
Flooding In South Sudan – Nov 2021

FROM RESEARCH TO APPLICATION: ASSESSING THE POTENTIAL OF GNSS-R FLOOD PRODUCTS FOR OPERATIONAL USE

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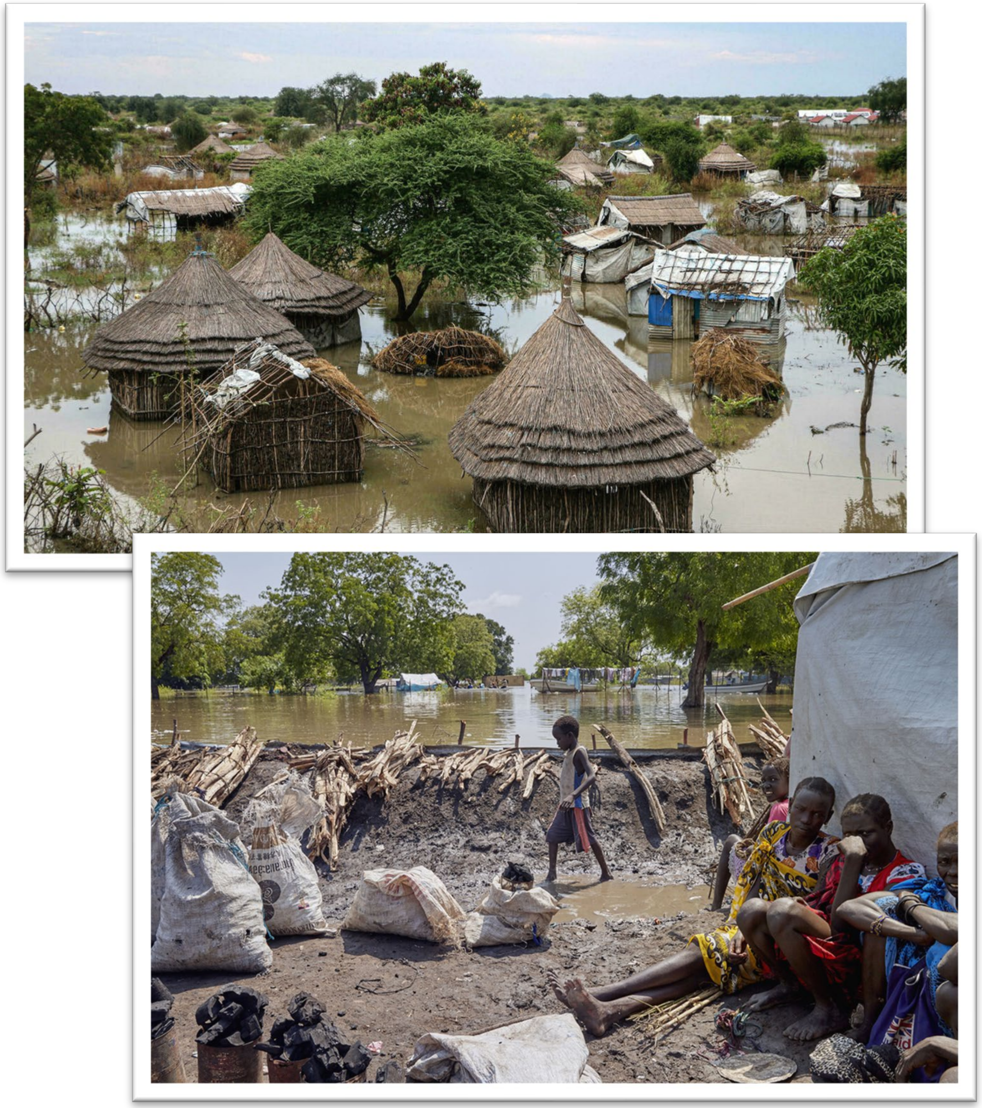
Motivation – Improving Global Flood Products

- Flooding is one of the deadliest and costliest natural disasters. Climate change-induced flooding events are increasing worldwide, impacting low-income and developing communities. Relief agencies and emergency managers need automated, near-real time flood inundation maps available for operational use.
- **Problem:** Current satellite-based operational flood products are largely based on optical remote sensing methods, which exhibit limited ability to detect water beneath rain, clouds, and vegetation.
- **Opportunity:** GNSS-Reflectometry (GNSS-R) has the potential to complement existing surface water and flood data products in all-weather, day/night conditions, as well as through vegetation.
- This presentation discusses our recent research into using GNSS-R to observe wetlands and inland waters and how our current effort is applying this work to progress toward an operational flood product.
- **Our Project Goal:** Apply NASA CYGNSS GNSS-R for inundation analysis and retrieval algorithms in support of the needs of the flood applications community and explore the benefits of GNSS-R data for use by practitioners in decision making.



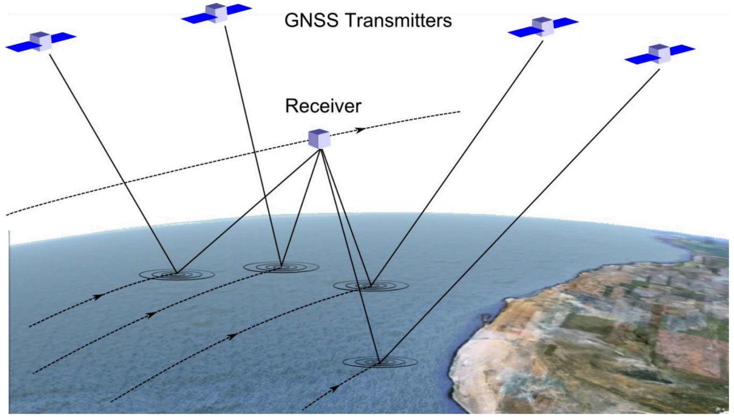
Background – Early GNSS-R Research in Observing Wetlands and Inland Water

- Our team at NASA JPL performed early investigations in the potential for spaceborne GNSS reflections for observing wetlands and inland water (before CYGNSS launch using TDS-1 satellite data).
- Wetlands, lakes, and other inland water environments play key roles in the Earth's hydrology and carbon cycles, ecosystems, methane production, surface fluxes, and heat balance, and are detectors of climate change.
- GNSS-R from aircraft and TDS-1 data showed high sensitivity of forward scattering in the presence of even small water features on land under vegetation. Identified potential to observe dynamic inundation with small satellite constellation enabled by GNSS-R [1-2].

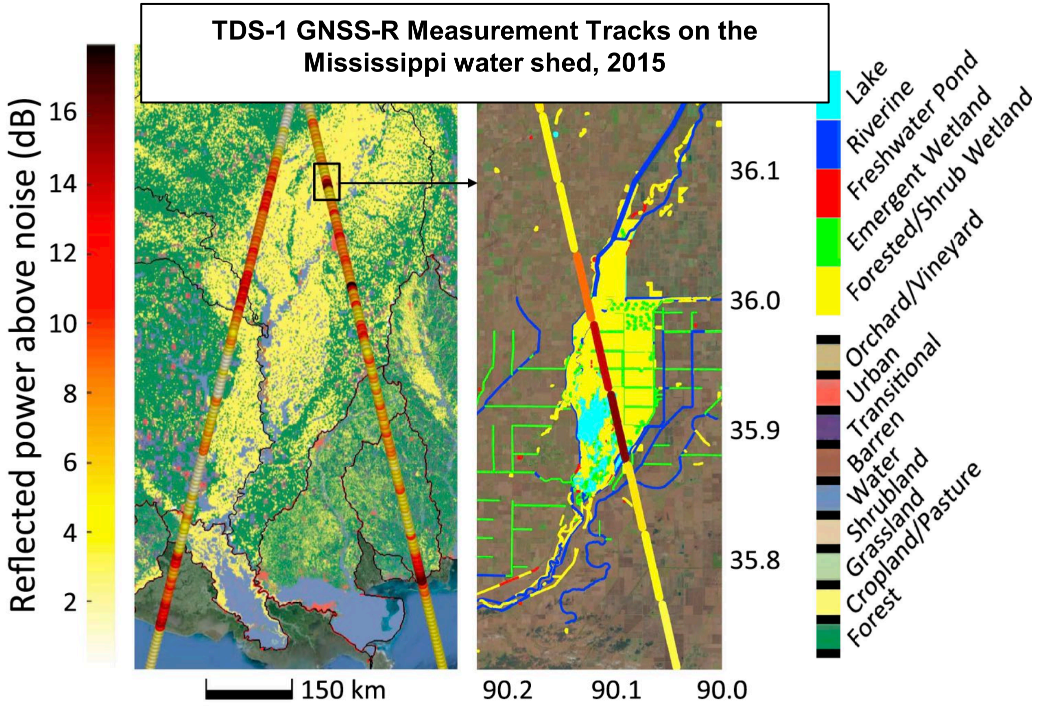
[1] *Zuffada, C. et al. (16). Advancing wetlands mapping and monitoring with GNSS reflectometry. Living Planet Symposium.*

[2] *Zuffada, C. et al. (16). Wetlands: a key component of the water cycle and driver of methane emission, WP submitted in response to the NASA RFI in preparation for the Decadal Survey for Earth Science and applications from space, 2017-2026.*

GNSS Reflectometry (GNSS-R)



TDS-1 GNSS-R Measurement Tracks on the Mississippi water shed, 2015



Reproduced from S. Nghiem et al. (17), Wetland monitoring with Global Navigation Satellite System reflectometry. AGU JESS.

Modeling GNSS-R Reflected Power from Inland Water

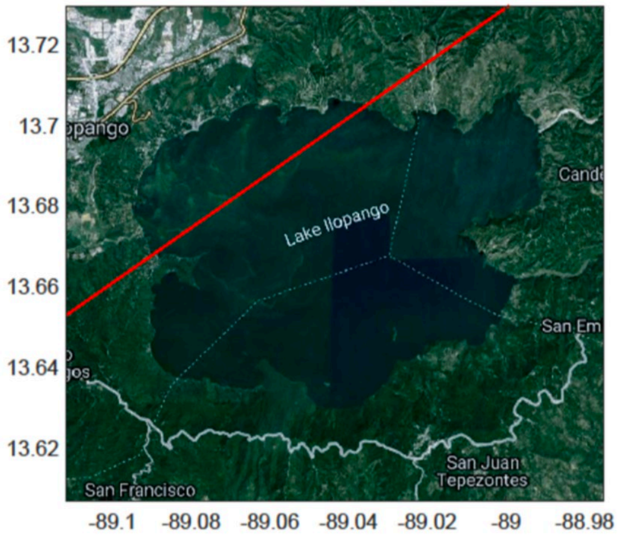
- The total received power (L1 DDM) can be written as a sum of coherent and non-coherent (diffuse) components. When the reflecting surface is sufficiently smooth, such as in water scenes, the coherent component dominates and the Friis transmission formula can be used, assuming that the **contribution comes from the first Fresnel zone only** and neglecting incoherent contributions. This introduces an error.
- To help understand scattering from heterogeneous scenes, we developed a model based on the Kirchhoff Approximation for coherent GNSS reflections with a number of varying surface parameters.

$$|Y(\tau, \delta f)|^2 = \frac{G_r G_t P_t}{(4\pi)^3} \left| \iint_S \frac{jk_c \sqrt{\gamma\psi}\, \cos(\theta)\Gamma(\theta)\chi(\tau + \tau_d, \delta f - f_D)}{R_1 R_2} exp[-jk_c(R_1 + R_2)]dS \right|^2$$

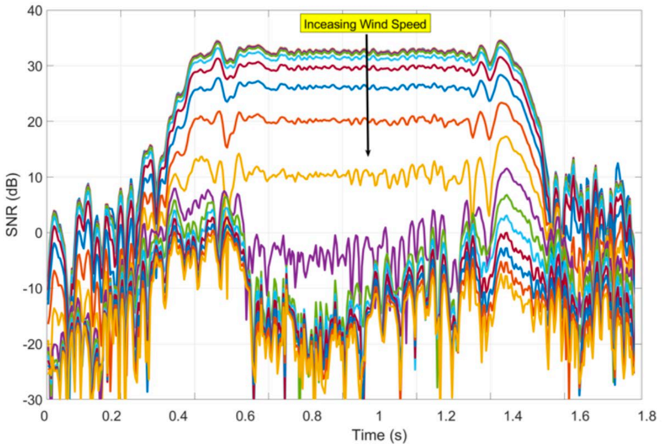
- Note that the surface of integration S is itself a parameter and is not limited to the first Fresnel zone! Model implemented into the CYGNSS E2E simulator.
    - **Accuracy of surface water extent determination affected by heterogeneity.**
    - **Strong sensitivity of peak power NSNR to the presence of even little water leads to overestimates of water extent.**

[3] E. Loria et al. (20) Analysis of scattering characteristics of inland bodies of water observed by CYGNSS. RSE.

CYGNSS Track Over Lake



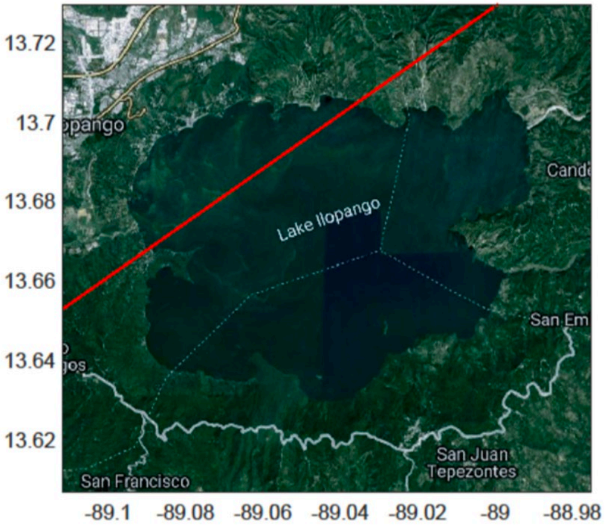
Simulated SNR for Varying Wind Speed



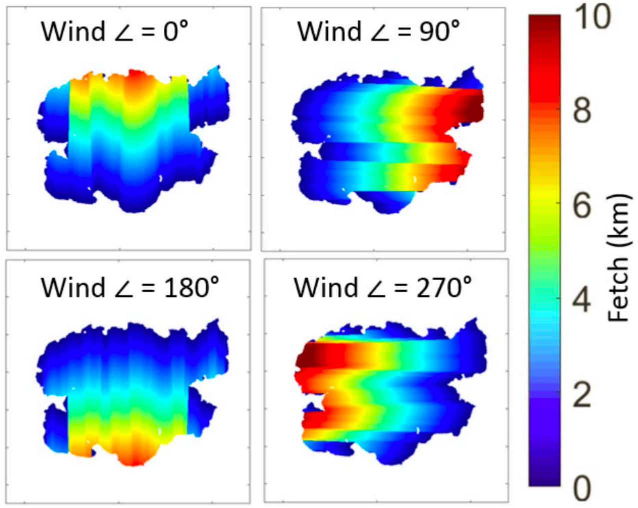
Modeling GNSS-R Reflected Power from Inland Water

- Modeling allows the development of enhanced retrieval algorithms over inland water, applicable to general situations. For example, wind-driven roughness has significant effects on GNSS-R NSNR. The effect of winds varies with water body size, shape, depth, vegetation (both coherent and incoherent scattering), and these effects can be modeled.
- Using a model-driven approach, we found evidence of sensitivity of GNSS-R to both wind amplitude and direction, which is a promising new approach to retrieve wind velocity over lakes [4].

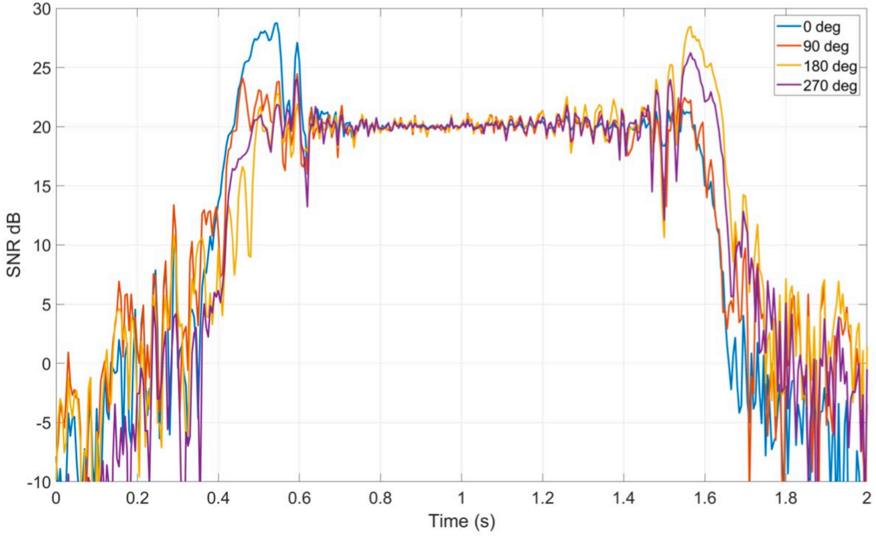
CYGNSS Track Over Lake



Modeled Surface Roughness Depends on Wind Direction



Forward Model Match-Up Shows CYGNSS SNR Sensitivity to Wind Direction

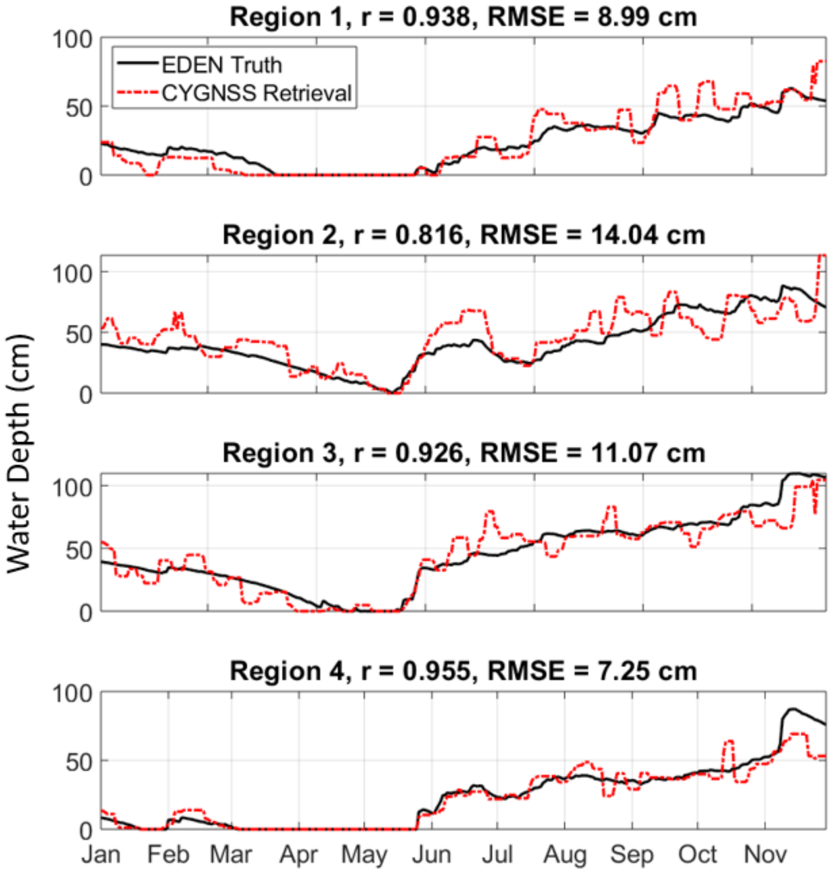


[4] E. Loria et al. (21) Towards Wind Vector and Wave Height Retrievals Over Inland Waters Using CYGNSS, AGU Journal of Earth and Space Science.

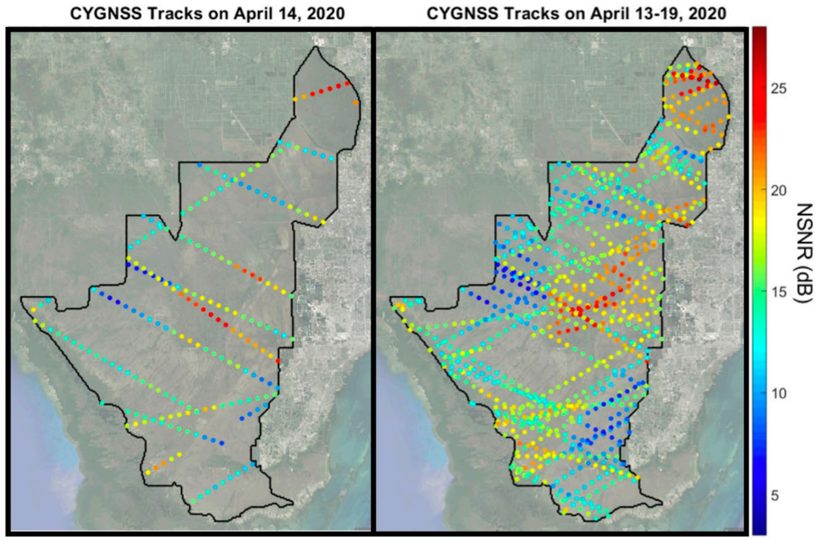
CYGNSS Sensitivity to Water Extent and Depth

- Working with L1 DDM peak NSNR (coherent approximation) we developed algorithms to retrieve both water extent and depth over the Everglades, showing sensitivity to depth in a shallow vegetated region [5].
- Using EDEN water gauge network in the Everglades as truth, CYGNSS-retrieved water depth shows good correlation (right).

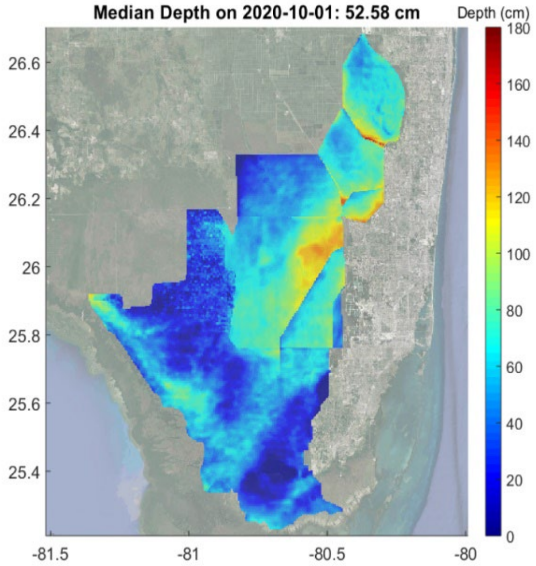
CYGNSS Retrieved Water Depth



CYGNSS Measurements



Water Depth from Sensor Network

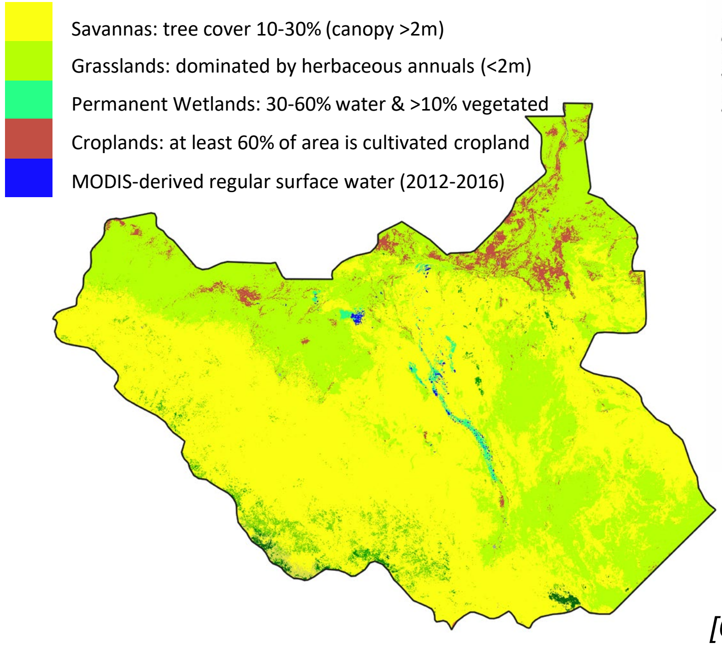


[5] B. Downs, A. O'Brien, M. Morris, C. Zuffada, "Water Depth Retrieval in the Everglades using CYGNSS", Proceedings of the IEEE IGARSS 2021, July 12-16, 2021.

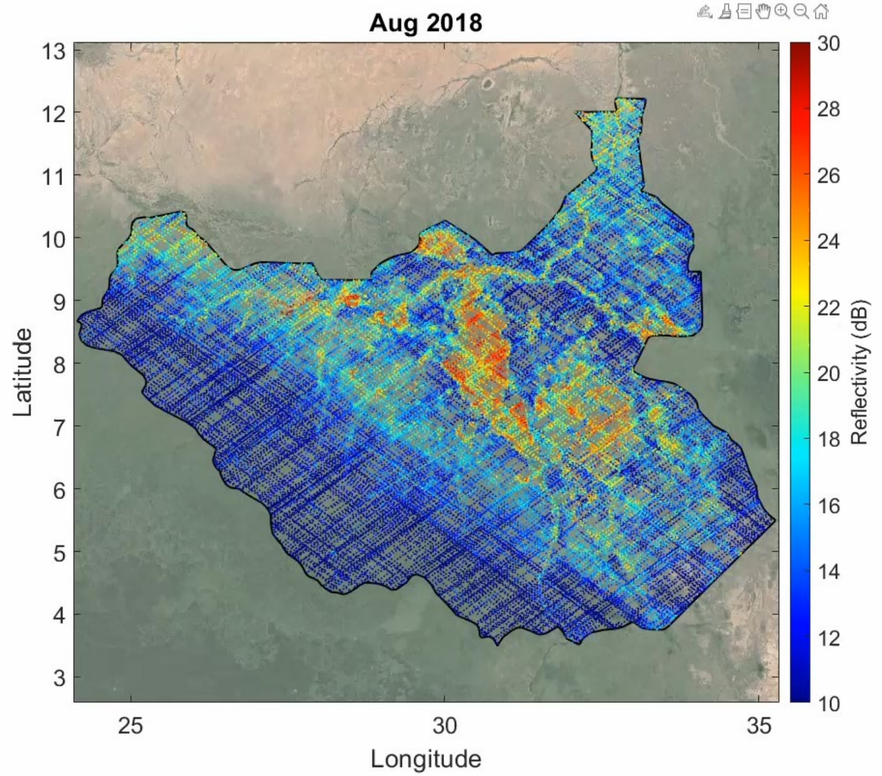
Case Study: South Sudan

- South Sudan flooding in summer/fall of 2021 has been characterized as the worst in decades and impacted over 700,000 people.
- Challenging location for optical-based operational satellite observations due to frequent cloud cover and vegetation (shown in land cover map below).
- The animation shows 30-day windows of CYGNSS NSNR from August 1, 2018 – November 30, 2021, revealing extensive flooding during the past 3 years of wet seasons.
- Surface water extent is highly variable on both short and long timescales.

A village along the White Nile River in the Al-Sudd region.



CYGNSS Observations over South Sudan
Aug 2018 – Nov 2021

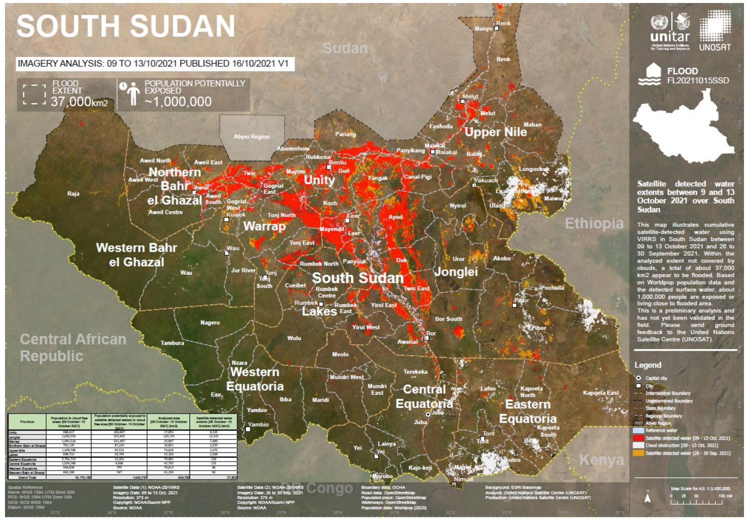


[6] B. Wilson-Downs et al: "CYGNSS Flood Applications To Support The UN Sustainable Development Goals", submitted to 2022 IGARSS.

Available Flood Products over South Sudan

- MODIS-derived surface water from Dartmouth Flood Observatory (DFO).
  - Uses 3 consecutive days of images, 2 images per day, of which at least 4 out of 6 images require unobstructed views to classify a pixel as water or not.
- VIIRS-derived surface water from United Nations Satellite Centre (UNOSAT).
  - Provides satellite imagery and analysis in response to natural disasters to support decision-making.
  - Shows “cumulative satellite-detected water … within the analyzed extent not covered by clouds”.
- Significant cloud cover in October 2021 and the two different algorithms to detect water explain the large discrepancy in surface water.

Oct 2021 – UNITAR Flood Map



SOUTH SUDAN

IMAGERY ANALYSIS: 09 TO 13/10/2021 PUBLISHED 16/10/2021 V1

FLOOD EXTENT 37,000km2

POPULATION POTENTIALLY EXPOSED ~1,000,000

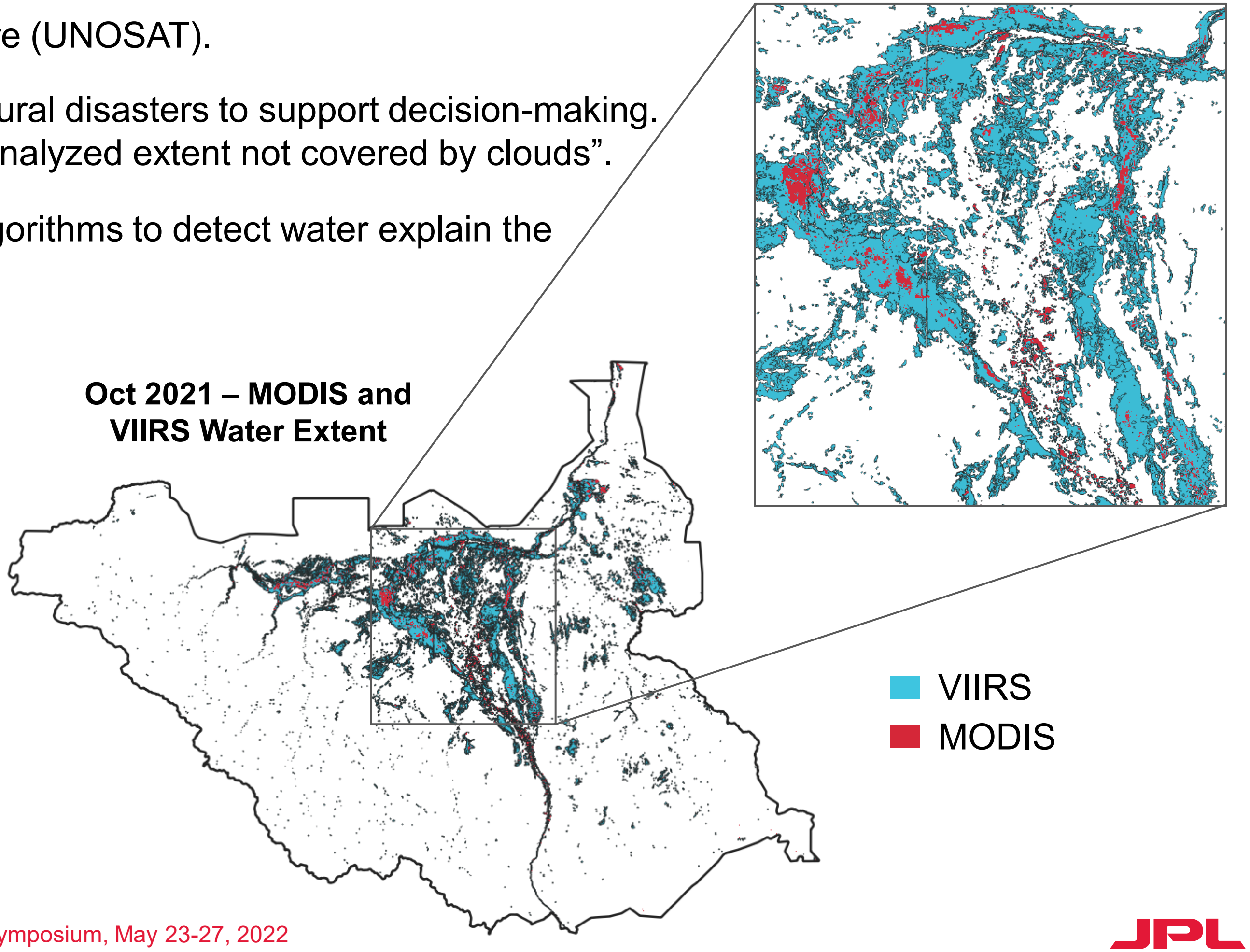
FLOOD
FL20211015SSD

Satellite detected water extents between 9 and 13 October 2021 over South Sudan

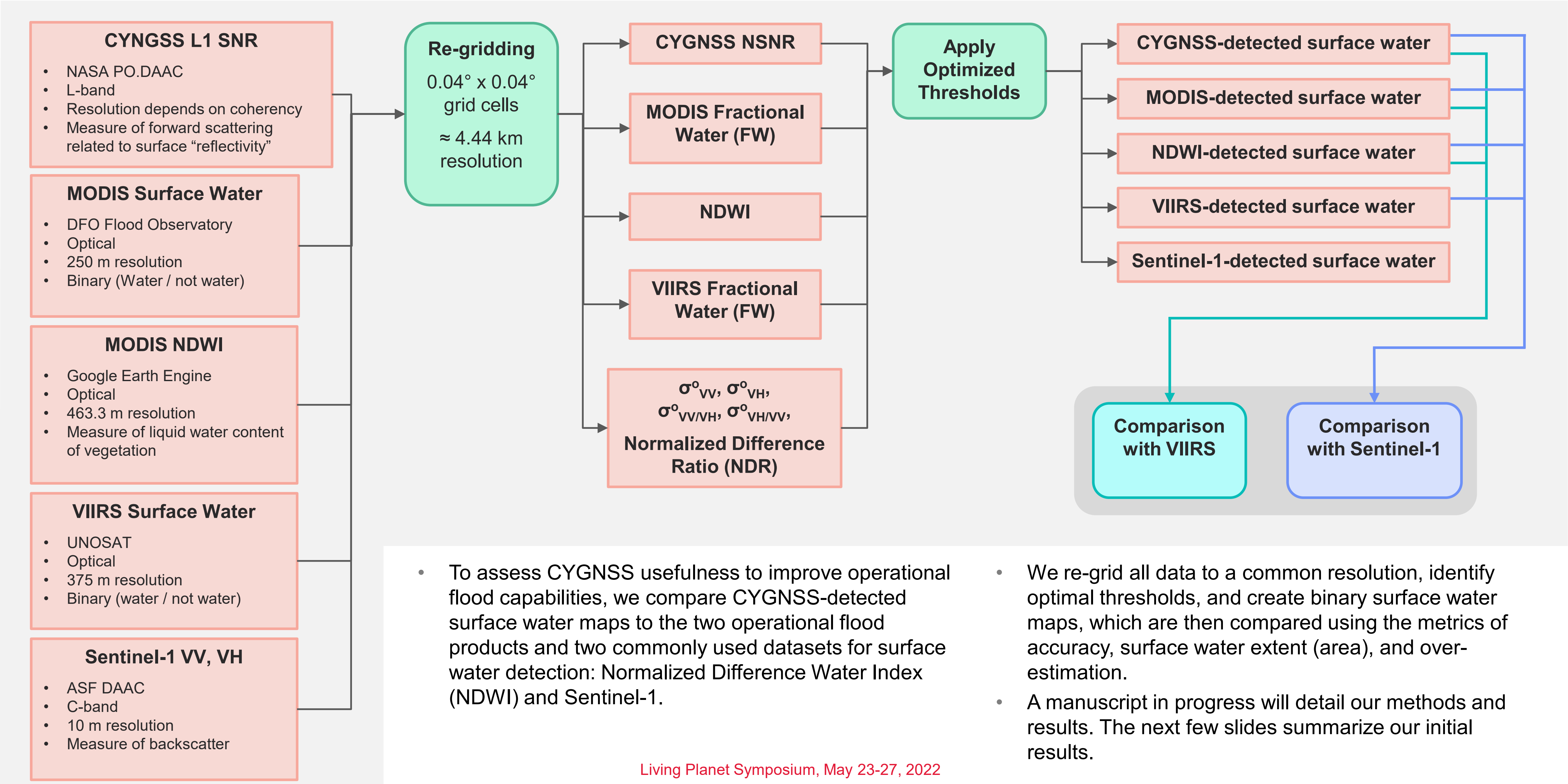
This map illustrates cumulative satellite-detected water using VIRRS in South Sudan between 09 to 13 October 2021 and 26 to 30 September 2021. Within the analyzed extent not covered by clouds, a total of about 37,000 km2 appear to be flooded. Based on Worldpop population data and the detected surface water, about 1,000,000 people are exposed or living close to flooded area.
This is a preliminary analysis and has not yet been validated in the field. Please send ground feedback to the United Nations Satellite Centre (UNOSAT).

Legend

Oct 2021 – MODIS and VIIRS Water Extent



Methodology and Workflow



CYNGSS L1 SNR
- NASA PO.DAAC
- L-band
- Resolution depends on coherency
- Measure of forward scattering related to surface “reflectivity”

MODIS Surface Water
- DFO Flood Observatory
- Optical
- 250 m resolution
- Binary (Water / not water)

MODIS NDWI
- Google Earth Engine
- Optical
- 463.3 m resolution
- Measure of liquid water content of vegetation

VIIRS Surface Water
- UNOSAT
- Optical
- 375 m resolution
- Binary (water / not water)

Sentinel-1 VV, VH
- ASF DAAC
- C-band
- 10 m resolution
- Measure of backscatter

Re-gridding

0.04° x 0.04° grid cells

≈ 4.44 km resolution

CYGNSS NSNR

MODIS Fractional Water (FW)

NDWI

VIIRS Fractional Water (FW)

σ^o_{VV}, σ^o_{VH}, $\sigma^o_{VV/VH}$, $\sigma^o_{VH/VV}$, Normalized Difference Ratio (NDR)

Apply Optimized Thresholds

CYGNSS-detected surface water

MODIS-detected surface water

NDWI-detected surface water

VIIRS-detected surface water

Sentinel-1-detected surface water

Comparison with VIIRS

Comparison with Sentinel-1

- To assess CYGNSS usefulness to improve operational flood capabilities, we compare CYGNSS-detected surface water maps to the two operational flood products and two commonly used datasets for surface water detection: Normalized Difference Water Index (NDWI) and Sentinel-1.
- We re-grid all data to a common resolution, identify optimal thresholds, and create binary surface water maps, which are then compared using the metrics of accuracy, surface water extent (area), and over-estimation.
- A manuscript in progress will detail our methods and results. The next few slides summarize our initial results.

CYGNSS – VIIRS Comparison

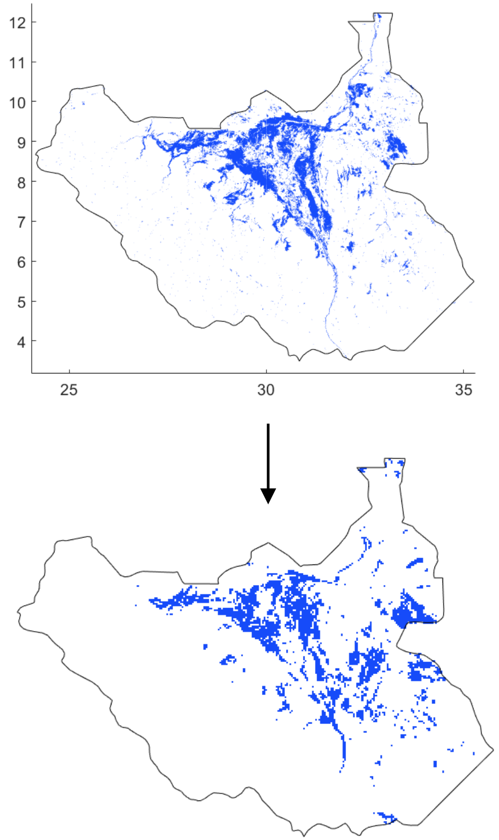
Using VIIRS as a reference,
CYGNSS over-estimates by 36.6%.

Original data at native resolution

Water detected at ~4.44 km resolution

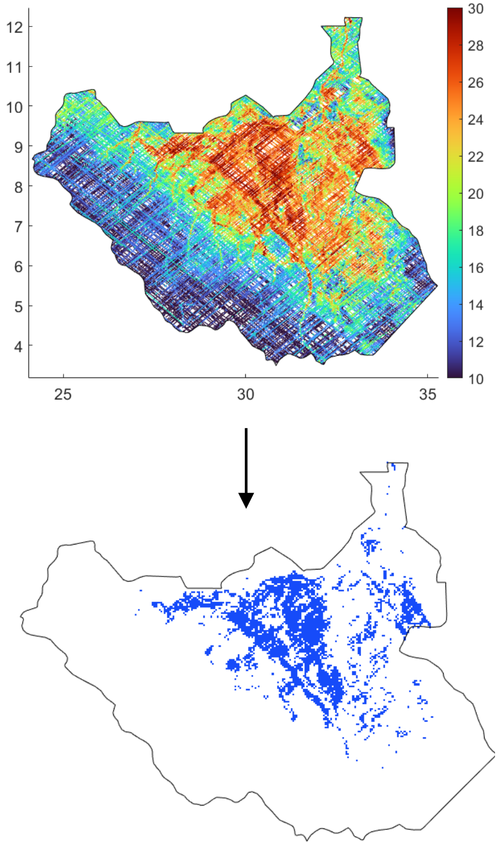
Reference Dataset

VIIRS Surface Water



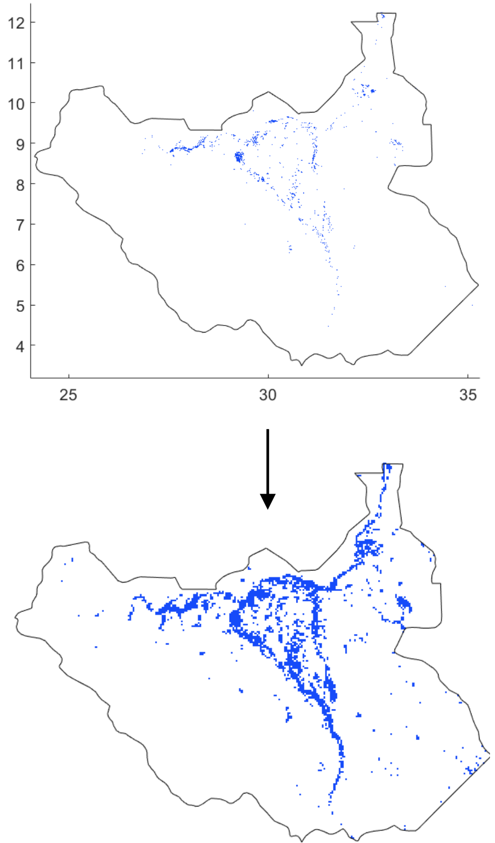
48,672 sq. km

CYGNSS NSNR (dB)



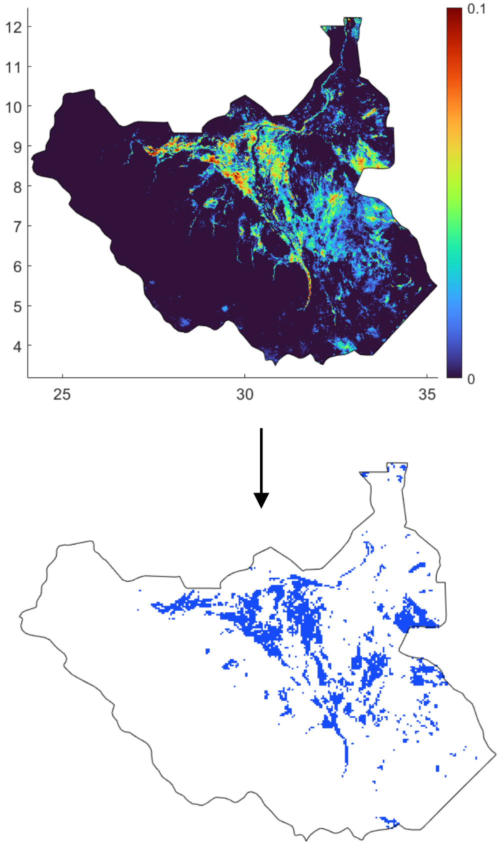
Accuracy: **93.4%**
Over-estimation: **36.6%**
Surface water extent: 66,512 sq. km

MODIS Surface Water



Accuracy: 93.4%
Over-estimation: -14.9%
Surface water extent: 41,415 sq. km

MODIS NDWI

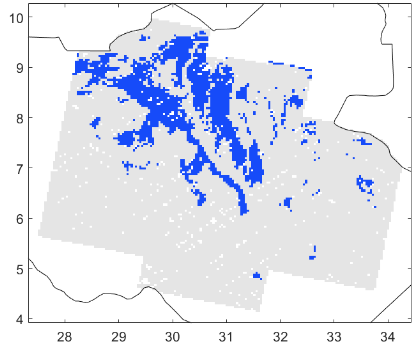


Accuracy: 91.6%
Over-estimation: 20.9%
Surface water extent: 58,926 sq. km

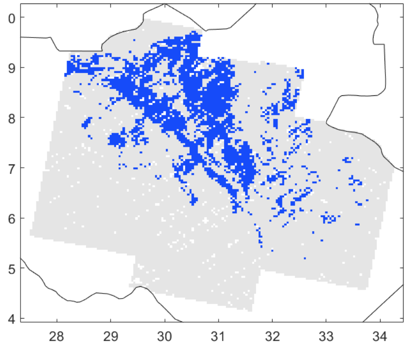
CYGNSS – Sentinel-1 Comparison

Reference Dataset

Sentinel-1 Detected Water

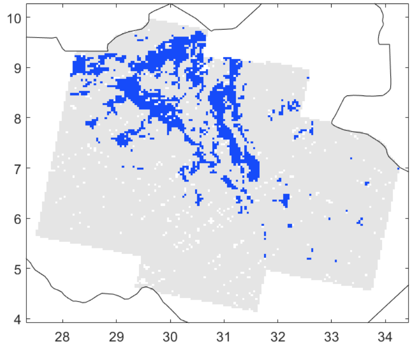


CYGNSS Detected Water



Accuracy: **91.2%**
Over-estimation: **13.4%**

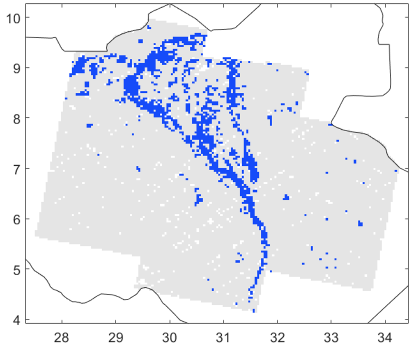
VIIRS Detected Water



Accuracy: 91.5%
Over-estimation: -21.8%

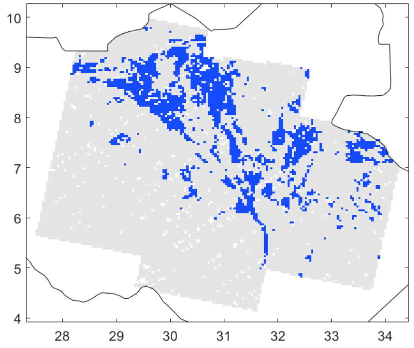
Using Sentinel-1 as a reference, **CYGNSS over-estimates by 13.4%.**

MODIS Detected Water



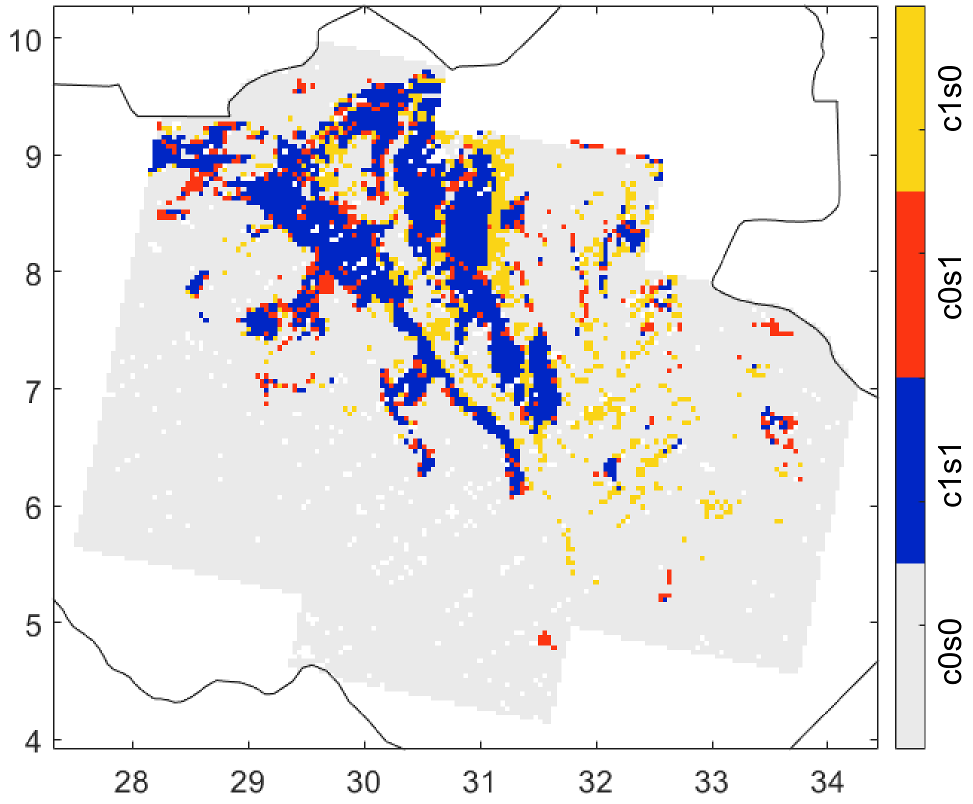
Accuracy: 85.2%
Over-estimation: -40.0%

NDWI Detected Water



Accuracy: 86.8%
Over-estimation: -1.7%

CYGNSS & Sentinel-1

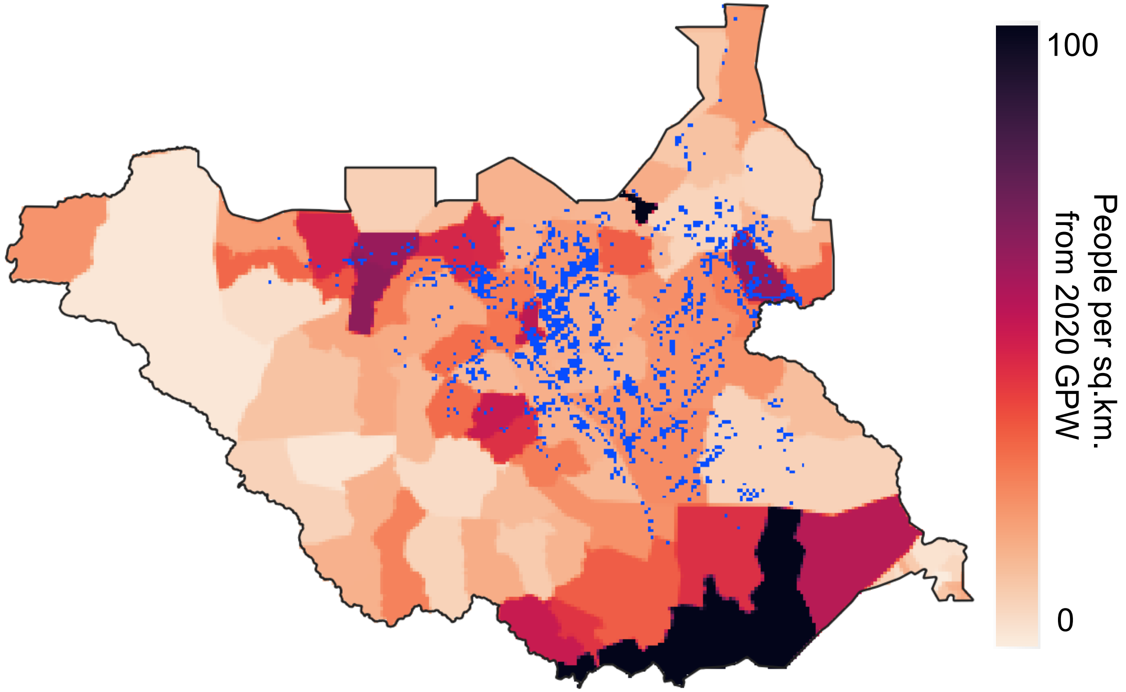


Is Excess Detected Water Real?

We are continuing to explore the utility of CYGNSS to enhance operational flood map products.

- The accuracy of satellite-based flood observations, and our understanding of impacts such as the total population exposed to a flood event, are extremely consequential.
- The CYGNSS flood maps show a potential over-estimation of surface water.
- Excess could be due to:
  - Enhanced CYGNSS sensitivity to water, particularly beneath vegetation and/or in cloudy conditions.
  - Over-sensitivity of CYGNSS peak power to even small amounts of water present in a heterogeneous scene.

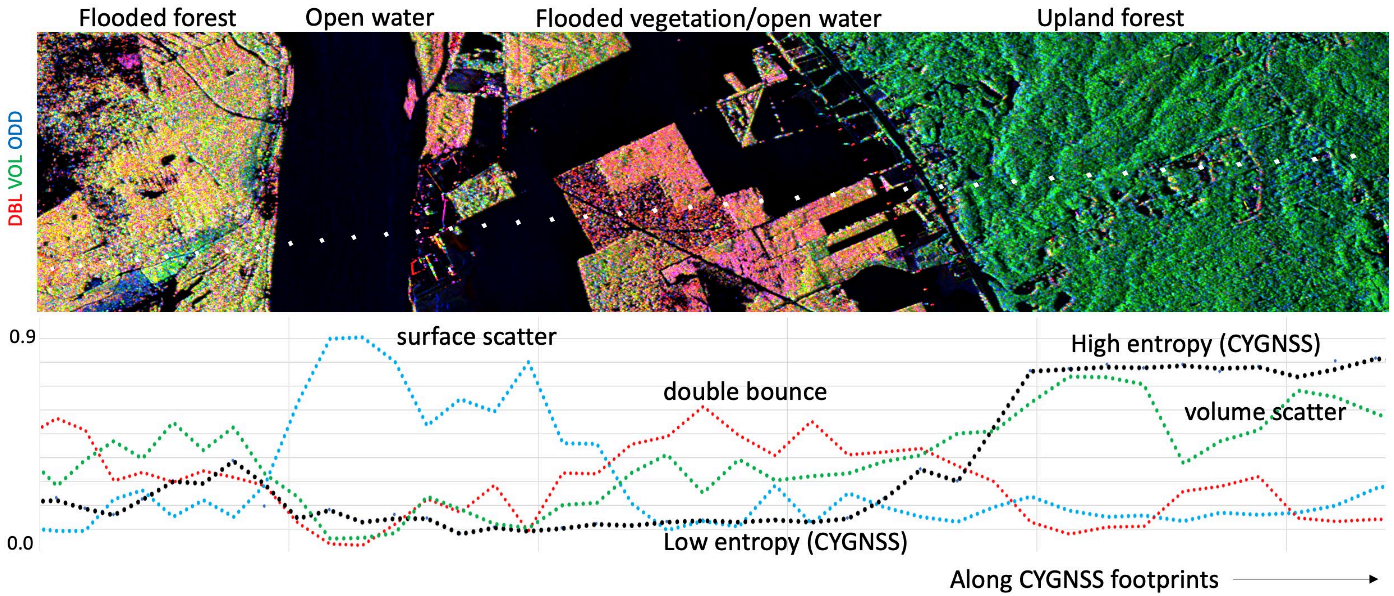
CYGNSS Excess Detected Water and Population Density



CYGNSS excess water (blue) is defined as pixels in which CYGNSS detected surface water and VIIRS did not.

Improving Accuracy

- Heterogeneous scenes give rise to variability in CYGNSS L1 DDMs due to area of collection constrained by choice of GPS C/A code, affecting accuracy of inundation extent retrieval.
- To improve accuracy, higher frequency sampling is required to resolve changes in scenes with water, based on detection of spots of coherency.
- CYGNSS can acquire ~1-minute sequences of "raw" signal samples useful for detailed study of heterogeneous areas since spatial resolution can be increased.
- Can be custom post-processed on the ground to produce complex correlation values. We developed two such approaches: 'signal decomposition and entropy' and 'normalized coherency'.
- These algorithms might be implemented in future GNSS-R receiver acquisition schemes tailored to heterogeneous scenes.



- **Top)** UAVSAR image swath acquired on June 22, 2019 at Yucatan Lake, LA, where the color composite is formed by combining the double bounce (red), volume (green), and odd bounce (blue) surface scattering values.
- **Bottom)** CYGNSS entropy and normalized UAVSAR scattering components [9] show good agreement between entropy and the high-res SAR technique taken as truth.

[7] I.M. Russo et al. (21). Entropy-Based Coherence Metric for Land Applications of GNSS-R. IEEE TGARS, 2021.

[8] E. Loria et al. (18). Detection & separation of coherent reflections in GNSS-R measurements using CYGNSS data. IEEE IGARSS 2018.

[9] B. Chapman et al. Comparison Of SAR And CYGNSS Surface Water Extent Metrics. IEEE JSTARS, 2022.

Conclusions

- CYGNSS has the potential to complement and improve current operational flood products due to its sensitivity to water beneath vegetation and its high temporal frequency.
- However, utilizing CYGNSS L1 total reflected power alone limits the ability to differentiate small water features in heterogeneous scenes.
- Because the L1 peak power is very sensitive to even small water features, this leads to an over-estimation of detected water.
- Future GNSS-R systems tailored to monitor inundation will need to consider higher frequency sampling and on-board processing algorithms, such as those discussed in the posters listed at right.

For further information, see posters in today's afternoon poster session:

- I.M. Russo et al., **Synergy of SAR and GNSS Reflectometry for Analysis of Wetlands Dynamics**.
- C. Galdi et al., **Real-Time Detection of Coherent Components in GNSS Land Reflectometry**.

Acknowledgements

The research reported here was carried out in part at the Jet Propulsion Laboratory, Caltech, under a contract with the National Aeronautics and Space Administration (80NM0018D0004). © 2021. All rights reserved.

CYGNSS L1 Data is available through the NASA EOSDIS Physical Oceanography Distributed Active Archive Center (PO.DAAC).

We are grateful to the CYGNSS Project and PI Prof. C. Ruf for making available L0 raw-IF data.

THANK YOU!