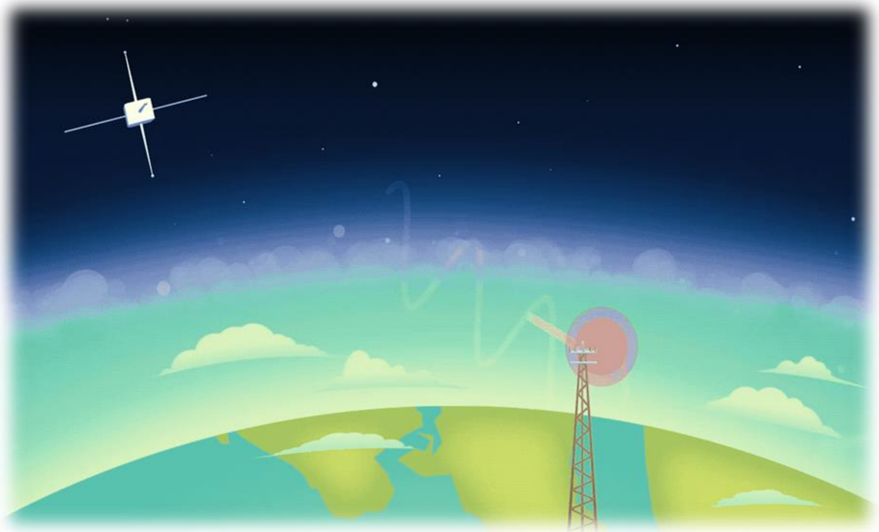


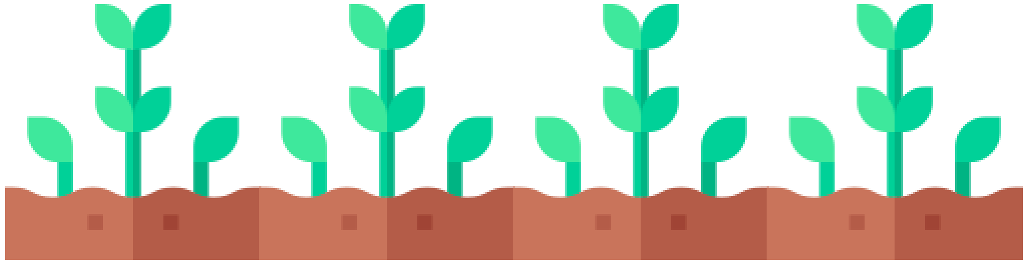
Image Credit: NASA/GSFC/CIL/Krystofer Kim

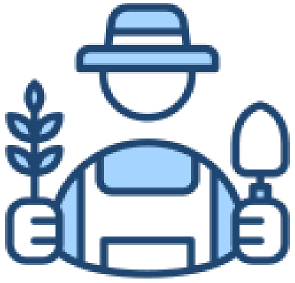
Image Credit: Arquivo/ABr

PROJECT END USERS

Companhia Nacional de Abastecimento (CONAB)

- **Managing** food supply and agricultural policies in Brazil using **GNSS** data
- **Working** to reduce issues related to family agriculture and food insecurity



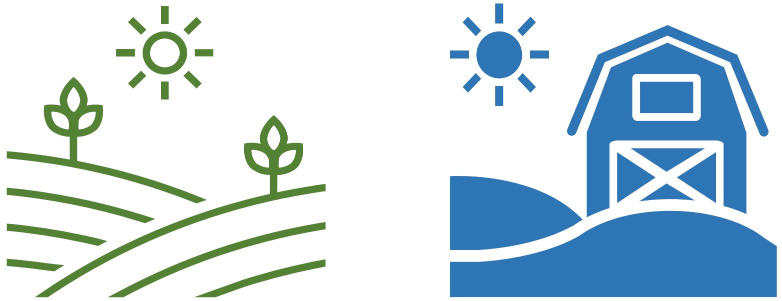


John Deere in Brazil

- **Equipping** agricultural tools with remote sensing technology
- **Providing** access to relevant field data
- **Utilizing** receivers in the field and explaining their functions

Icon Credits: Freepik, Iconjam

PROJECT COLLABORATORS

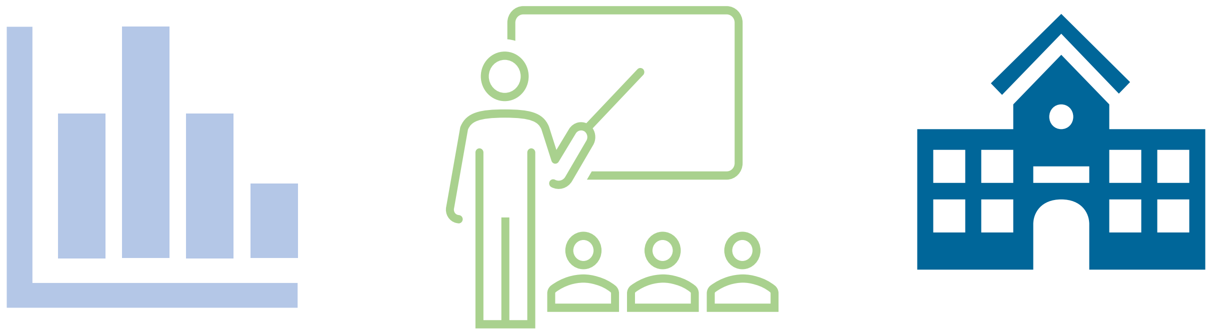


UNESP – São Paulo State University – Study Group on Space Geodesy (GEGE)

- **Mitigating** impacts of ionospheric scintillations
- **Modifying** models to improve accuracy
- **Organizing** constellations of receivers to reduce navigation error
- **Suggesting** methodologies to analyze EPBs

SLC Agrícola

- **Producing** cotton, soybean, and corn
- **Usage** of technical knowledge to achieve farming efficiency and productivity



PROJECT OBJECTIVES & END PRODUCTS

CHARACTERIZE
spatiotemporal features of equatorial plasma bubbles to aid in forecasting

IDENTIFY
GNSS errors to assist farmers in adjusting locations of rovers in fields

DETERMINE
uncertainty in precision agriculture for farmers to modify finances

VISUALIZE
determined features of EPBs over Brazil and globally

CHART
GNSS positioning errors over Brazil by ground station

QUANTIFY
operational times, plus financial and temporal waste

Icon Credits: Freepik, juicy_fish

STUDY AREA & PERIOD

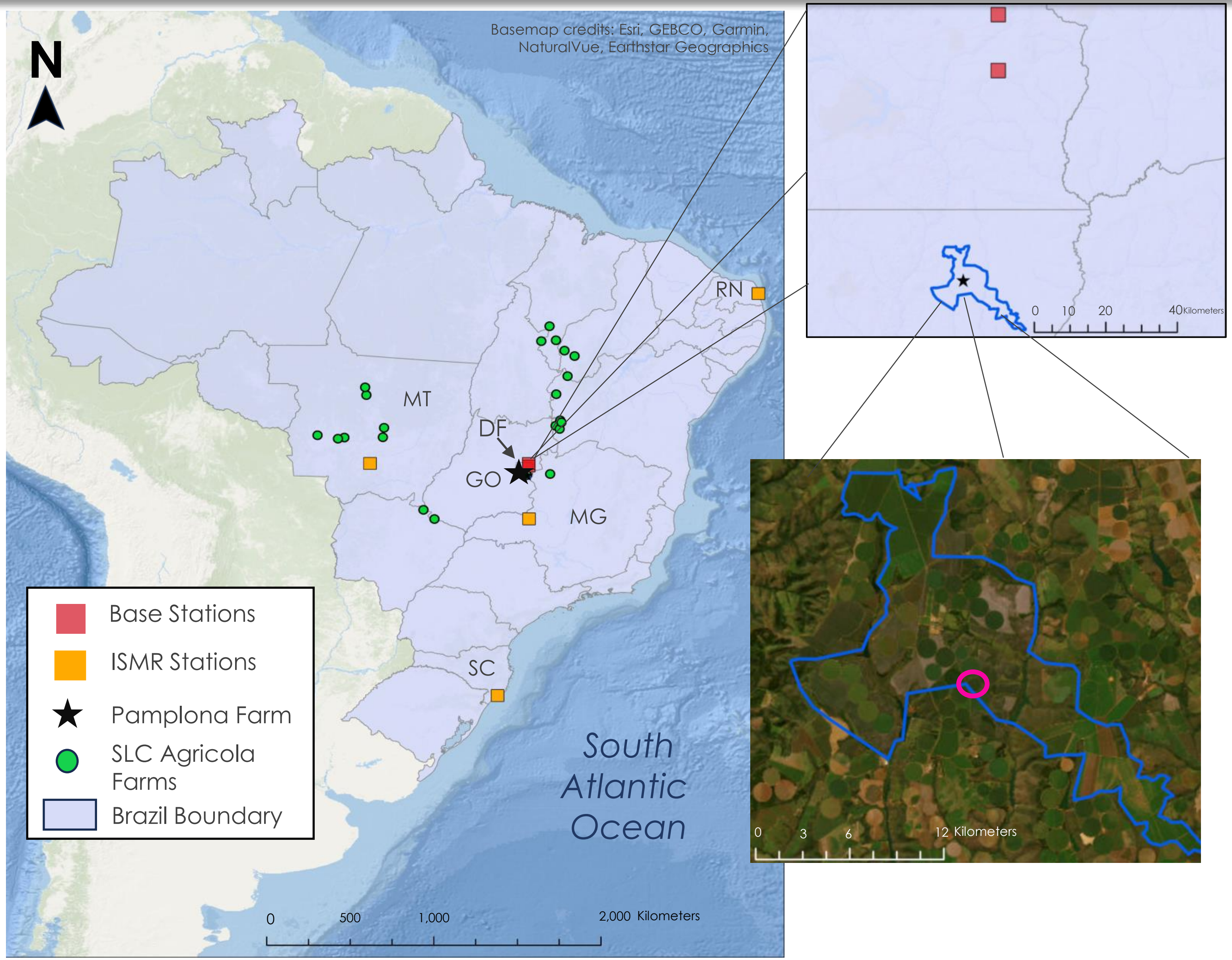
Country: Brazil
- Geomagnetic equator

GNSS Stations: Across Brazil
- Near Pamplona farm

Year: 2024
- Solar Cycle 25

Month: March equinox
- Harvesting season

Days: Comparing two evenings
- 1 – 2: strong scintillations
- 24 – 25: weak scintillations



NASA OBSERVATION MISSIONS

Global-scale Observations of the Limb and Disk (GOLD) Far-Ultraviolet Imager

Located on the SES-14 satellite

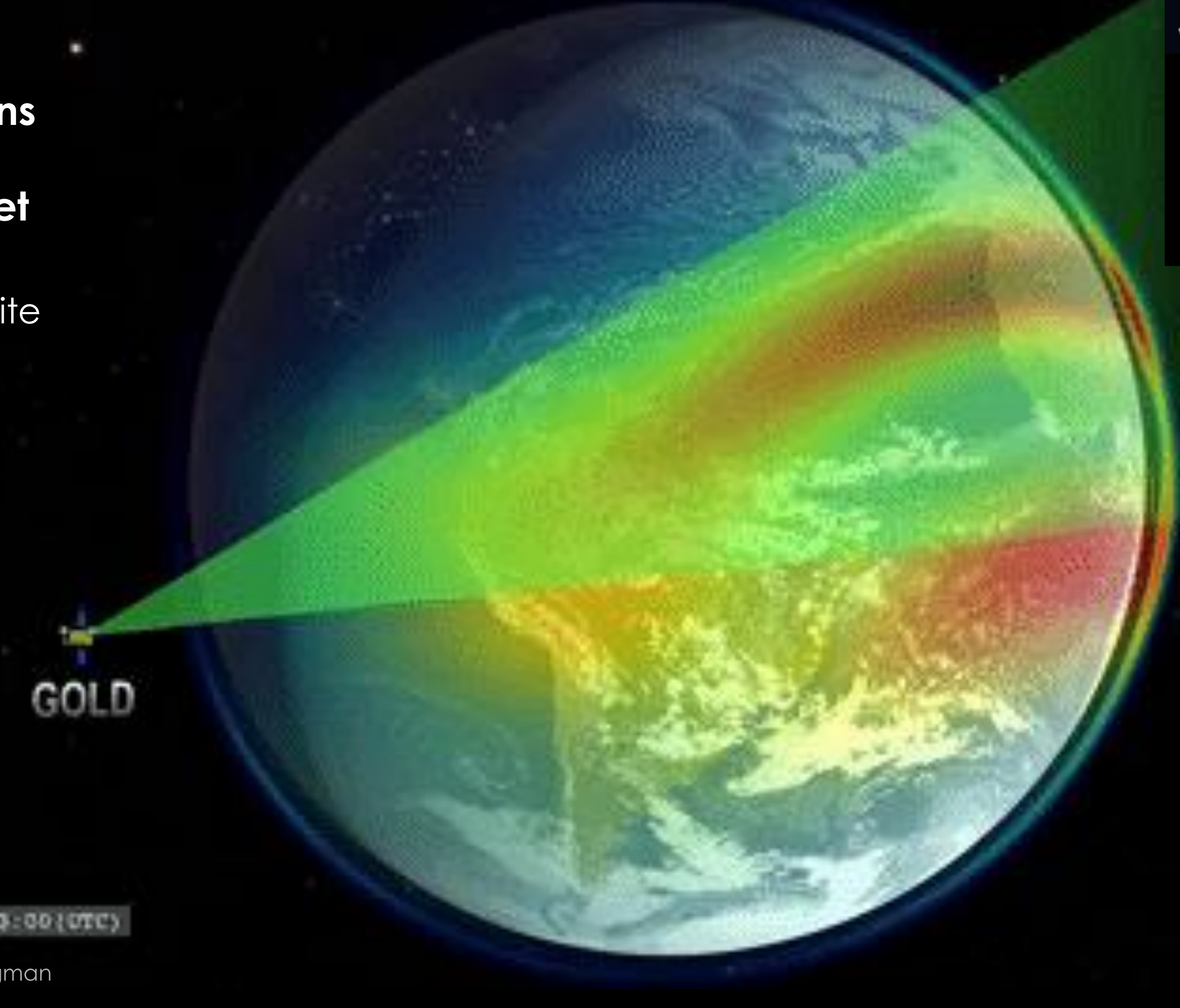


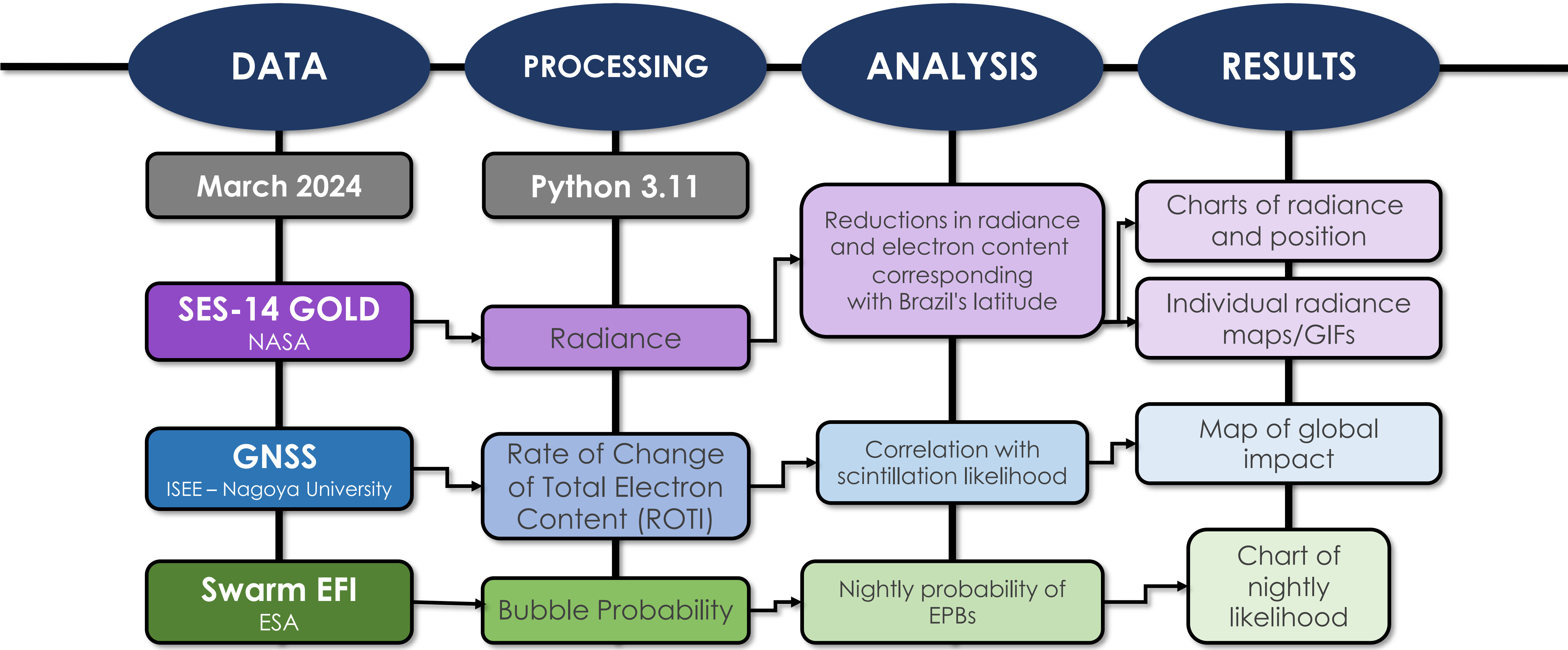
Image Credit: NASA Goddard/SVS/Tom Bridgman

Electric Field Instrument (EFI)

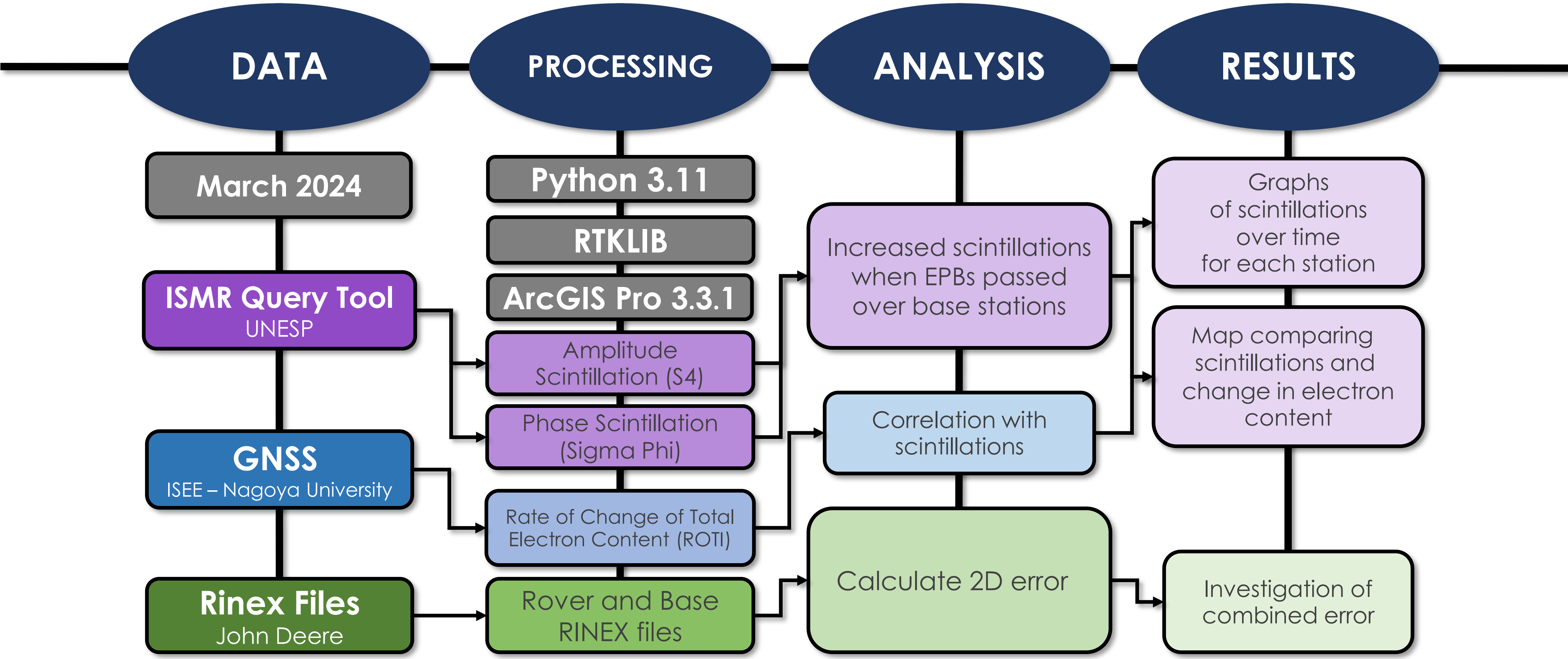
Swarm Magnetic Field Mission (Swarm)

Image Credit: European Space Agency (ESA)

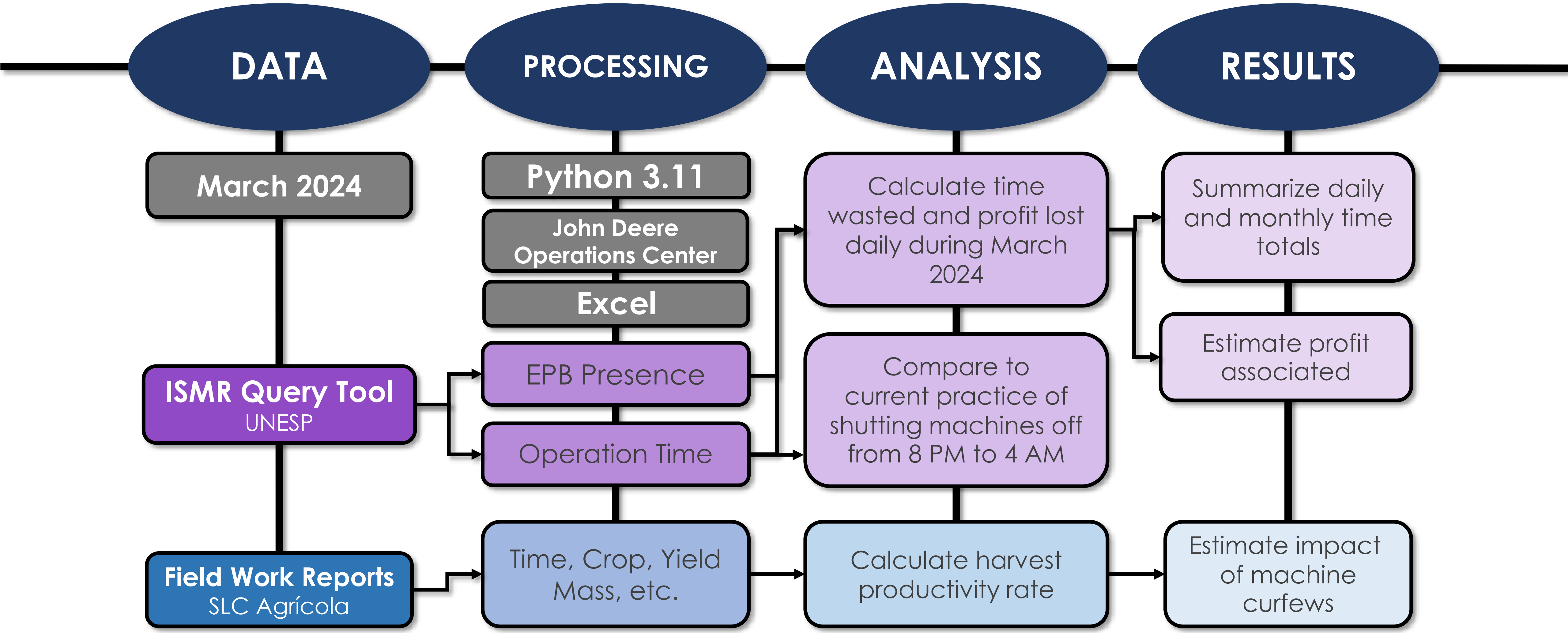
METHODOLOGY – Characterizing EPBs



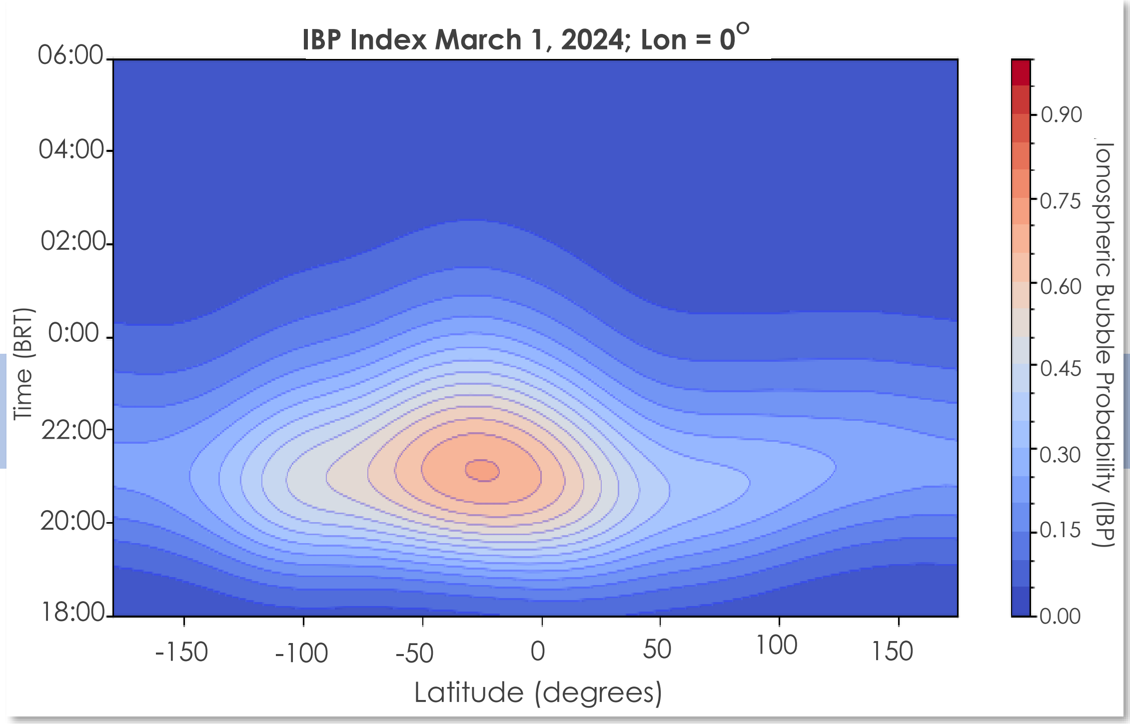
METHODOLOGY – Identifying GNSS Error

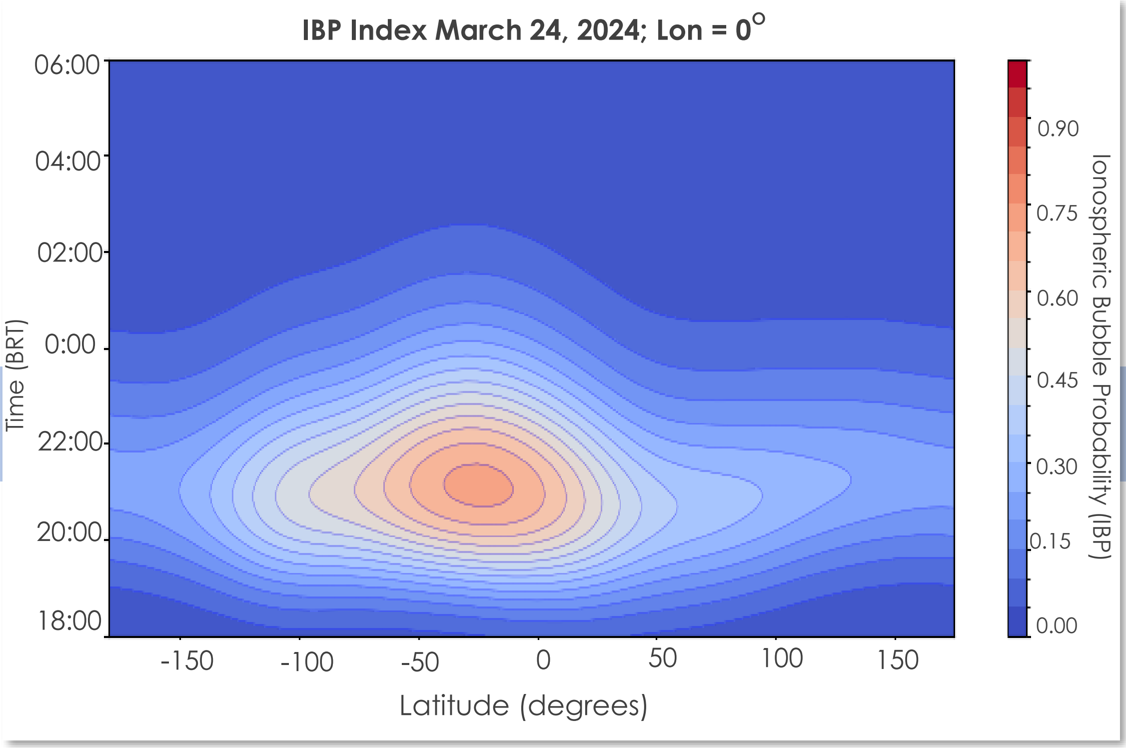


METHODOLOGY – Precision Uncertainty



RESULTS – Probability of Ionospheric Bubbles Over Brazil

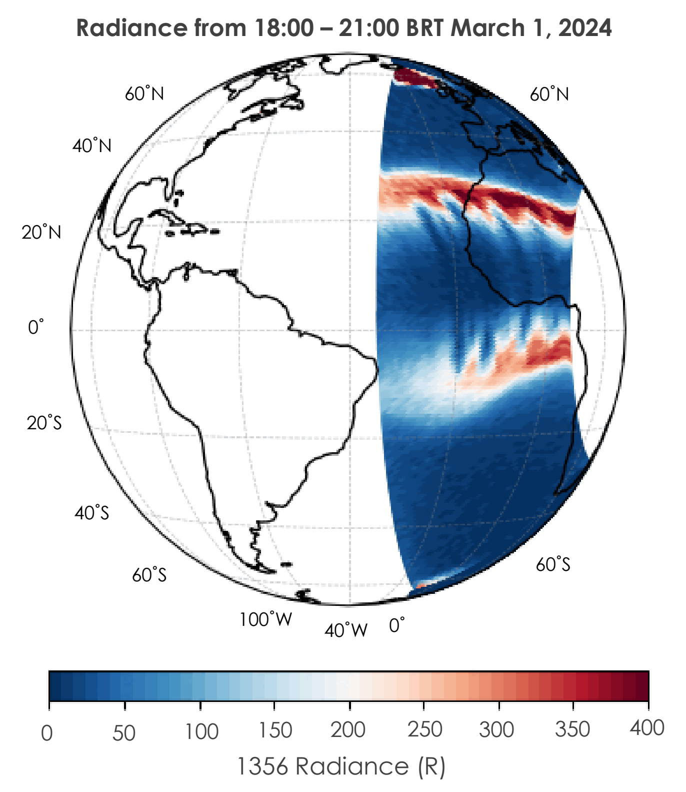


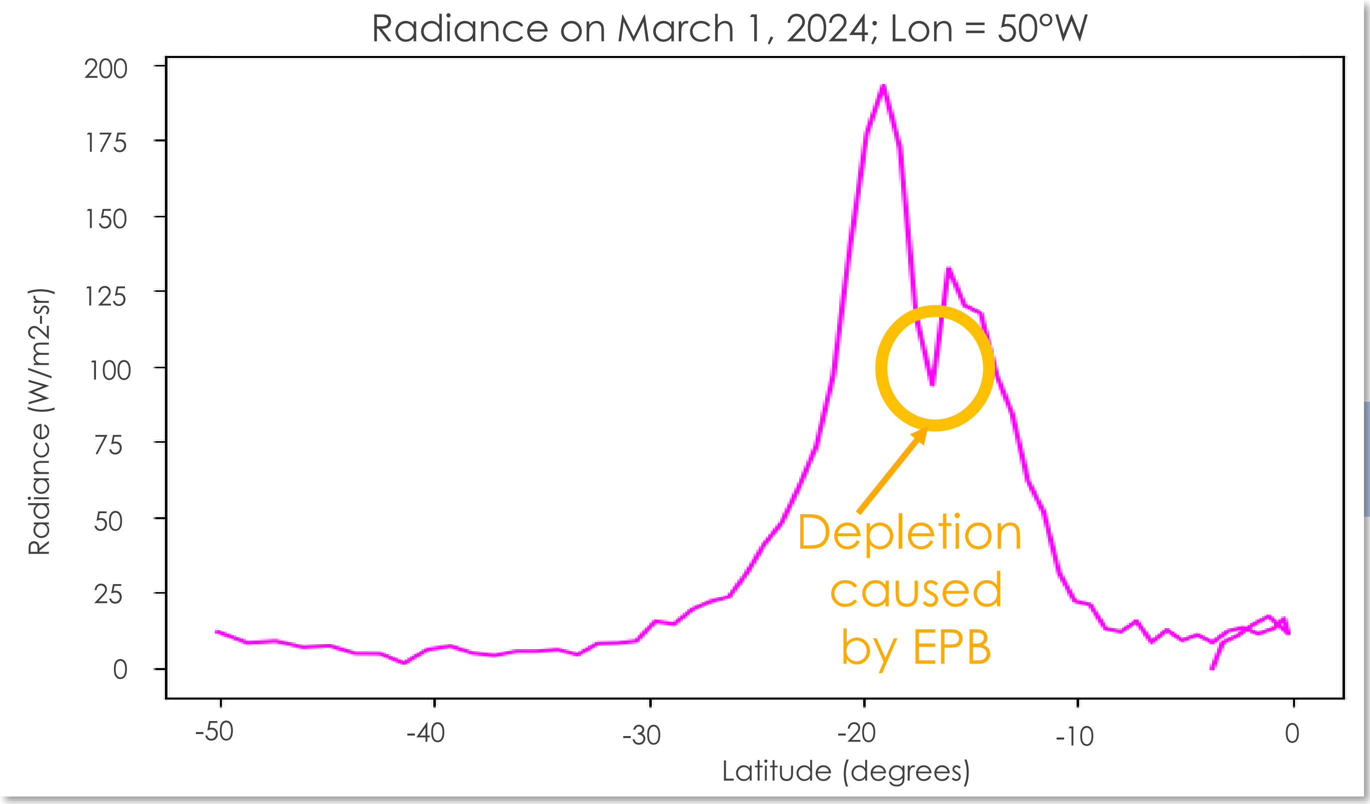


Ionospheric Bubble Probability (IBP)

Increases at night

RESULTS – Characterizing Strong Scintillations

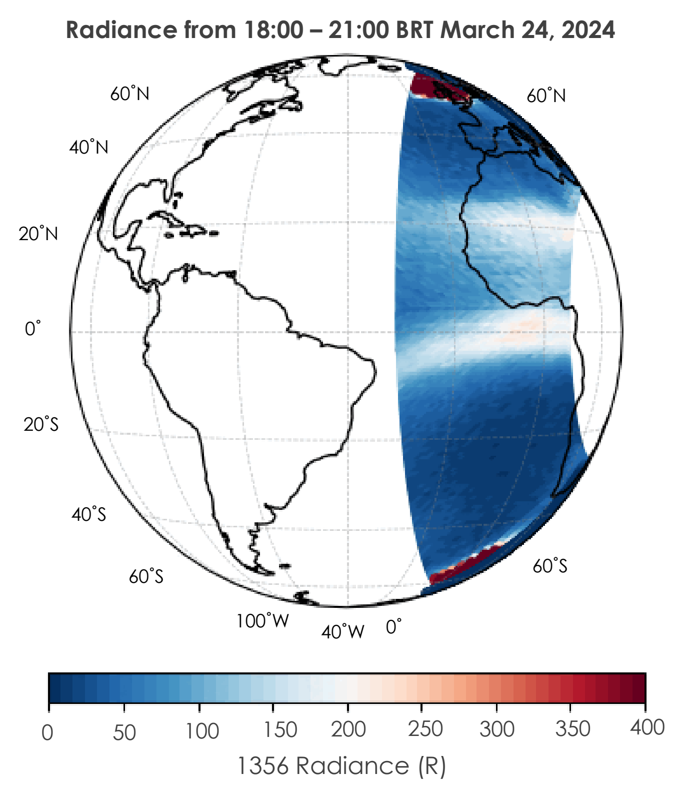


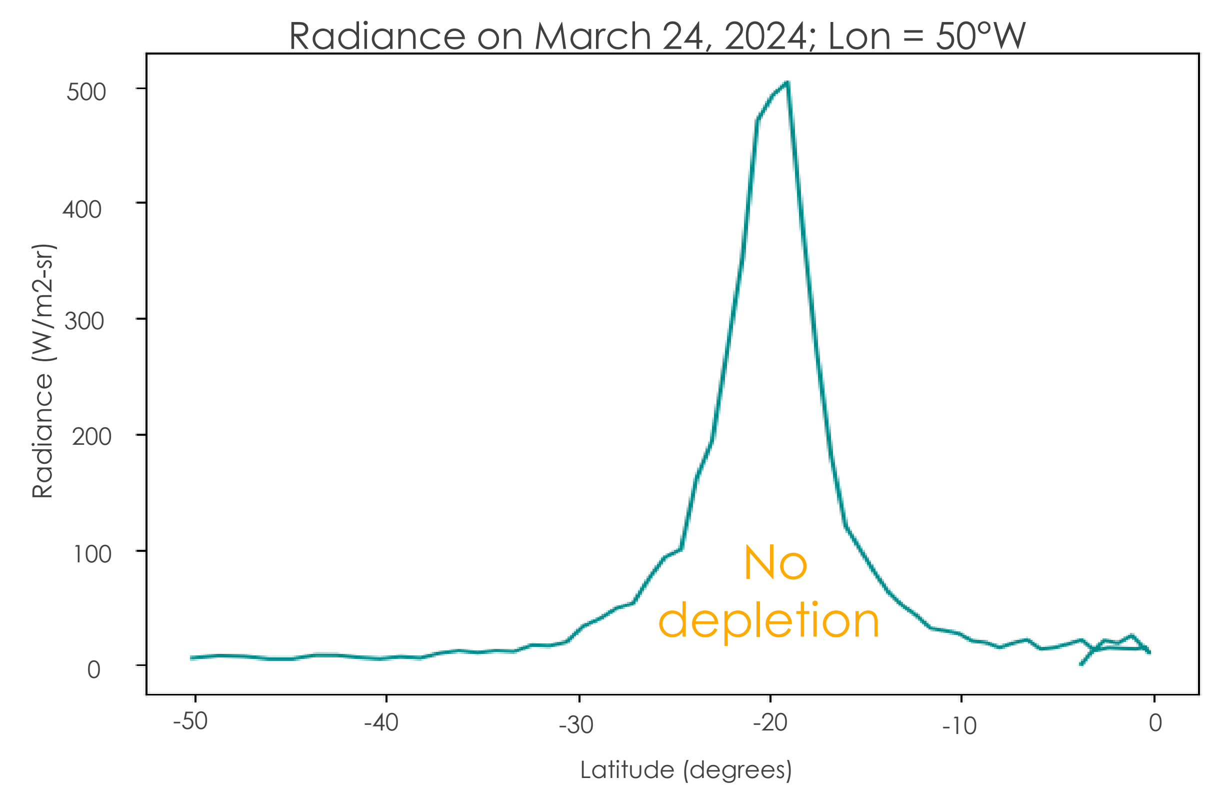


Radiance at 135.6 nm

Decreases March 1

RESULTS – Characterizing Weak Scintillations

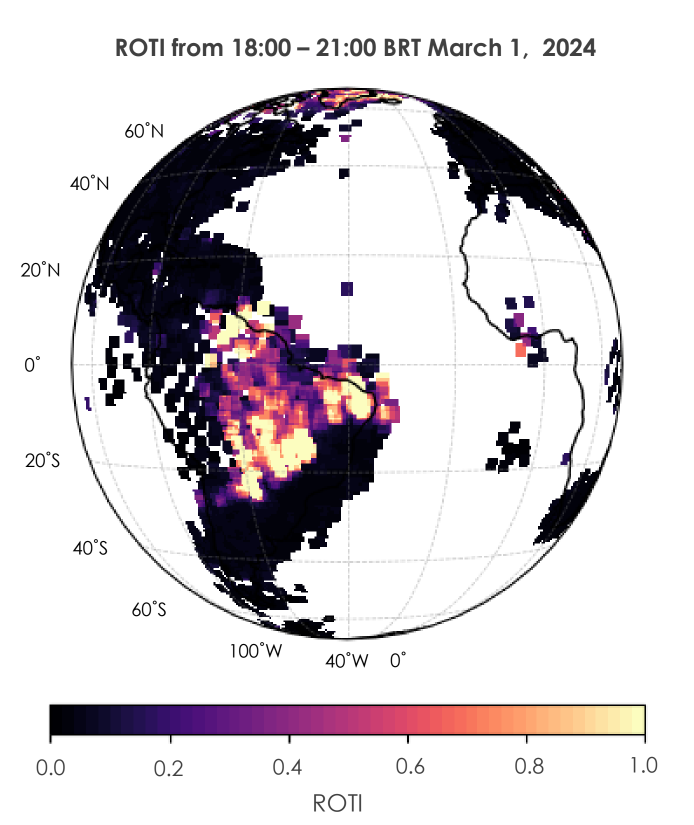


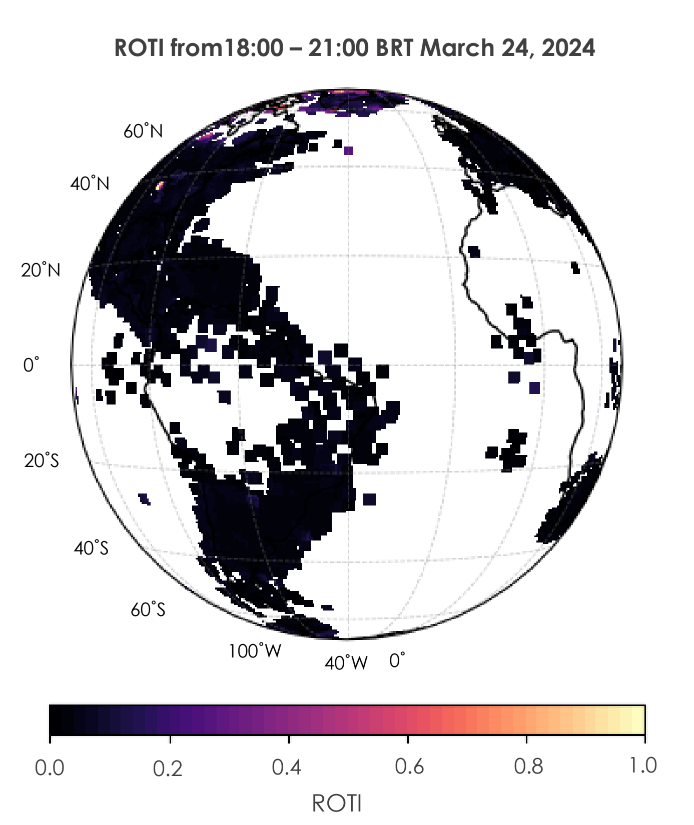


Radiance at 135.6 nm

Constant March 24

RESULTS – EPB Characteristics



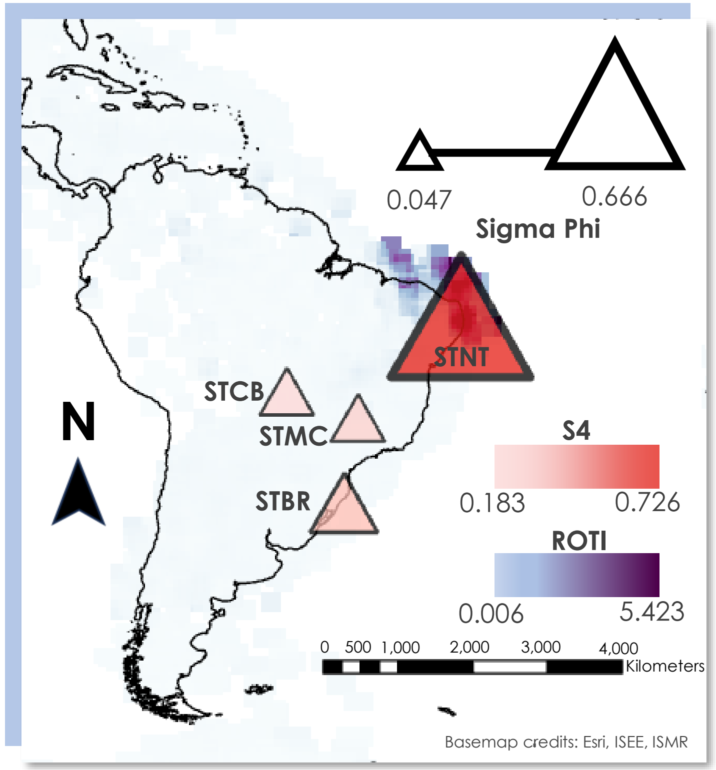


Rate of Change of Total Electron Content (ROTI)

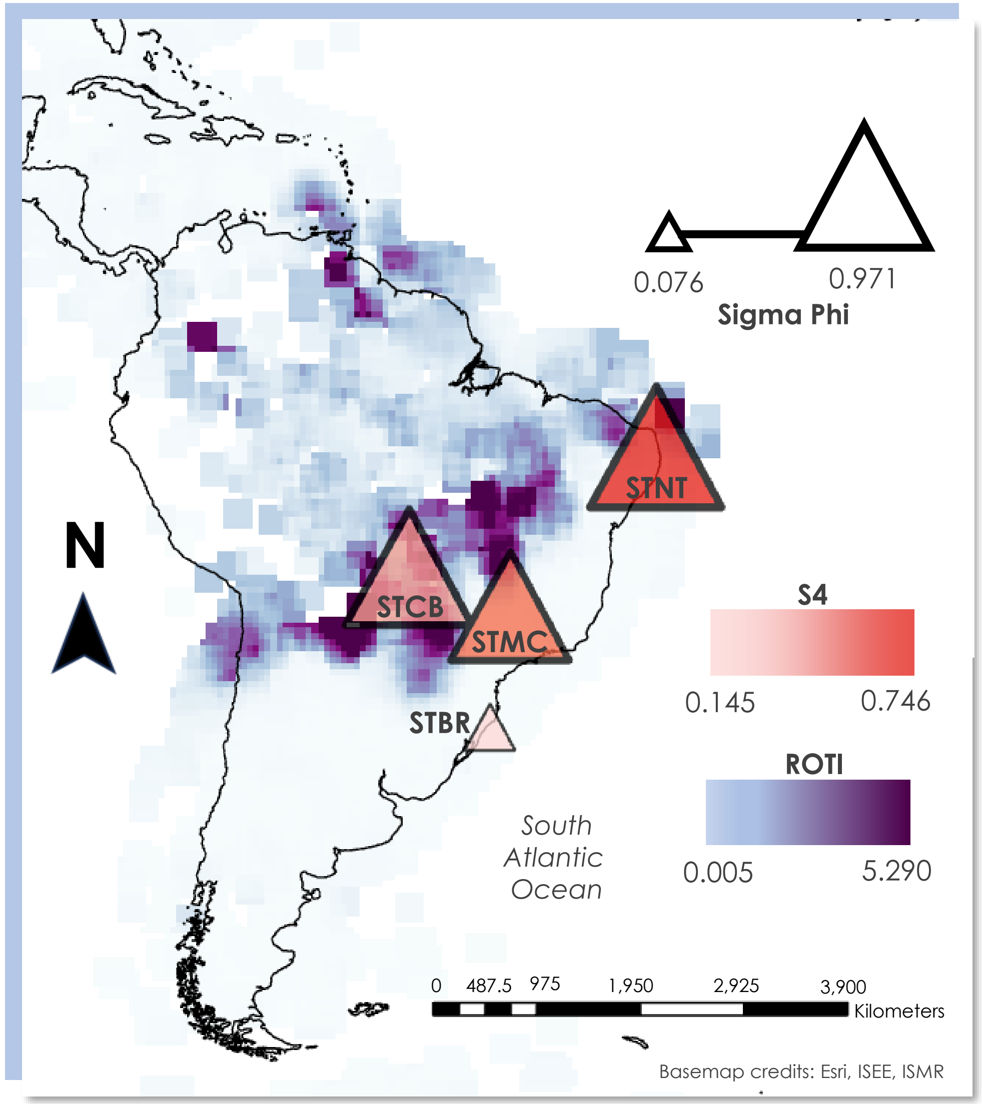
Constant March 24 – 25

RESULTS – Scintillation Variation

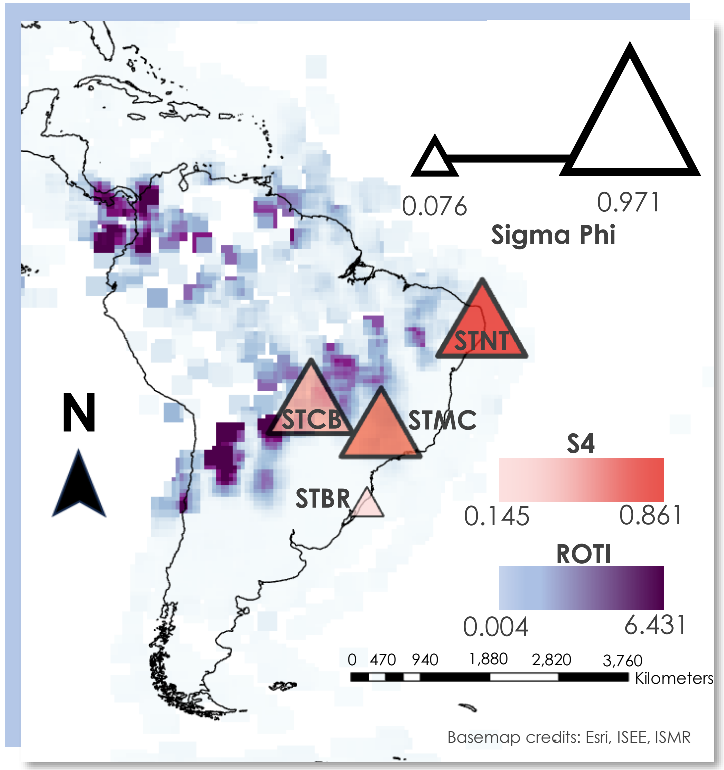
ROTI: rate of change of total electron content
S4: changes in signal strength
Sigma Phi: changes in signal timing as it travels between satellites & receiver



8 PM BRT

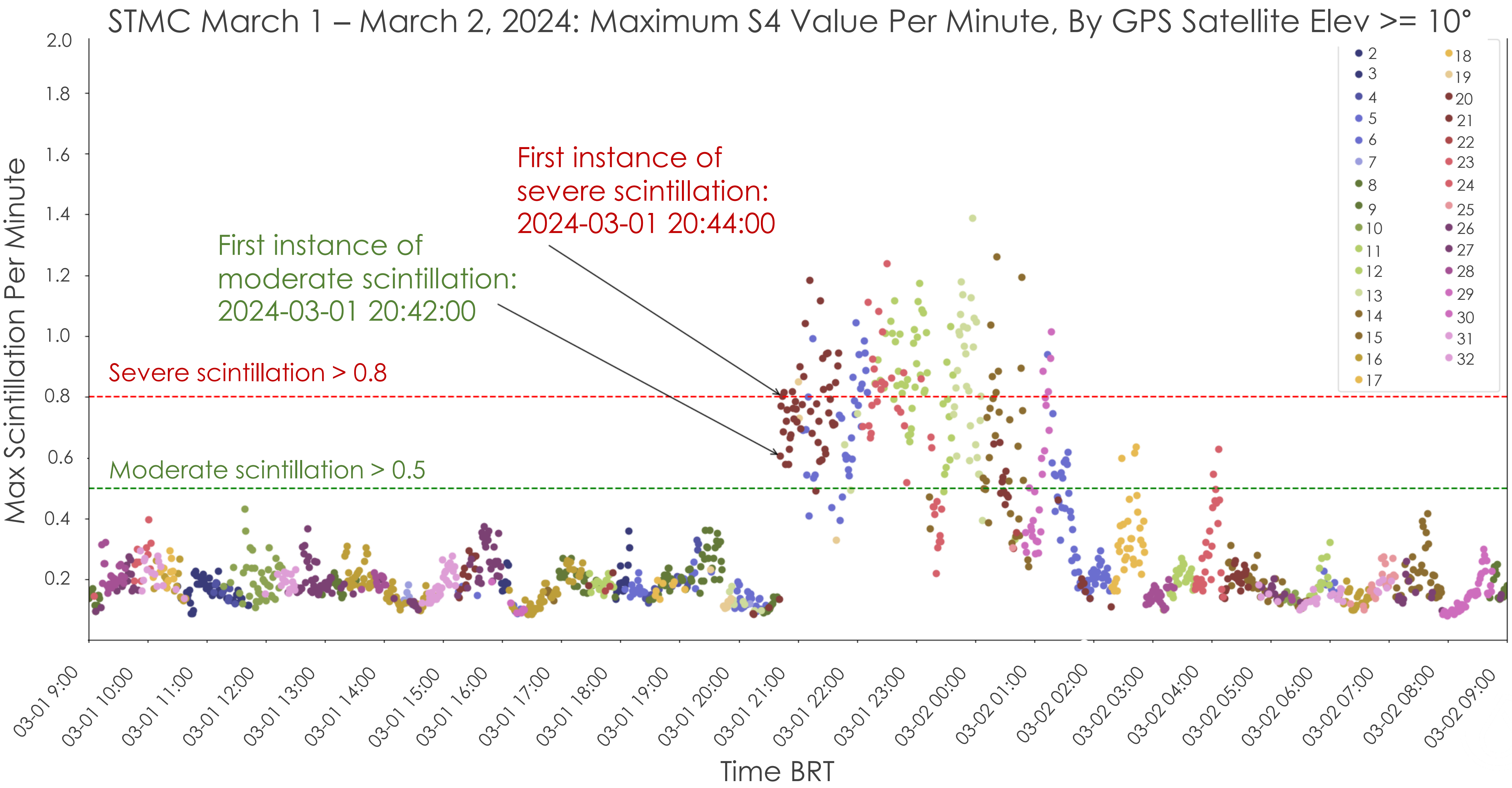


10 PM BRT



12 AM BRT

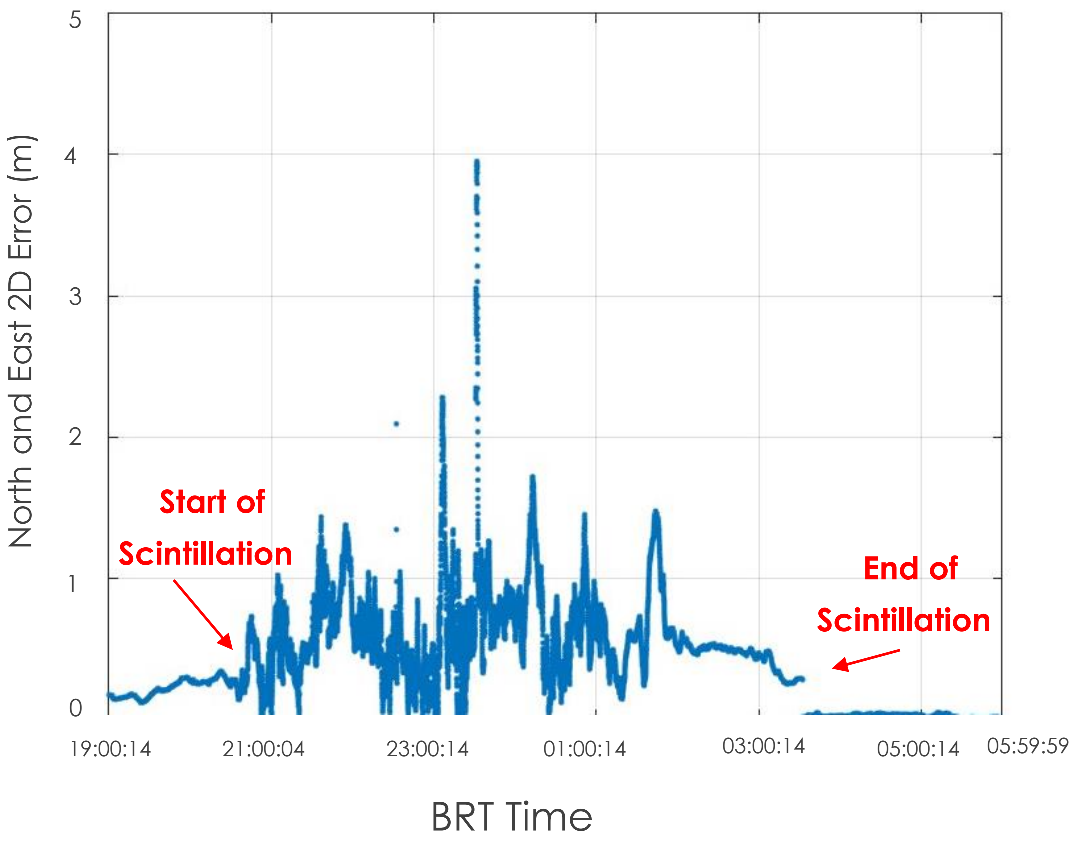
RESULTS – GNSS Scintillations



RESULTS – Positioning Error in Pamplona Farm

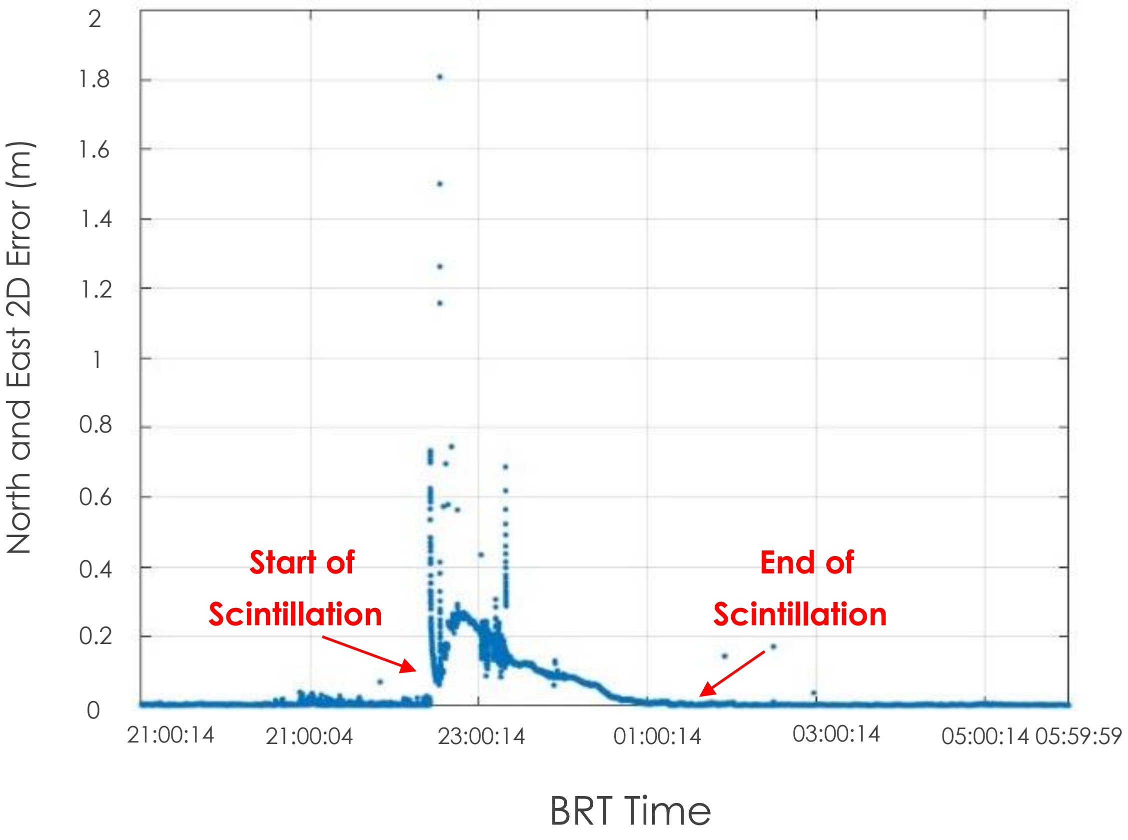
March 1 – 2, 2024

RTK Rover (100633) – Base Receiver (100152)



Mean 2D error = 0.5 m

Precise Point Positioning – Receiver (100626)



Mean 2D error = 0.4 m

RESULTS – Available Work Time

					1 Start: 04:10 End: 23:42 **Available operating time: 19 h, 32 m**	**2** Start: 07:07 End: 22:50 **Available operating time: 15 h, 43 m**
3 Start: 03:39 End: 23:59 **Available operating time: 20 h, 20 m**	**4** Start: 00:00 End: 23:24 **Available operating time: 23 h, 24 m**	**5** Start: 04:01 End: 23:12 **Available operating time: 19 h, 11 m**	**6** Start: 04:03 End: 23:04 **Available operating time: 19 h, 1 m**	**7** Start: 03:52 End: 23:33 **Available operating time: 19 h, 41 m**	**8** Start: 03:25 End: 23:01 **Available operating time: 19 h, 36 m**	**9** Start: 03:51 End: 23:59 **Available operating time: 20 h, 8 m**
10 Start: 03:19 End: 23:09 **Available operating time: 19 h, 50 m**	**11** Start: 03:15 End: 23:30 **Available operating time: 20 h, 15 m**	**12** Start: 03:32 End: 23:42 **Available operating time: 20 h, 10 m**	**13** Start: 03:13 End: 23:33 **Available operating time: 20 h, 20 m**	**14** Start: 03:09 End: 22:44 **Available operating time: 19 h, 35 m**	**15** Start: 04:05 End: 22:44 **Available operating time: 18 h, 39 m**	**16** Start: 04:15 End: 23:55 **Available operating time: 19 h, 40 m**
17 Start: 04:13 End: 23:26 **Available operating time: 19 h, 13 m**	**18** Start: 04:29 End: 22:44 **Available operating time: 18 h, 15 m**	**19** Start: 01:23 End: 23:59 **Available operating time: 22 h, 36 m**	**20** Start: 02:12 End: 23:34 **Available operating time: 21 h, 22 m**	**21** Start: 02:46 End: 23:59 **Available operating time: 21 h, 13 m**	**22** Start: 00:00 End: 23:26 **Available operating time: 23 h, 26 m**	**23** Start: 03:24 End: 23:25 **Available operating time: 20 h, 1 m**
24 Start: 00:00 End: 23:59 **Available operating time: 23 h, 59 m**	**25** Start: 00:00 End: 23:13 **Available operating time: 23 h, 13 m**	**26** Start: 03:45 End: 23:09 **Available operating time: 19 h, 24 m**	**27** Start: 00:00 End: 23:05 **Available operating time: 23 h, 5 m**	**28** Start: 00:29 End: 23:01 **Available operating time: 23 h, 0 m**	**29** Start: 03:46 End: 22:57 **Available operating time: 19 h, 11 m**	**30** Start: 02:52 End: 23:59 **Available operating time: 20 h, 47 m**
31 Start: 00:00 End: 22:48 **Available operating time: 22 h, 48 m**						

MARCH 2024 – STMC

Periods of Max S4 < 0.5

Standard operating window:
07:00 – 23:00 UTC | 4 AM – 8 PM BRT | 16 hours

RESULTS – Time Lost

Average work time beyond standard window:

+ 4 h, 31 m

Total wasted work hours:

+141 h, 50 m

MARCH 2024 – STMC

Available Work Time Beyond Standard Window

					1 + 3 h, 42 m	**2** - 0 h, 17 m
3 + 4 h, 21 m	**4** + 7 h, 24 m	**5** + 3 h, 11m	**6** + 3 h, 1 m	**7** + 3 h, 41 m	**8** + 3 h, 36 m	**9** + 4 h, 8 m
10 + 3 h, 50 m	**11** + 4 h, 15 m	**12** + 4 h, 10 m	**13** + 4 h, 20 m	**14** + 3 h, 35 m	**15** + 2 h, 39 m	**16** + 2 h, 40 m
17 + 3 h, 13 m	**18** + 2 h, 15 m	**19** + 6 h, 36 m	**20** + 5 h, 22 m	**21** + 5 h, 13 m	**22** + 7 h, 26 m	**23** + 6 h, 1 m
24 + 8 h	**25** + 7 h, 13 m	**26** + 3 h, 24 m	**27** + 7 h, 5 m	**28** + 7 h	**29** + 3 h, 11 m	**30** + 4 h, 47 m
31 + 6 h, 48 m						

Standard operating window:
07:00 – 23:00 UTC | 4 AM – 8 PM BRT
16 h/day|496 h/month

RESULTS – Crop Yield Impacts

Utilized data from one corn field located in Pamplona Farm

Total Yield Mass: **576.09 tons** ÷ Time of Operation: **12.00 hours** = 48.01 tons/hour

48.01 tons/hour x 4.50 hours/day = **216.05 tons/day**

4.50 hours/day → Average Time Lost Daily

216.05 tons/day → Opportunity Lost Daily

216.05 tons/day x Corn Price: $285.00/ton = **$61,574.25/day**

$61,574.25/day → Opportunity Lost Daily

CONCLUSIONS

Anomalous positioning errors in Brazil are largely driven by the formation and movement of plasma bubbles in the ionosphere

Increased knowledge of ionospheric disturbances can **guide** farmers' decision-making processes regarding GNSS-reliant equipment

Optimizing performance of farming equipment in accordance with ionospheric scintillations maximizes **efficiency** and **profit**

ERRORS & UNCERTAINTIES

GOLD data from the Northern and Southern Hemispheres **overlapped**

Calculation errors for positioning and yield estimations

GOLD **nighttime** observations end just past midnight

RTK receivers used a **single frequency** and harvest data was for **unique dates**

ACKNOWLEDGMENTS

Project Users and Collaborators

- Patricia Maurício Campos (CONAB)
- Dr. Joao Francisco Galera Monico & Brian Machado (UNESP)
- Edmundo Beinecke & Renato Abreu (John Deere)
- Ronei Sana (SLC Agrícola)
- Tom Bridgman (Scientific Visualization Studio, NASA GSFC)

Advisors

- Dr. Xia Cai (NASA LaRC)
- Dr. Min-Yang Chou (Catholic University, NASA GSFC)
- Jamie Favors (NASA HQ)

Fellows

- Marisa Smedsrud (Virginia – Langley)
- Laramie Plott (Virginia – Langley)

Special thanks to DEVELOP's Program Manager, Dr. Kenton Ross

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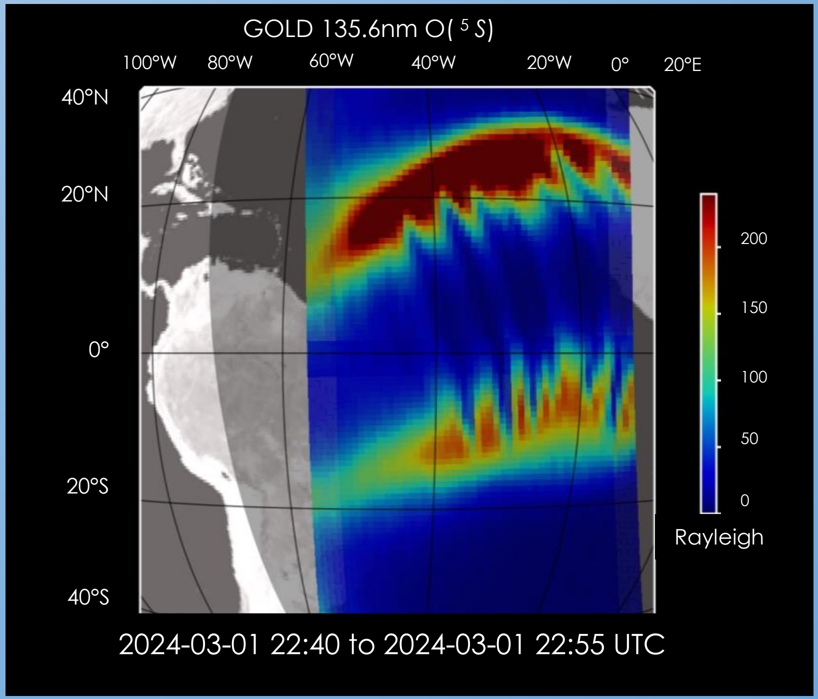
Plasma Bubbles and Brazilian Agriculture



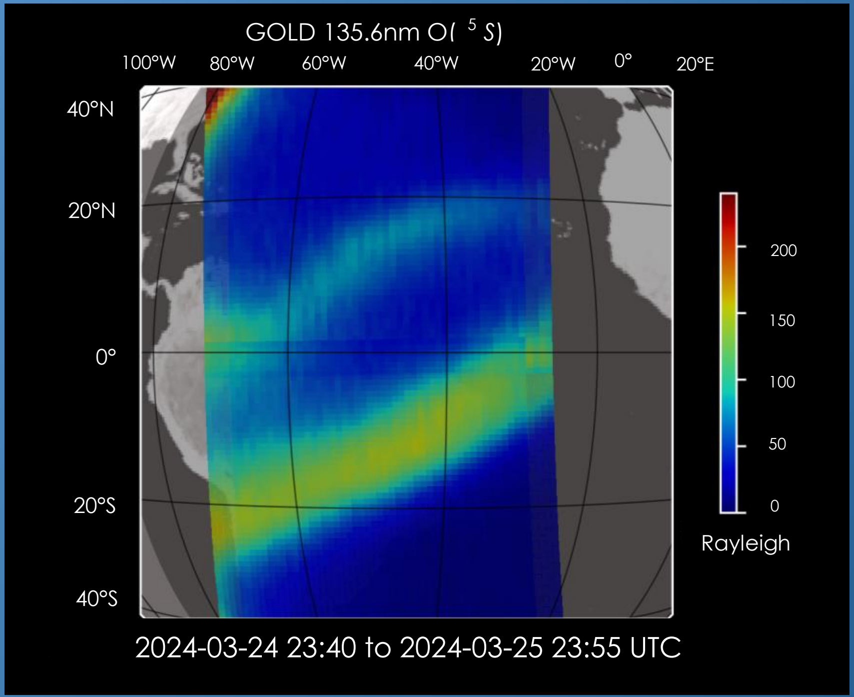
Above: GOLD data visualizes the formation of plasma bubbles in the ionosphere. As time passes, these bubbles will continue to move over Brazil and South America.

Data from Global-scale Observations of Limb and Disk (GOLD) instrument enables the visualization of scintillations in the Ionosphere including Equatorial Plasma Bubbles (EPBs). The variations in plasma density affect global navigation satellite system (GNSS) signals passing through the ionosphere, leading to high positioning error.

This GOLD visualization highlights approaching EPBs over Brazil on the evening of March 1 – March 2, 2024. In the areas of Brazil underneath the bubbles, GNSS-equipped machinery experienced 2D error of up to half of a meter. To avoid such error, many farmers keep their machines turned off after sunset, significantly reducing potential operating hours.

The night of March 24 – 25 shows little to no EPB activity despite a geomagnetic storm. There was little to no scintillation recorded for that night, showing the relationship between the presence of EPBs and disruptions in GNSS signals.

While the lack of plasma bubbles meant that GNSS equipment could have been operated without error, many farmers could not take advantage of this opportunity due to a lack of information about ionospheric conditions.



Right: GOLD data visualizes weak or low ionospheric scintillations over Brazil and South America.

Hall, J., Bergamini, A., Ehrlich, A., Marquez, M., *Brazil Space Weather*

Brazil Space Weather Project Summary/Synopsis

The Brazil Space Weather team assessed the impact of space weather on precision agriculture using the global navigation satellite system (GNSS) in Brazilian farms. This relates to a number of concerns raised by agronomists in Brazil. Farm technology for planting, fertilizing, watering, and harvesting relies on GNSS, which is affected by solar activity. Inaccurate crop yield estimation impacts the ability to manage resources. Map distortion hinders farmers' abilities to identify locations requiring attention.

Brazil is significant agriculturally and relevant to space weather considering its location on the geomagnetic equator, which sees greater ionospheric scintillations, such as Equatorial Plasma Bubbles (EPBs). In this study, the team focused on two nights, March 1-2, 2024 and March 24-25, 2024. This timeframe included harvest season in Brazil, an important season for estimating profits. The beginning of March typically saw more occurrences of EPBs, while the end of the month had weaker or lower Ionospheric scintillation. Data from the Global-scale Limb and Disk (GOLD) proved this point. EPBs can be seen over Brazil in the night between March 1st and 2nd, while EPBs were not present in the latter dates of the month.

Scintillations over March 1-2, 2024 did cause disruption to the GNSS signals causing positioning error of farm equipment. The study concluded that a correlation can be observed between EPB likelihood, ground station instability, and error in data collection from those locations. This supports that EPBs impact the accuracy of GNSS and, therefore, the data used for precision agriculture. It is feasible to characterize EPBs with GOLD data, estimate the positioning error of GNSS signals, and quantify the impacts on precision agriculture.