spire | weather & earth intelligence

GNSS-R Data Assimilation Efforts at Spire Global: from Ocean Winds to DDM's

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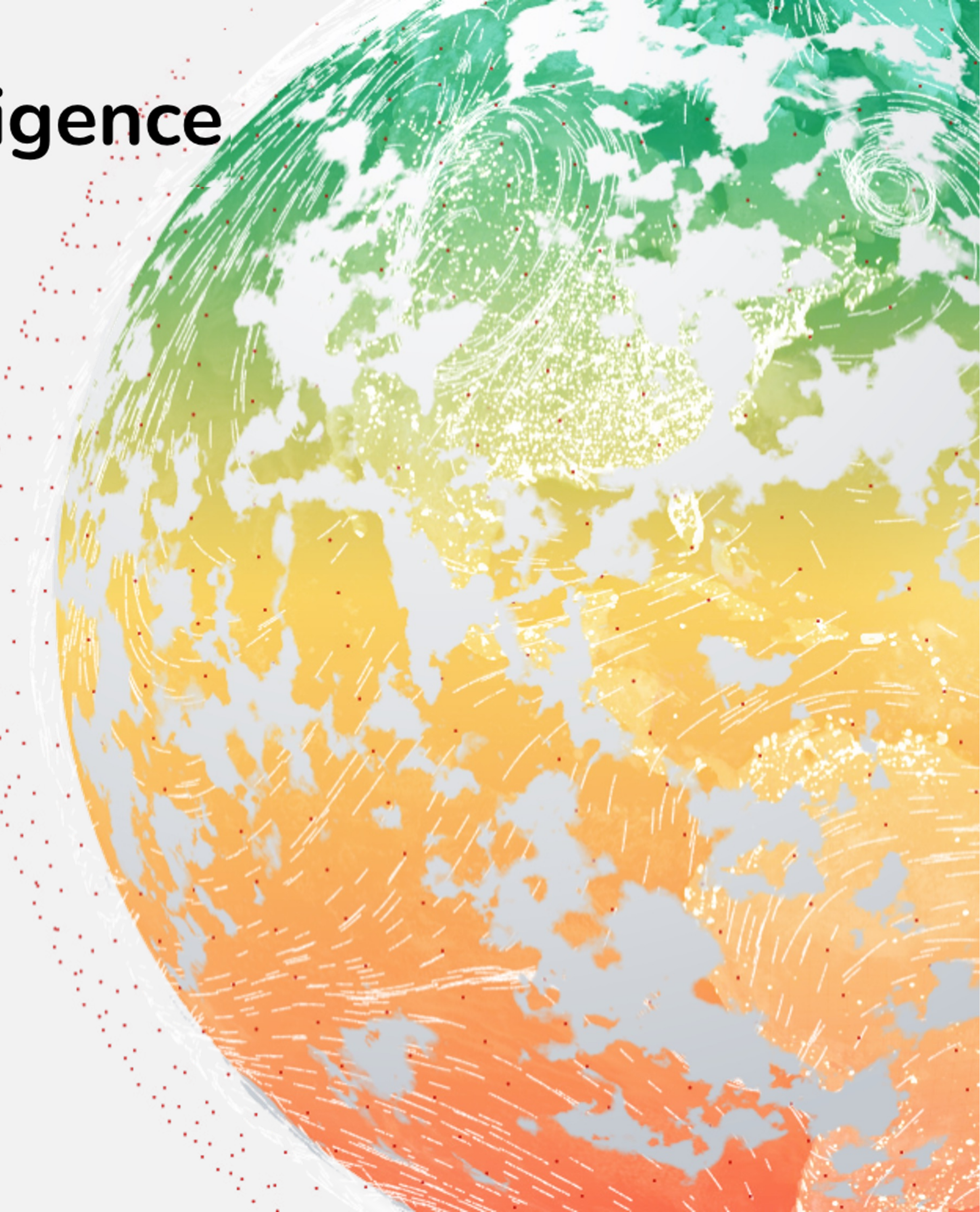
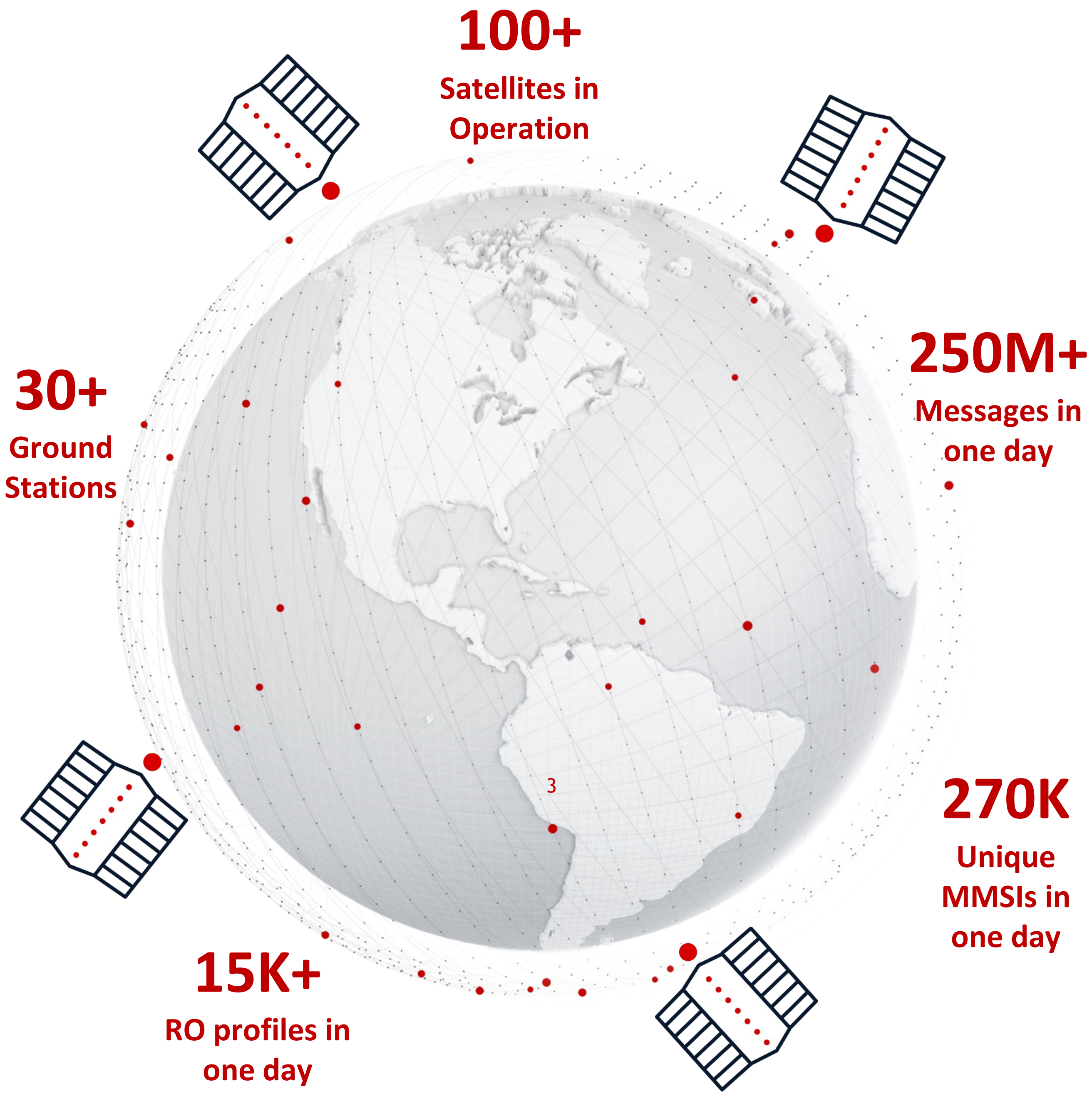


Spire Constellation

- The Low Earth Multi-Use Receiver (LEMUR) tracks maritime, aviation, weather, and more from space
- Our data provides a global view with coverage in remote oceanic and polar regions; all data can be refreshed within 15-minute cycles
- Continuously launching improved sensors and upgrading in orbit
- Turning ideas into live data from space in as little as 6-12 months



Spire Business Units

Satellite-driven global data products & space services

Maritime

Continuously refreshed information on the state of the global waterways leveraging the International Maritime Organization (IMO) Automatic Identification System (AIS) standard

Aviation

Near real-time aircraft movement data on civilian aircraft worldwide, following the Automatic Dependent Surveillance - Broadcast (ADS-B) standard

Weather

Precise space-based data, insights, and predictive analytics used to create highly accurate weather forecasting solutions to improve customer operations and safety

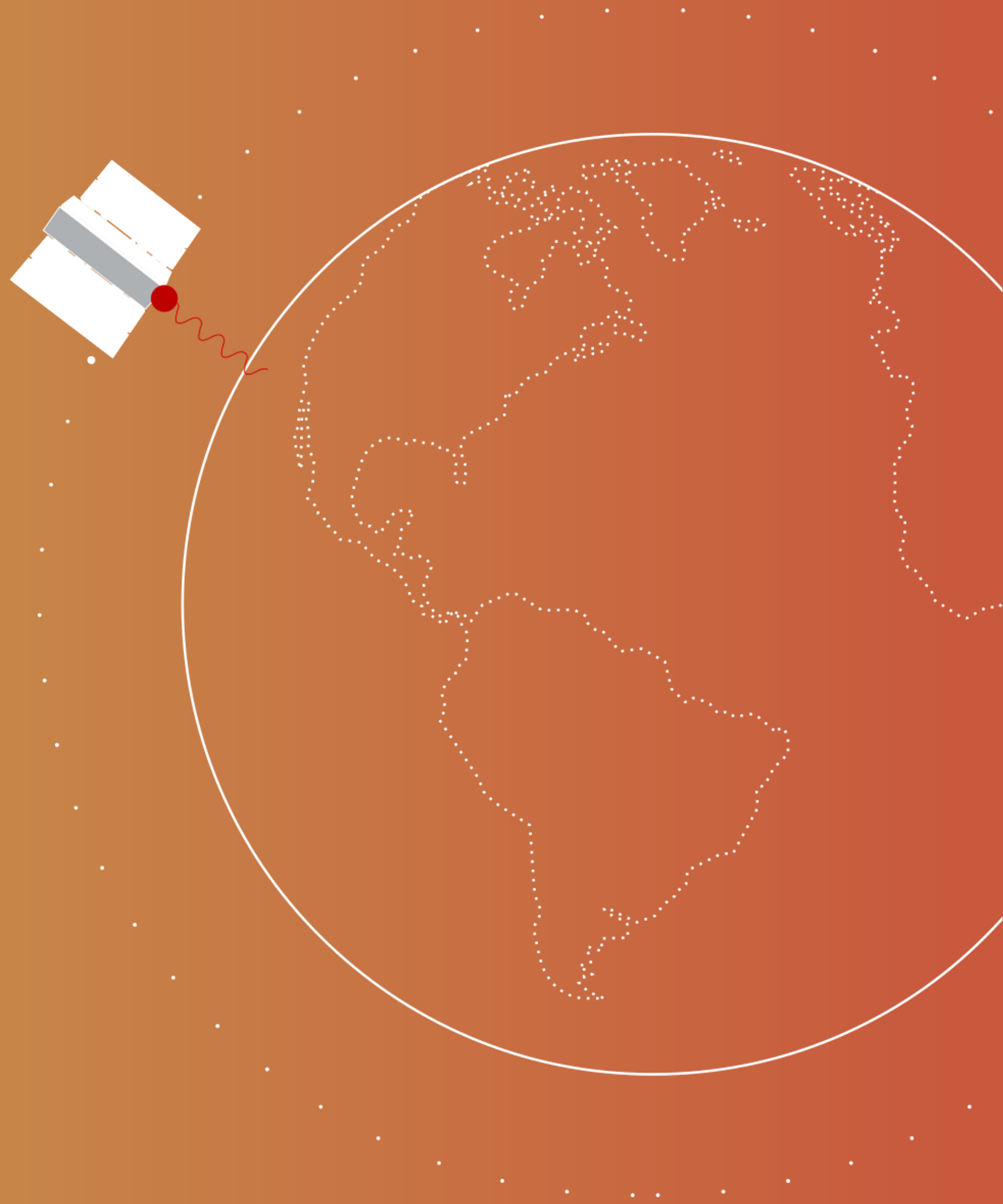
Earth Intelligence

Unique data sets of Earth's atmosphere and surface using GNSS-based remote sensing techniques such as radio occultation, reflectometry, and ionospheric electron density

Space Services

Access to Spire's proven LEMUR satellite platform and infrastructure for a wide range of customer-driven missions, API access, constellation management, and ground station network

Spire's GNSS-R constellation



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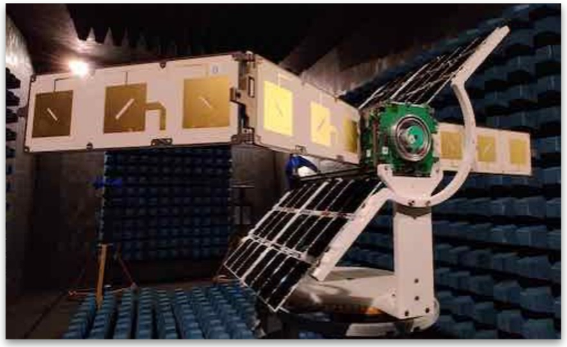
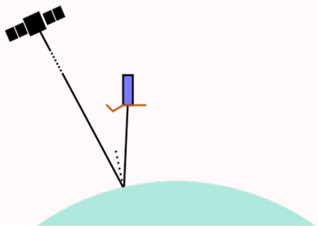
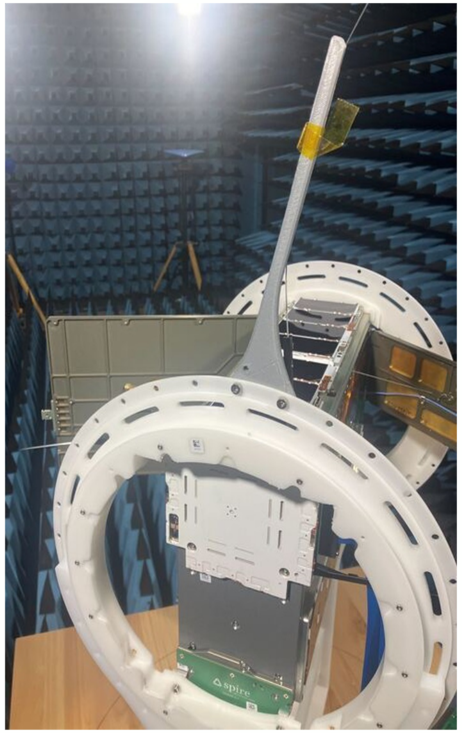
Spire GNSS-R Ocean Winds Status

- **Satellites:**
  - **Batch-1 in 2020:** 2 satellites in 37 deg inclination
  - **Batch-2 in 2021:** 2 satellites in SSO
  - **Batch-3 launching in 2023:** 3 satellites in SSO



- **Data Products:**
  - Level 1 (sigma-0 **`grbNRCS`**) 1 Hz Delay Doppler Maps (DDMs)
  - Level 2 (ocean wind speed and mean-squared-slope **`gbrOcnm`**)





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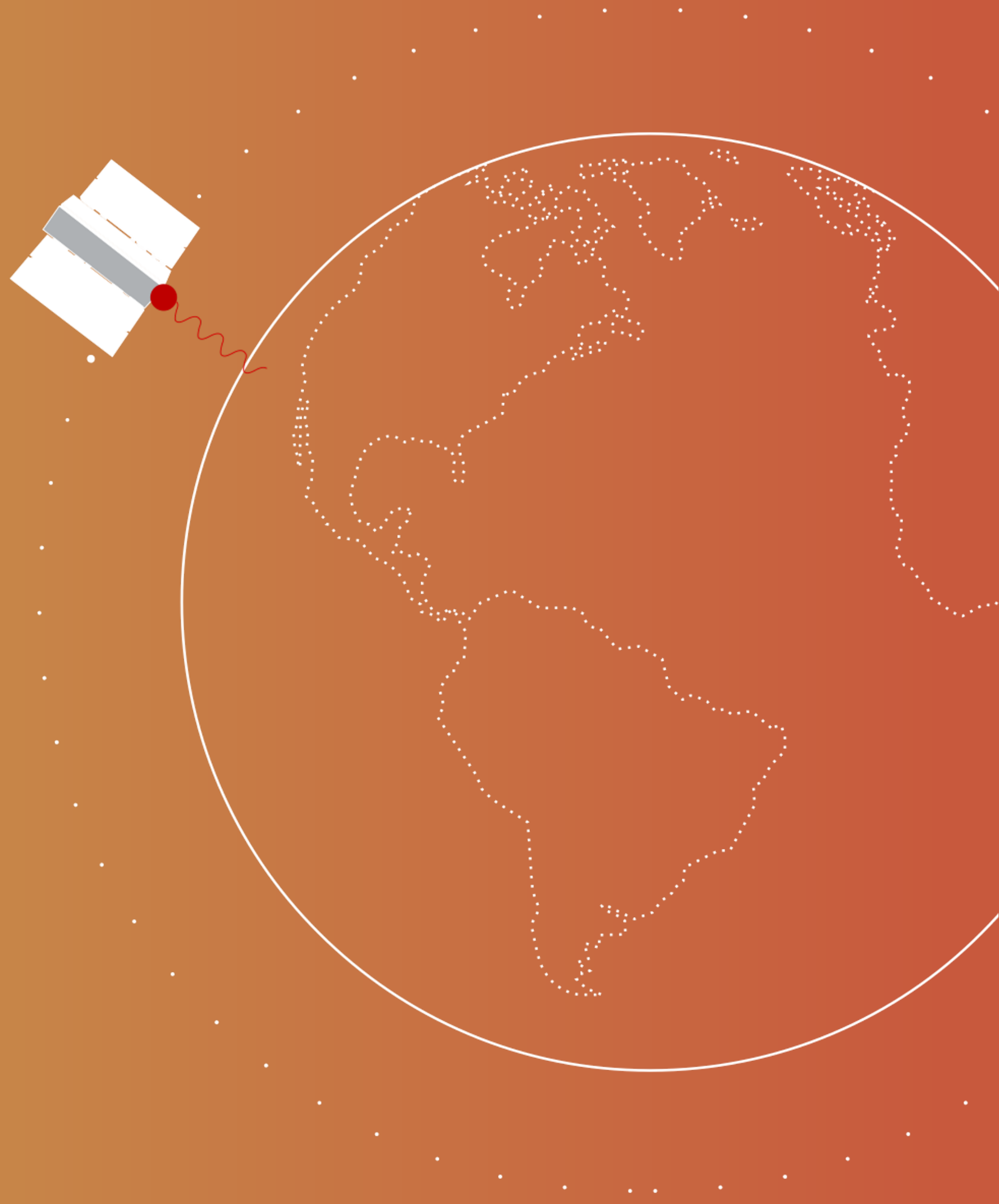
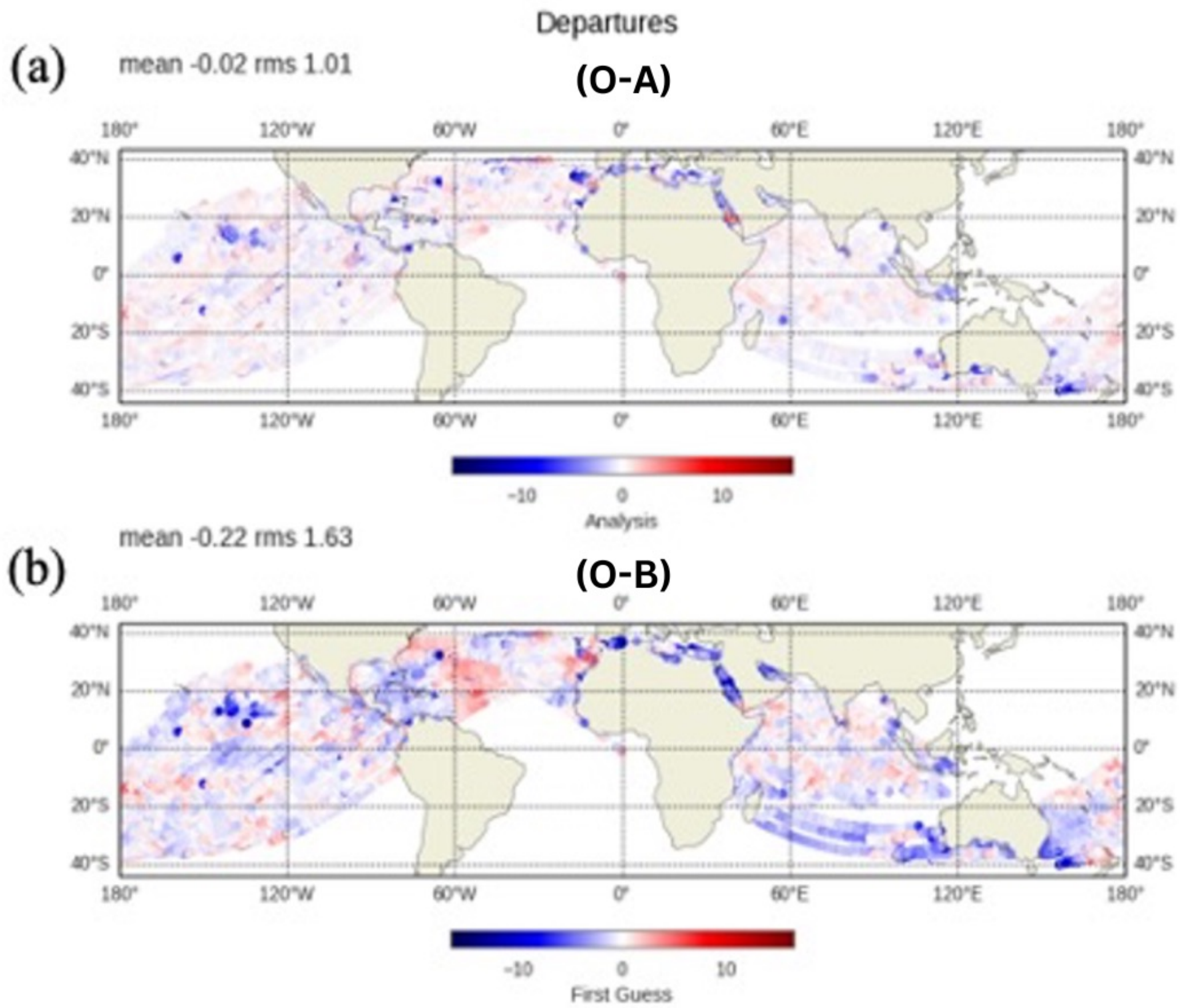
CYGNSS L2 ocean wind speed assimilation



CYGNSS and Spire L2 Surface Ocean Wind Speed Assimilation

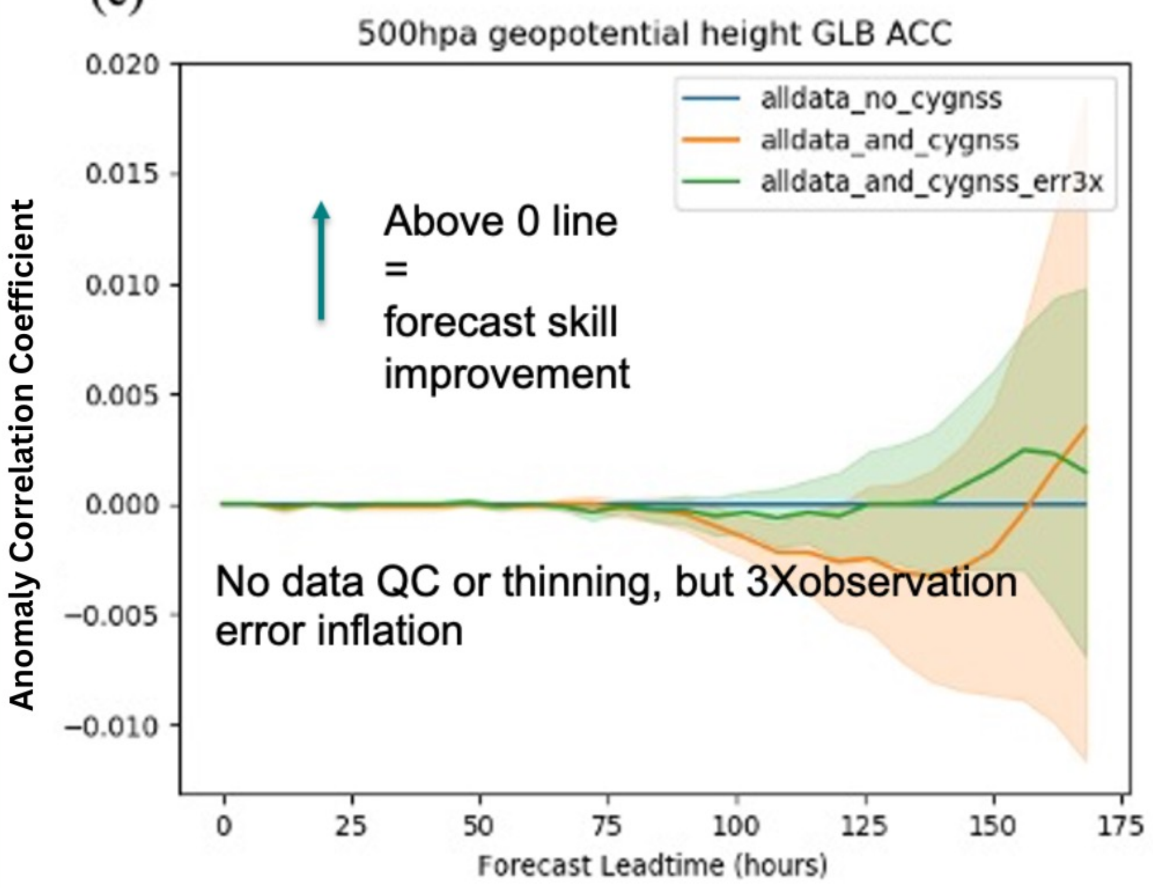
- Spire's operational GSI-based DA system assimilates CYGNSS L2 ocean surface wind speed (v3.1) and recently, Spire's L2 ocean wind speed
- Impact assessment experiments in a UFS-FV3-based global forecast model
- Replicating Spire's operational conditions (conventional, satellite radiances, and GNSS-RO)
- Assimilating CYGNSS produces realistic shapes and magnitudes of (a) (O-A) and (b) (O-B) along CYGNSS tracks with a magnitude reduction on analyses residuals



CYGNSS and Spire L2 Surface Ocean Wind Speed Assimilation

- CYGNSS L2 wind speed retrievals, if assimilated without thinning, superobing, or inflating observation errors could overwhelm the data assimilation system and ultimately degrade forecast performance
- Initial results with observation error inflation (by a factor of 3) used as a simple mitigation measure resulted in an overall improvement of global forecast skill as seen in Anomaly Correlation Coefficient (ACC) scores for geopotential height at 500 hPa (Figure 1c) at the 95% confidence level.
- Improved observation error treatment and QC are expected to maximize global forecast skill.

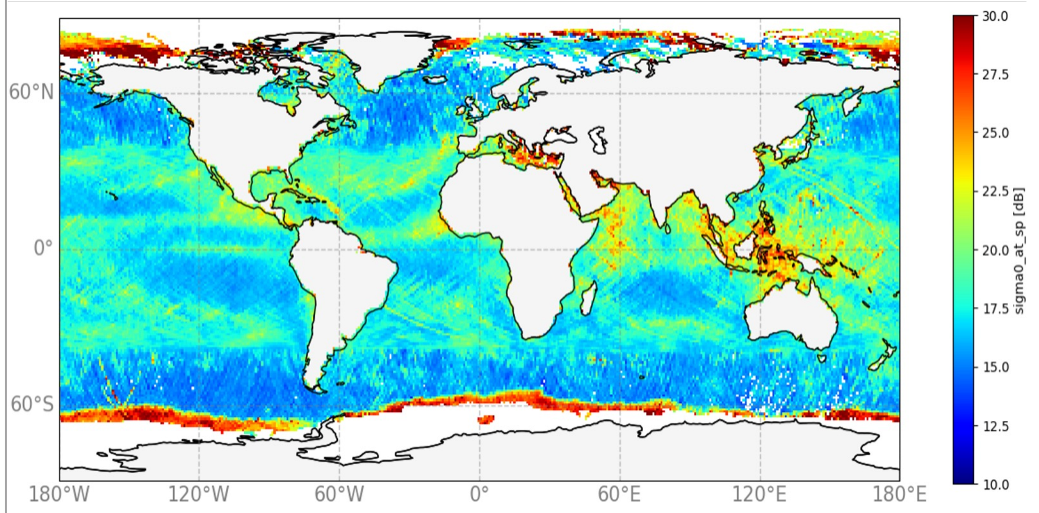
(c)



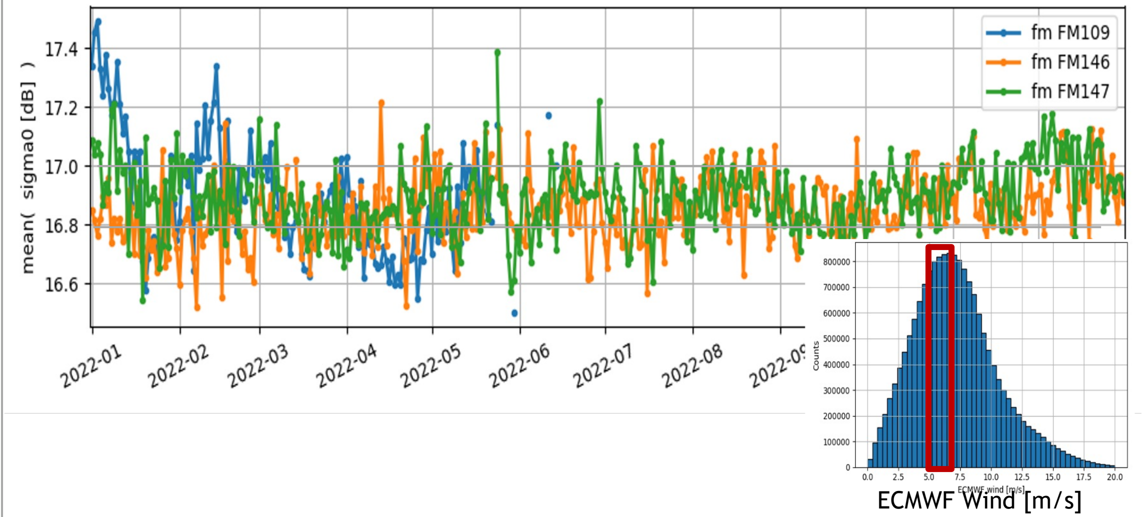
Spire differentiators compared to CYGNSS

- **Global coverage:**
  - Spire has satellites in polar orbits giving coverage beyond CYGNSS's +/- 40 deg latitude
- **Multi-GNSS receiver:**
  - More observations per receiver using GPS, QZSS, Galileo, Beidou
- **Relative calibration:**
  - Compensates for transmitter power variation, non-linearities in the radio receiver, different transmitter constellations
  - Long-timescale calibration stability to 0.2 dB sigma-0 bias
- **Low latency:**
  - Utilises Spire's ground station network and mature GNSS-RO ground processing to allow low latency

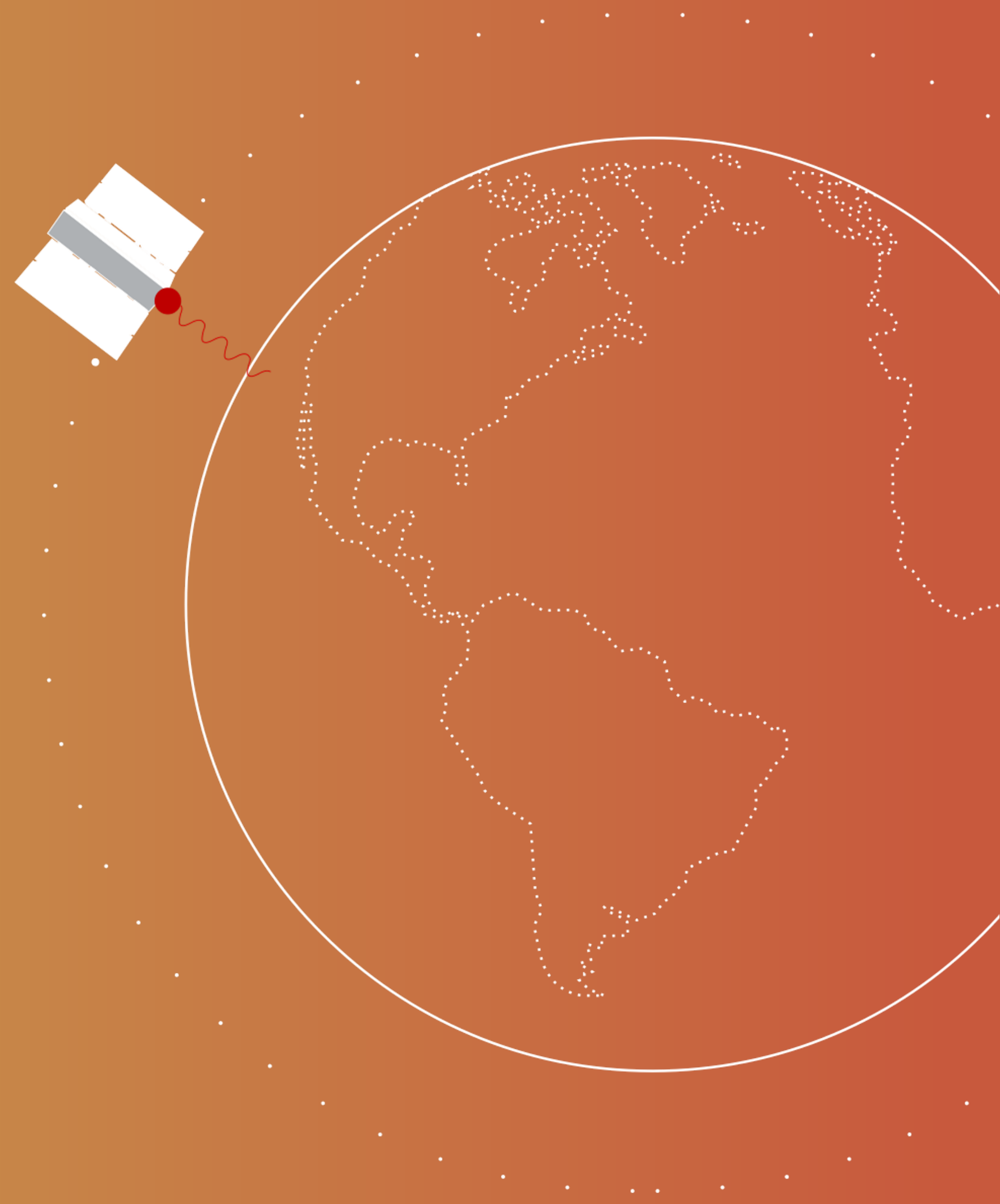
Level 1 sigma-0 Gridded mean at 100 km



Daily averaged sigma-0 filtered to ECMWF U10 5-7 m/s



Physics-based DDM operator



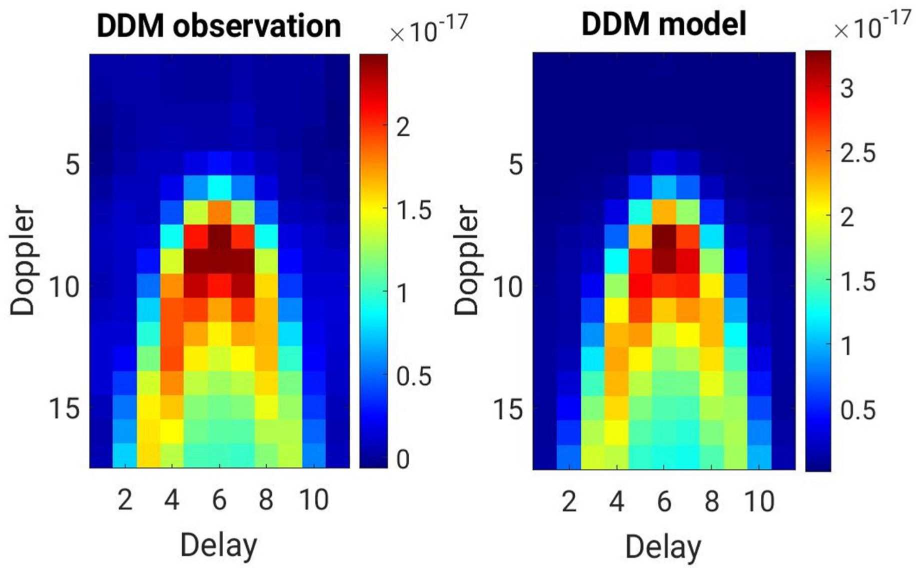
CYGNSS DDM Physics-Based Forward Operator in GSI or JEDI

Equations (from Huang et al. 2021):

- $P_{DDM}(\tau, f) = h(\tau, f, x) + v(\tau, f)$ is an unbiased measurement; $h(\tau, f, x)$ is the modelled DDM; x is a vector of wind speed values in lat, lon at the ocean surface, resolution of x is 0.125° degrees; v is the measurement error

- DDM is power measurement as a function of time delay and frequency

- For $h(\tau, f, x)$ we use Zavorotny and Voronovich, 2000



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DDM forward operator flow

The diagram below shows the general flow of the CYGNSS E2ES DDM operator, similar sequential processes can be applied to the DDM forward operator in JEDI. Naturally, this is also what the Huang et. al 2021 work (available at Code Ocean) is based on.

user config file
load input files
load user defined parameters → **Initialize DDM**

CYGNSS & GPS orbits
(IODA metadata) → **Find Specular Point (SP)**

Model wind fields
Antenna patterns → **Get Parameters Over SURF Grid:**
- Wind -> MMS field -> NRCS
- Antenna Gain
- Delay and Doppler values
- Scattering Angle
- etc

Calculate Scattered Fields on SURF
(complex algebra with speckle)

Update phase on surface to account for motion

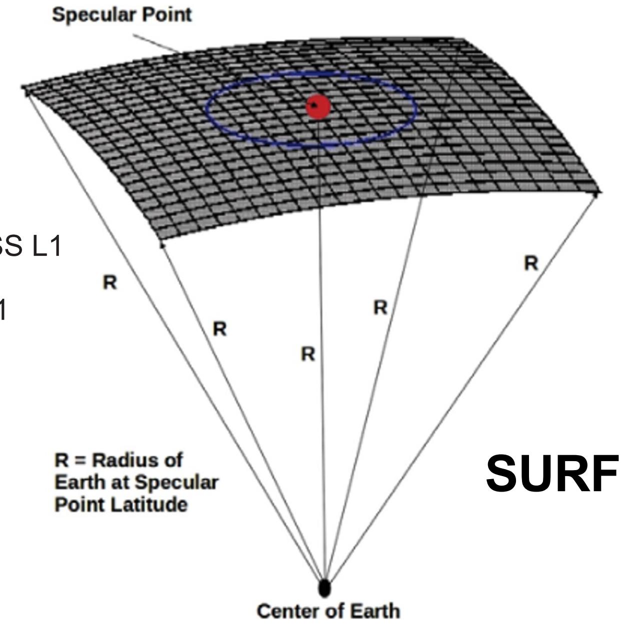
1 ms product → **Map Surface Fields to DDM**
Add thermal noise
Convolve with ambiguity function ↔ **Use external FFTW library for convolution**

1 s product → **Non-Coherent Averaging**

Inputs

- Geometry, Metadata, Power are all from CYGNSS L1
- Receiver and antenna patterns for CYGNSS v3.1
- Wind field: from background at model resolution
- Empirically calculated mean sea square slope

Geometry



SURF

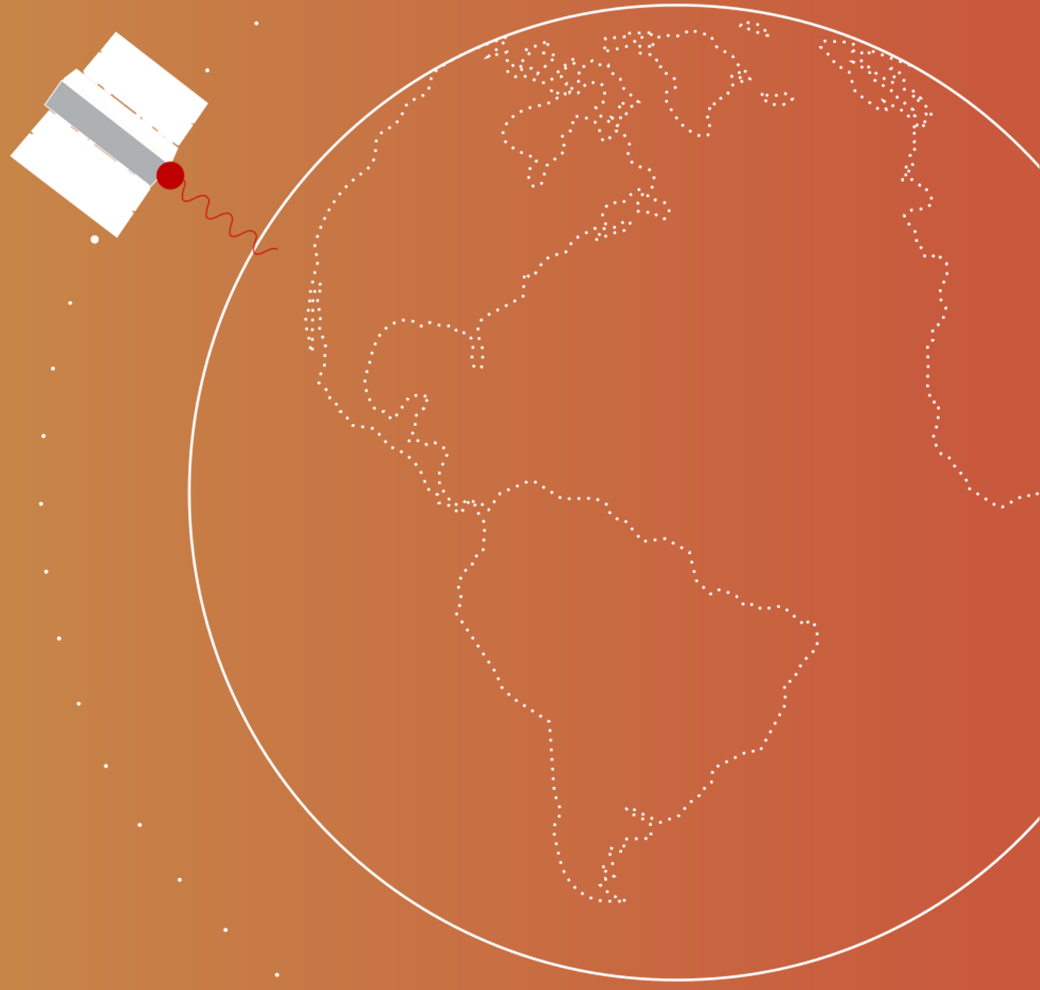
Figure 5: Surface grid.

Source: CYGNSS Handbook, Chris Ruf et al.

CYGNSS L1 variables interpolated to a surface area grid surrounding a specular point

Based on http://cygnss.engin.umich.edu/wp-content/uploads/sites/534/2021/07/148-0123_CYGNSS_E2ES_EM.pdf

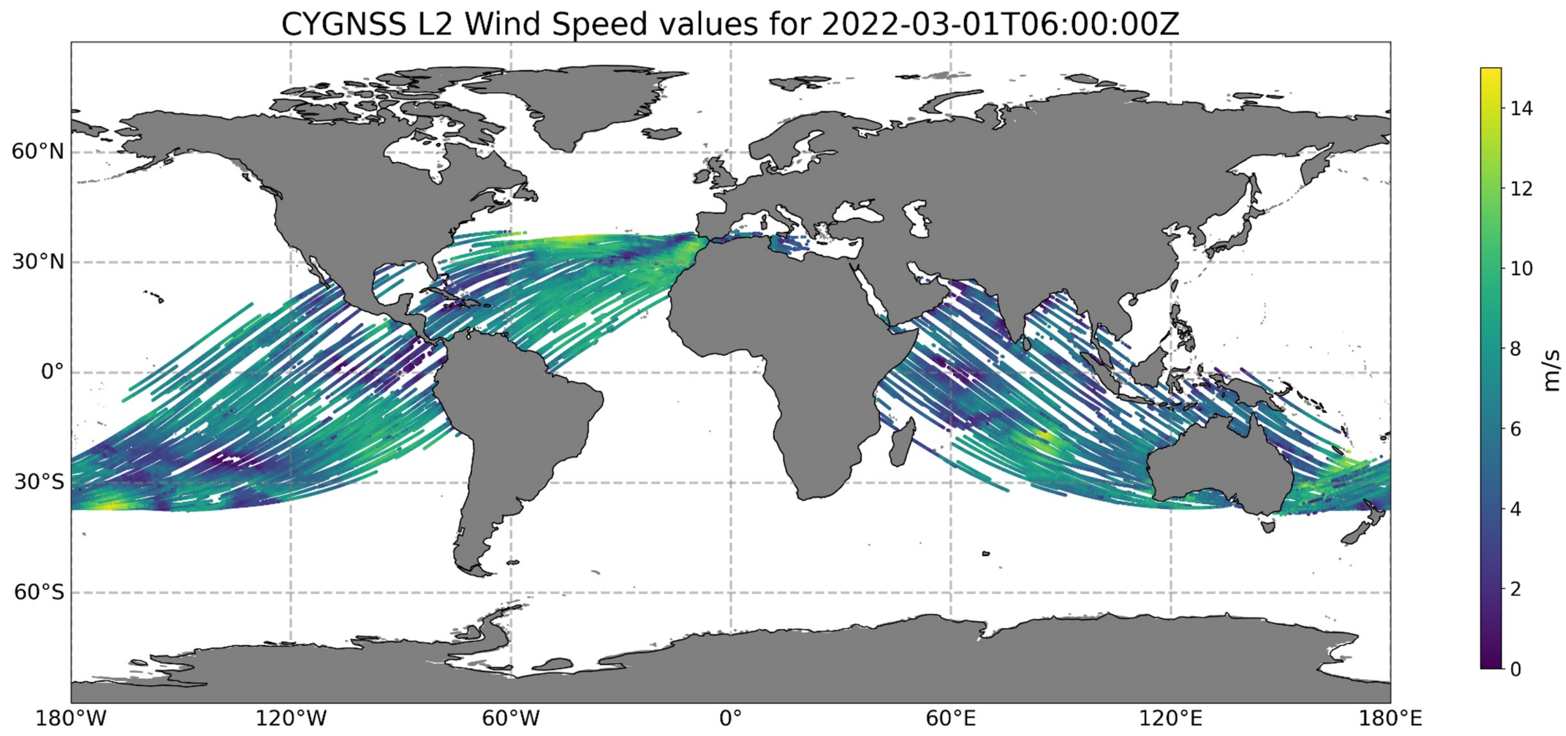
IODA and BUFR format converters: Ocean wind speed and Doppler Delay Maps



CYGNSS L2 IODA-Converter implementation

To allow for larger DA community to benefit from this work we also have coded CYGNSS L2 IODA converter:

- **Wind speed:** the main observable (value, error, bias, and PreQC)
- **Receiver/Transmitter metadata:** positions and velocities
- **Diagnostics:** quality flags, CYGNSS files used to produce IODA file
- QC retains ~90% of data
- 6h DA window contains around ~300’000 observations.



Similar processing done for NCEP’s BUFR format

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CYGNSS L1 IODA clean data coverage for FM04

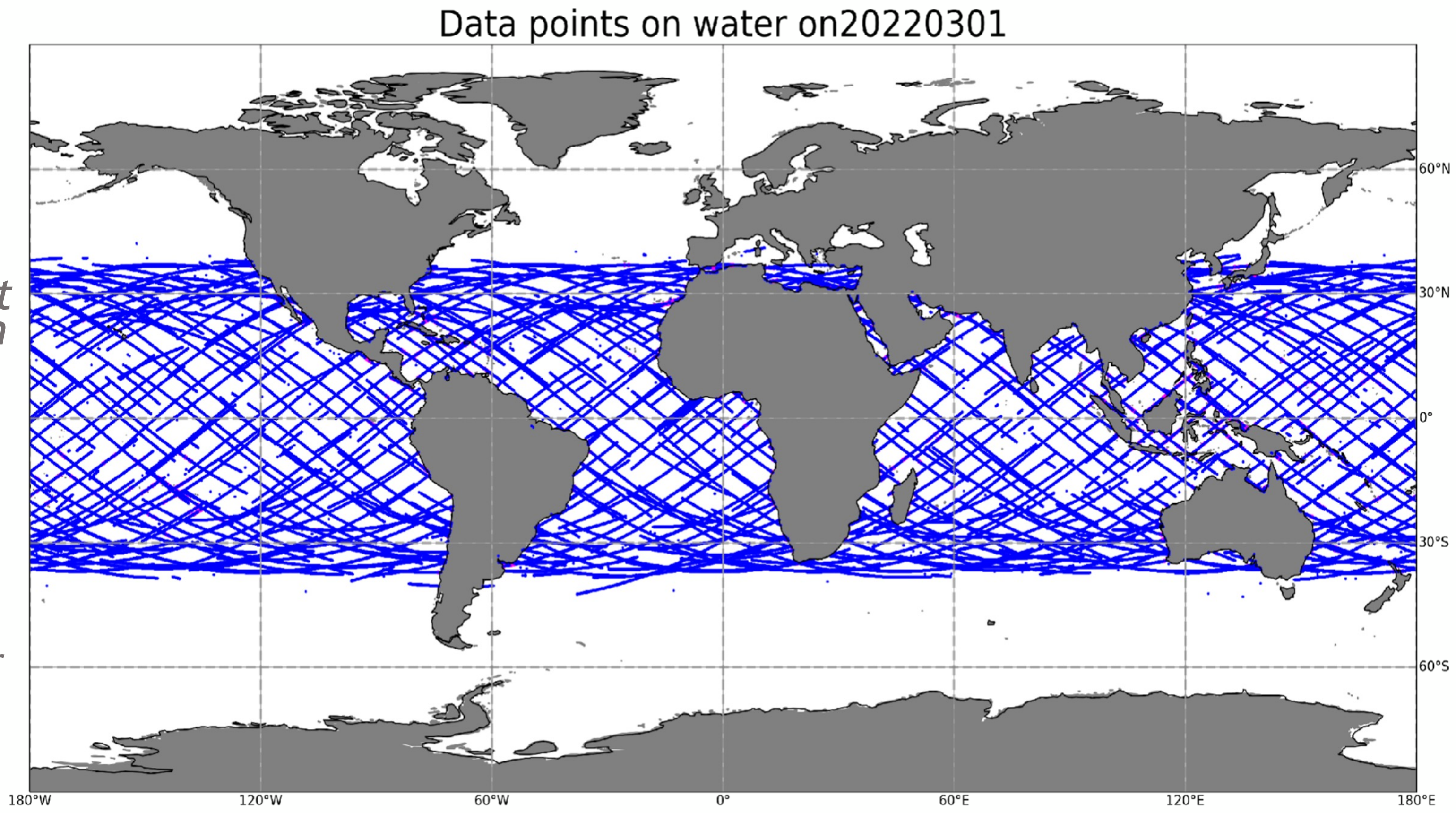
We start with 'best quality' data selection with the following QC:

- CYGNSS Quality Flags = 0
  Removes data from over/near land, satellite has attitude rotation larger than 1deg, the transmitter power has a high uncertainty or there are some calibration issues

- Incidence angle <= 60 deg
  Data with incidence angle > 60 deg can result in glistening area larger than 120km x 120km and cannot be modelled accurately by the forward operator

- DDM SNR > 3dB
  DDMs with SNR < 3 dB indicated high power noise and hence not informative DDM

- RMS ratio of power analog > 2
  Captures other DDMs where maximum power is not well differentiated from the rest of the DDM



Similar processing done for NCEP BUFR data format

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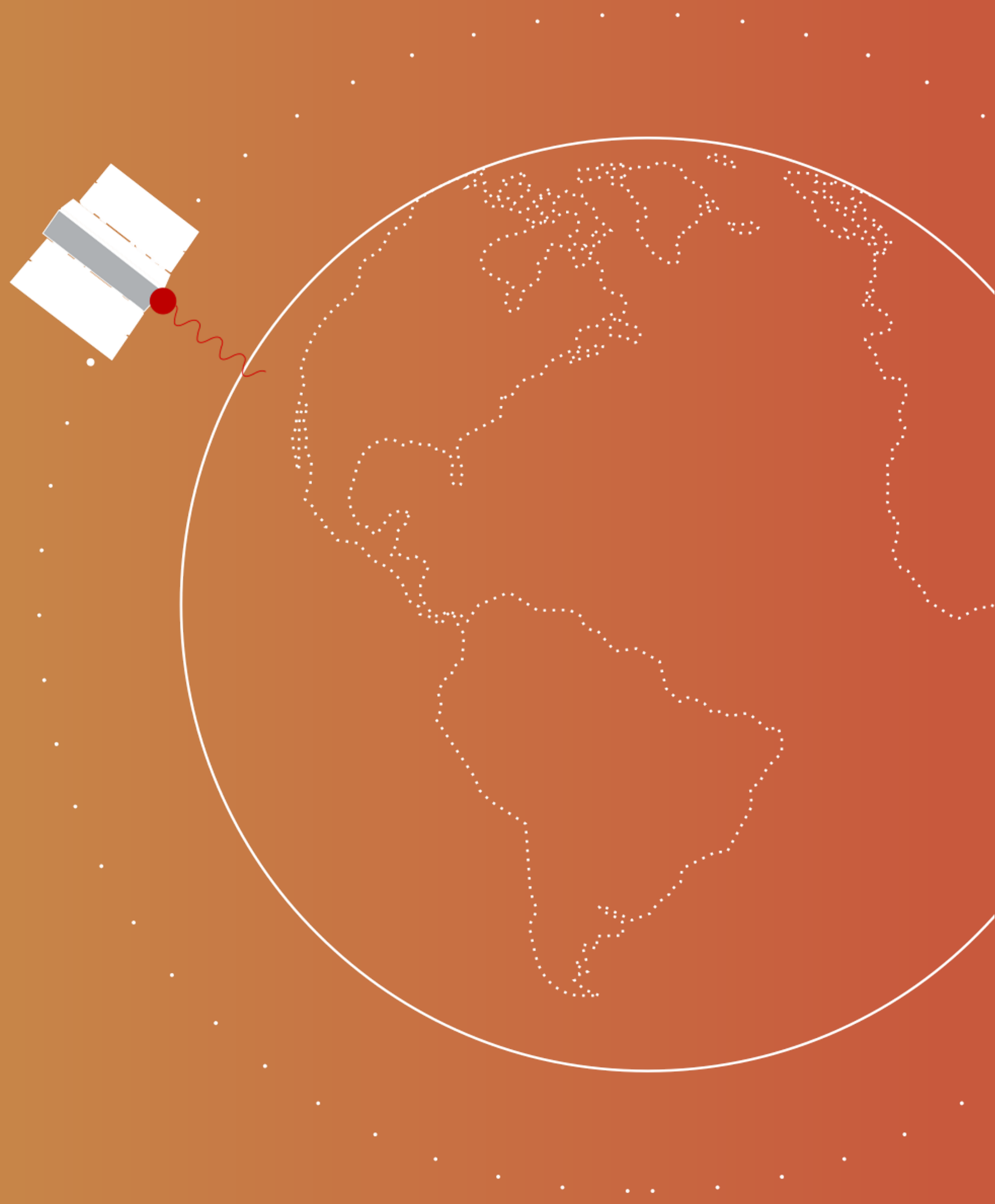
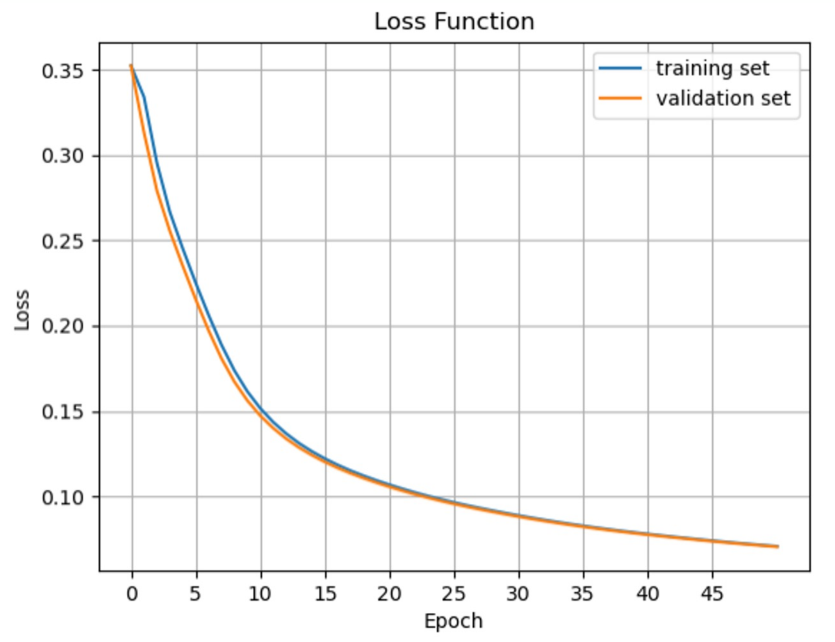
Machine learning - based DDM operator

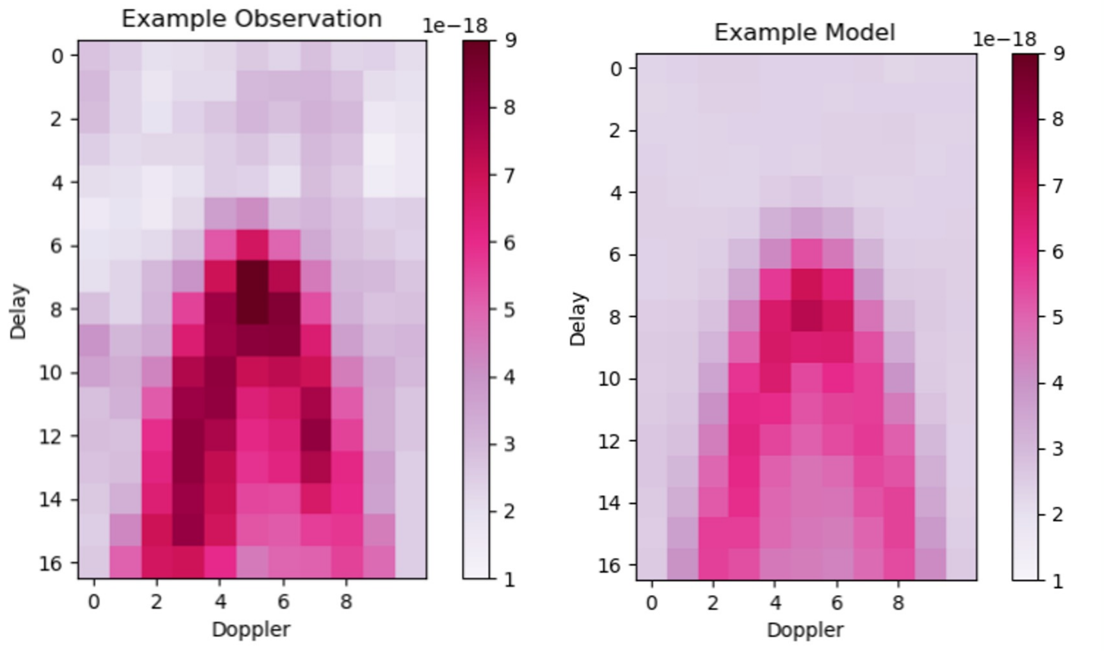


CYGNSS L1 Machine Learning operator

- We have generated a preliminary training dataset using the NASA CYGNSS L1a DDM files, the ECMWF 10m zonal and meridional wind analyses, with data from February 2022 to December 2022.
- The wind and wave height fields are interpolated around DDM observations so that the ML operator uses a model-native grid.
- An initial version of the ML operator has also been developed and trained.



The loss $\Sigma((y_{obs}-y_{model})^2)$ of the training and validation sets (observations are standardized)



An example DDM observation, and the neural network model of that observation.

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Next Steps

- Conduct global/regional forecast impact with assessment Spire L2 ocean speed observations
- Finalize L1 DDM operator development in GSI and conduct global forecast impact assessment experiment
- Public dissemination of GNSS-R IODA data converters and forward operators for community testing of CYGNSS and Spire’s data
- Alignment with NASA’s Commercial Smallsat Data Acquisition (CSDA) Program
- Optimize ML operator architecture and compare the impact of the ML and physics-based operators

References

- Huang, F., Garrison, J.L., Leidner, S.M., et al., 2021: Assimilation of GNSS reflectometry delay-Doppler maps with a two-dimensional variational analysis of global ocean surface winds. *QJR Meteorol Soc.*, **147**, 2469-2489, https://doi.org/10.1002/qj.4034.
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- Zavorotny, V.U., and Voronovich, A.G., 2000: Scattering of GPS signals from the ocean with wind remote sensing application. *IEEE Trans. Geosci. Remote Sens.*, **38**, 951–964.

Thank you!

From our team, to yours.