# Validation of COSMIC-2 Space Weather Science Products

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# *COSMIC-2 Space Weather (SpWx) Cal/Val Overview*

- On the US side of the COSMIC-2 program, Cal/Val is a joint NOAA-USSF effort
  - *NOAA was responsible for TGRS neutral atmospheric Cal/Val (now completed)*
  - *USSF is responsible for space weather Cal/Val (all sensors)*
- SpWx Cal/Val is organized into 4 work areas
  - *TGRS TEC*
  - *TGRS Scintillation*
  - *IVM in-situ ion density, drifts, composition and temperature*
  - *RF Beacon Scintillation & TEC*

# *TGRS TEC Requirements*

*Per COSMIC-2 JL1PRD*

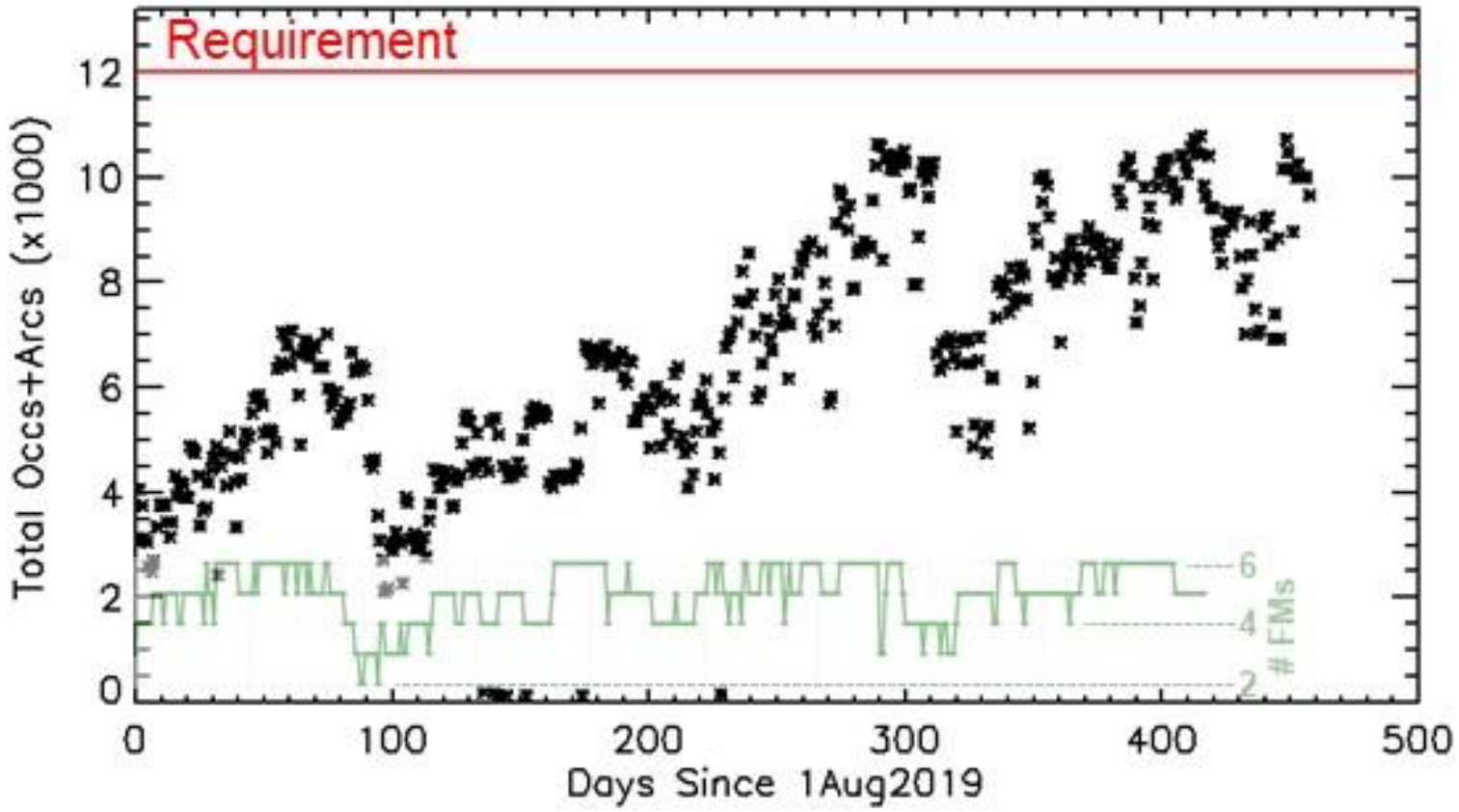
| Parameter | Requirement | Status |
|---|---|---|
| • Measurement uncertainty (relative) | 0.3 TECu | Verified |
| • Measurement uncertainty (absolute) | 3 TECu | Verified* |
| • Tangent altitude range (occultations) | 60 km to s/c alt. | >90 km |
| • # of occultations & “overhead arcs” | | |
| – *Limb TEC profiles* | *>6,000/day* | |
| – *Overhead TEC arcs* | *>3,675/day* | |
| – *Total profiles + arcs* | *>12,000/day* | *~10,000/day* |
| • Median data latency | 30 minutes | ~35 min |

***See Pedatella et. al. for details**

# *Quantity of TGRS Observations is Increasing*

*Getting close to meeting Arc & Occultation count requirements*

- Continued TGRS flight software refinements have improved performance
  - *Better quality GLONASS data, more efficient use of sensor resources*
  - *Most occultations now span required altitude range*




***Further flight s/w refinements are planned to fully satisfy requirements***

# *TGRS Ionospheric Scintillation Requirements*

COSMIC-2 JL1PRD Requirements

| Parameter* | Requirement |
|---|---|
| • S4 Measurement Range | 0 to 1.5 |
| • S4 Measurement Uncertainty | 0.1 |
| • $\sigma_\varphi$ Measurement Range | 0-20 radians |
| • $\sigma_\varphi$ Measurement Uncertainty | 0.1 radians |
| • On-board S4 calculations | All tracks (every 10s) |

- High rate (HR) SNR/phase sent to ground up to 10% of TGRS telemetry volume
  - *TGRS sends down high rate (50 Hz) amplitude & phase profiles when the calculated on-board S4 exceeds a programmable threshold*

*All scintillation parameters measured at GNSS L1 & L2

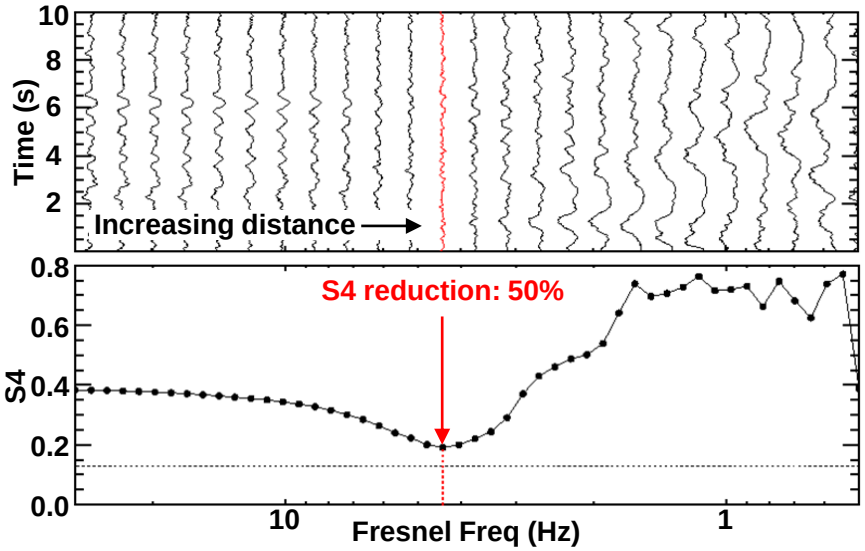
Cal/Val Objectives to Optimize Operational Utility

- Geolocate irregularity regions to 100-500 km accuracy
- Develop/assess an RO-based “All Clear” product
- “Limb-to-Disk”: Conversion of RO limb S4 to ground-to-space geometry
- Develop & evaluate “Bubble Maps” (joint TGRS/IVM product)

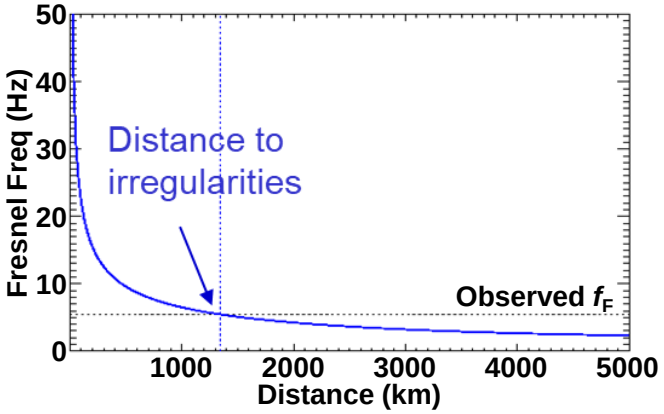
***Public release of quality controlled on-board S4, $\sigma_\varphi$ and HR data expected April 2021***

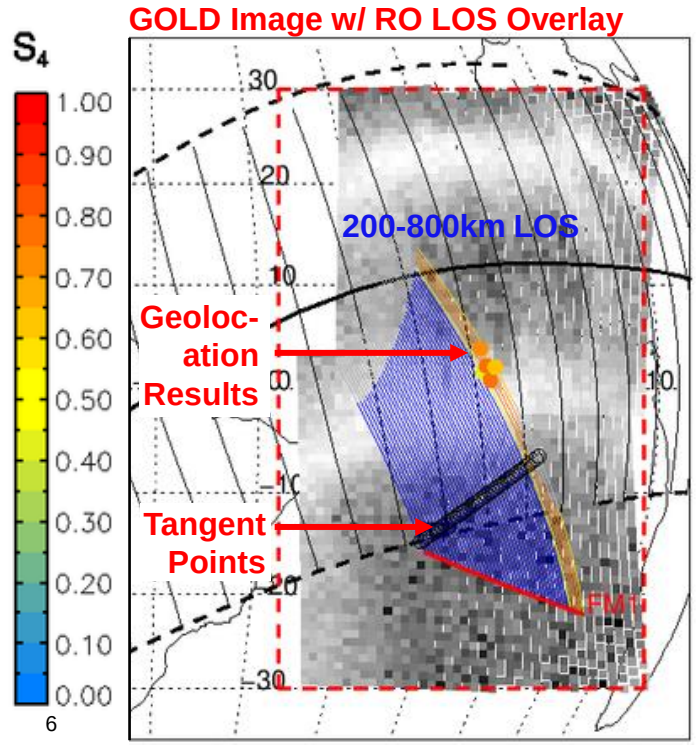
Note: Geolocation, limb-to-disk and $\sigma_\varphi$ are derived from high rate SNR and/or phase data

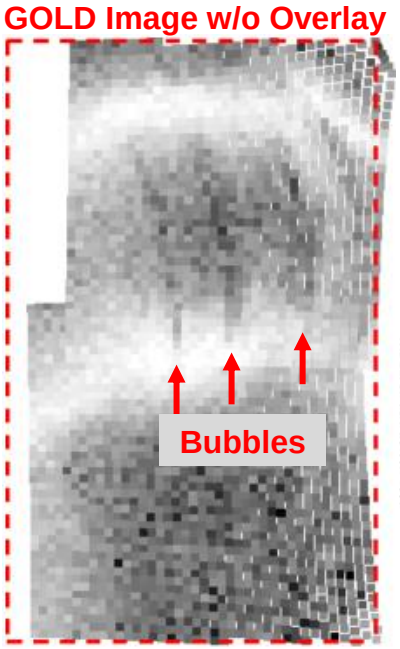
# Geolocation via Back-Propagation/GOLD Comparisons

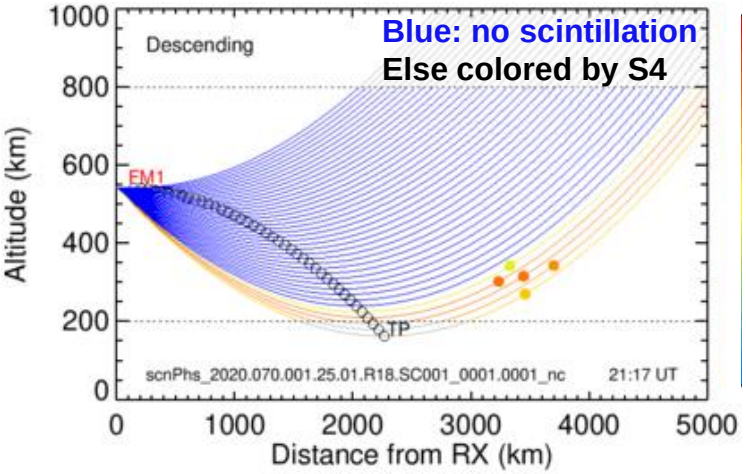



- Boston College (Carrano) back-propagation code operates in time domain, with Fresnel frequency as independent variable
- Rino (1977) scintillation model generalized to RO geometry relates Fresnel frequency to Fresnel scale & then to distance to irregularities
- GOLD 135.6 nm bubble imagery used for validation



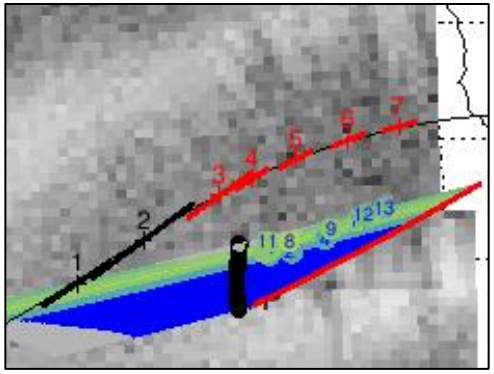



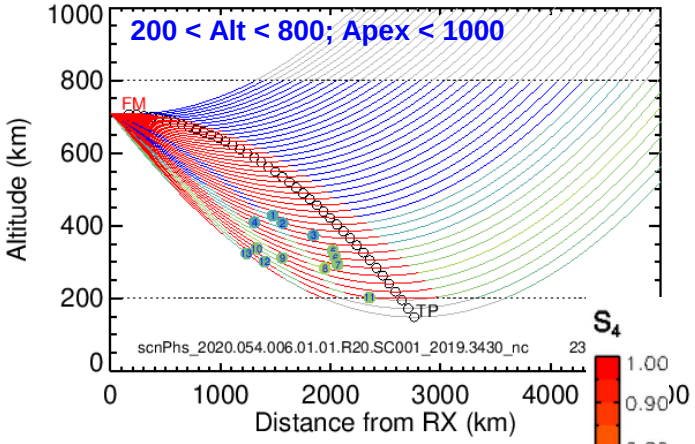



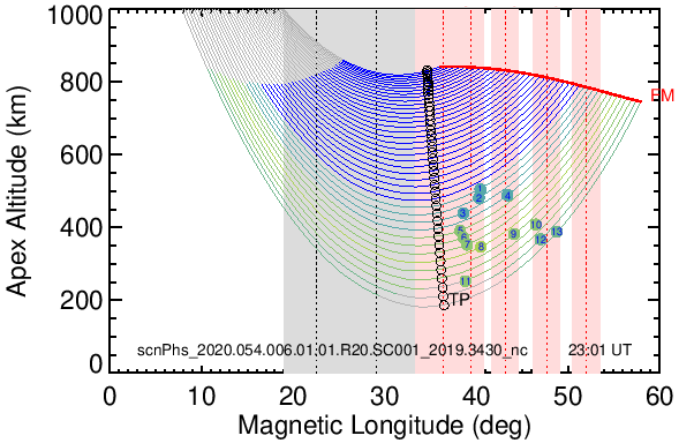



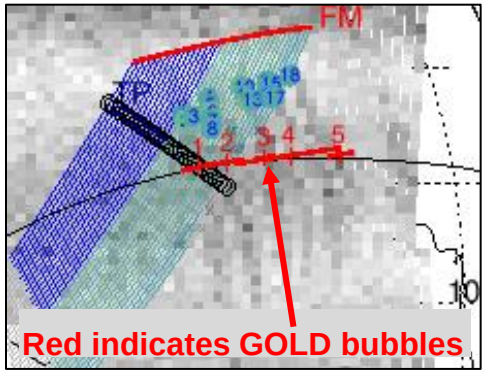
# *Multiple Bubbles Detected in Single Occultations*

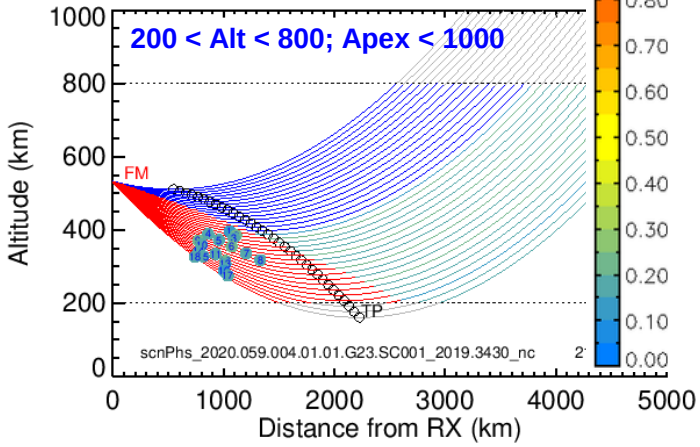
- Bubble locations/widths in GOLD data initially identified by UCAR algorithm, then manually sanity checked by BC/UCAR/Aerospace Cal/Val team
  - *GOLD bubbles validated vs. ground-based VHF scintillation data (Sao Luis, Brazil): 100% agreement wrt pre-midnight scintillation*
- Bubble geolocation determined based on 10s segments of high rate SNR/phase data
- Various occultation geometries result in potential detection of multiple bubble regions

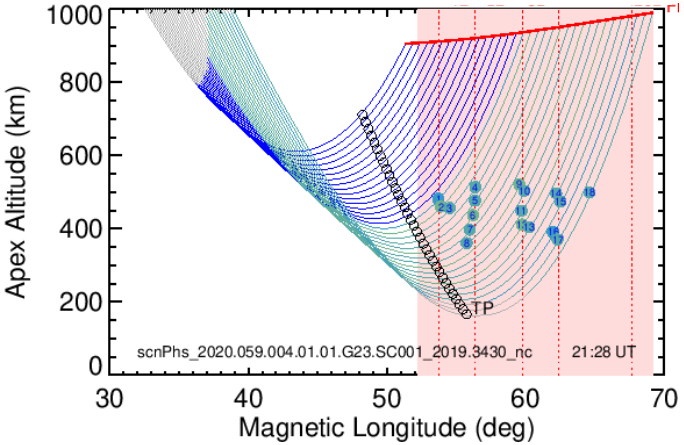




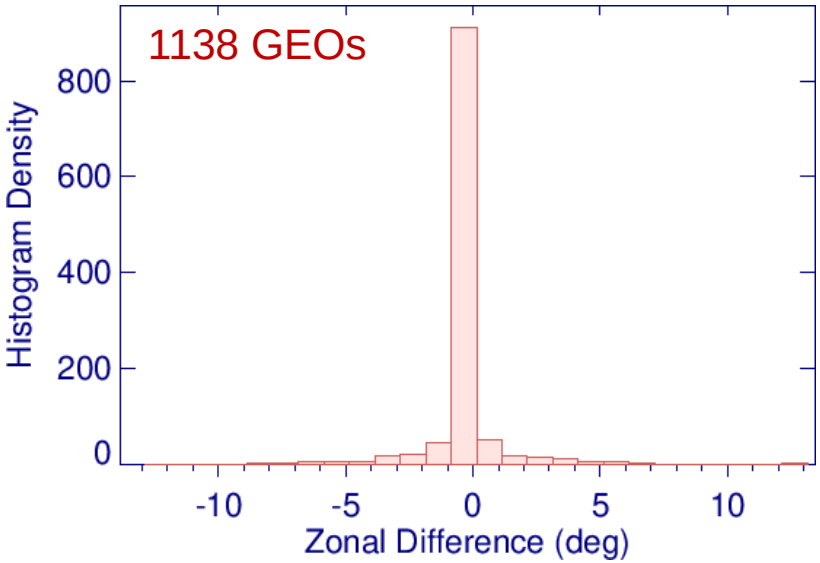



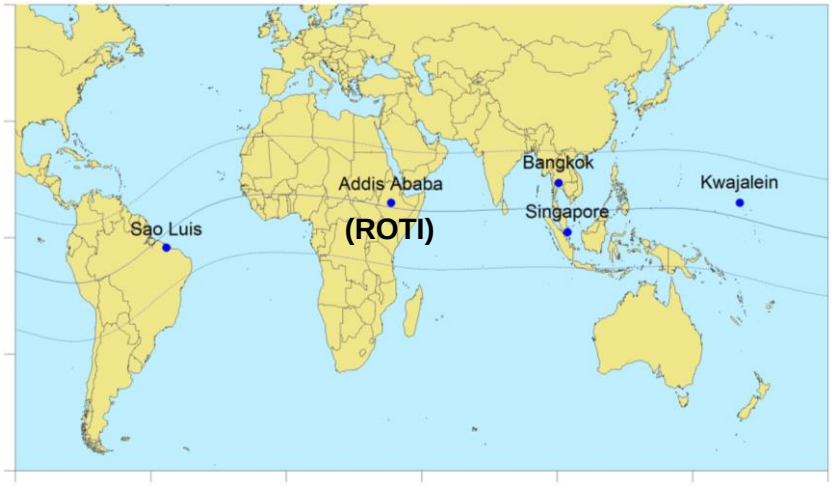
# Results of Validation with GOLD

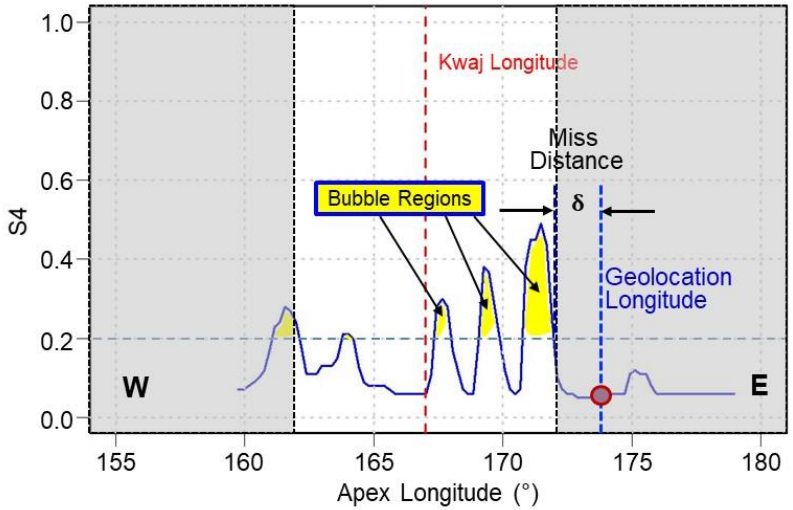
- February-April 2020 selected for performance evaluation
- Comparison of RO geolocations with bubbles detected by GOLD indicate agreement to within 2° geomagnetic longitude for better than 90% of cases
- Outliers are mostly associated with cases with poorly defined GOLD imagery structures, so truth was not well established (bubbles may be present at geolocation points)
- Caveat: in S. American/Atlantic sector scintillating nights often have long trains of bubbles – it may be easier to "hit" a bubble than to miss it!
- However, restricting the observational dataset to only cases containing isolated GOLD bubbles does not change the validation statistics
  - *This bolsters our confidence in the geolocation algorithm*



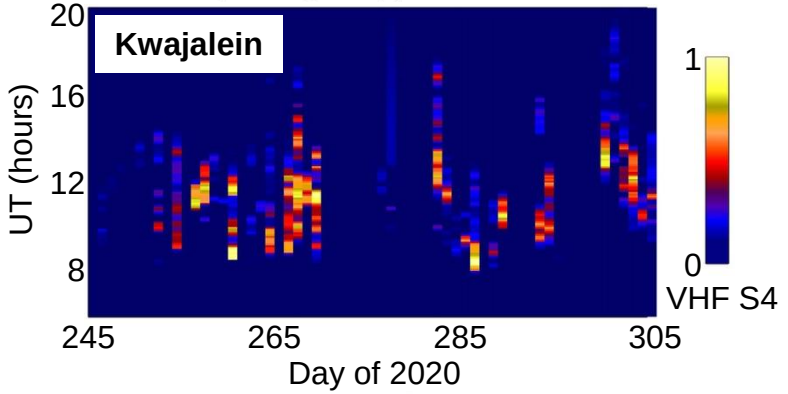

| | All Bubbles | Isolated Bubbles |
|---|---|---|
| Error | % Cases | % Cases |
| 0° | 71 | 73 |
| <1° | 85 | 84 |
| <2° | 91 | 92 |
| <5° | 97 | 98 |

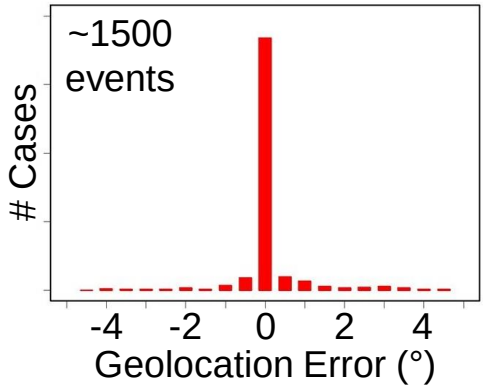
# Geolocation Validation Outside of S. America



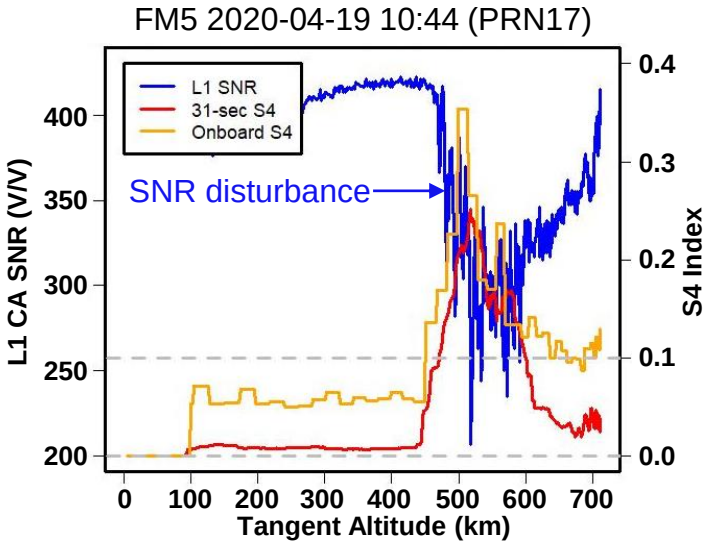

- Ground sensor for geolocation accuracy evaluation
  - *Receivers tracking VHF geostationary satellite signals*
  - *GPS receiver ROTI data (Addis Ababa station only)*
- Analysis assumes bubble structures observed by ground are “frozen in” and drift at 75 m/s
  - *Bubbles identified relative to 0.2 S4 sensor noise floor & projected out for 2 hours (5° longitude)*
  - *Pre-midnight events only*
- Geolocation accuracy for 4 non-S. American stations exceeds GOLD analysis (90/96% are within 1°/2° longitude)
- Restricting comparisons to isolated bubbles doesn’t significantly degrade accuracy

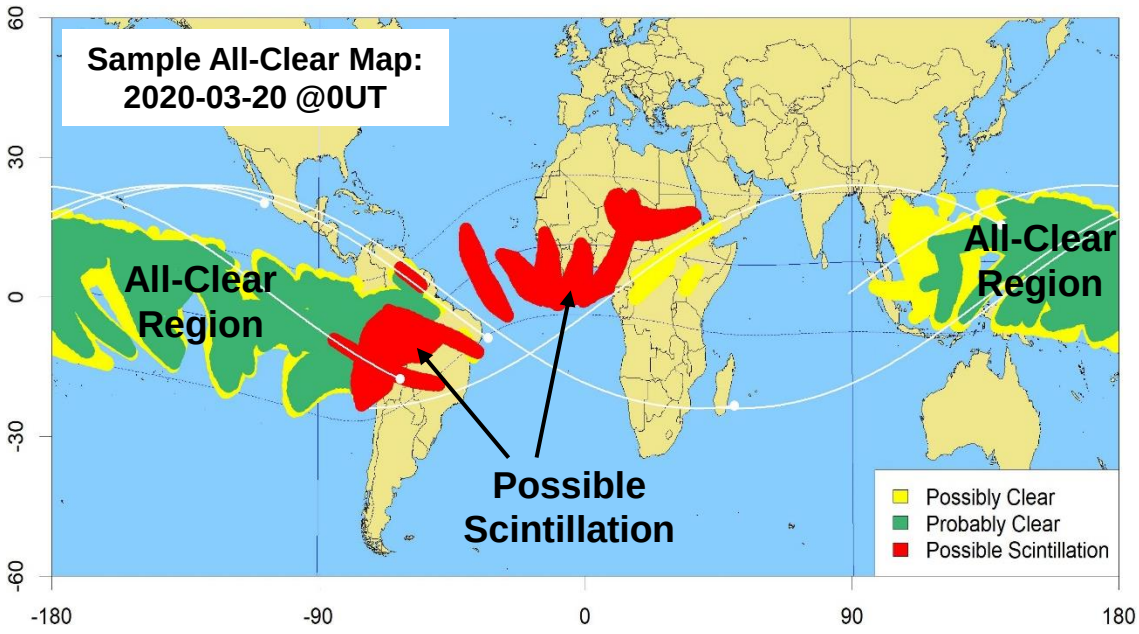


# TGRS Scintillation "All-Clear" Product

- All-Clear algorithm identifies irregularity-free regions using bubble physics to determine where along RO ray paths scintillation would be detected if present
  - *Irregularity locations limited by apex altitude & plasma density (based on climatology)*
  - *Algorithm specifies absence of UHF scintillation for a ground-based observer*
  - *Employs "pseudo-S4" derived from 31s of TGRS L1 1Hz SNRs*
- TGRS SNR disturbances caused by ground-based RFI create spurious pseudo-S4 values
  - *RFI filtering algorithms developed to exclude bad data*
- Validation w/ Kwajalein, Singapore, Sao Luis VHF stations
  - *< 3% error in All Clear at Kwaj/Singapore, but almost 20% error at Sao Luis*
  - *Problem has been traced to incorrect exclusion of scintillated RO data (RFI filtering error)*
  - *Improved RFI filtering algorithm developed by JPL and will be tested*



# *IVM Performance Requirements*

COSMIC-2 JL1PRD Requirements

| Parameter | Requirement | Status |
|---|---|---|
| • In-situ density accuracy/precision | 5% & 1% | Verified* |
| • In-situ density measurement range | $10^3$ to $5\times10^6$ $cm^{-3}$ | $8\times10^3$ to $5\times10^6$ $cm^{-3}$ |
| • In-track drift accuracy/precision | ±10 m/s & ±5 m/s | |
| • Cross-track drift accuracy/precision | ±5 m/s & ±1 m/s | |
| • Plasma drift measurement range | ±1000 m/s | |
| • Ion composition accuracy/precision | 5% & 5% | |
| • Ion temperature accuracy/precision | 10% & 5% | |

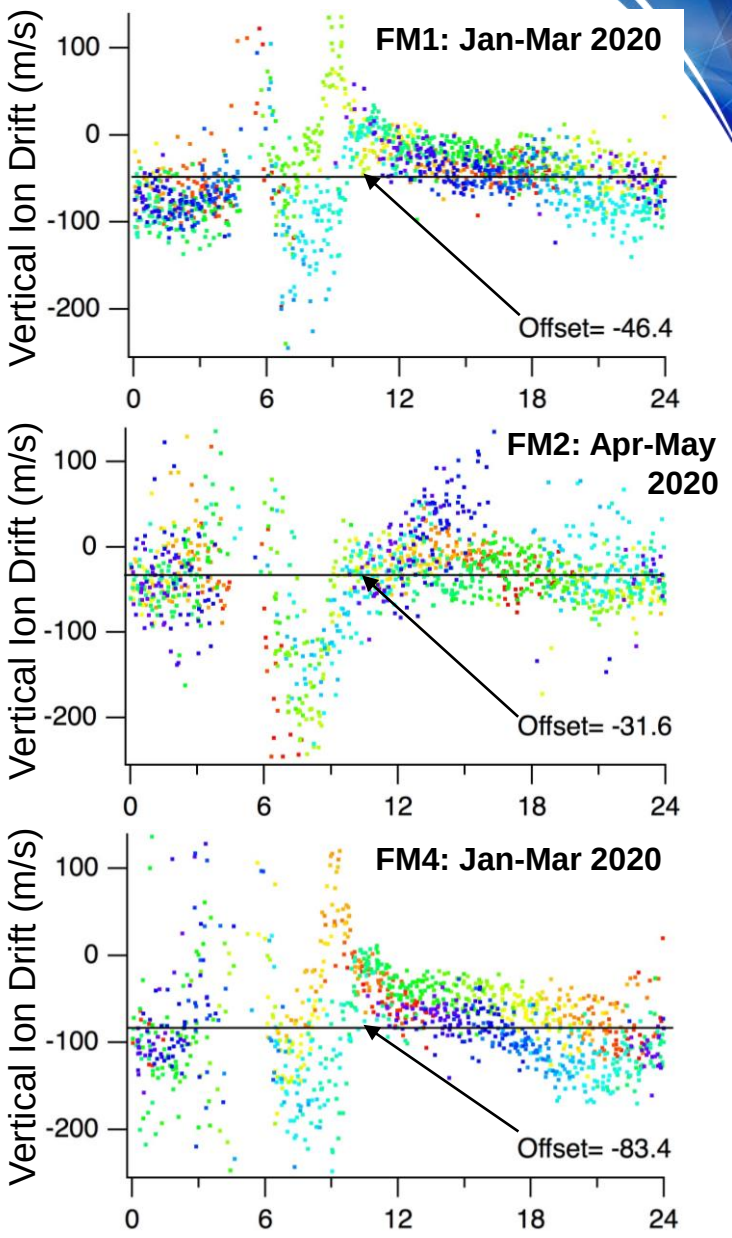
Cal/Val Objectives to Optimize Operational Utility

- Develop & evaluate “Bubble Maps” (joint TGRS/IVM product)

***See Wu et. al. poster for details**

# *IVM Ion Drifts*

- Ion drift products can only be produced for COSMIC-2 satellites after lowering to 550 km
  - *$H^+$ ion dominance at 720 km corrupts drift data*
  - *Even at 550km, low solar minimum nighttime densities & high $H^+$ fractions result in noisier drifts*
  - *Daytime data are highest quality, but pre-noon data required correction for photoelectron (PE) effects*
  - *Initial PE corrections have been developed, but further improvements are needed*
- Local time variation of vertical drift at magnetic equator determined over ~60 day periods
  - *Drift offsets determined for FM1, FM2 & FM4 for median drifts at 1800 LT*
  - *Currently investigating bias changes that occurred near the end of 2020*
  - *Offsets will be validated through comparisons to Jicamarca ISR*




UTD analysis

# *RF Beacon Scintillation Requirements & Plan*

COSMIC-2 JL1PRD Requirements

| Parameter | Requirement |
|---|---|
| • S4 Measurement Range | 0 to 1.5 |
| • S4 Measurement Uncertainty | 0.1 |
| • $\sigma_{\varphi}$ Measurement Range | 0-20 radians |
| • $\sigma_{\varphi}$ Measurement Uncertainty | 0.1 radians |

Cal/Val Plan

- Two RF Beacon Receiver (RFBR) ground sites
  - *Kwajalein (AFRL Roi-Namur site)*
  - *Sao Luis, Brazil*
- Areas of work
  - *Quality control assessment (leading to RFBR s/w improvements)*
    - Algorithms to distinguish between real scintillation & multipath effects
    - Mapping the RF Beacon antenna pattern on the COSMIC-2 spacecraft (particularly L-band)
  - *ALTAIR radar validation campaigns*
    - Dry run in October 2020/final in April or September 2021
    - ALTAIR measures 2-way scintillation to compare with RFBR 1-way measurements
    - Signal propagation models will be used to extrapolate between radar & RFBR frequencies

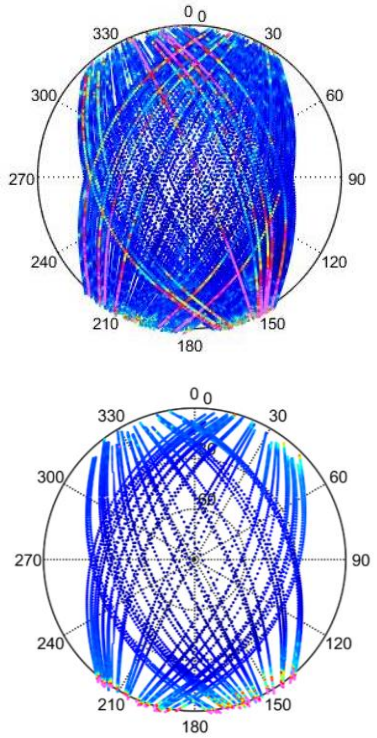
# *RF Beacon Cal/Val Status*

- Cal/Val is comparing two different RFBR antennas
  - *Higher gain steerable Yagis (@Kwaj May 2019)*
  - *Fixed tri-band patch (@Sao Luis Feb 2020)*
- COVID-19 site restrictions delayed 2nd RFBR installs & has slowed system troubleshooting
  - *Patch system added to Kwaj (Aug 2020)*
  - *Steerable system added to Sao Luis (Oct 2020)*
- Steerable system performance problems caused by antenna polarization errors → corrected!
- Working to understand predicted vs actual performance for the different RFBRs & extract accurate phase observations

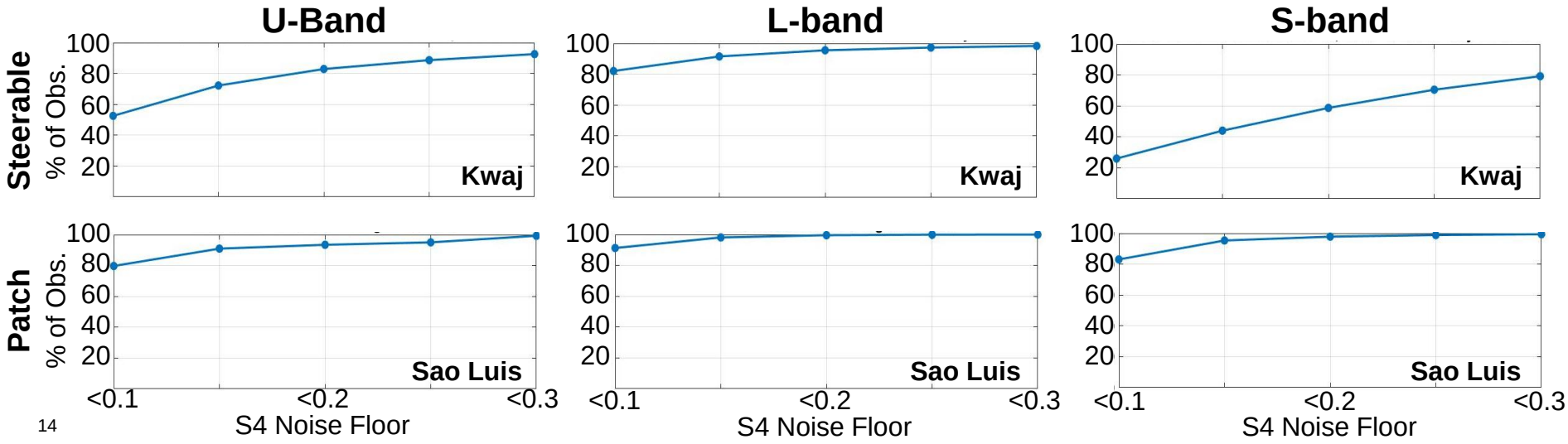
**Steerable**

**Patch**

**UHF SNR Maps**




Figures courtesy AFRL/Boston College



# Summary

- The COSMIC-2 space weather Cal/Val is ongoing
- COSMIC-2 sensor products in the areas of ionospheric density, scintillation and plasma drift specification are being validated for operational and scientific use
  - *TGRS GPS & GLONASS TEC product validation is complete*
  - *IVM in-situ density validation is complete*
  - *TGRS scintillation & additional IVM products will be made available for operational and scientific use as validation work completes (spring – summer 2021)*
- RF Beacon signals are available to any one that fields a receiver capable of measuring them

**The COSMIC-2 sensors provide unprecedented coverage and refresh in support of equatorial space weather applications**