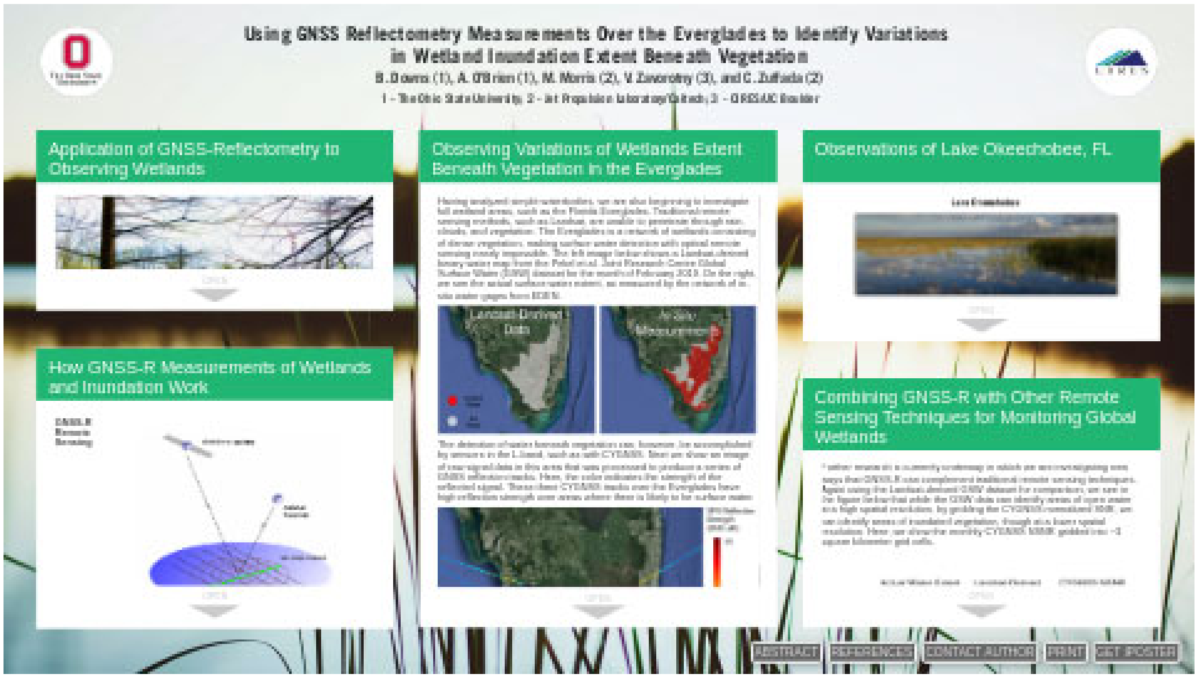
Using GNSS Reflectometry Measurements Over the Everglades to Identify Variations in Wetland Inundation Extent Beneath Vegetation



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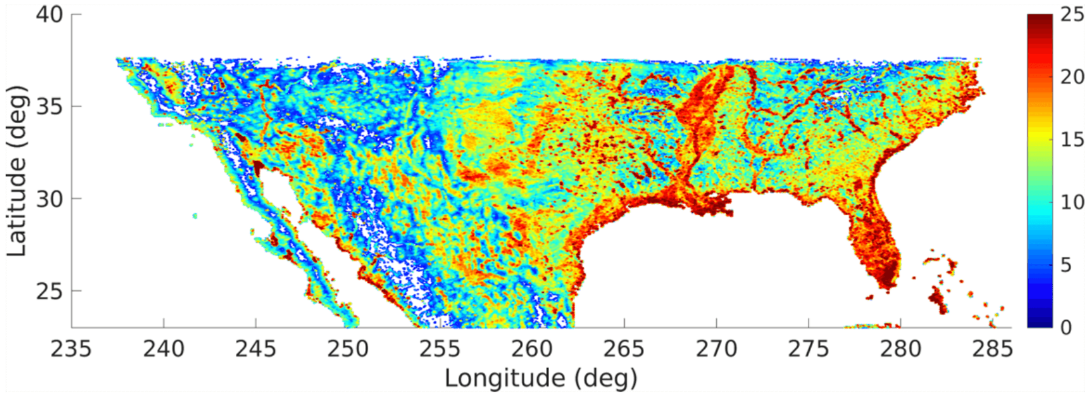
APPLICATION OF GNSS-REFLECTOMETRY TO OBSERVING WETLANDS

Background: Wetlands are among the most biologically diverse and productive ecosystems in the world, providing flood control, carbon storage, and habitat for a broad range of species. However, their health and existence is threatened by the effects of sea level rise, climate change, and habitat destruction. Understanding and monitoring wetlands is important for political decision-making and requires the ability to accurately identify and measure wetland extent and change in extent on short time scales.

The Everglades, in the U.S. state of Florida, is a Ramsar Site of global importance, supporting several threatened and endangered species of flora and fauna, and is especially important for wintering birds.

Problem: Observations of water beneath vegetation is limited. In situ methods are difficult given the nature of the surrounding environment, and optical methods of remote sensing are unable to see through dense vegetation.

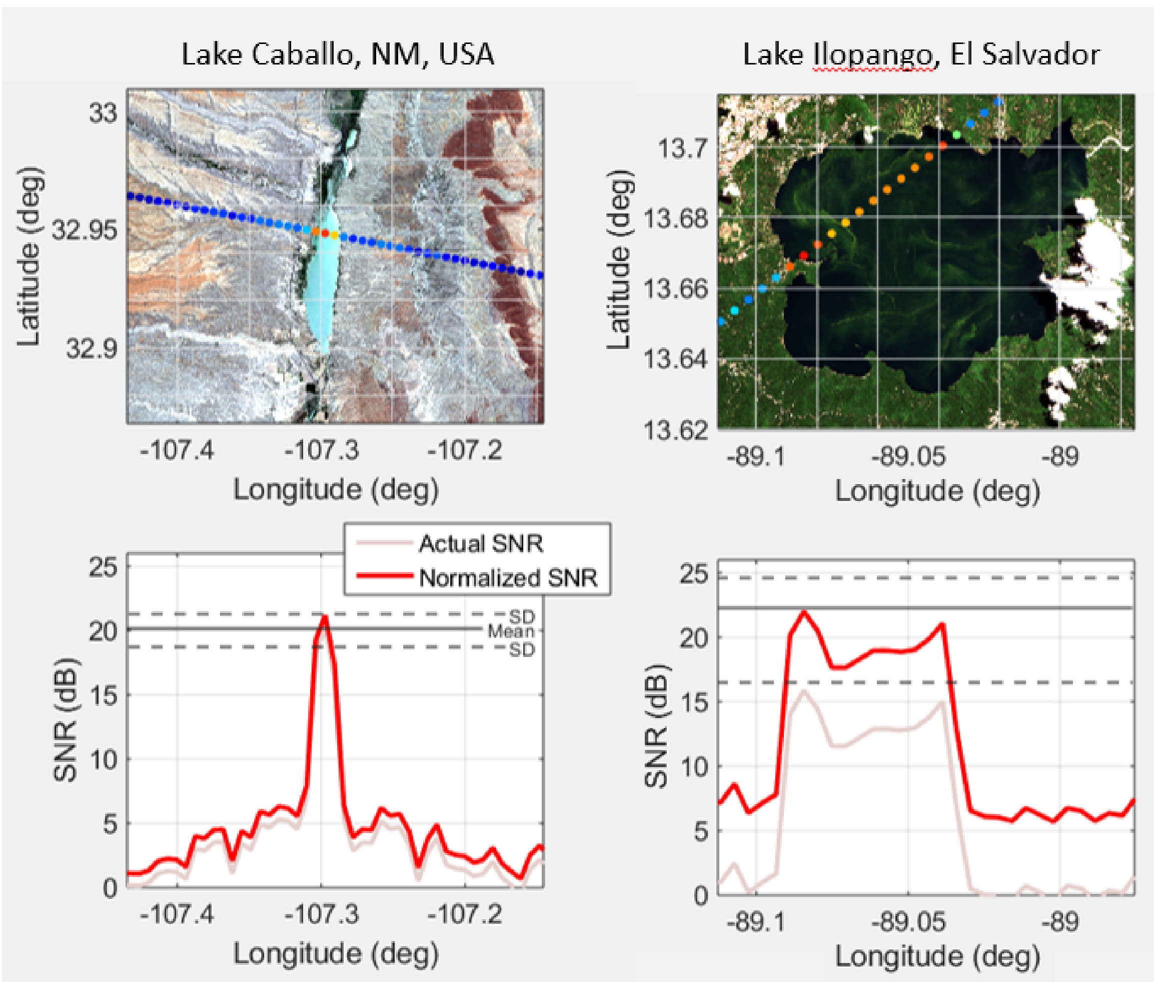
Opportunity: NASA's Cyclone Global Navigation Satellite System (CYGNSS) has shown promising results using ***GNSS Reflectometry*** (GNSS-R) in identifying the presence and extent of inland water. Utilizing GNSS as a signal of opportunity in an L-band passive bistatic radar, it can penetrate rain, clouds, and vegetation. Its 8-satellite constellation exhibits daily or sub-daily revisit rates, enabling the observation of dynamic changes on short time scales. Small satellite constellations like CYGNSS represent a new observing system as compared to traditional, monolithic satellites. The image below from [1] demonstrates the sensitivity of CYGNSS SNR to surface water, where high SNR is correlated with the presence of water. Here, plots of peak power, corresponding to CYGNSS measurements' specular points, aggregated over a period of time, and displayed over the Southeast United States, clearly shows the potential of CYGNSS to map surface hydrology of intricate scenes at the continental level.



Goal: We utilize a combination of CYGNSS data and ancillary information to understand the observability of inundation beneath vegetation.

Contributions of This Work:

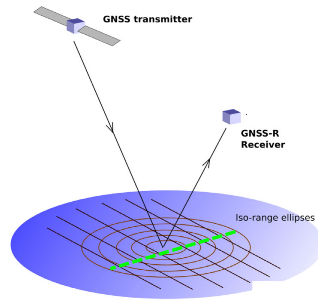
- Our initial studies began by analyzing CYGNSS's response over simple water bodies - those with little to no vegetation and exhibiting clear binary water/not water boundaries. The figure below illustrates CYGNSS's sensitivity to these binary states over two different water bodies, both of which exhibiting distinct boundaries between land and water.



- We then investigated the ability of CYGNSS to detect the presence of water beneath vegetation in the Everglades and compared it with truth data obtained from the Everglades Depth Estimation Network (EDEN).
- Using a priori knowledge of the average spatial extent of water for a given month, we then used CYGNSS to distinguish between dry/wet states of regions within the Everglades over a period of seasonal change.
- By leveraging CYGNSS's high temporal frequency of observations and ability to see under vegetation, measurements of inundated vegetation and its change can complement other remote sensing and in situ methods of wetland monitoring.

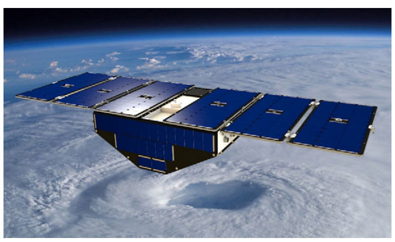
HOW GNSS-R MEASUREMENTS OF WETLANDS AND INUNDATION WORK

GNSS-R Remote Sensing Concept: Global Navigation Satellite Systems (GNSS) is a term we use to refer to multiple satellite navigation systems, such as GPS, Galileo, GLONASS, Beidou, QZSS.

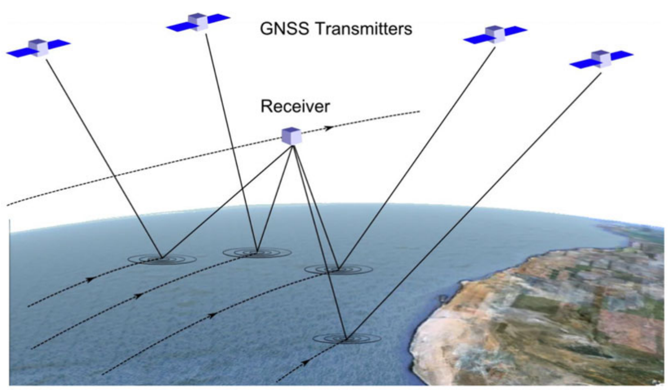


GNSS Reflectometry (GNSS-R) utilizes reflections of GNSS signals off the Earth for remote sensing. The amplitude, phase, polarization, and other properties of the reflected signal contain information about the surface. In this sense, we are using GNSS signals to form a passive bistatic radar.

CYGNSS (Cyclone Global Navigation Satellite System) is a constellation of 8 small satellites launched in December 2016 that is now providing datasets to the science community.

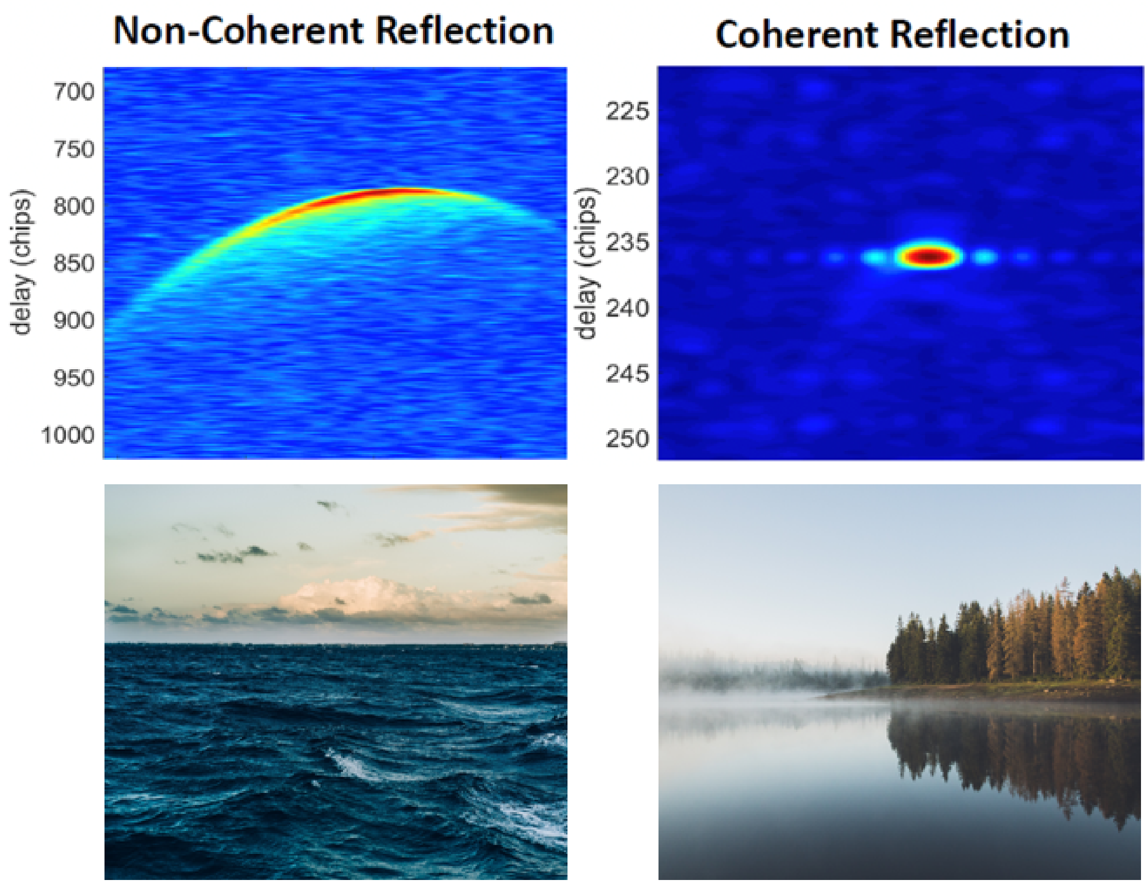


The 8 CYGNSS micro-satellites each make 4 simultaneous measurements. The standard CYGNSS data product (L1) is 1, 2, or 4 Hz measurements. Satellite motion causes the reflection point to move at 6 km/s. For coherent scattering, the spatial resolution is 1 km x 7 km (first Fresnel zone x along-track non-coherent integration assuming 1 Hz measurement rate). For diffuse scattering, the spatial resolution is ~20 km x 27 km (resolution defined by radar ambiguity function projected onto the surface).



Coherent Reflections from Wetlands

There are two types of scattering in GNSS-R: non-coherent scattering results in a surface resolution of 20-30 km; coherent scattering comes from an area ~1 km around the specular point and is assumed to be limited to the first Fresnel zone. The figure below from [2] shows a non-coherent reflection over the ocean (left) and a coherent reflection over a river (right) measured from CYGNSS.



In [3] and [4], it was hypothesized that there are strong coherent specular reflections in the collection area of the signal over wetlands/surface water. This hypothesis was based on reflected signal characteristics such as peaked (limited spread in delay and doppler) and symmetric shape, and very high reflected peak power. These signals can originate from even small areas of standing water, resulting in the measurements' magnified sensitivity to water because of its high electric permittivity compared to dry land and/or vegetation.

Scattering Model Development: To take full advantage of coherent reflection and best retrieve geophysical information, it is necessary to develop new scattering models, perform simulation studies, and understand how future GNSS-R receivers can be optimized to receive these types of signals. A scattering model based on the Kirchoff Approximation was developed for coherent GNSS reflections over complex scenes with a number of varying surface parameters [2].

We identified 3 significant sources of variability:

- Surface roughness (wind, waves, and vegetation)
- Vegetation attenuation
- The geometry of the surface

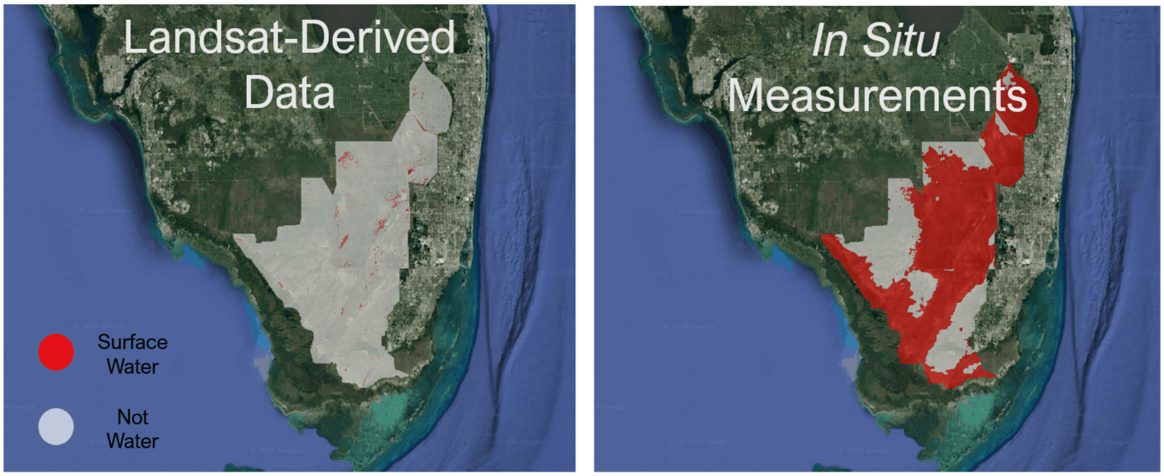
Scattering Model for Vegetated Water: The models work well in unprotected inland waters, but other effects, particularly those due to vegetation, may influence the final surface roughness. Initial work to identify and incorporate several vegetation effects into our GNSS-R coherent scattering model is presented in [5].

We highlight four physical components common in the heterogeneous inland water scene and examine the interactions between them: surface water, wind, vegetation, and the coherent electromagnetic signal. For increased vegetation, we expect the signal attenuation to also increase. However, there may be waves on the water surface below the vegetation. In this case, we expect that increased vegetation would reduce the size of these water waves. Thus, the surface roughness loss would decrease. We are interested in finding a simplified model to compare the attenuation of the GNSS signal and the reduction in wave heights due to vegetation.

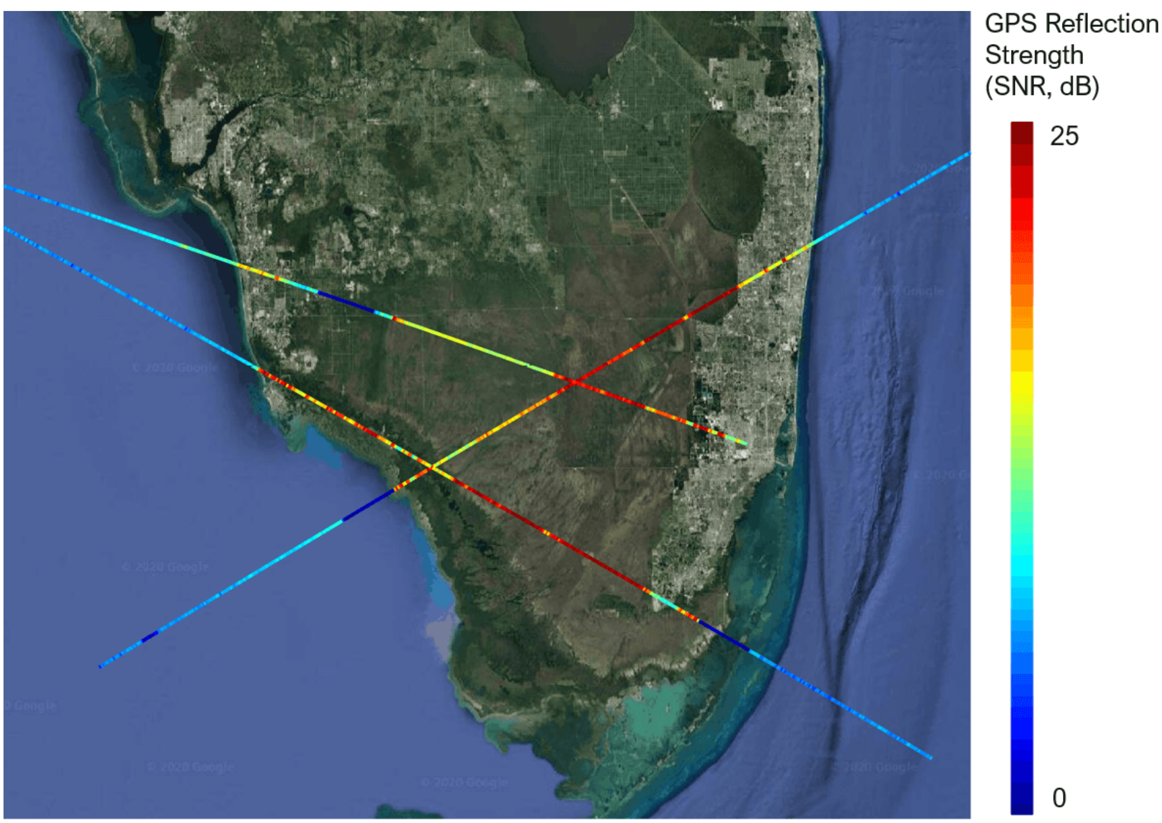
Vegetation also imparts a drag force on water waves. This drag dissipates wave energy from the water, which reduces the size of the waves. The amount of drag that vegetation imparts on the water is influenced by many parameters: thickness, density of plants, height of vegetation (if submerged), the rigidity of the plants (does it move in the water?), viscosity of surface bottom, etc.

OBSERVING VARIATIONS OF WETLANDS EXTENT BENEATH VEGETATION IN THE EVERGLADES

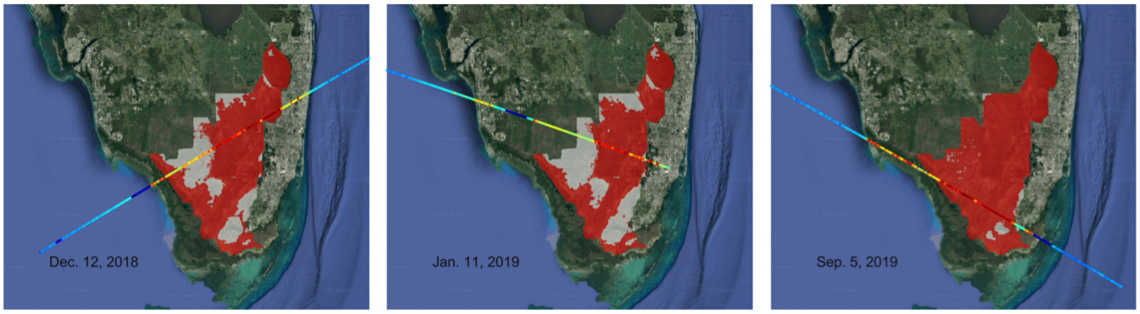
Having analyzed simple waterbodies, we are also beginning to investigate full wetland areas, such as the Florida Everglades. Traditional remote sensing methods, such as Landsat, are unable to penetrate through rain, clouds, and vegetation. The Everglades is a network of wetlands consisting of dense vegetation, making surface water detection with optical remote sensing nearly impossible. The left image below shows a Landsat-derived binary water map from the Pekel et al. Joint Research Centre Global Surface Water (GSW) dataset for the month of February 2019. On the right, we see the actual surface water extent, as measured by the network of in-situ water gages from EDEN.



The detection of water beneath vegetation can, however, be accomplished by sensors in the L-band, such as with CYGNSS. Next we show an image of raw signal data in this area that was processed to produce a series of GNSS reflection tracks. Here, the color indicates the strength of the reflected signal. These three CYGNSS tracks over the Everglades have high reflection strength over areas where there is likely to be surface water.



We can verify that high CYGNSS SNR corresponds to the presence of surface water by comparing each track individually with the distribution of water from the EDEN data. Comparing the SNR with the boundaries of water/not water allows us to establish a distribution of CYGNSS data that corresponds to the presence or absence of surface water. The figure below shows each GNSS reflection track superimposed on the EDEN in-situ data. Here, we see a good agreement between high SNR values (>16 dB) and surface water, even when that water is under vegetation.



Mapping Extent in the Everglades

At the regional scale, availability of in-situ and other correlative data that can be used as truth in classifying an area as wet or dry have led to introduce thresholds in reflected peak power values that differentiate between two binary states, i.e. dry and wet associated with inundations [6-7].

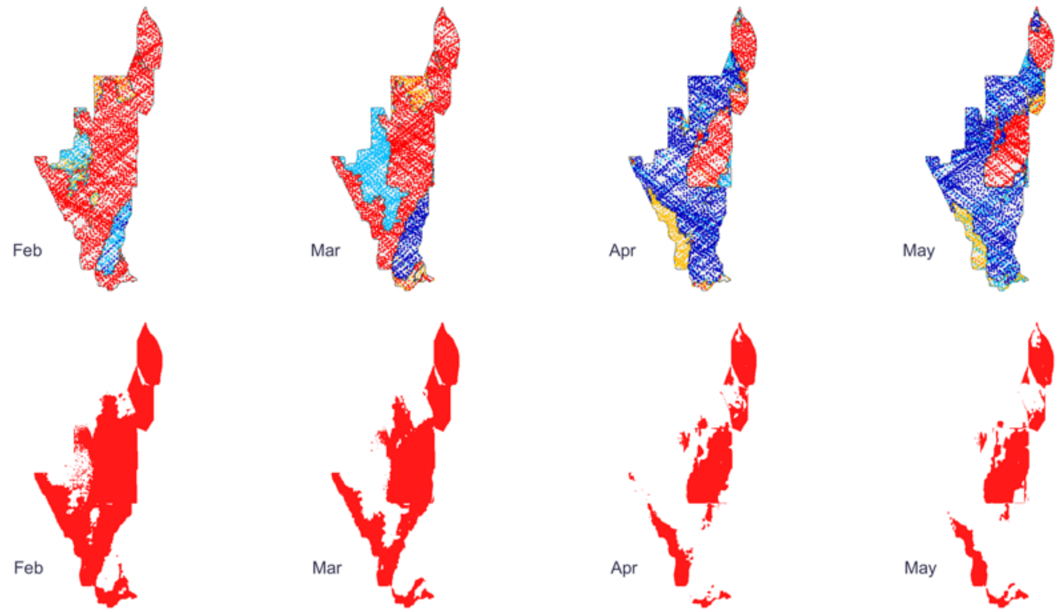
Maps of wetlands and inundation were first formed based on a simple scattering model that assumes the signal to be coherent and the peak power contribution to come from the first Fresnel zone [8]. Morris et al. focused on data analysis at a smaller scale than the Amazon basin, with particular attention to detecting dynamic changes in very short time scales typical of flooding and seasonal variability in heterogenous scenes [7].

Maps of extent can be formed by setting a threshold in the reflected peak power of each pixel to categorize them as wet or dry based on the distribution of the truth. Over time, one can obtain maps of dry-wet state of a region, as illustrated below for the Everglades. First, we establish boundaries between areas of surface water and dry land using the EDEN data for March, 2020. In the absence of truth data, however, we could use a hydrology model that depicts how an area is likely to flood, and use that model to create predictions of spatial boundaries.

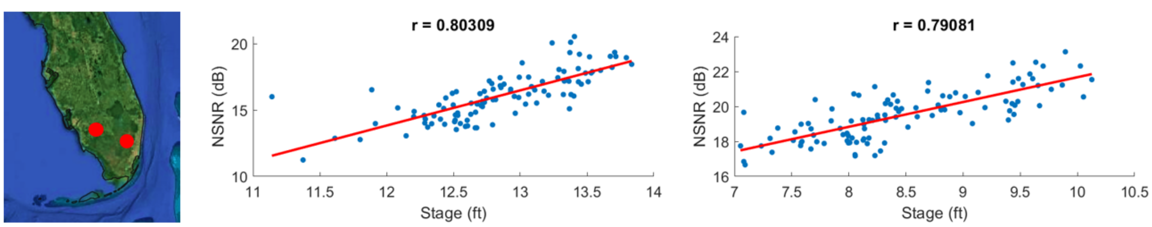
Next, we plot the daily CYGNSS tracks across the Everglades and take a daily cumulative average of the CYGNSS SNR within each boundary. This allows us to see how well CYGNSS can detect the presence of water within these pre-established boundaries using SNR alone.

[VIDEO] https://www.youtube.com/embed/gXAWGeatmqA?rel=0&fs=1&modestbranding=1&rel=0&showinfo=0

Using the EDEN data collected from February through May of 2020, we show similar agreement between the CYGNSS SNR-mapped regions and the actual water extent provided by the in-situ gages.



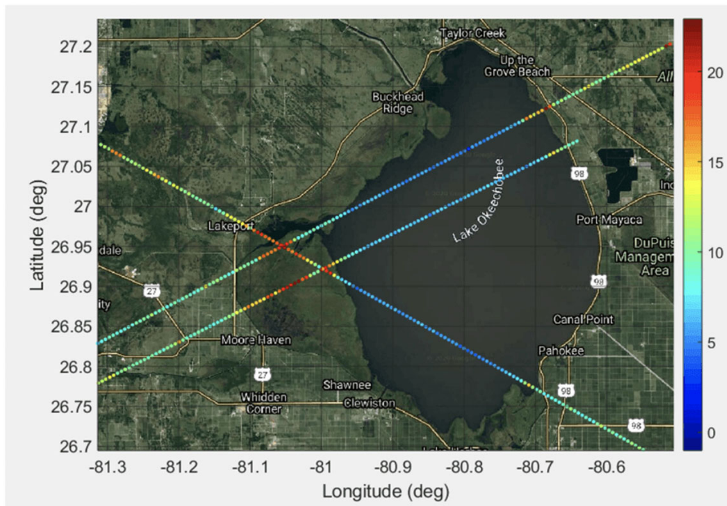
CYGNSS measurements were further validated by comparing the SNR, normalized to account for varying satellite geometry and receiver parameters (NSNR), to the stage data from individual water gages in the EDEN network. The regression plots for two of the gages are shown below, showing high relative correlation coefficients, with the gage locations shown as red dots on the map.



OBSERVATIONS OF LAKE OKEECHOBEE, FL

Lake Okeechobee

Lake Okeechobee - Requested CYGNSS Raw IF Tracks

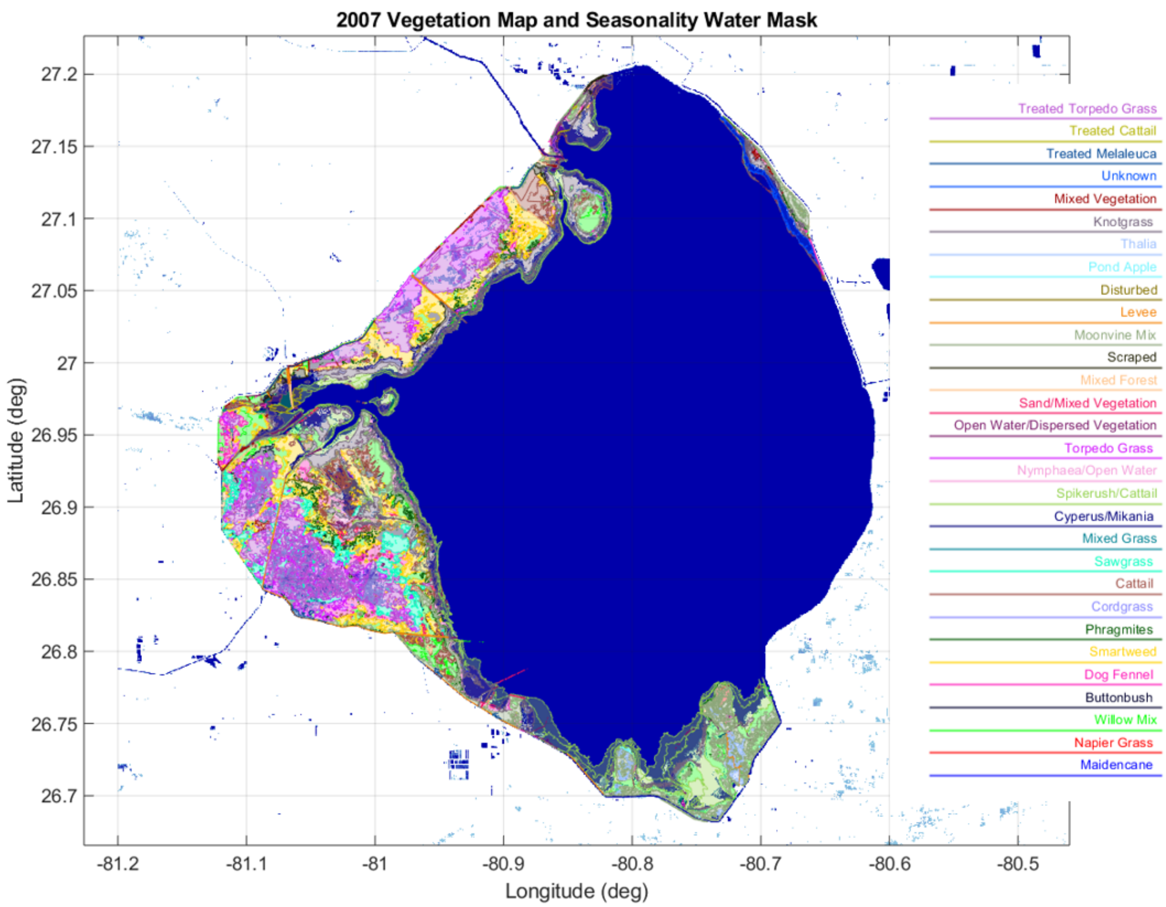


Observing Vegetated Waters in Lake Okeechobee

Currently, we are working to understand how the presence of vegetation affects the coherent reflections over simple water bodies with vegetation. ***Lake Okeechobee*** in Florida's Greater Everglades Watershed is one such water body.

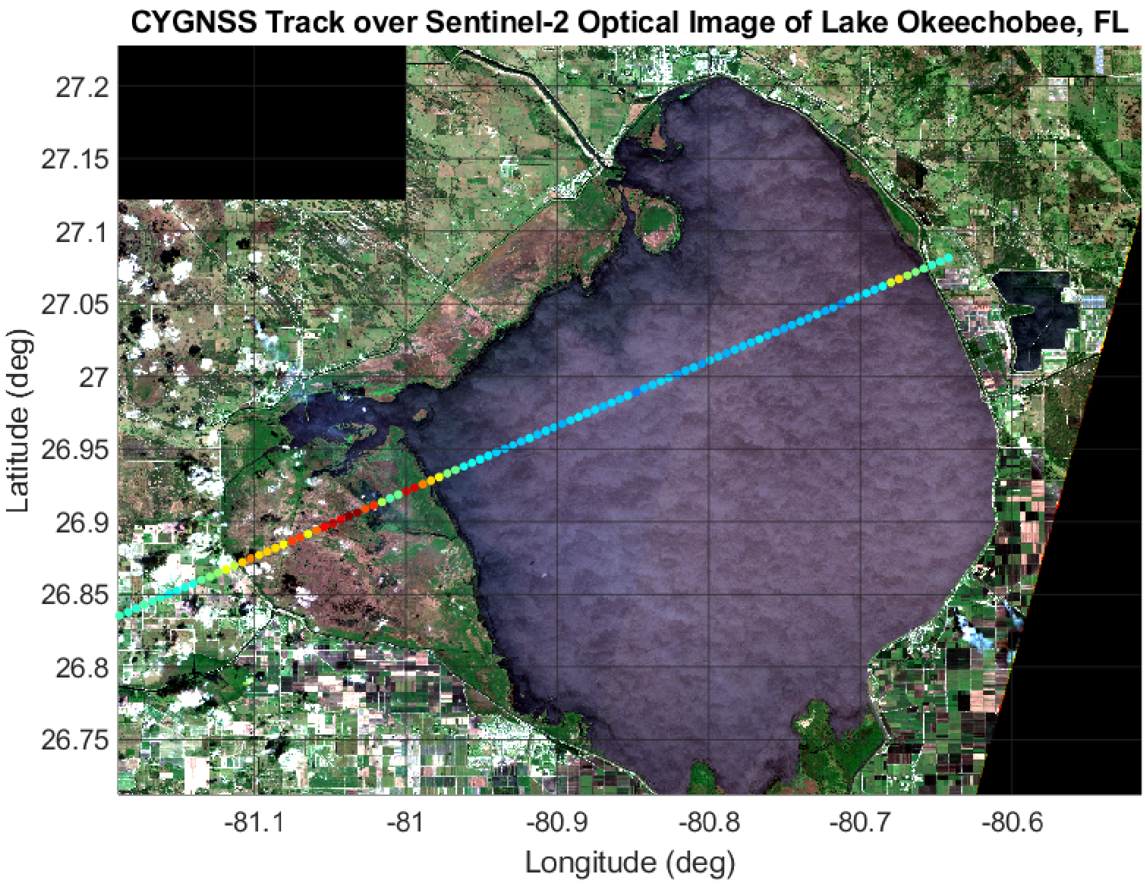
Previously, we requested periodic Raw-IF tracks to be collected over Lake Okeechobee. The figure above shows three of those tracks that passed over the lake and nearby vegetated water areas in late February, 2020. In our analysis of these tracks, we found ancillary data from the South Florida Water Management District to be useful in establishing boundaries between land types.

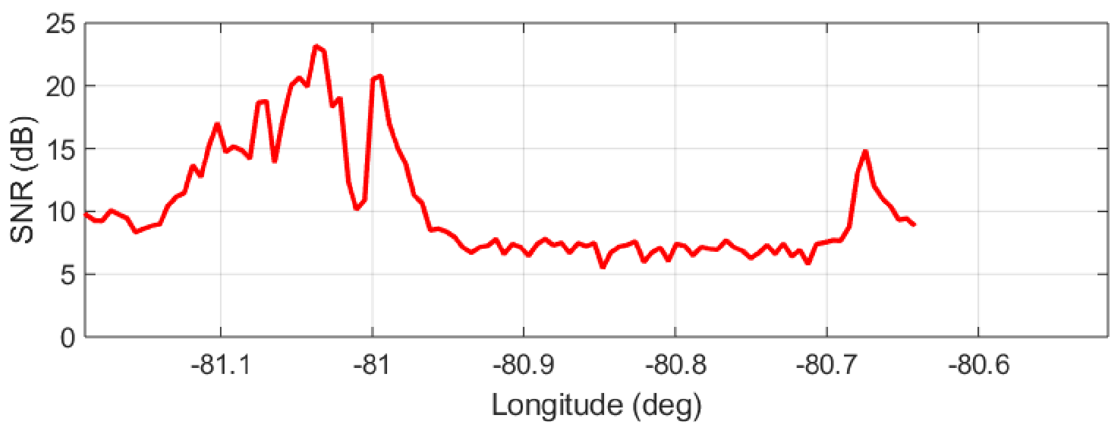
Lake Okeechobee presents an ideal, intermediate 3-state target: it contains open water, dry land, and inundated vegetation in well-defined boundaries. The transition between land, vegetated water, and open water is clearer than for a full wetland, and vegetation is well mapped (see below).



At nearly 1900 square kilometers, Lake Okeechobee is a large body of water and its surface is susceptible to wind-induced surface roughness. This roughness tends to scatter the GNSS signal, resulting in lower SNR at the CYGNSS receiver over the open water portion of the lake. While vegetation attenuates electromagnetic signals, it also shields the surface of water from wind and waves, resulting in higher SNR over the vegetated portion to the west of Lake Okeechobee.

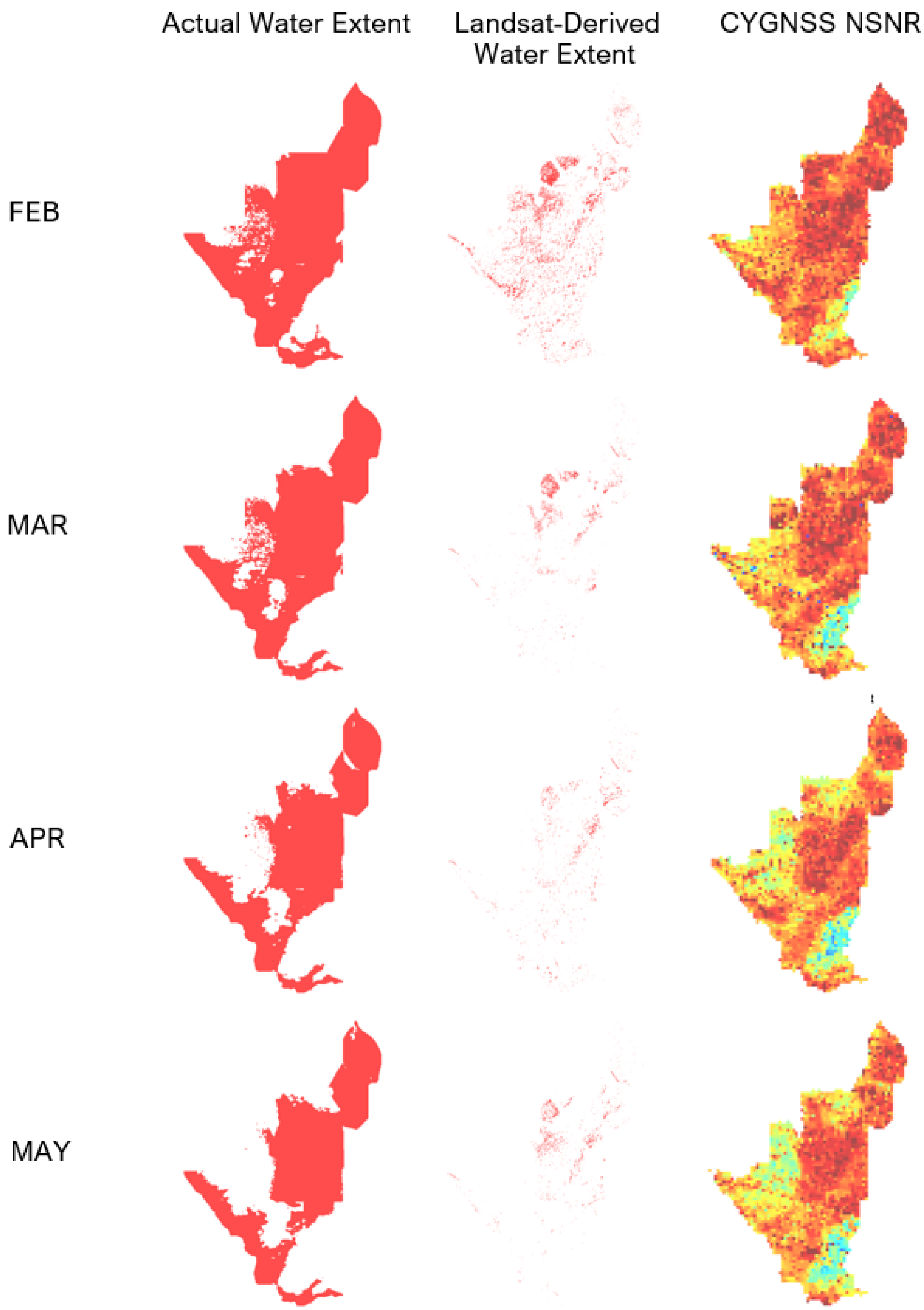
The figure below demonstrates this effect. Here, we have one of the Raw IF tracks plotted over a Sentinel-2 image that was collected on February 28, 2020, just three days after the CYGNSS track was collected. We can see in the Sentinel-2 image that the vegetated area on the west shore of the lake appears to be mostly land. However, by taking a closer look at the CYGNSS SNR, we see peaks in reflected power of ~18-23 dB, indicating the presence of water. Similar to the Landsat-derived water map over the Everglades, CYGNSS reveals surface water beneath vegetation that is missed by the optical image. However, the 10-meter spatial resolution of Sentinel-2 images provides detail that only a longer time aggregate of CYGNSS tracks would be able to observe.


CYGNSS Track over Sentinel-2 Optical Image of Lake Okeechobee, FL
Latitude (deg)
27.2
27.15
27.1
27.05
27
26.95
26.9
26.85
26.8
26.75
-81.1
-81
-80.9
-80.8
-80.7
-80.6
Longitude (deg)

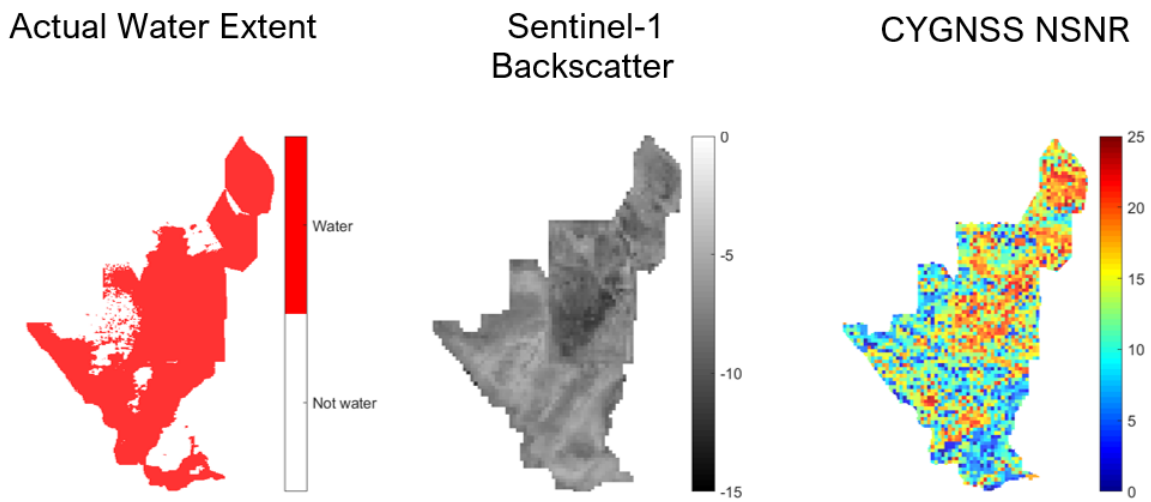

SNR (dB)
25
20
15
10
5
0
-81.1
-81
-80.9
-80.8
-80.7
-80.6
Longitude (deg)

COMBINING GNSS-R WITH OTHER REMOTE SENSING TECHNIQUES FOR MONITORING GLOBAL WETLANDS

Further research is currently underway in which we are investigating new ways that GNSS-R can complement traditional remote sensing techniques. Again using the Landsat-derived GSW dataset for comparison, we see in the figure below that while the GSW data can identify areas of open water at a high spatial resolution, by gridding the CYGNSS normalized SNR, we can identify areas of inundated vegetation, though at a lower spatial resolution. Here, we show the monthly CYGNSS NSNR gridded into ~3 square kilometer grid cells.



Below, we show comparisons of CYGNSS data with Sentinel-1 backscatter for February, 2020. High backscatter values can indicate flooded vegetation due to a dominance of double bounce reflections, but using a threshold approach with backscatter values alone can lead to ambiguous results. GNSS-R has the potential to improve current water detection techniques that rely on the C-band Sentinel-1 data.



Preliminary Conclusions and Next Steps

Combining the high spatial resolution of optical remote sensing and synthetic aperture radar (SAR) techniques with the high temporal frequency of GNSS-R and its ability to detect water beneath vegetation presents an exciting new opportunity for global wetlands monitoring. GNSS-R can be leveraged to detect changes in water extent on short time scales and observe surface water that is undetectable by other remote sensing methods, while optical imagery and SAR observations can provide information on vegetation health, terrain, and other parameters of interest to wetland scientists. Works in progress include a quantitative analysis of the spatial and temporal resolution of change in surface water extent that CYGNSS is capable of observing and incorporating machine learning algorithms that combine GNSS-R and backscatter measurements to develop a more robust and comprehensive understanding of wetland state and change over time.

ABSTRACT

Wetlands represent an essential ecosystem, providing flood control, carbon storage, and supporting biodiversity. In particular, the Everglades is a Ramsar Wetland of International Importance, supporting several threatened and endangered species of flora and fauna, and is especially important for wintering birds. Understanding and monitoring wetlands like the Everglades requires the ability to accurately identify and measure wetland extent and change in extent on short time scales. However, in situ methods are difficult given the nature of the surrounding environment, and optical methods of remote sensing are unable to see through dense vegetation. NASA's Cyclone Global Navigation Satellite System (CYGNSS) has shown promising results using GNSS Reflectometry to identify the presence and extent of inland water. Utilizing GNSS as a signal of opportunity in an L-band passive bistatic radar, it can penetrate rain, clouds, and vegetation. Its 8-satellite constellation exhibits daily or sub-daily revisit rates, enabling the observation of dynamic changes on short time scales. In this work, we utilize a combination of CYGNSS data, ancillary information, and simulations to understand the observability of inundation beneath vegetation. Simulations were used to predict the received power using a water mask derived from Landsat imagery over the Everglades. By analyzing the differences between expected and actual received power, we identified areas of flooded vegetation. These differences were then combined with ancillary data sets to measure seasonal changes and create a seasonal map of open water and inundated vegetation throughout the Everglades network. We also investigated the ability of CYGNSS to discern and measure different vegetation types. Results were then compared with optical and radar imagery and verified with truth data from the Everglades Depth Estimation Network (EDEN) and littoral vegetation maps from the South Florida Water Management District. By leveraging CYGNSS's high temporal frequency of observations and ability to see under vegetation, measurements of inundated vegetation and its change can complement other remote sensing and in situ methods of wetland monitoring.

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