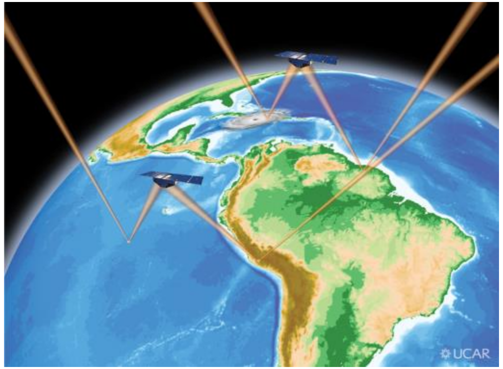


Remote Sensing of the Earth's Atmosphere and Surface Using Global Navigation Satellite System Radio Signals

J. Weiss, B. Kuo, J. Zhang

Seminar at City College of New York

October 31, 2024

Outline

- Introduction to UCAR/NCAR and the COSMIC Program
- Introduction to GNSS radio occultation (RO)
- RO tropical cyclone prediction
- Introduction to GNSS-R
- Soil moisture and flood inundation from GNSS-R

UCAR and COSMIC Introduction

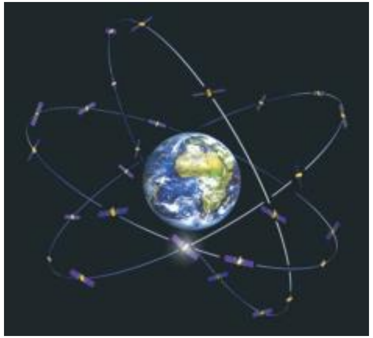
- University Corporation for Atmospheric Research (UCAR)
- A consortium of 131 North American universities
- Founded in 1960 to create, operate, and manage National Center for Atmospheric Research (NCAR) on behalf of National Science Foundation and the universities
- ~1400 staff including ~800 scientists and engineers
- Science, computational and observational facilities, huge data sets, high-end numerical models of the sun, atmosphere, oceans, coupled climate system
- COSMIC Program
  - Constellation Observing System for Meteorology, Ionosphere, and Climate
  - ~30 scientists, engineers, programmers, IT, support staff
  - Expertise in ground and space GNSS processing, radio occultation, reflections, spacecraft integration/testing, atmospheric, space weather, and climate science

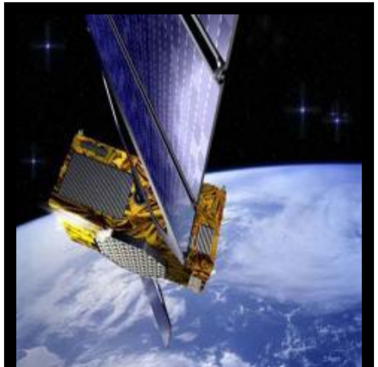
Global Navigation Satellite System (GNSS)

- Today, multiple GNSSs provide navigation signals globally
  - GPS (USA), GLONASS (Russia), Galileo (Europe), BeiDou (China)
  - There are additional regional navigation systems as well (e.g. IRNSS, QZSS)
- We currently process GPS, GLONASS, Galileo, BeiDou data

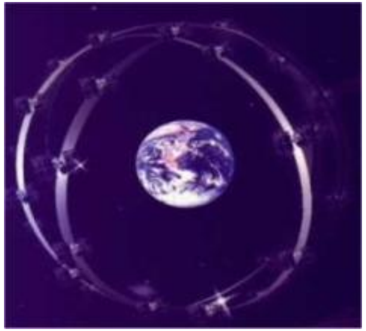
GPS

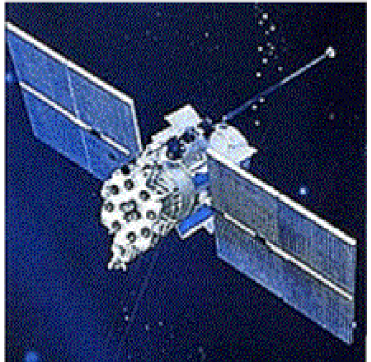
Galileo



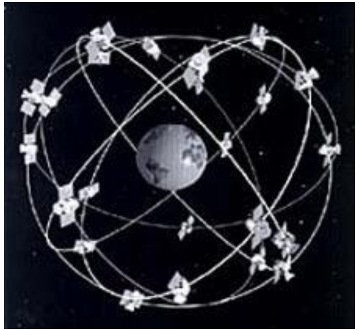


GLONASS



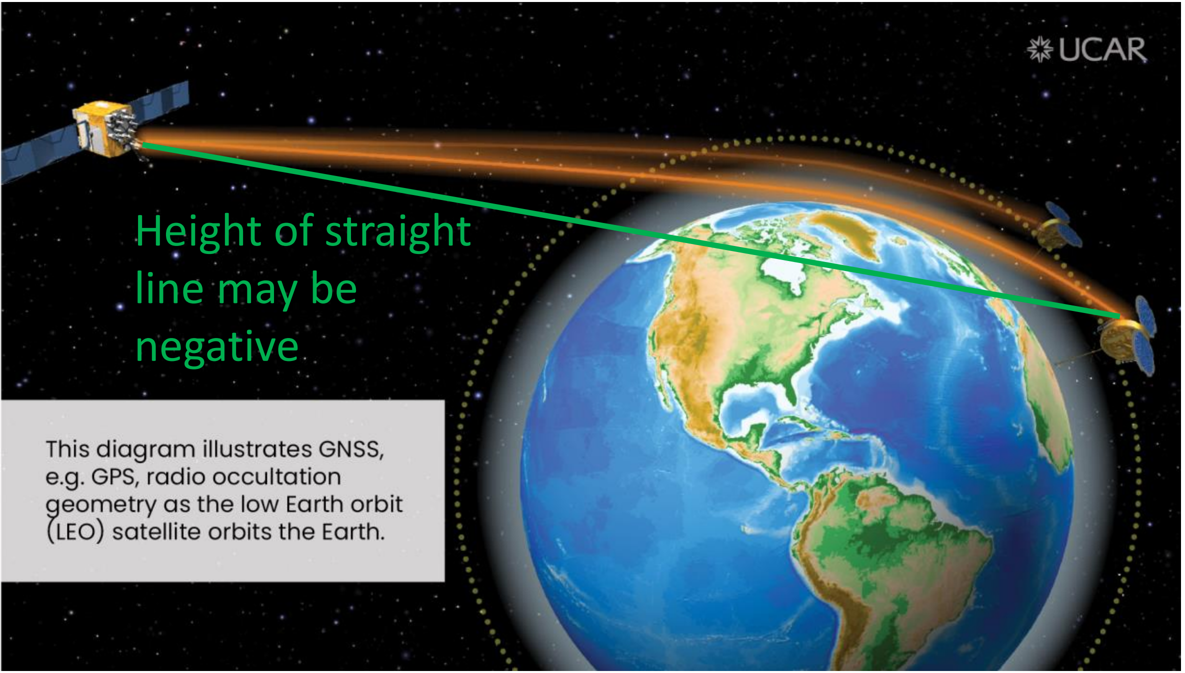


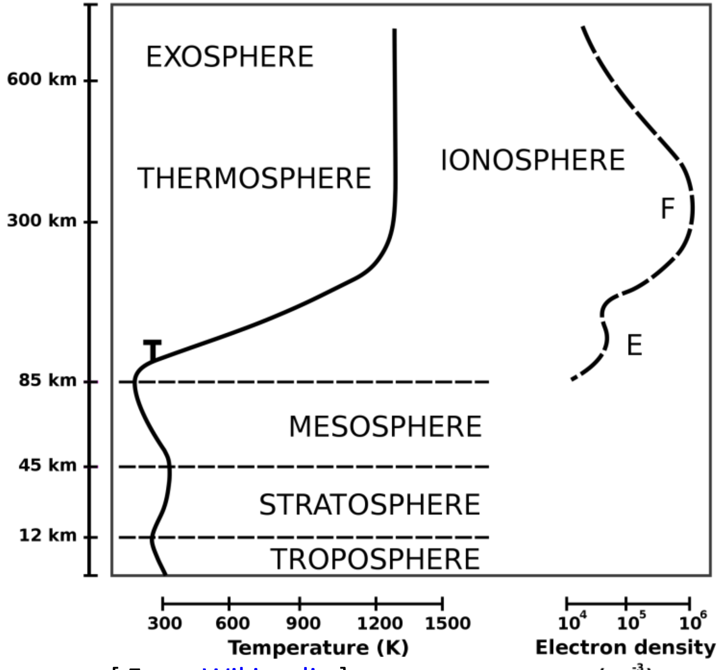
BeiDou



Introduction to Radio Occultation (RO)

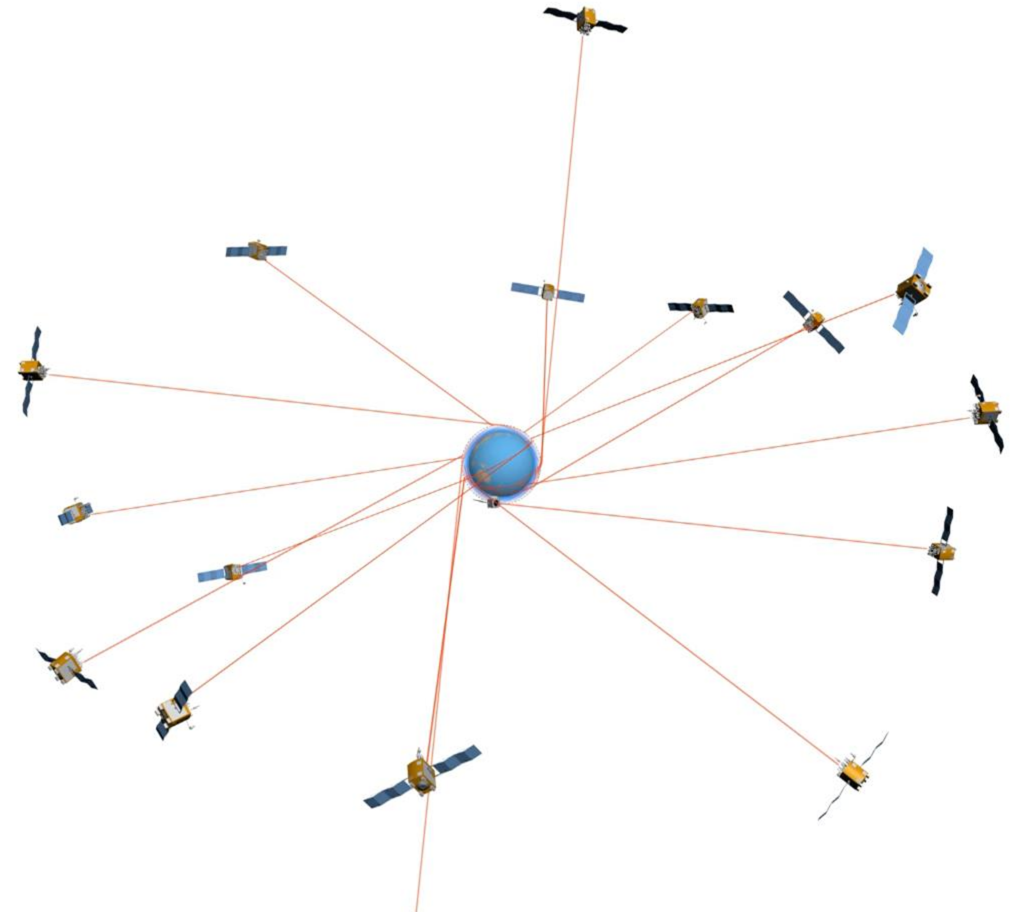
- Radio occultation (RO) technique looks at bending of radio waves traversing an atmosphere
  - First applied to planetary atmospheres by teams at JPL and Stanford University with Mariner IV spacecraft (Kliore et al., 1965)
- COSMIC, NASA, NSF first demonstrated technique on Earth with GPS/MET mission in 1995
  - Utilizing open Global Navigation Satellite System (GNSS) signals





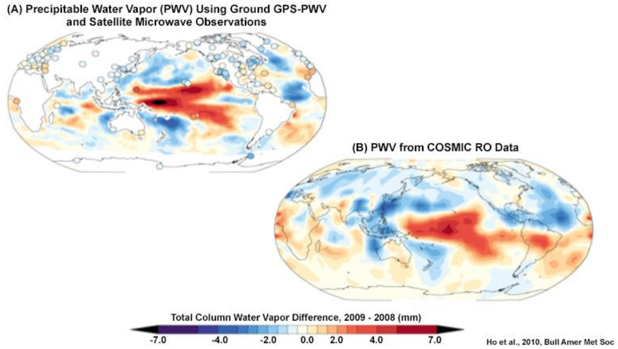
[From Wikipedia]

Introduction to Radio Occultation (RO)

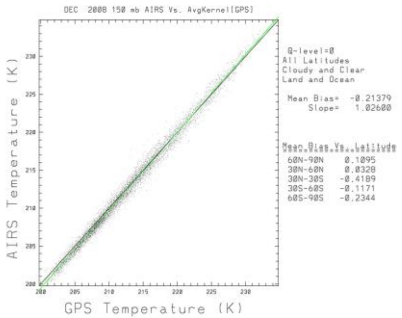


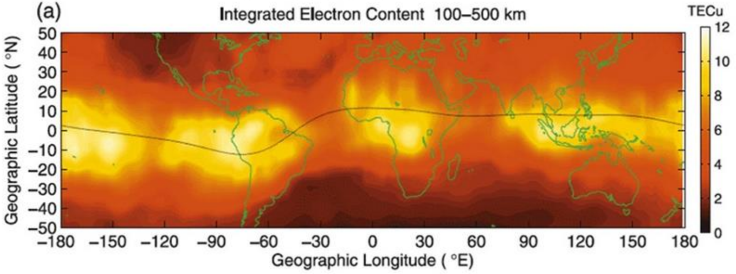
Scientific Uses of RO Data Products

- Weather
  - Improve global weather analyses, particularly over data sparse regions such as the oceans, tropics, and polar regions
  - Increase accuracy of numerical weather model forecasts
  - Improve understanding of tropical, mid-latitude and polar weather systems and their interactions
- Climate
  - Monitor climate change and variability with unprecedented accuracy – “World’s most accurate, precise, and stable thermometer from space!” (Rick Anthes)
  - Evaluate global climate models and reanalyses
  - Calibrate infrared and microwave sensors and retrieval algorithms
- Ionosphere and space weather
  - Observe global electron density distribution and total electron content
  - Monitoring of scintillation (e.g. equatorial plasma bubbles, sporadic E clouds)



Ho et al., 2010, Bull Amer Met Soc

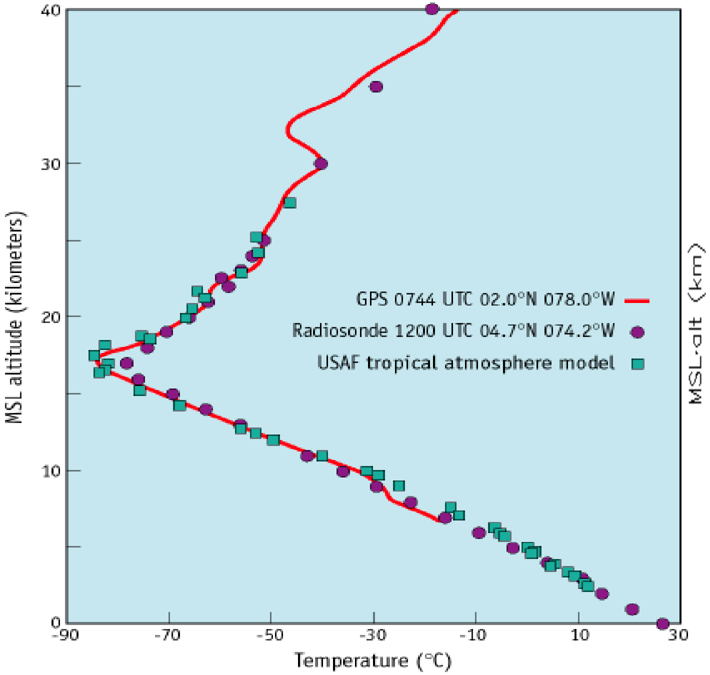


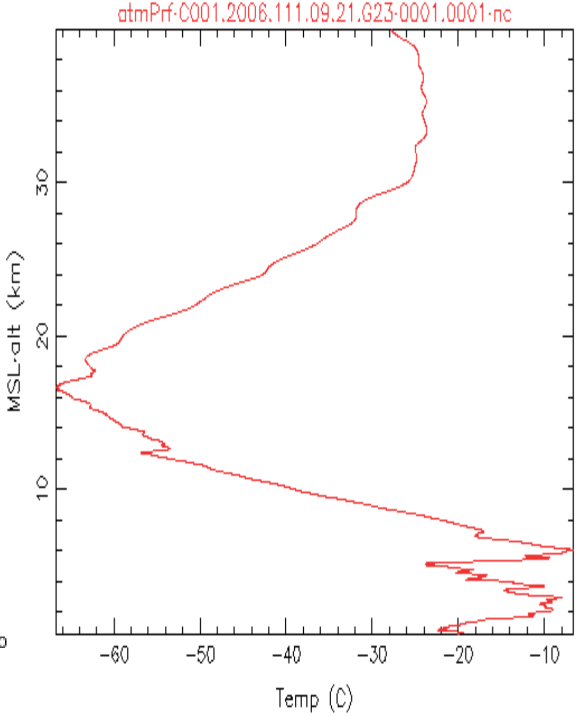


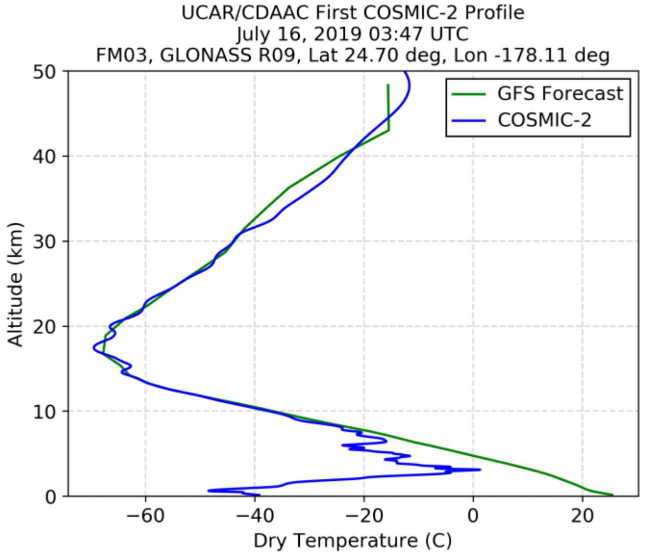
Lin et al, Geophys. Res. Lett., 2007

First Radio Occultation Profiles by Mission

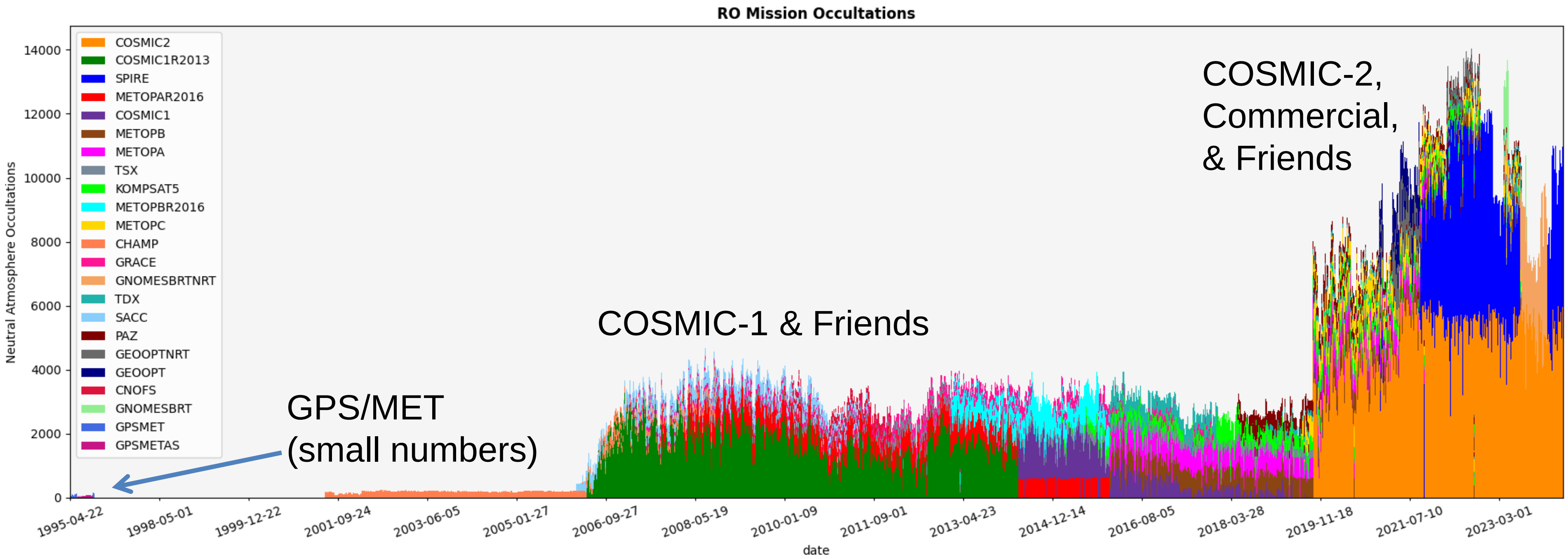
GPS/MET	COSMIC-1	COSMIC-2
First GPS RO sounding of Earth UCAR, April 16, 1995	First sounding April 21, 2006	First sounding July 16, 2019







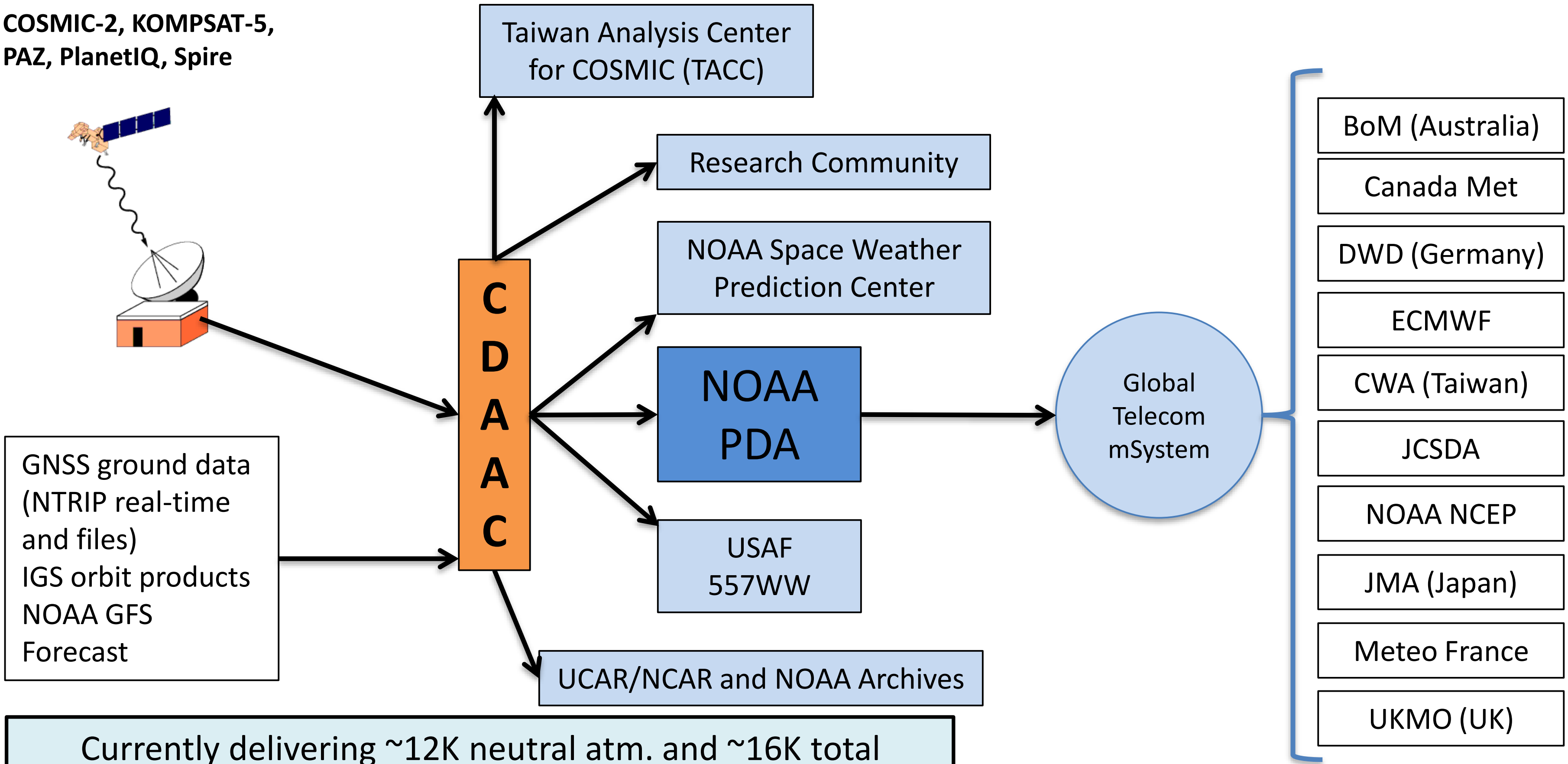
RO Missions Processed at UCAR



- Public repository at data.cosmic.ucar.edu
  - Simple https downloads, daily tar file by mission and file type
- Data descriptions, file formats at this link

Courtesy M. Perrotta, UCAR

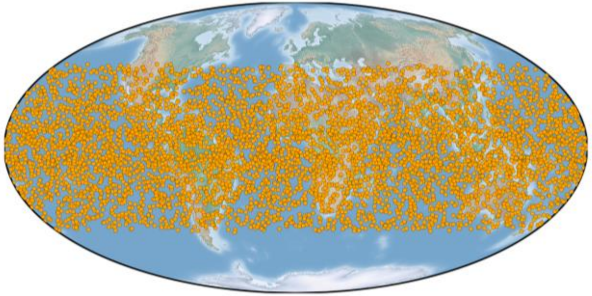
Near Real-Time (NRT) Operations

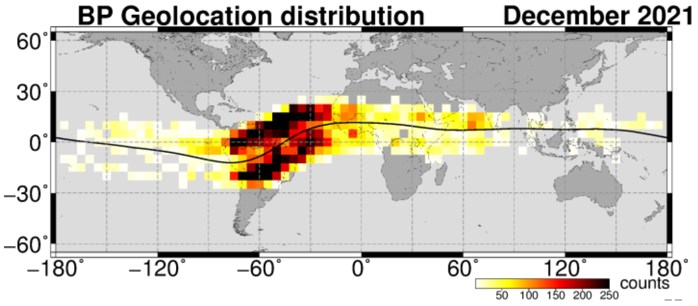


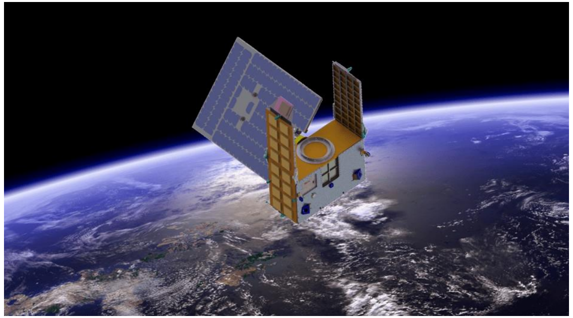
Currently delivering ~12K neutral atm. and ~16K total electron content products daily in near real-time

FORMOSAT-7/COSMIC-2

- US/Taiwan partnership (NOAA, USSF, NASA, NSF, TASA)
- Spacecraft constellation
  - Launched June 25, 2019
  - 6 satellites, orbit inclination 24 deg, altitude ~520 km
  - Final orbit configuration reached in March 2021
- Payloads
  - JPL/BRE GNSS payload is primary
    - GPS and GLONASS tracking
  - Secondary payloads are ion velocity meter (IVM), tri band RF beacon, laser retro reflector
- All neutral atm. and ionosphere products routinely produced, except IVM drifts
  - 172 TB served to public in 2022
- Neutral atm FOC reached 9 month after launch
- Achieved several "firsts" for RO
  - GLONASS radio occultation for neutral atm and ionosphere
  - Demonstrated GPS & GLONASS absolute total electron content accuracy < 3 TECU
  - Scintillation geolocation and all-clear
  - Under 30 min (median) product latency

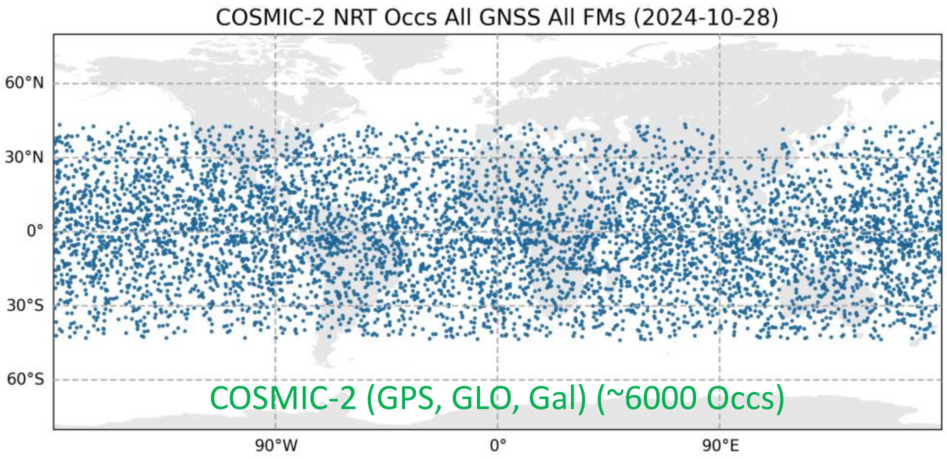


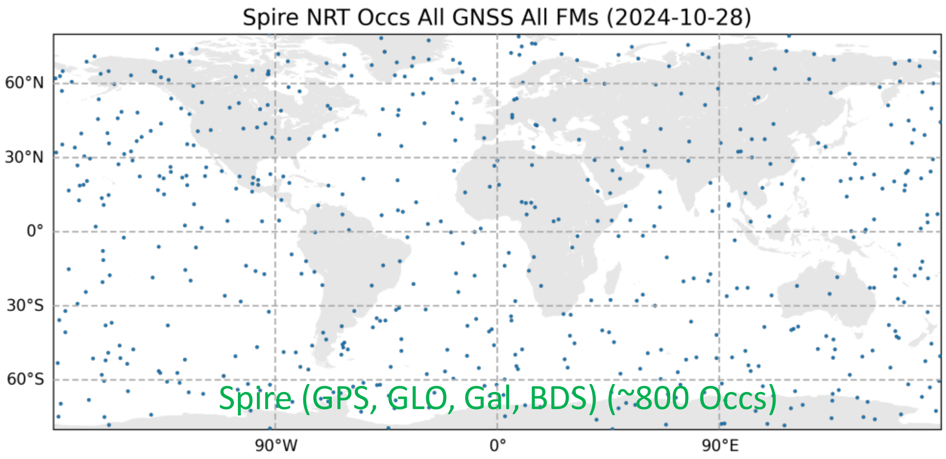


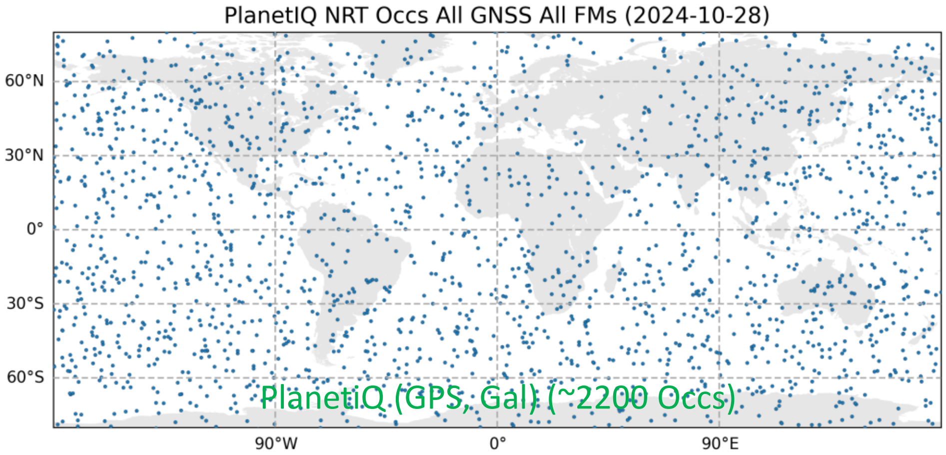


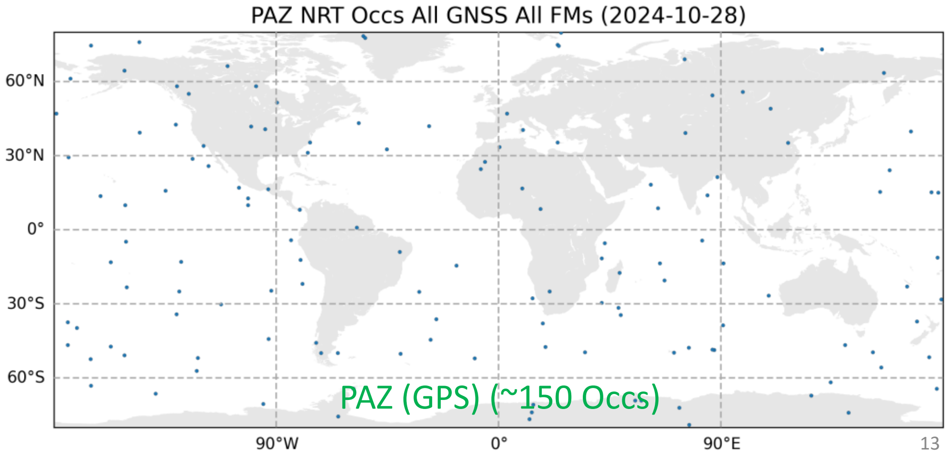
- GeoOptics
  - 3 6U satellites
  - Cion (TGRS heritage) GNSS receiver
  - Single POD and 2 RO antennas
- Planet IQ
  - 2 6U satellites
  - PlanetIQ developed GNSS receiver
  - 2 POD and 2 RO antennas similar to C2
- Spire
  - 60+ 3U satellites processed
  - Spire developed GNSS receiver
  - Single POD and 1-2 RO antennas

Near Real-Time Neutral Atm. Coverage (2024-10-28)



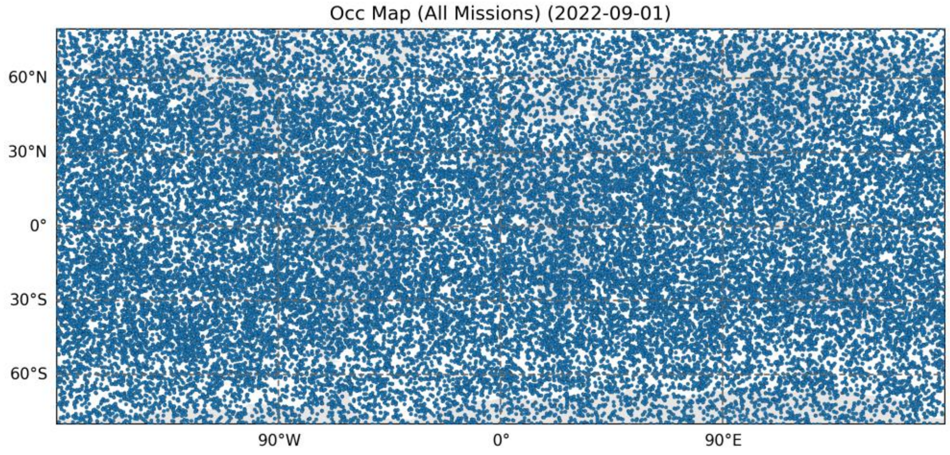


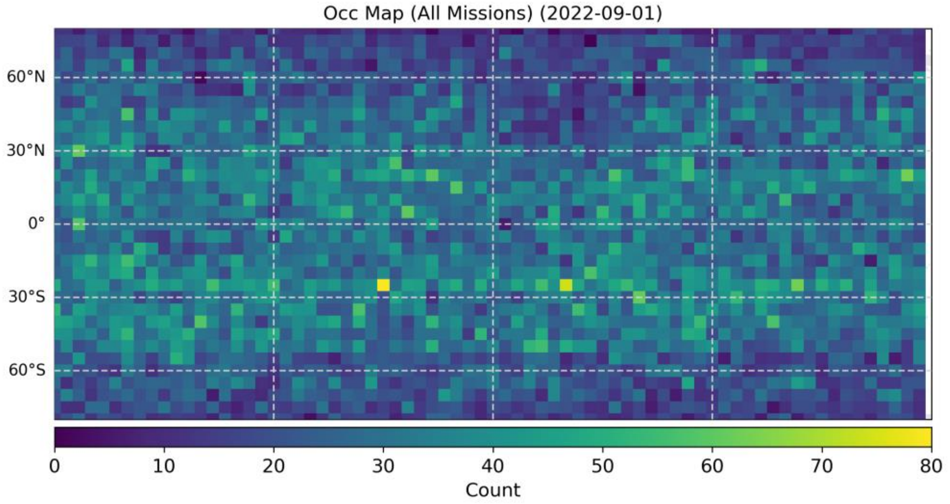




Geographic Coverage (All ROMEX Missions)

- RO Modeling EXperiment (ROMEX) project is assessing impacts of RO data on NWP using all available data between Sep.-Nov. 2022
- On average, there are about 36,000 occultations per day available during this time
- Showing daily occultation locations (left) and daily count in 5x5 deg lat/lon bins (right)
- In addition to NWP studies, these data should lead to many interesting scientific studies



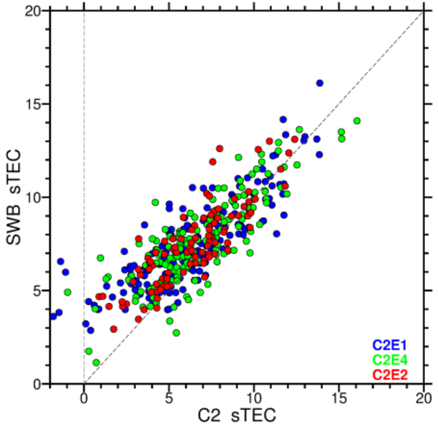


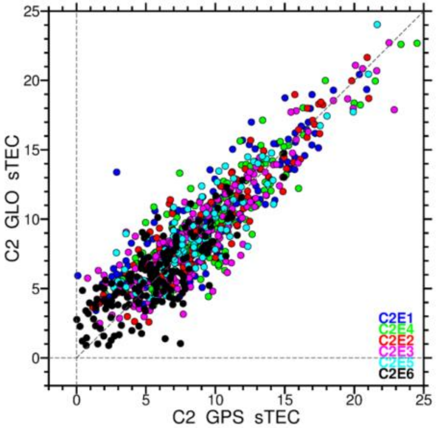
COSMIC-2 GNSS Space Weather Products

- Space weather cal/val team has developed and validated a number of higher level products for operational and science use
- Team includes Aerospace, AFRL, Boston College, NOAA/SWPC, UCAR, USSF, UTD
- Table summarizes GNSS-based products
  - Additional products from in-situ Ion Velocity Meter not discussed here

Product	Status	
Abs total electron content	Operational	
Electron density profiles	Operational	
Line of sight scintillation amplitude and phase indices	Operational	
Scintillation geolocation	Operational	Discussed in next slides
Scintillation bubble map	Operational	
Scintillation all-clear	Operational	
Limb-2-disk	Future	

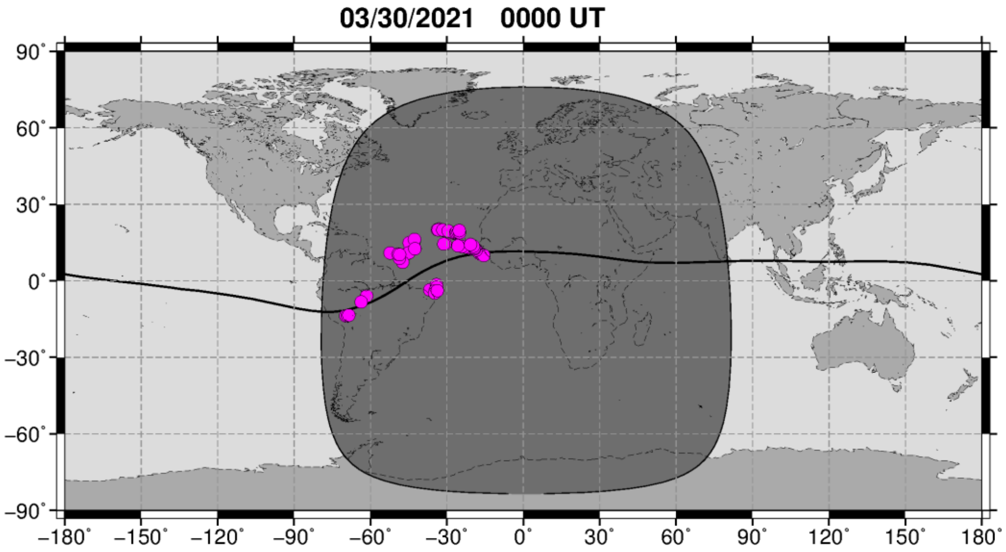
- Absolute TEC validated and released to ops and science users since July 2020 (GPS) and Jan. 2021 (GLONASS)
- GPS TEC validated through collocation with SWARM-B mission
  - C2 and SWARM-B collocations based on same time, same transmitter, angle between SWARM-B and C2 less than 2 degrees
- GLONASS TEC validated via comparison to GPS
- Results: GPS TEC error ~2.5 TECU, GLO TEC error ~2.6 TECU (requirement <= 3 TECU)

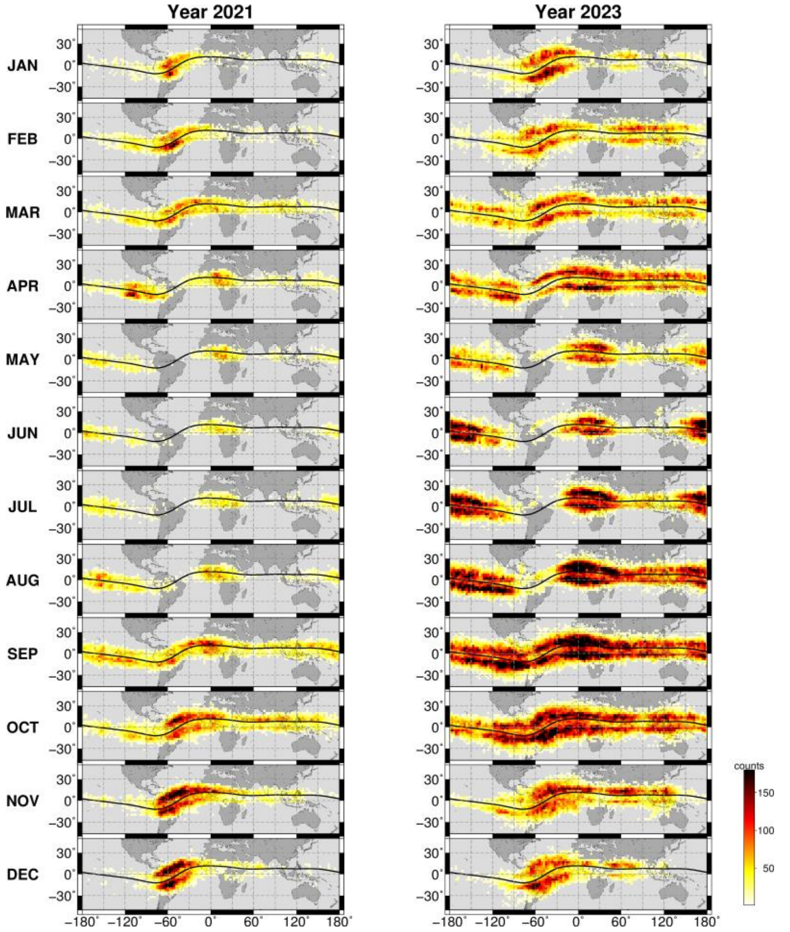




Courtesy N. Pedatella, I. Zakharenkova, UCAR

- Example geolocations over 1 day (left)
- Monthly geolocation density in 2021/2023 (right)





[Courtesy I. Zakharenkova, UCAR]

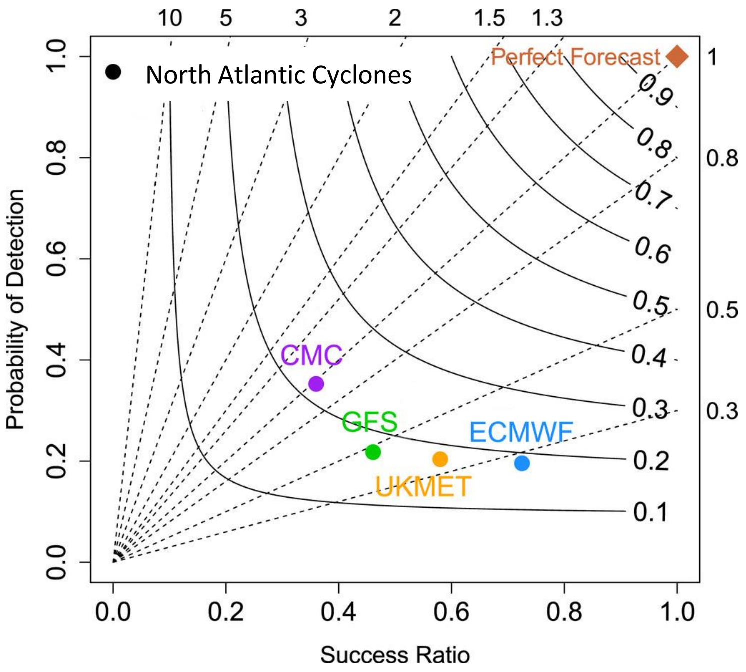
Summary

- GNSS radio occultation is a mature technique making valuable contributions to weather, space weather, and climate science and operations
- COSMIC Data Analysis and Archive Center makes available neutral atmosphere and ionosphere products from more than a dozen missions going back to GPS/Met
- COSMIC-2 mission has accomplished significant milestones since launch in 2019 including several "firsts":
  - High volume/coverage super-refraction detection capability
  - Absolute total electron (TEC) with < 3 TECU accuracy, GLONASS TEC
  - Scintillation geolocation, plasma bubble and all-clear specification
- RO modeling experiment (ROMEX) is helping to establish impacts of many RO observations on weather prediction using real data

Outline

- Introduction to UCAR/NCAR and the COSMIC Program
- Introduction to GNSS radio occultation (RO)
- RO tropical cyclone prediction
- Introduction to GNSS-R
- Soil moisture and flood inundation from GNSS-R

Skill of Tropical Cyclogenesis Prediction by Global Models: 2004-2014



False alarm ratio = 1 – success ratio

NOAA/NCEP Global Forecast System (GFS) Model:
Probability of detection = 0.20
False alarm = 0.55

ECMWF and UKMO have similar probability of detection, but has less false alarm.

CMC: Canadian Meteorological Center

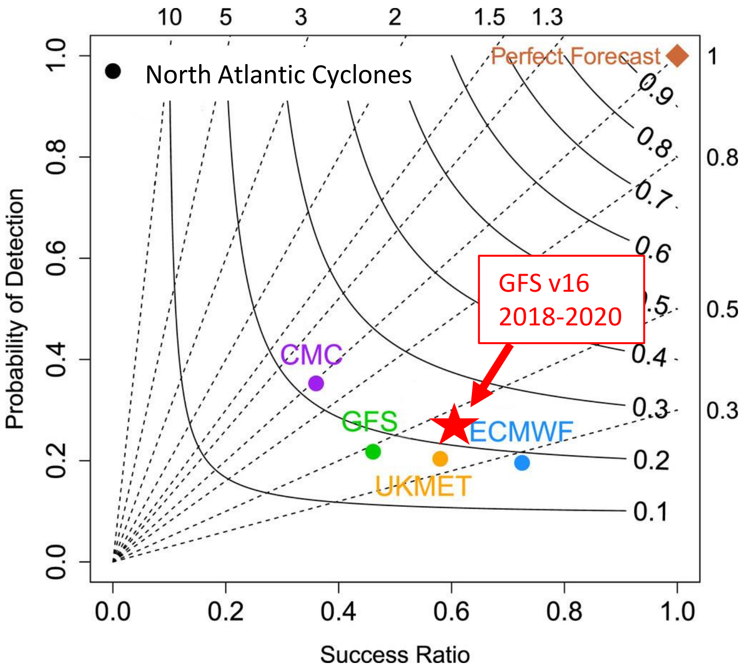
GFS: NOAA/NCEP Global Forecast System

UKMET: U.K. Meteorological Office

ECMWF: European Center for Medium Range Forecast

From Halperin et al 2016

Skill of Tropical Cyclogenesis Prediction by Global Models: 2004-2014



False alarm = 1 – success ratio

NOAA/NCEP Global Forecast System (GFS) Model:
Probability of detection = 0.20
False alarm = 0.55

ECMWF and UKMO have similar probability of detection, but has less false alarm.

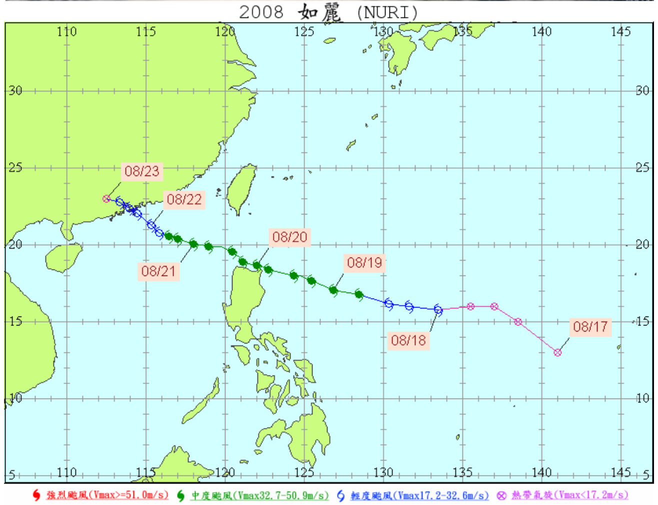
NCEP GFS v16 (2018-20):
Probability of detection = 0.25
False alarm = 0.4

Issues:
- Lack of observations
- Data assimilation
- Physical parameterizations

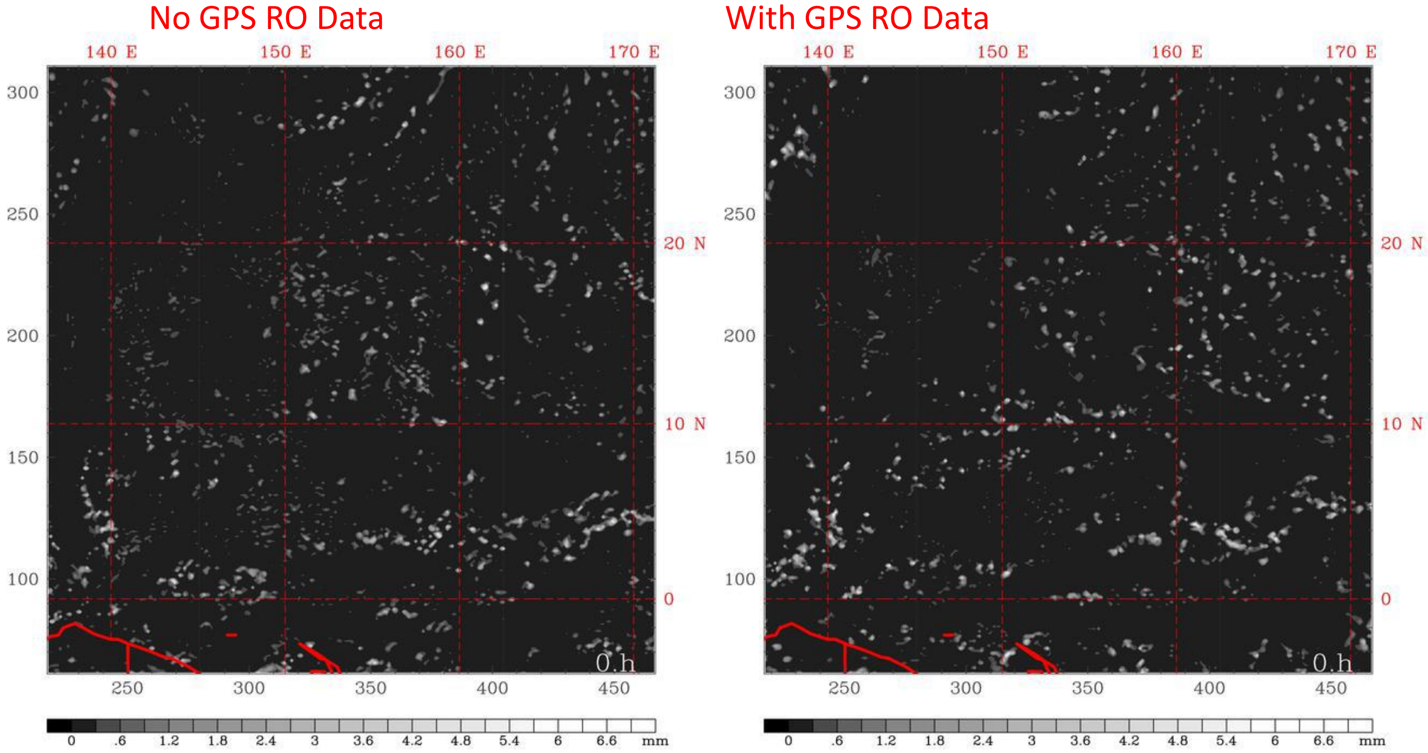
From Halperin et al 2016

Typhoon Nuri (2008)

- Formed at 1800 UTC 16 August 2008 over Western Pacific Ocean.
- Most of the global operational models failed to predict the formation of this tropical storm.
- Perform 3-Day data assimilation with and without the use of GPS RO data, starting at 1800 UTC 11 to 1800 UTC 14 August 2008.
- We then compare the forecasts with and without the use of radio occultation observations from the COSMIC mission.

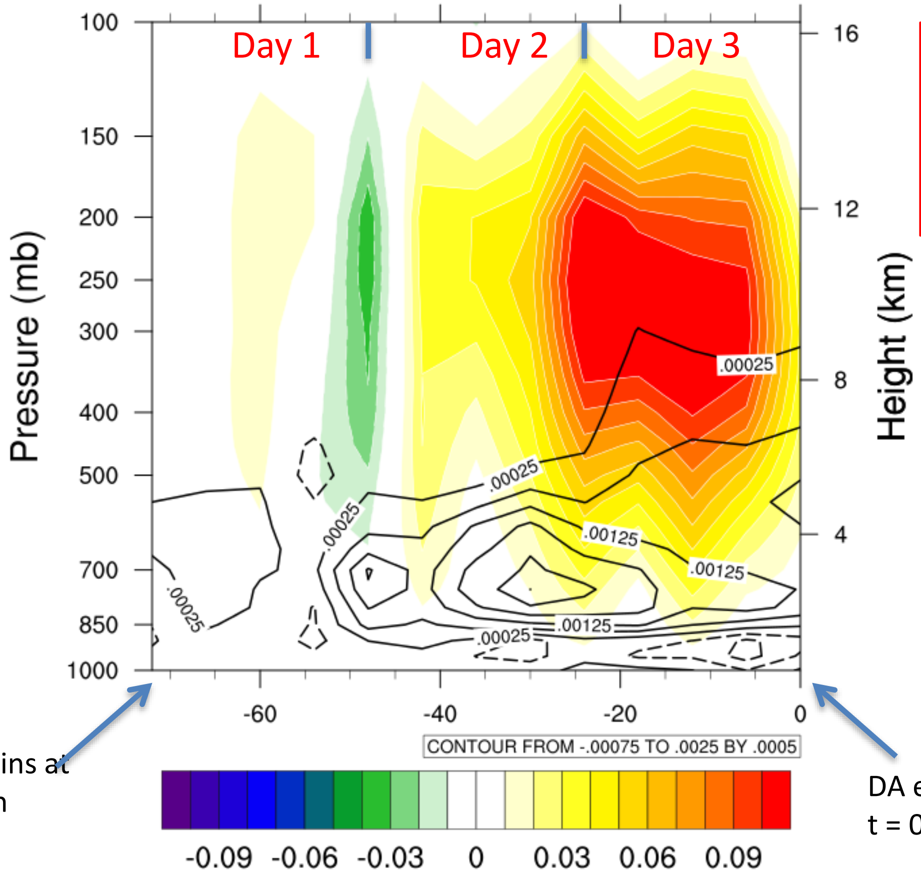


WRF Model Forecast After 3-day of Data Assimilation
Starting at 1800 UTC 14 August 2008



Integrated Cloud Hydrometeors

Time-Height section of differences in water vapor (contour) and vertical motion (color) between experiments with and without GPS RO assimilation



Units:
Vertical motion: m/s
Water Vapor: Kg/kg

Averaged over a 6º x 6º box following the 500 mb vorticity center

DA begins at t = -72h

DA ends at t = 0h

How did GPS RO data impact the genesis of Typhoon Nuri (2008)?

- **Day 1**: Not much difference
- **Day 2**: GPS RO assimilation substantially increased low-level moisture, steadily increasing convective instability
- **Day 3**: Outbreak of convection produced
  - Large-scale upward motion
  - Mid-level potential vorticity (enhanced by latent heating)
  - A robust mid-level vorticity center with high humidity
- **Day 4 and beyond**: The mid-level vorticity center confined the area of convection, interacted with convection and boundary layer processes to produce surface cyclogenesis

Summary of Sensitivity Experiments

- **Without GPS RO assimilation**
  - Lower troposphere was too dry
  - No convection, no strong mid-level vorticity center with high humidity
  - No genesis
- **With GPS RO assimilation, but no latent heating**
  - Low-level moisture was increased
  - No large-scale ascent, no mid-level vorticity generation
  - No genesis
- **With 16 GPS RO soundings near storm removed**
  - Results similar to no GPS RO assimilation
  - No genesis
- **With local observation operator**
  - Less moisture in the lower tropical troposphere
  - Genesis delayed by 30 hour

Statistics for 10 Typhoons over the NW Pacific, 2008 - 2010

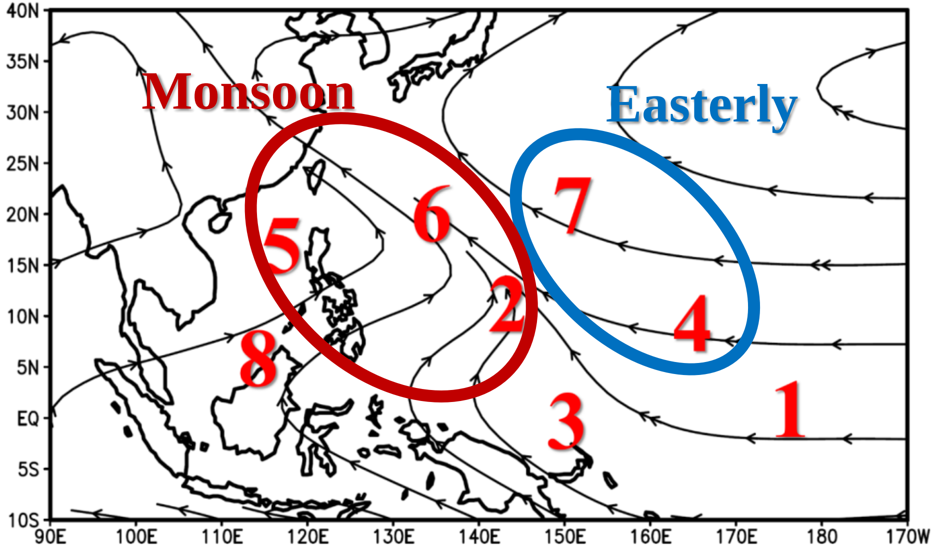
TYPHOON	AMOUNTS OF GNSS RO	JTWC TD GENESIS	GTS	LOC	EPH
2008_KALMAEGI	500	2008/07/14 0000UTC	-48h	-42h	-42h
2008_FUNGWONG	606	2008/07/24 0600UTC	-36h	-36h	-42h
2008_NURI	730	2008/08/16 1800UTC	x	30h	0h
2008_SINLAKU	474	2008/09/08 0000UTC	x	x	6h
2008_HAGUPIT	696	2008/09/18 1800UTC	24h	0h	-12h
2008_JANGMI	654	2008/09/23 1200UTC	6h	6h	-12h
2009_MORAKOT	661	2009/08/03 1800UTC	-48h	-24h	-6h
2009_PARMA	624	2009/09/27 1200UTC	-6h	6h	-12h
2010_FANAPI	443	2010/09/14 1200UTC	x	x	36h
2010_MEGI	393	2010/10/12 1800UTC	36h	60h	24h
PROBABILITY OF DETECTION			**30%**	**40%**	**70%**

Hit is counted when model produced genesis within ±24h of the observation.

x: No genesis
- : Early formation
+: Late formation

Tropical Cyclone Environment Types

- Teng et al 2020 examined 531 tropical cyclone (TC) cases from 1981-2009, classifying them into 8 different cluster types
- Two dominant synoptic-scale environments: Easterly TC (ETC: type 4, 7), Monsoon TC (MTC: type 2, 5, and 6)

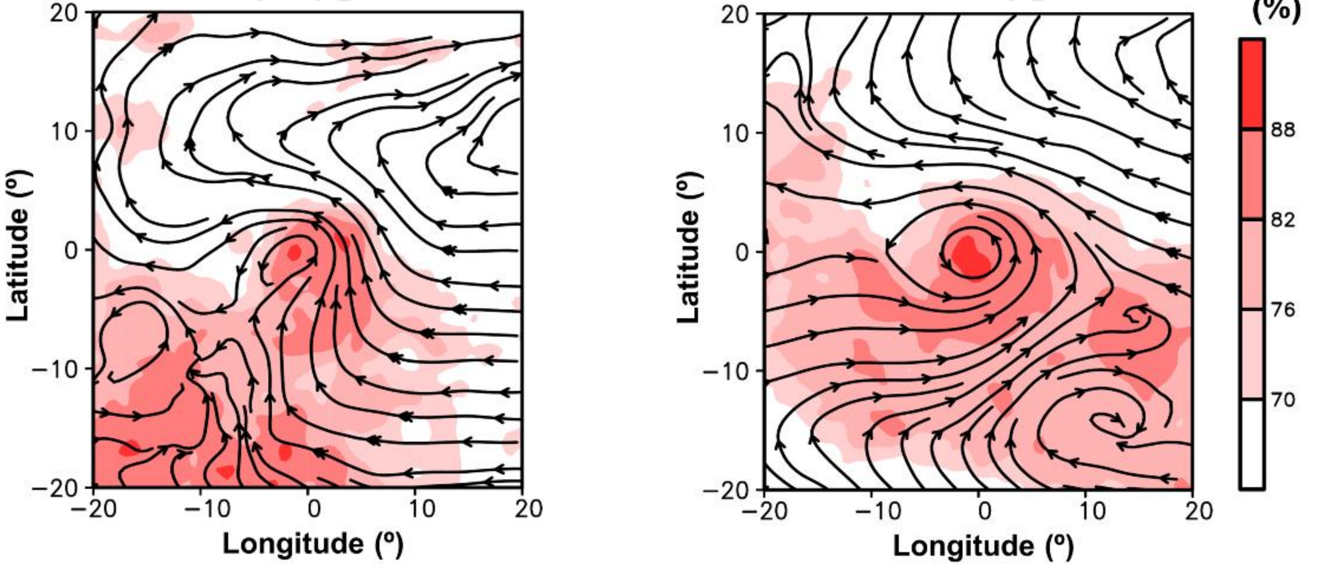


(Teng et al. 2019)

Composite Tropical Cyclone Structure

At time of formation

Easterly-type TC | **Monsoon-type TC**



13 cases

22 cases

- Streamline: 850 hPa wind
- Shading: 700 hPa RH

Probability of Detection

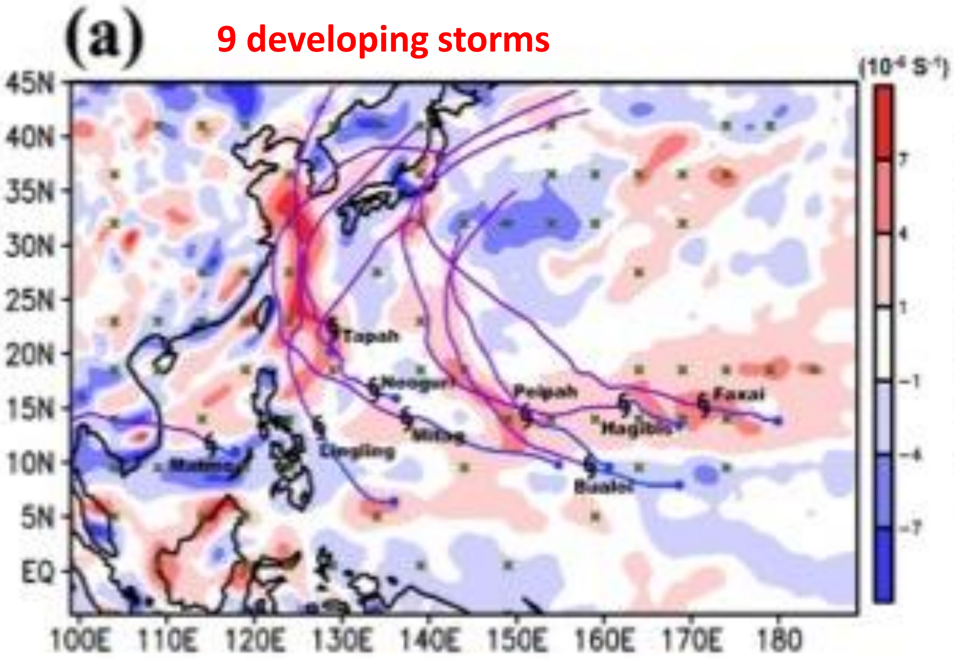
Type	Percentage	Detection rate No RO	Detection rate With RO
4. Easterly southwest of subtropical high	20.0	0.0*	57.1*
7. Easterly west of subtropical high	17.1	16.7*	66.7*
5. Monsoon trough	22.9	87.5	87.5
6. North of trough	22.9	37.5	62.5
2. Monsoon confluence	17.1	33.3	66.7
Easterly-type (4,7)	37.1	7.7*	61.5*
Monsoon-type (2,5,6)	62.9	54.5	72.7
Total	100	37.1*	68.6*

- Asterisk: Significance

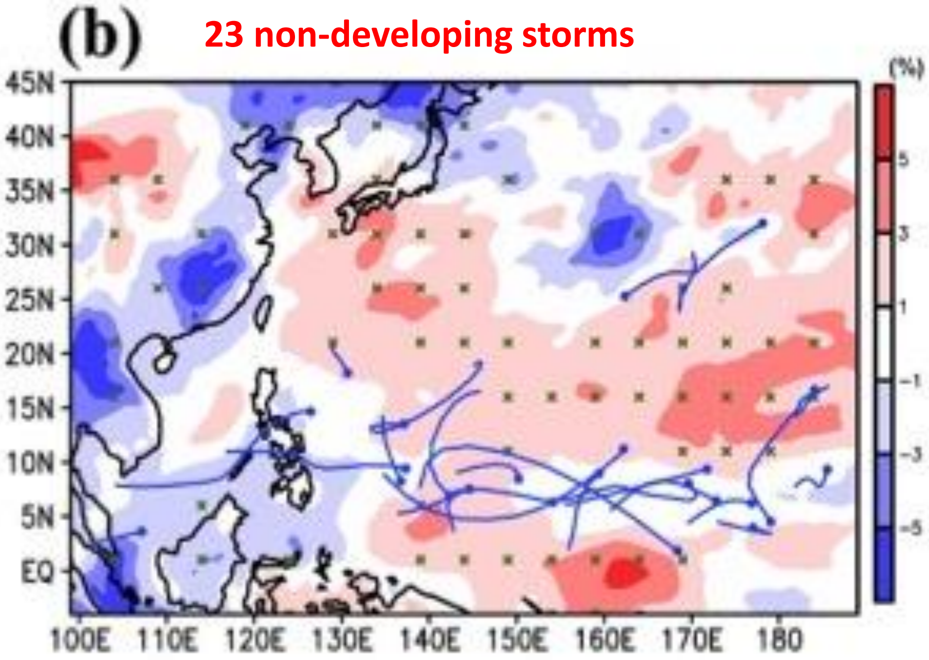
Summary

- The impact of GPS RO on the prediction of 22 tropical cyclones (TCs) that form in monsoon environments and 13 TCs that form in easterly environments over the period 2006-2010 are assessed and compared.
- Because of higher environmental moisture, the probability of detection for tropical cyclone formation is higher for monsoon TCs than easterly TCs, when GPS radio occultation data are not assimilated.
- The assimilation of GPS RO data increases the probability of TC formation detection from 7.7% to 61.5% for easterly TC, and from 54.5% to 72.7% for monsoon TCs.

Impact of RO on Tropical Cyclogenesis



850 hPa relative vorticity anomaly



850 hPa relative humidity anomaly

Backgrounds are anomalies of September – October 2019 minus 40-year climatology (1979 – 2019).

COSMIC-2 RO Data Impact Study

		Observation		Total	Hit rate	False alarm ratio
		Developing	Non-developing			
No RO Forecast	Detected	4 (hits)	11 (false alarms)	15	0.44	0.73
	Non-detected	5 (misses)	12 (correct negatives)	17		
With RO Forecast	Detected	7 (hits)	8 (false alarms)	15	**0.78**	**0.53**
	Non-detected	2 (misses)	15 (correct negatives)	17		
Total		9	23	32	**0.34**	**0.20**

Assimilation of COSMIC-2 RO increases the probability of detection by 34% and reduces false alarm by 20%

Apples and Oranges

Model improvement in 10 years

Probability of detection: 0.05

Reduction of False Alarm: 0.15

COSMIC-2 assimilation

Probability of detection: 0.34

Reduction of False Alarm: 0.20

Summary

- Typhoon Nuri (2008): RO assimilation recovers moisture from low to mid levels, supports convective development, critical for tropical cyclogenesis
- Experiment on 10 cases over Western Pacific shows that the use of nonlocal operator is important:
  - Nonlocal Operator: POD increases from 0.3 to 0.7
  - Local Operator: POD increases from 0.3 to 0.4
- Evaluation of 35 tropical cyclogenesis shows that the impact of RO assimilation is sensitive to large-scale environment:
  - Easterly TC: POD increases from 0.08 to 0.62
  - Monsoon TC: POD increase from 0.55 to 0.73
- Assimilation of COSMIC-2 RO on 9 developing and 23 non-developing events in September-October 2019 over Western North Pacific shows that COSMIC-2 increases probability of detection by 0.34 and reduces false alarm by 0.20.

Outline

- Introduction to UCAR/NCAR and the COSMIC Program
- Introduction to GNSS radio occultation (RO)
- RO tropical cyclone prediction
- Introduction to GNSS-R
- Soil moisture and flood inundation from GNSS-R

GNSS Reflectometry (GNSS-R)

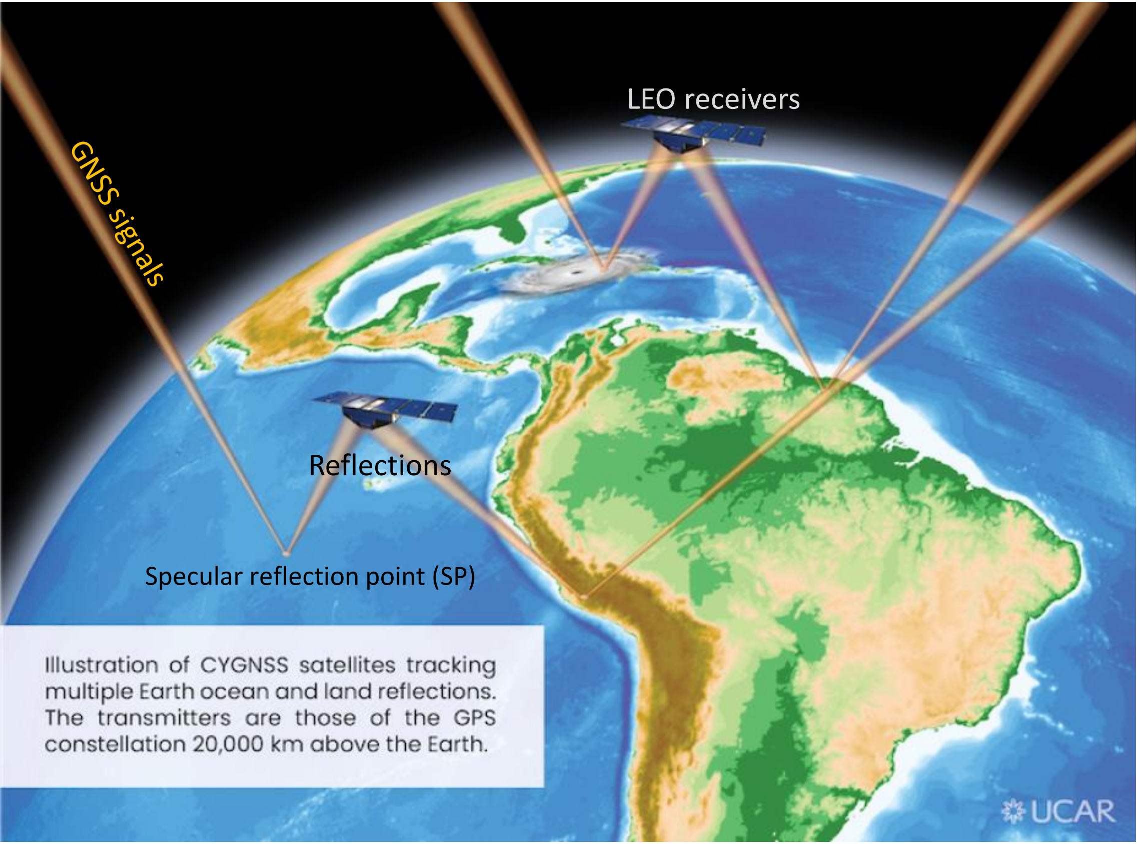


Illustration of CYGNSS satellites tracking multiple Earth ocean and land reflections. The transmitters are those of the GPS constellation 20,000 km above the Earth.

Using GNSS transmissions as an illumination source for **bistatic radar**.

Features:

- Facilitate building constellations of Low Earth Orbit (LEO) receivers
  - A large volume of reflection data
  - Short revisit time (hours – a few days)
- Footprint size: hm – km
- L-band signals
- Relatively insensitive to dense vegetation
- All-weather, day & night operations

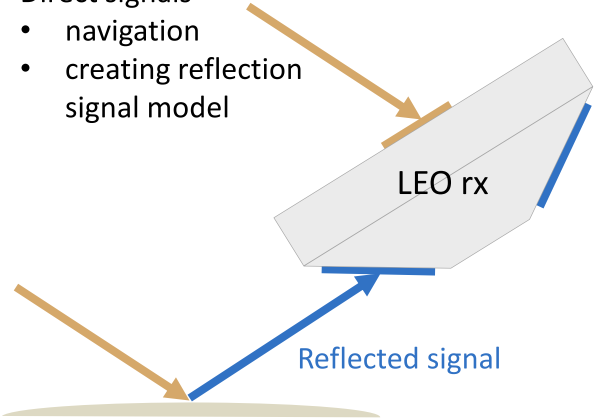
Applications:

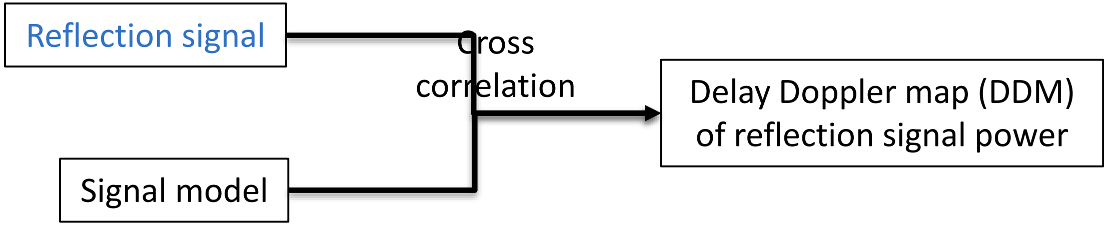
Ocean: ocean surface wind, significant wave height, sea ice extent, etc.

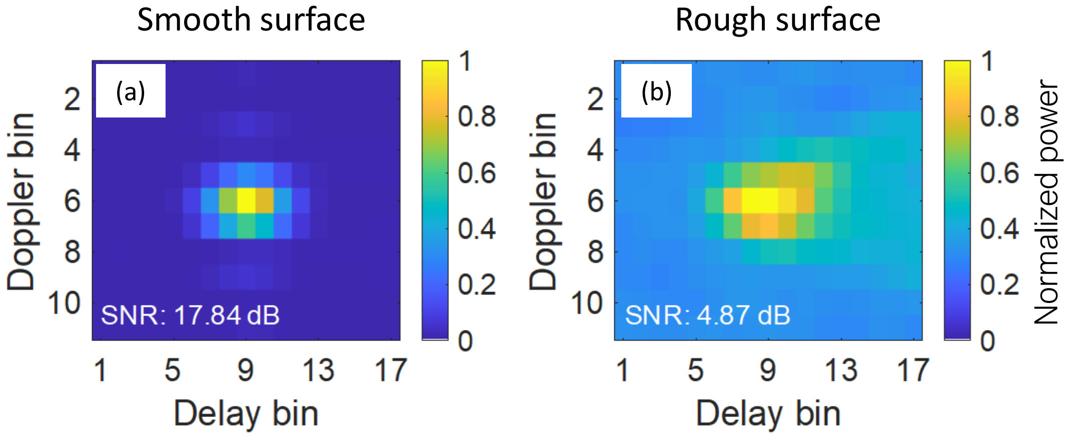
Land: soil moisture, surface water extent, above-ground biomass, etc.

GNSS-R Observables

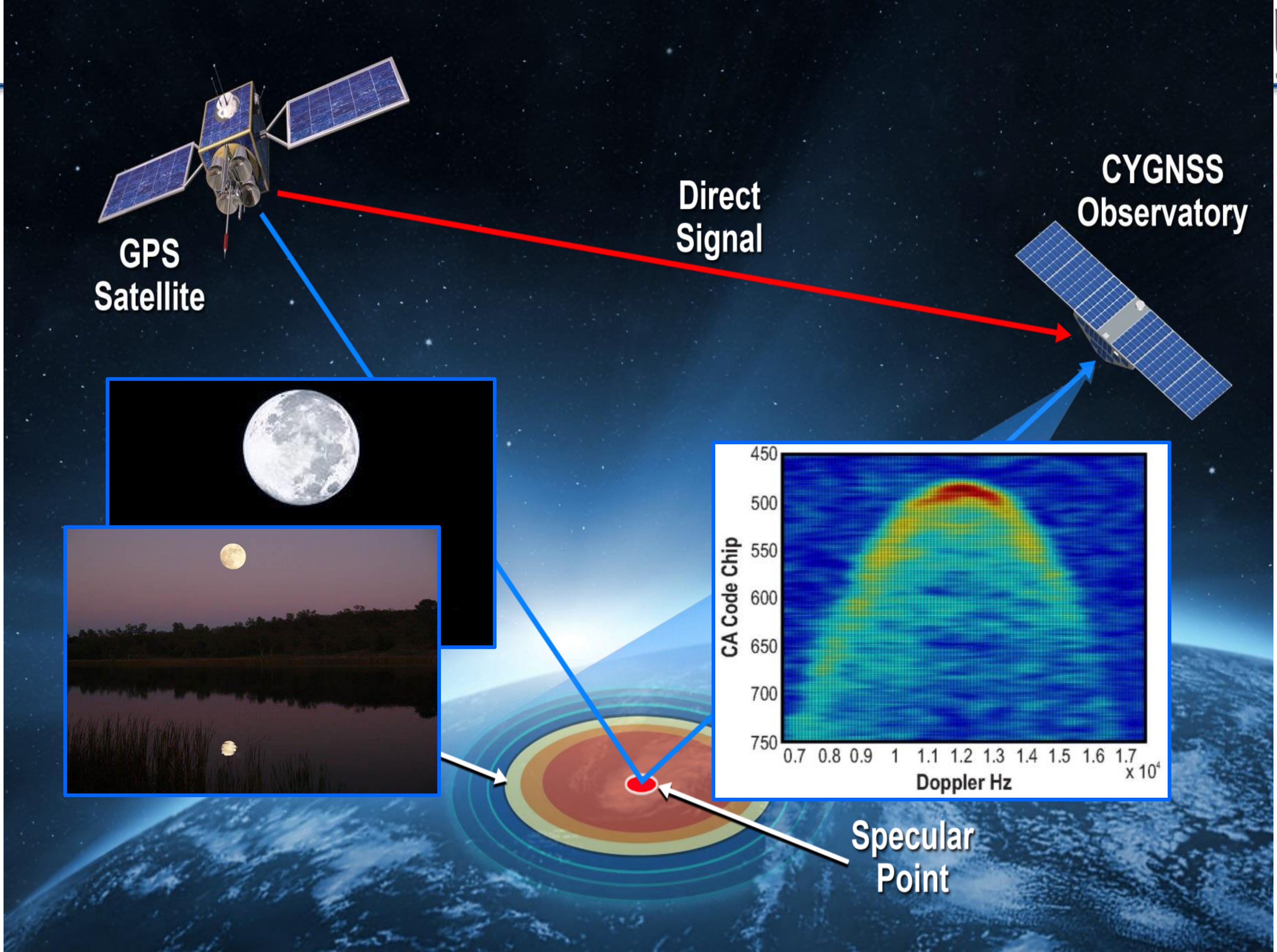
Direct signals
- navigation
- creating reflection signal model



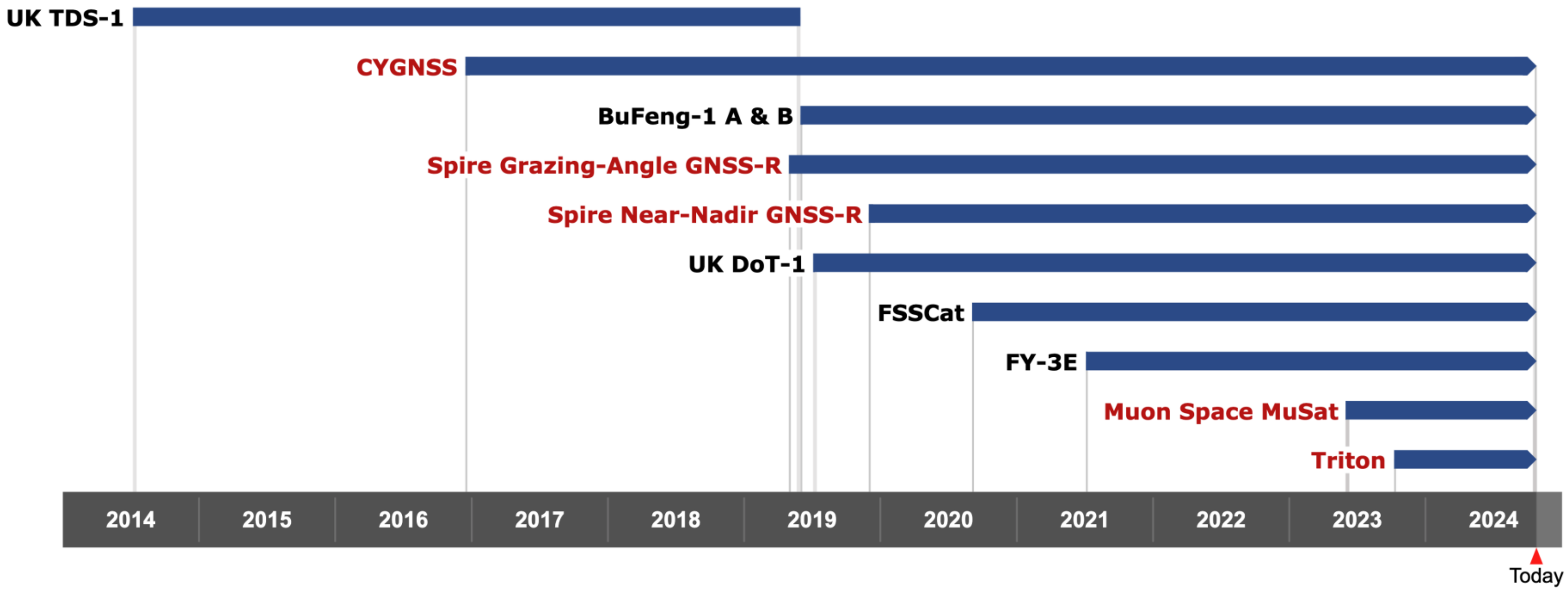




The **DDM peak** is used to derive geophysical parameters, e.g., reflectivity and scattering coefficient.


GPS
Satellite
Direct
Signal
CYGNSS
Observatory
450
500
550
600
650
700
750
CA Code Chip
0.7 0.8 0.9 1 1.1 1.2 1.3 1.4 1.5 1.6 1.7
x 10^4
Doppler Hz
Specular
Point

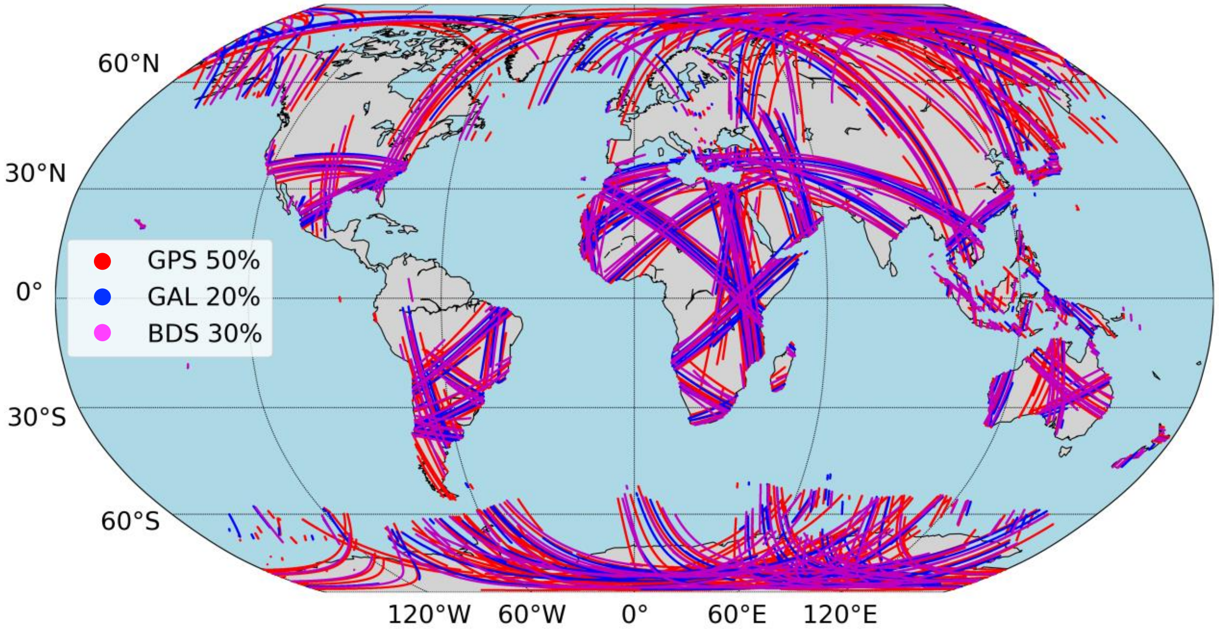
GNSS-R Satellite Missions



We focus on **Spire Near-Nadir GNSS-R data** to map soil moisture and inland water bodies under a NOAA Commercial Data Program (CDP) pilot study.

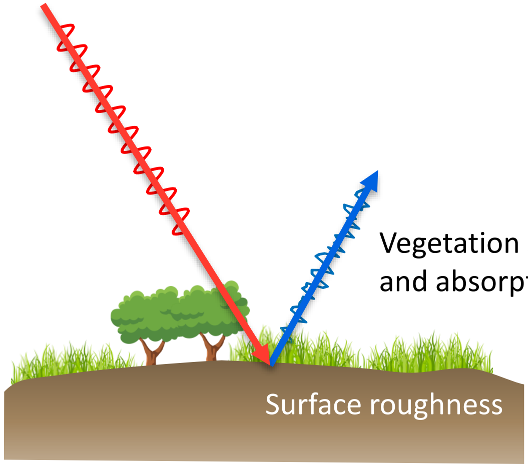
Spire Near-Nadir GNSS-R Satellites and Data

- 4 LEO receivers: FM110 (low-inclination orbit) & FM 146, 147, and 172 (near-polar orbit)
- L1 band signals from multi-GNSS, e.g., GPS, Galileo, and Beidou
- DDMs and **calibrated reflectivity at 2 Hz** during Jan–Jul 2024. Along-track sampling spacing is ~3 km.
- ~30% of the 36 km land grids is covered by quality-controlled observations



Ground tracks of reflection data over land and sea ice on Feb 1, 2024

GNSS-R Reflectivity and Soil Moisture (SM)



Reflectivity (Γ) refers to the ratio between the reflected signal power (P_R) and the incidence signal power (P_I).

A simplified reflectivity model (w/o considering vegetation scattering):

$$\Gamma_{RL} = \Gamma_{RL,\,smooth}\, exp[-4(k\boldsymbol{\sigma_{RMS}}\cos\theta)^2]\, exp(-2\tau\, sec\,\theta)$$

Fresnel reflectivity   Roughness impact   Vegetation attenuation

R/L: right/left-hand circular polarization
k: wavenumber
σ_{RMS}: surface roughness as root mean square height
θ: incidence angle
τ : vegetation opacity

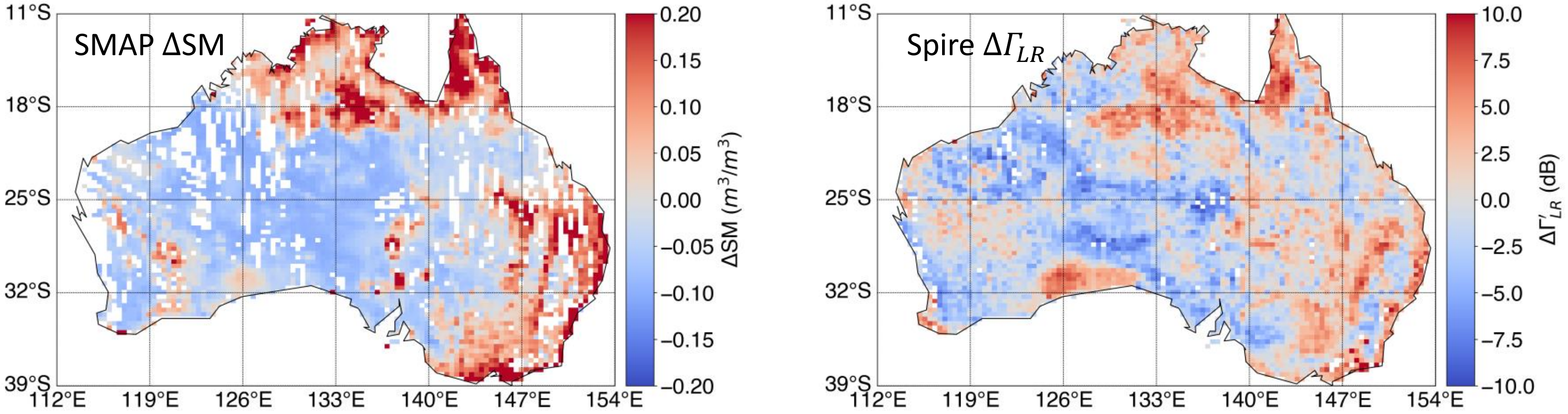
$$\Gamma_{RL,\,smooth} = f(\theta, \boldsymbol{SM}, soil\ texture, soil\ temperature)$$

Reflectivity is essentially a function of SM.

GNSS-R Reflectivity and Soil Moisture

Reflectivity changes respond well to SM variations.

Difference in the mean of SMAP SM/Spire reflectivity at 36 km **between April 1–15 and March 16–31, 2024** over Australia**.**



* SMAP: Soil Moisture Active Passive, a satellite mission to provide L-band radiometry-based soil moisture at 9 & 36 km every two/three days. The accuracy is ~0.04 cm^3/cm^3 in regions with vegetation water content less than 5 kg/m^2.

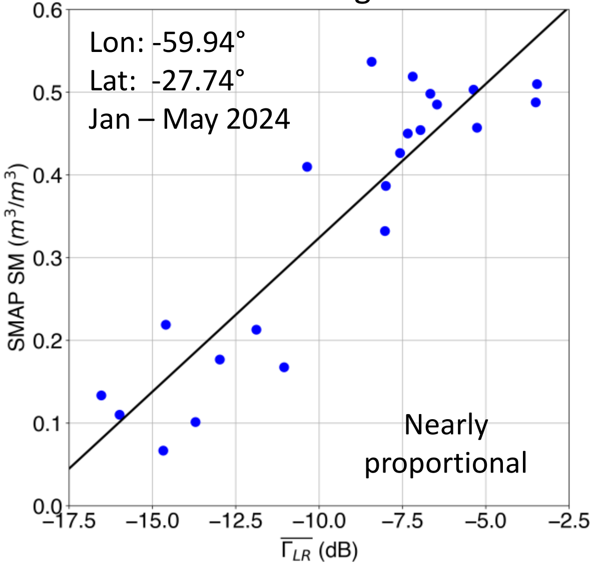
Soil Moisture Inversion Algorithms

1. Empirical algorithm:
    1. linear regression, change detection, time series retrieval method, etc.
    2. Relatively easy to implement
    3. Dependent on external SM data to determine parameters

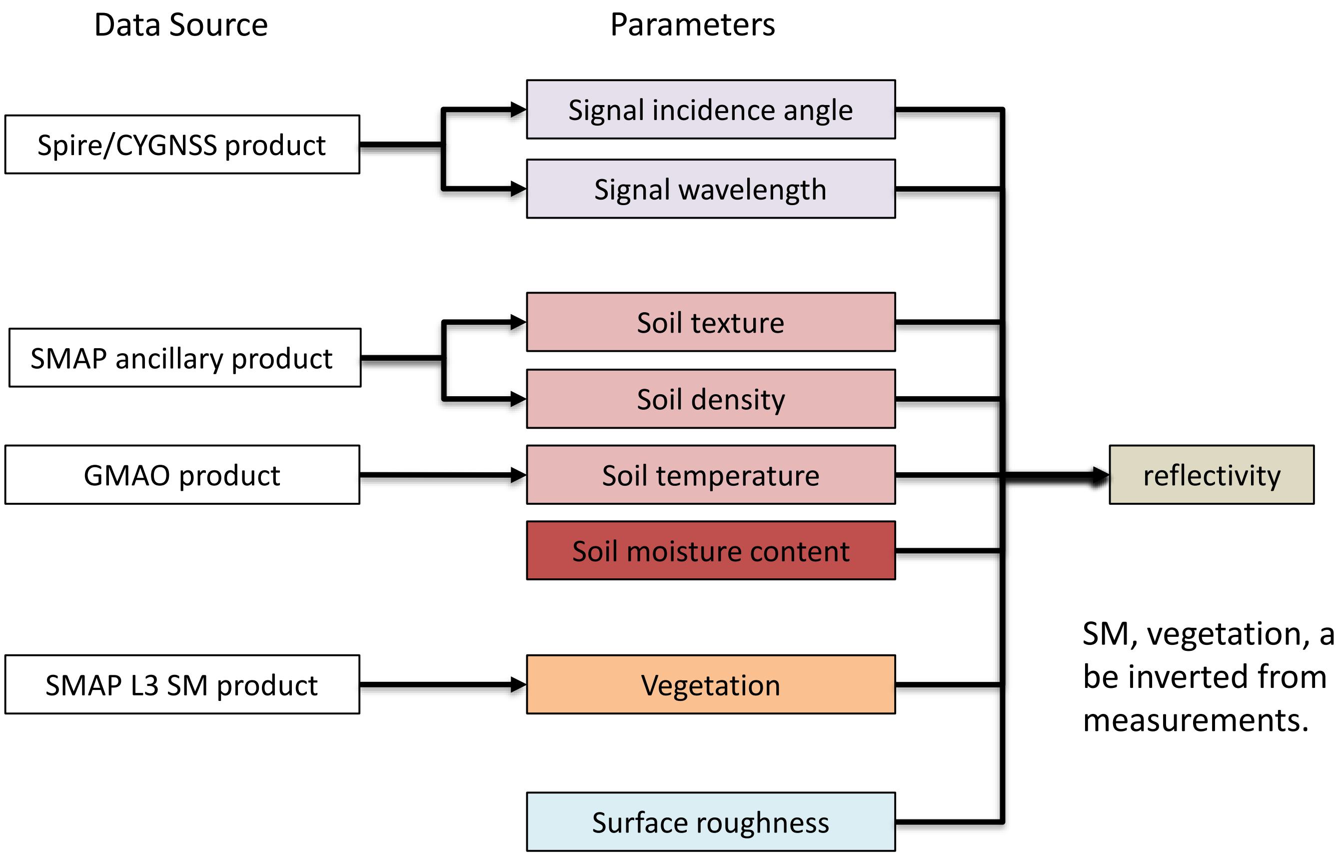
2. **Semi-empirical inversion algorithm**
    1. Based on the forward model of reflectivity
    2. Providing independent SM observations
    3. Challenging to realize as it requires accurate corrections for surface roughness and vegetation

3. Machine learning & deep learning methods

A 36-km grid



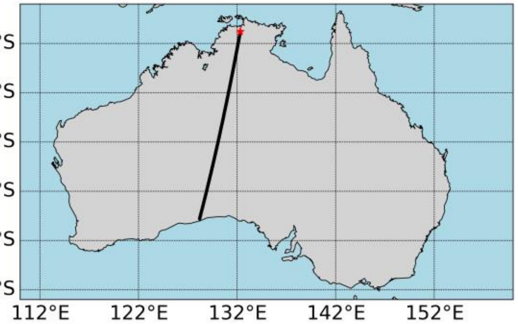
Forward Model of Reflectivity

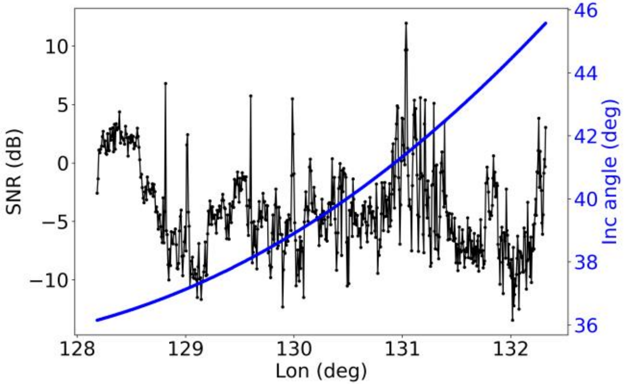


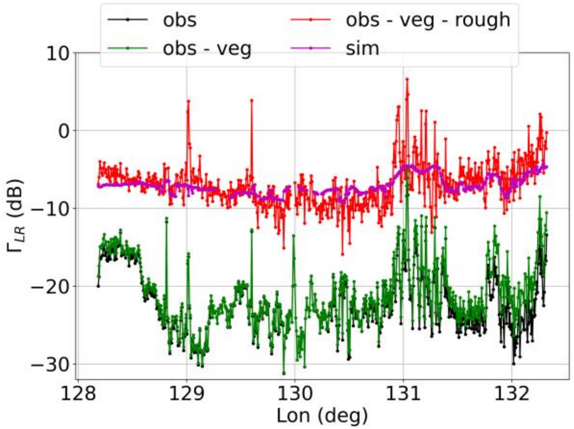
SM, vegetation, and surface roughness can be inverted from reflectivity measurements.

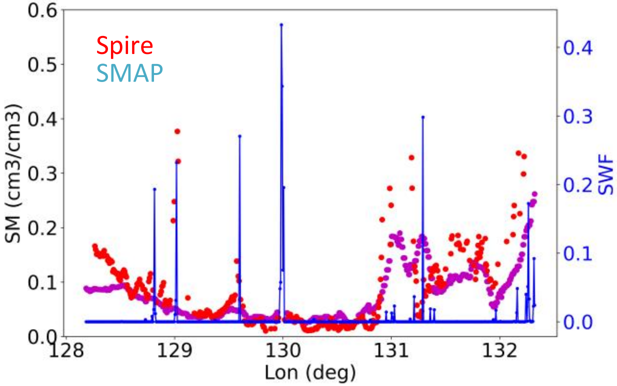
Semi-Empirical Soil Moisture Inversion Process

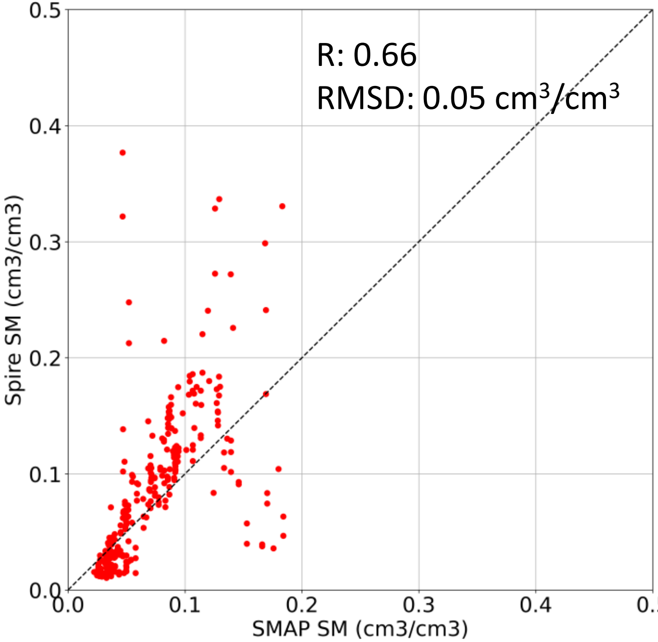
SM ← Soil dielectric constant ϵ_{soil} ← Fresnel reflectivity for a smooth surface ← (Vegetation & surface roughness impact) ← Reflectivity obs. $\Gamma_{LR} = f(SM)$









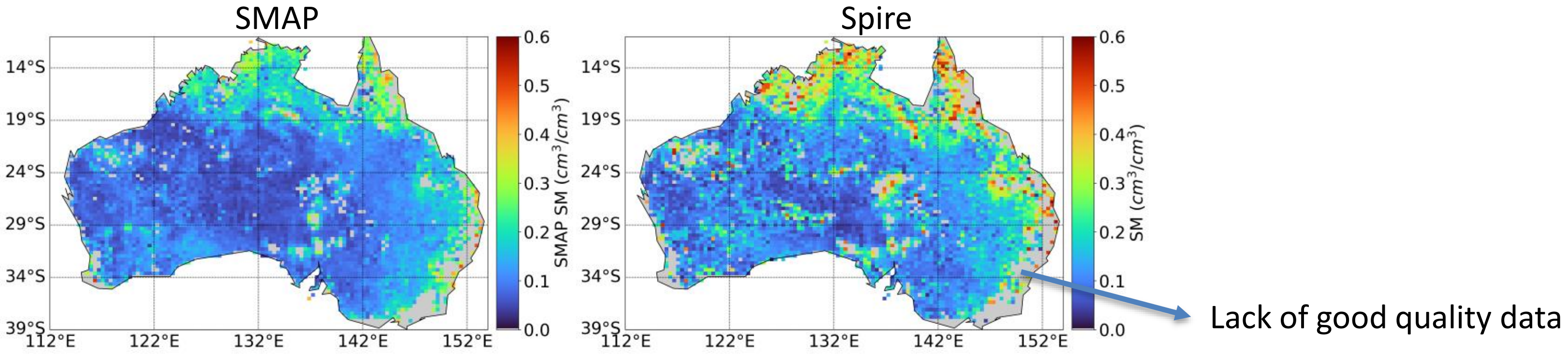


Semi-Empirical Soil Moisture Inversion Process

Operationally, instead of processing data track by track, we generate gridded maps of reflectivity observations and then use them to invert SM.

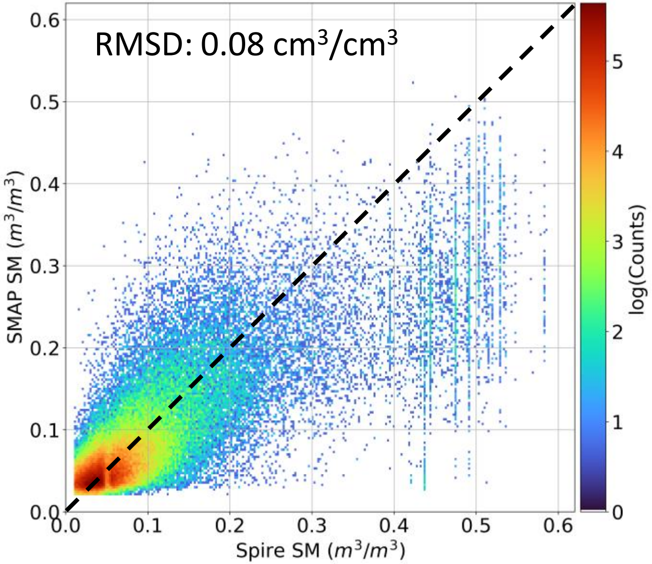
On any given day:
1. Quality control using quality flags, water masks, and snow cover data
2. Correcting for vegetation absorption, surface roughness, incidence angle impact
3. Gridding Spire reflectivity observations with a resolution of 36 km & calculating the mean for each grid
4. Estimating soil dielectric constant and then soil moisture content

Averaged Spire & SMAP SM during Feb–Jul at 36 km. Grids with both SMAP and Spire data are considered.

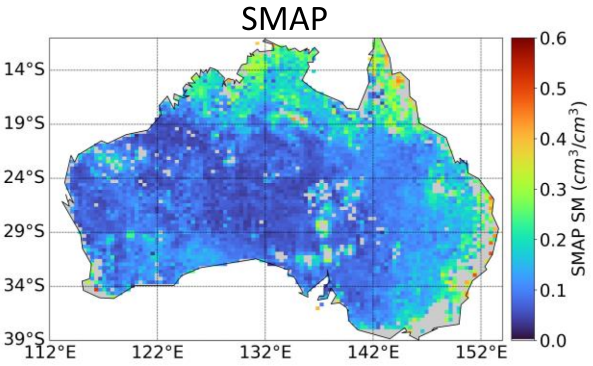


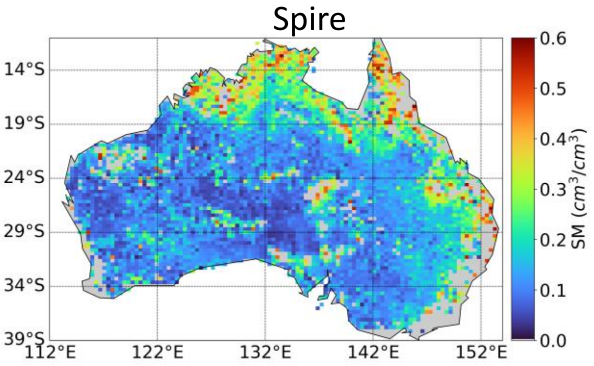
Compare Spire and SMAP Data

Comparing daily Spire and SMAP data



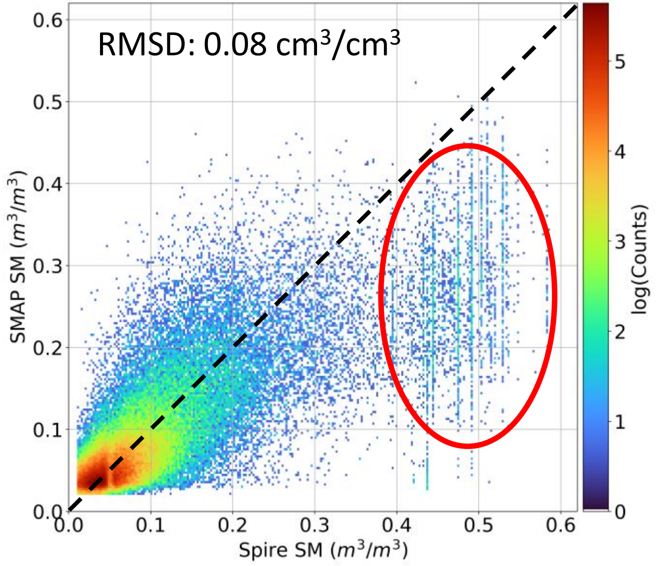
Averaged Spire & SMAP SM during Feb–Jul at 36 km.



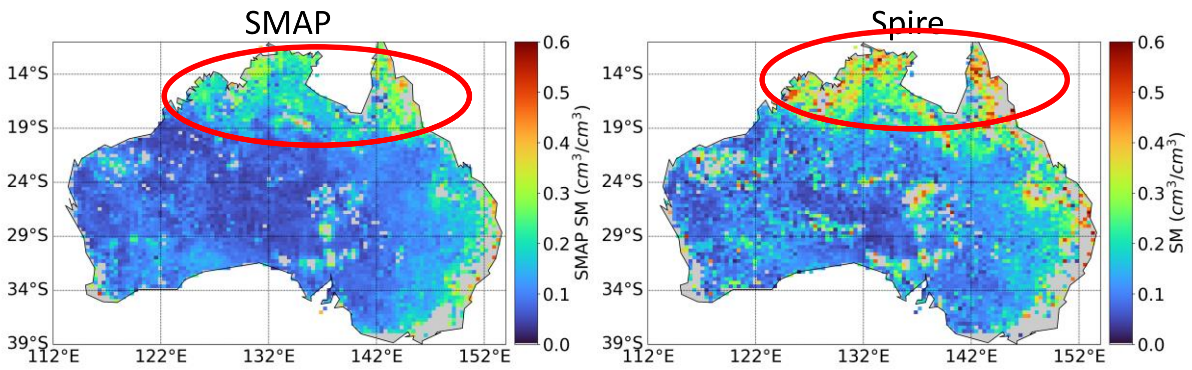


- Spire SM retrievals agree well with the SMAP data generally
- Spire SM overestimation occurs when SMAP SM is relatively high

Comparing daily Spire and SMAP data



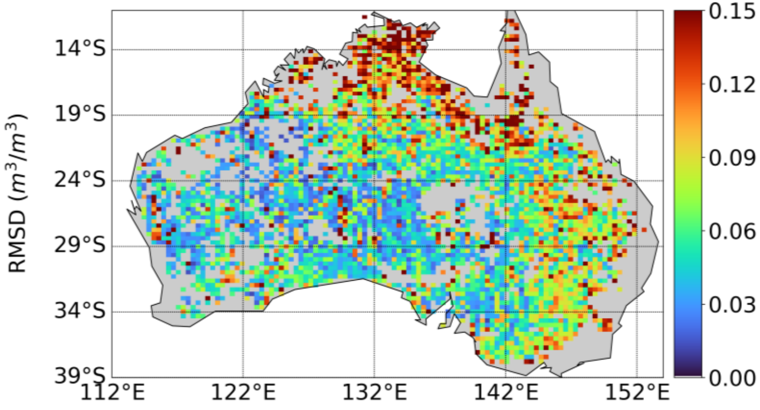
Averaged Spire & SMAP SM during Feb–Jul at 36 km.



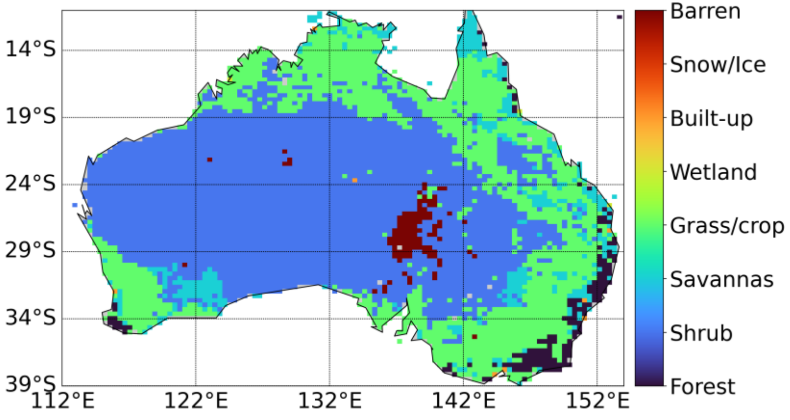
- Spire SM retrievals agree well with the SMAP data generally
- Spire SM overestimation occurs when SMAP SM is relatively high

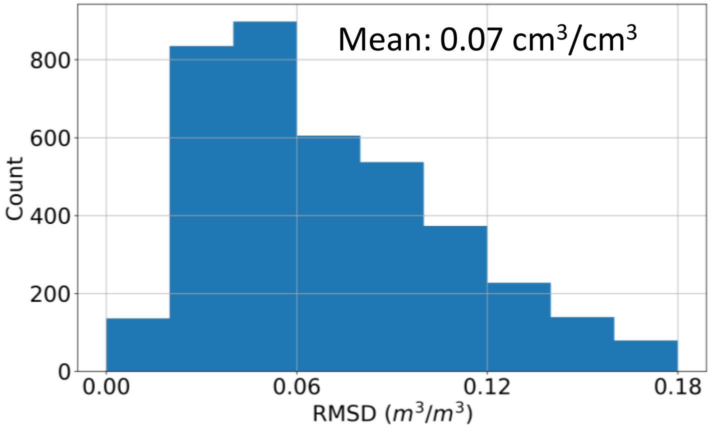
Compare Spire and SMAP Data

RMSD at grids with at least five daily SM samples.



MODIS landcover types





Large RMSD typically occurs over relatively dense vegetations

Expected Accuracy Levels

The accuracy of soil moisture retrievals using **SMAP's active radar (backscattering)** varies depending on landcover types

Bare soil and sparse vegetation:

- higher accuracy
- Estimated error: 0.06 cm^3/cm^3

Moderate vegetation (grassland, savannas, shrublands):

- Moderate accuracy
- 0.06 – 0.08 cm^3/cm^3
- Radar signals become partially absorbed and scattered by the vegetation canopy

Dense vegetation (forest):

- Low, with significant degradation
- > 0.08 cm^3/cm^3
- Radar signals are significantly absorbed and scattered by the tree canopy

Urban:

- Poor
- Complex geometry, interference

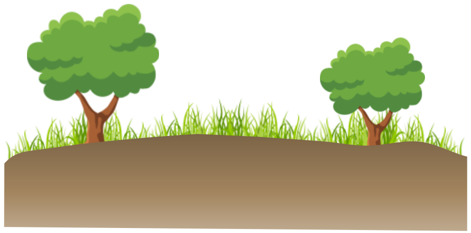
Although this table shows expected accuracy levels for backscattering-based SM, it provides insights into the anticipated accuracy of our forward-scattering results.

Our results have expected accuracy levels.

Landcover	RMSD (cm^3/cm^3)
Barren	0.06
Closed shrublands	0.06
Open shrublands	0.05
Crops	0.07
Grasslands	0.09
Savannas	0.09

Reflectivity for Soil Inundation Mapping

Conceptual diagrams of how soil and water surface affect reflectivity:



- Vegetation
- Soil surface roughness
- lower dielectric constant compared to water

Rough water surface

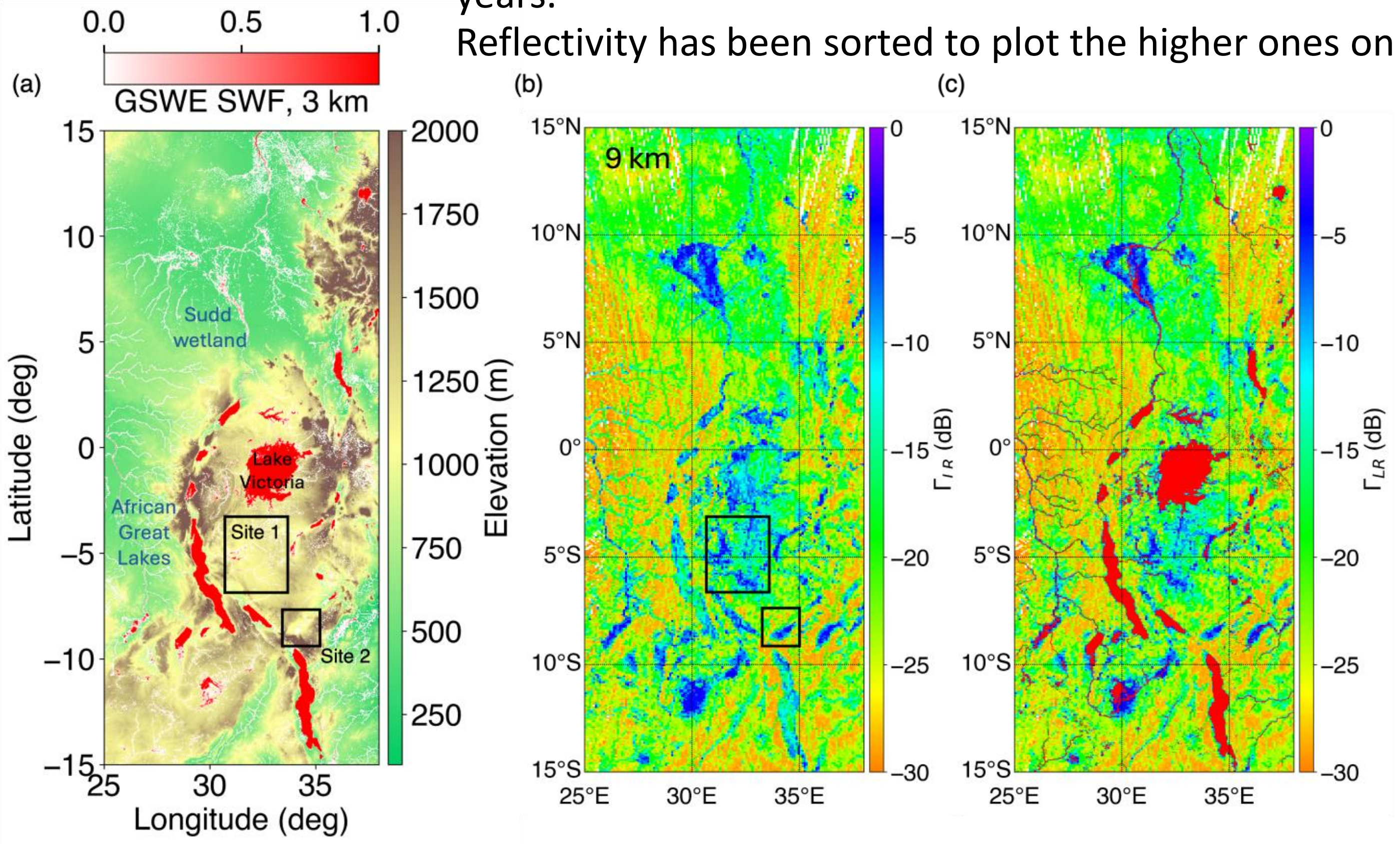
- No vegetation effect
- Water surface roughness
- Higher dielectric constant

Calm water surface

Higher reflectivity

Soil Inundation in East Africa

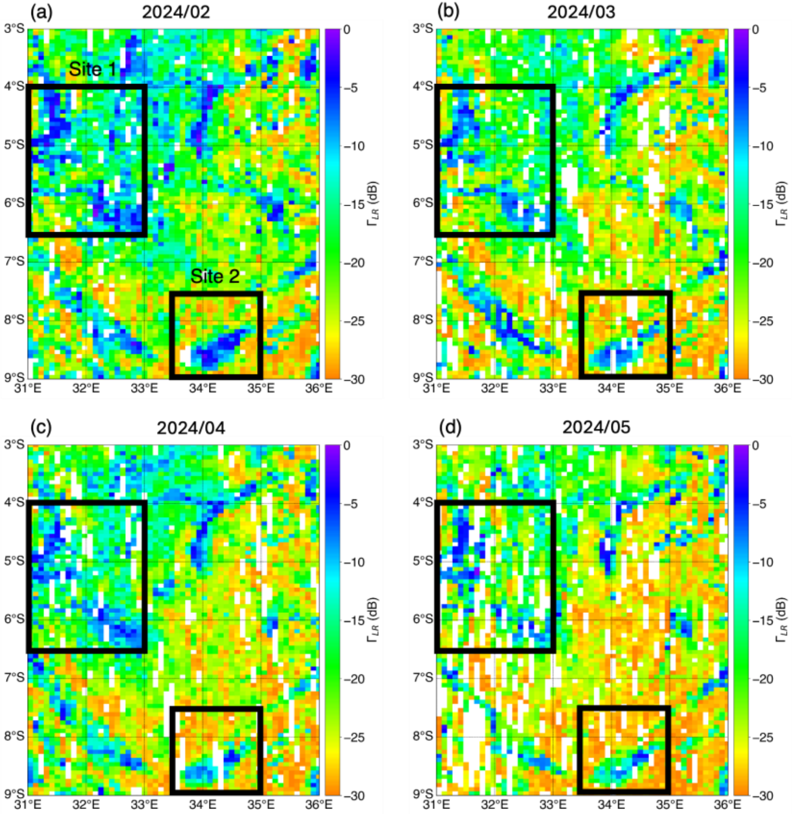
East Africa has been experiencing more frequent and severe flooding in recent years.
Reflectivity has been sorted to plot the higher ones on top of the lower ones.



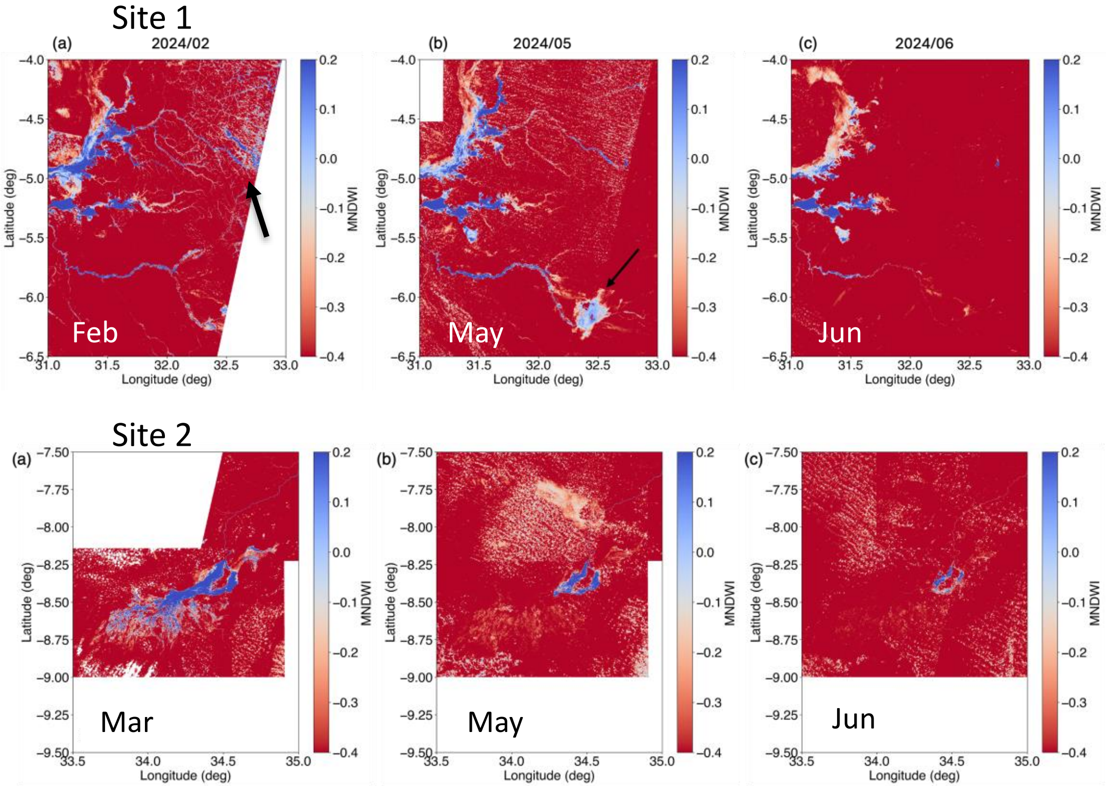
- Reflectivity maps indicate the maximum extent subject to soil inundation.
- Large lakes not always have high reflectivity observations due to water waves.

Soil Inundation in East Africa

Monthly reflectivity observations



Sentinel-2 optical images

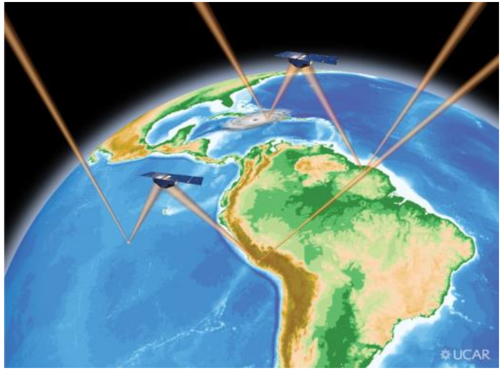


Spire reflectivity observations are usable for delineating soil inundation evolution.

Summary

- Soil moisture
  - Implement a forward model of reflectivity
  - Generate maps of effective surface roughness impact at various incidence angles
  - RMSD of 0.08 cm3/cm3 of Spire SM results compared to SMAP data
  - Higher accuracy in regions with bare soil & short vegetation canopy (RMSD: 0.05 – 0.07 cm3/cm3)
  - Spire SM overestimation over wet soils
- Inland water bodies
  - GNSS-R reflectivity is useful for delineating soil inundation evolution

Thank you!



Backup

COSMIC Data Analysis and Archive Center

- Redundant, geographically separate processing centers
- Modular framework with broad capabilities in GNSS processing, POD, atmospheric retrievals, science analysis
- Extensive data management system
  - Coordinates downlink scheduling, telemetry data transfer, payload commanding
- Able to incorporate external algorithms
  - For example, ion velocity meter processing with UT Dallas, all-clear product with Boston College
- FISMA IT security
  - Authorized to operate at moderate level
- Redundant archives at UCAR/NCAR and NOAA NCEI
- Product delivery to operational weather/space weather centers at NOAA, USAF, and globally via GTS
- Leveraged for operational COSMIC-1, COSMIC-2, KOMPSAT-5, PAZ, and commercial RO processing (GeoOptics, PlanetIQ, Spire)