# OSU GNSS Research Update

**Jihye Park**
with
Su-Kyung Kim, Hoda Tahami
School of Civil and Construction Engineering
Oregon State University

- NGS Research project
- GNSS based tide gauge system
- GNSS based hurricane tracking model

# Research collaboration with NGS

- From Oct 2019, multi-GNSS PPP software has been developed funded by NGS through The Cooperative Institute for Marine Resources Studies' (CIMRS)

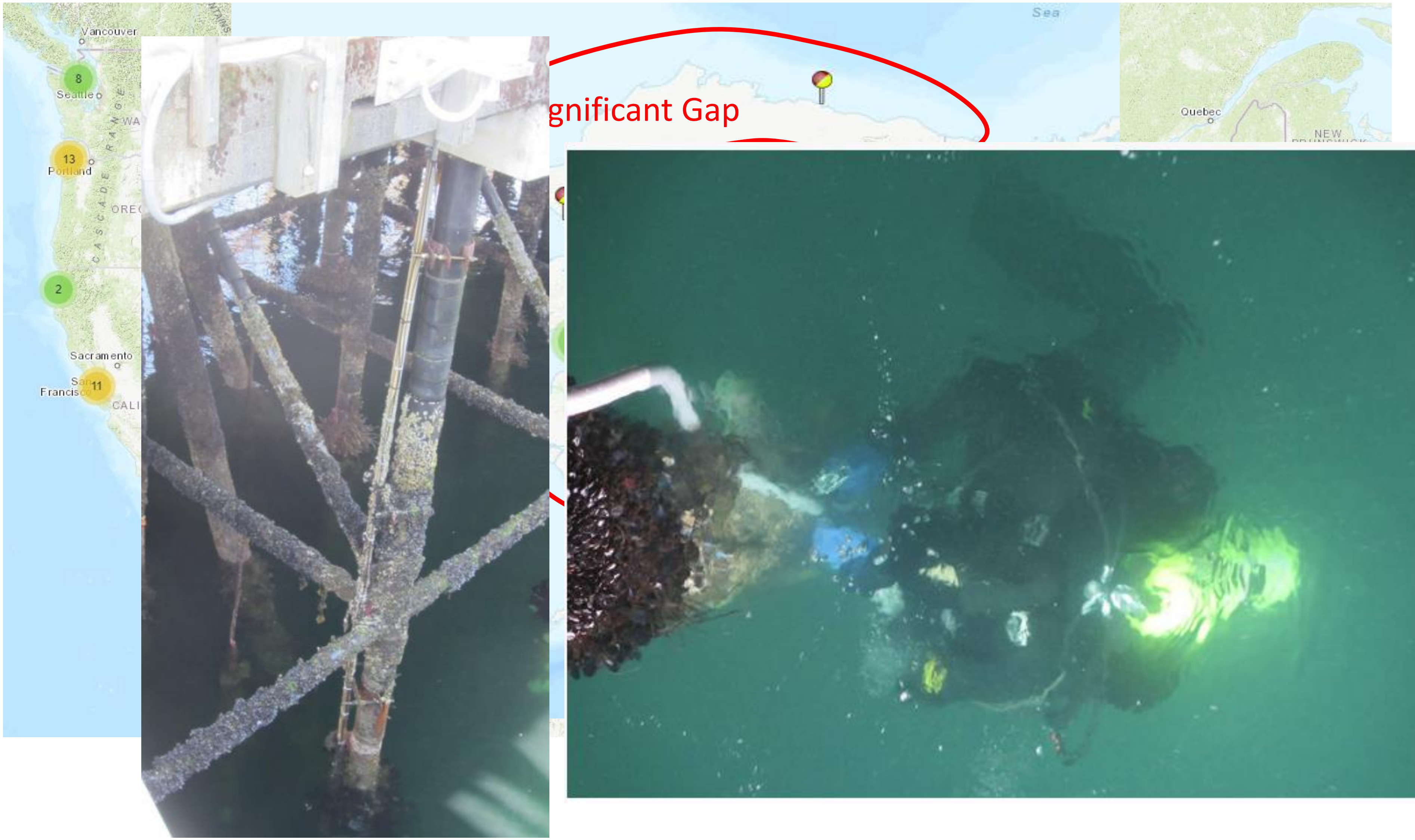
- To be done by September 2019 (end of FY19)
  - Working fine with four multi frequency, multi GNSS constellation
  - More corrections should be added for high accuracy

- Will continuously work on specially Cycle slip detection and repair research project

# GNSS based tide gauge system

Su-Kyung Kim
(PhD student of Geomatics, OSU)

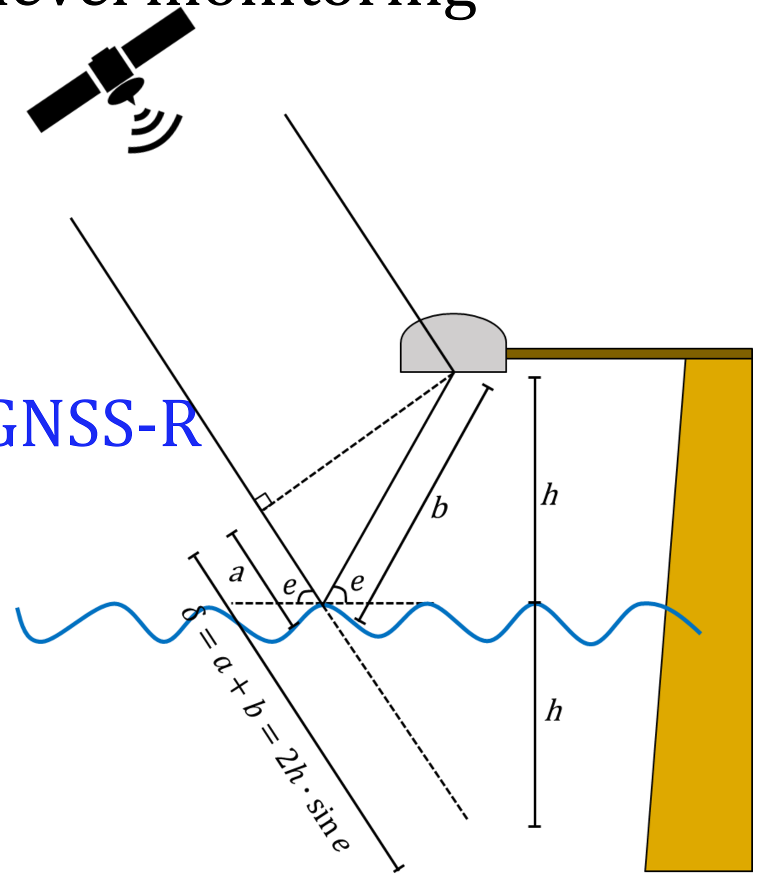
# Water level monitoring



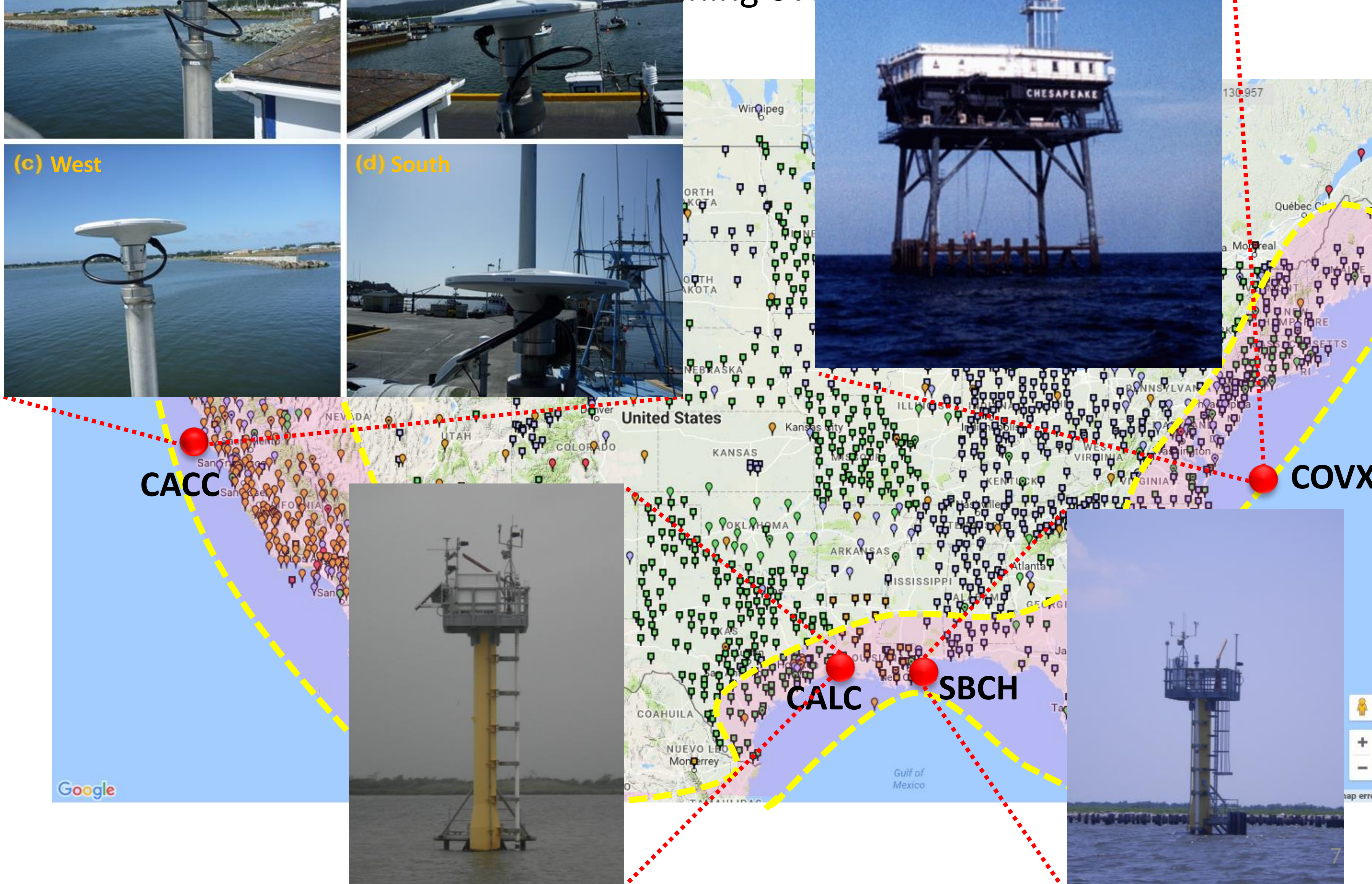
# GNSS-Reflectometry for water level monitoring

- GNSS-Reflectometry (GNSS-R) was suggested as an alternative approach for water level monitoring (Martin-Neira, M., 1993)

- Multipath as an error!
- Multipath for the earth environmental monitoring → GNSS-R
  - **Water level**
  - Soil moisture
  - Snow depth
  - Ocean wind

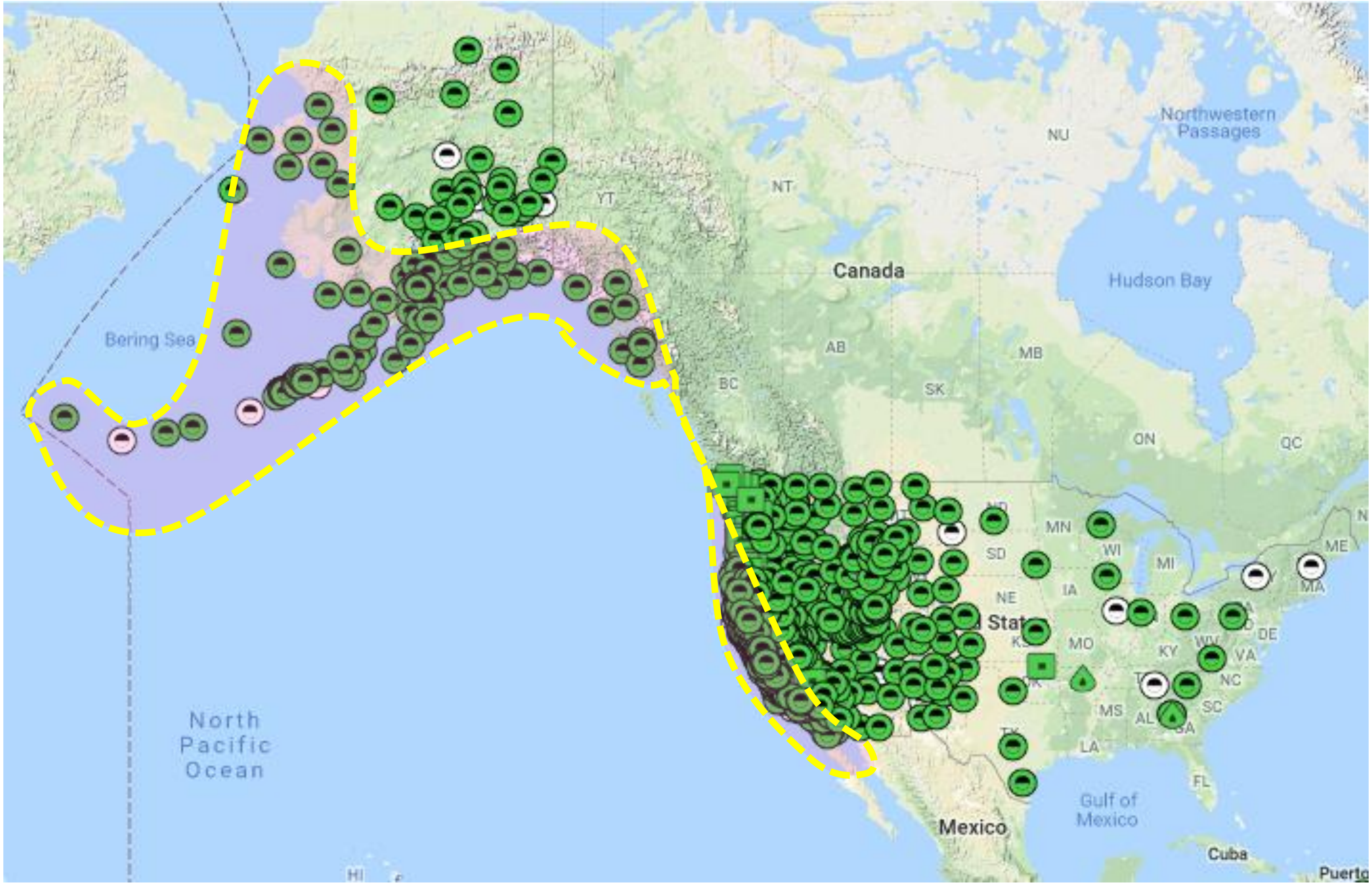


ng fa
ining ove



# The utilization of pre-existing facilities – cont.

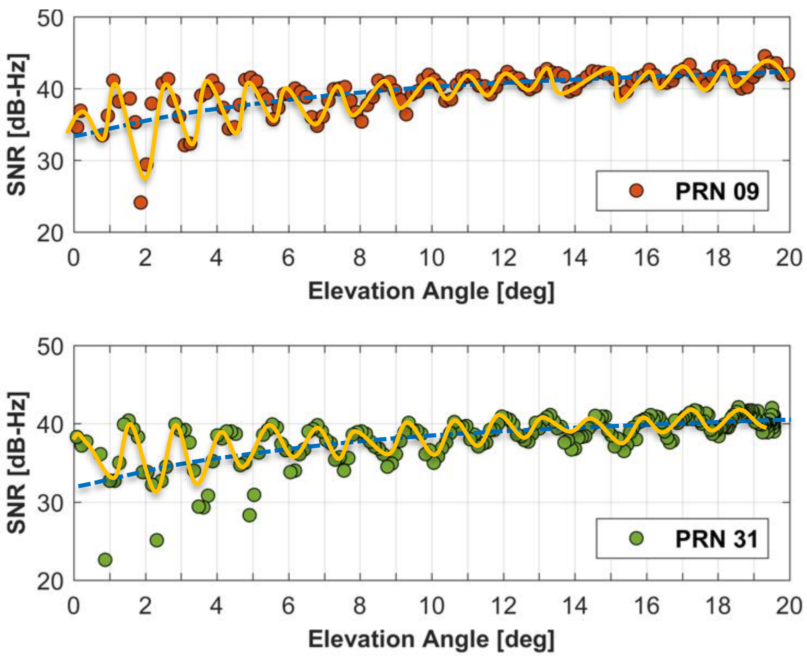
- UNAVCO PBO Networks



# GNSS-R equipment installation in Newport, OR

# SNR (Signal to Noise Ratio) data analysis

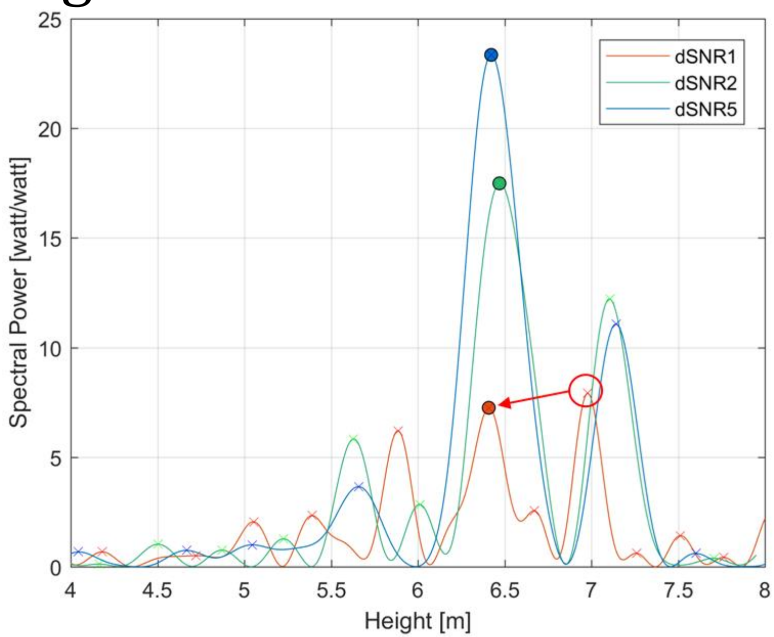
- When a GNSS satellite moves across the sky, an *interference pattern* is created by the phase difference in the receiver between the direct and reflected satellite signals.
- The interference patterns are particularly *noticeable in the SNR data*

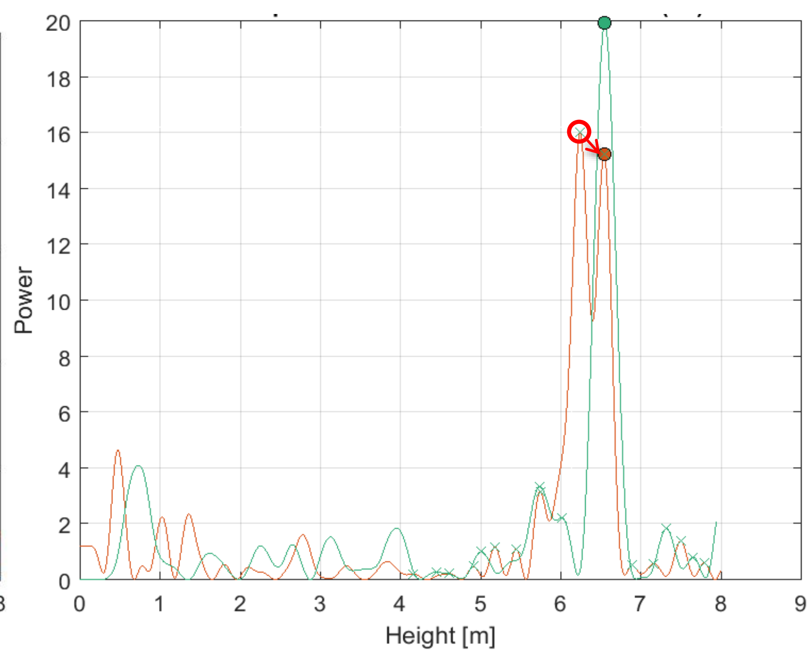



– Overall arc mostly depends on the signal strength and the antenna gain pattern
– *multipath* is in the *form of oscillations.*
– The *frequency of the oscillation* is depend on the geometry between satellite, reflector and antenna, i.e., frequency *contains the information* about the *water level height*.
– To *isolate* the *multipath effect*, the overall arc is usually removed by *applying curve fitting*.

# Enhanced Spectral Analysis

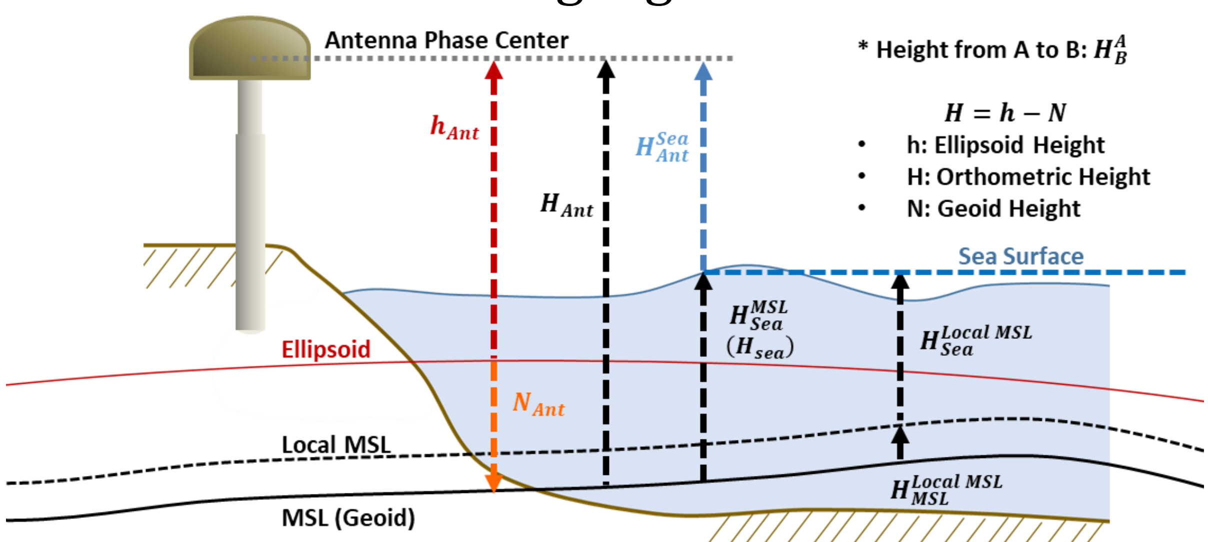
- The *determination of the dominant frequency* is important
- Taking the advantage of ***multi-frequency*** *of GNSS signals*,
- Errors can be minimized by *comparing* the dominant height extracted from the multiple frequencies on same ray-path, based on *a local maximum* of each frequency signal.



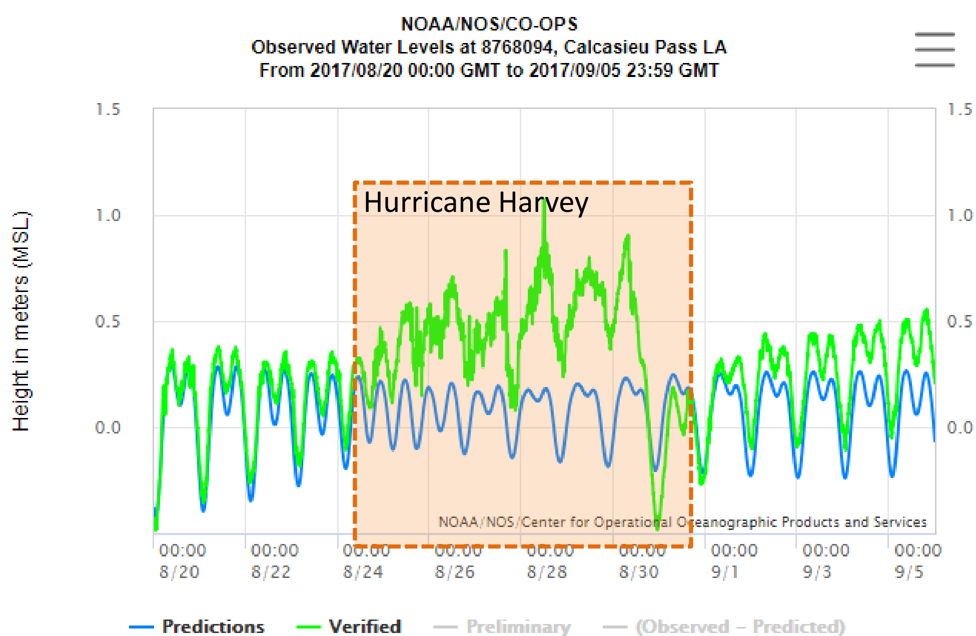
# Datum Synchronization

- GNSS-R based tide gauge provides *sea level from the reflecting surface w.r.t. GNSS reference system* while the tide gauge station derives sea level referring to the tidal datum (Local MSL).
- In addition, there is an *elevation difference between the tidal and geodetic datums*, which varies depending on the different regions.
- Therefore, the *datum synchronization* between GNSS-based tide gauge and the traditional tide gauge should be conducted.

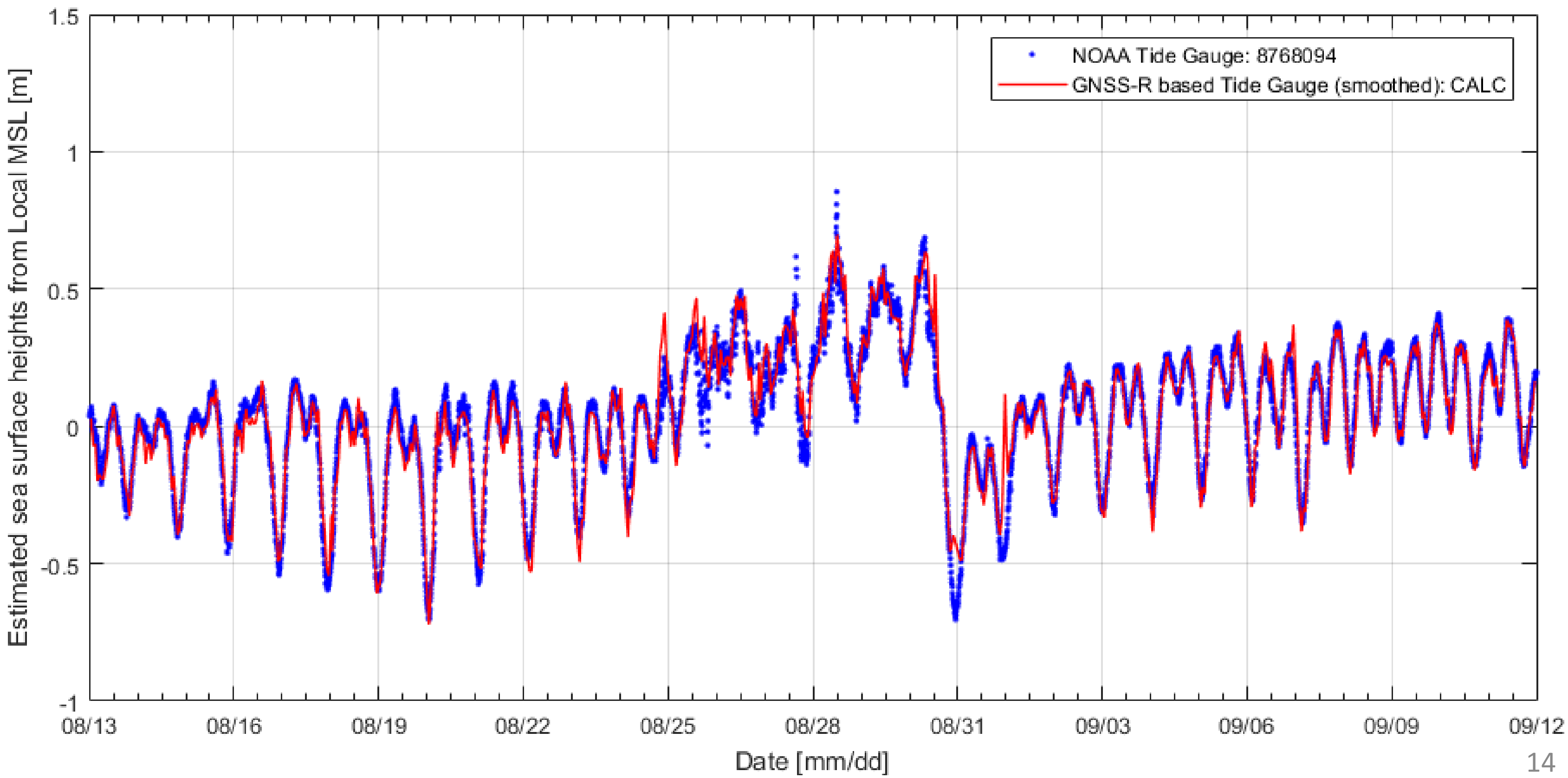


# Case Study 1: WL detection during Hurricane Harvey

- NGS CORS, CALC, in Cameron, LA (Gulf of Mexico)
- Co-located NWLON tide gauge station (ID: 8768094 ) as a ground truth
- Analysis periods: 8/13/2017 – 9/12/2017

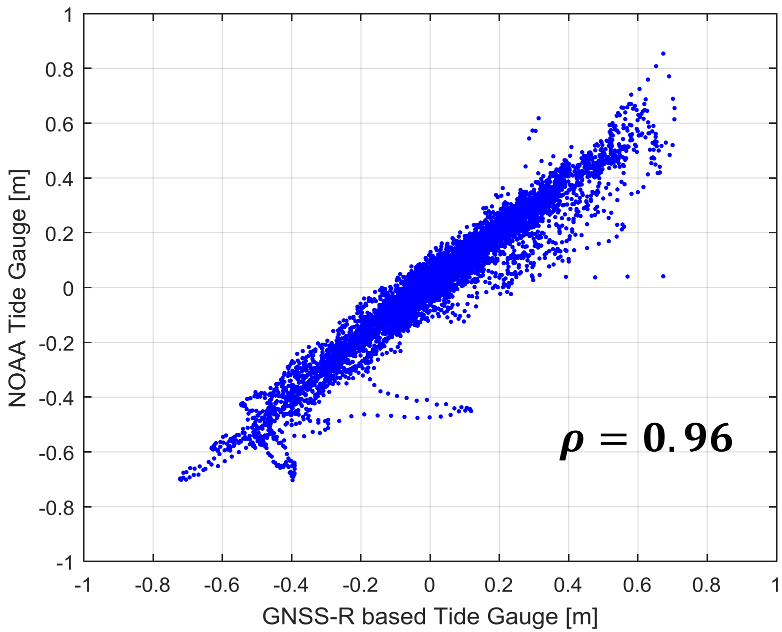


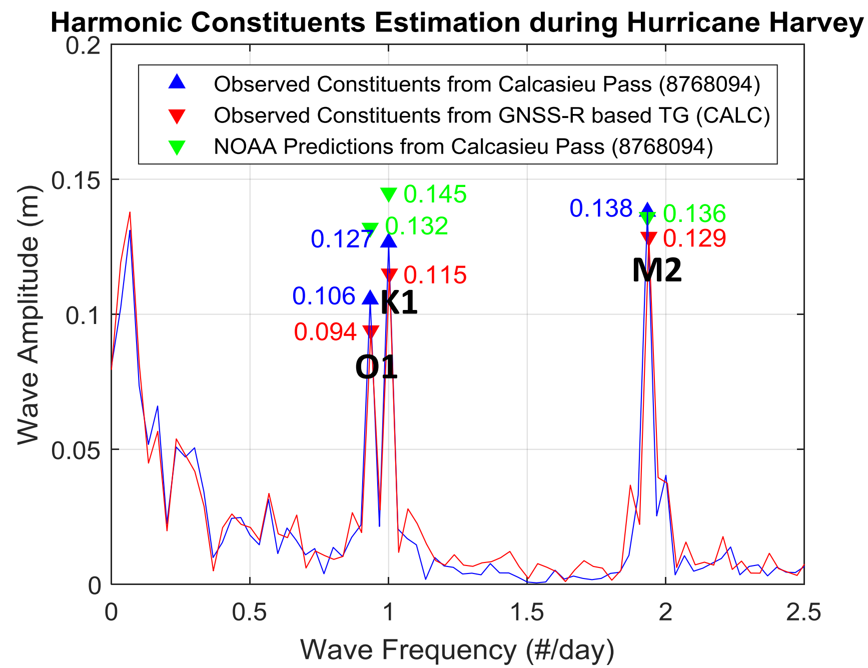

- Overall, the time series of water level changes by GNSS-based tide gauge well represent the one from the co-located tide gauge station.
- The abruptly changing water level during the Hurricane Harvey was successfully observed by utilizing the GNSS reflected signals.



Date [mm/dd]

- Correlation coefficient: **0.96**
- Tidal harmonic constituents: **consistent peaks** from the GNSS-based tide gauge and co-located tide gauge!




| Tidal Constituent | Observed Constituents (CALC) | Observed Constituents (8768094) | NOAA Predictions (8768094) |
|---|---|---|---|
| M2 (Semidiurnal) | 0.129 | 0.138 | 0.136 |
| K1 (Diurnal) | 0.115 | 0.127 | 0.145 |
| O1 (Diurnal) | 0.094 | 0.106 | 0.132 |



https://tidesandcurrents.noaa.gov/harcon.html?unit=1&timezone=1&id=8768094&name=Calcasieu+Pass&state=LA

# Case Study 2: GNSS-R based tide gauage in Alaska

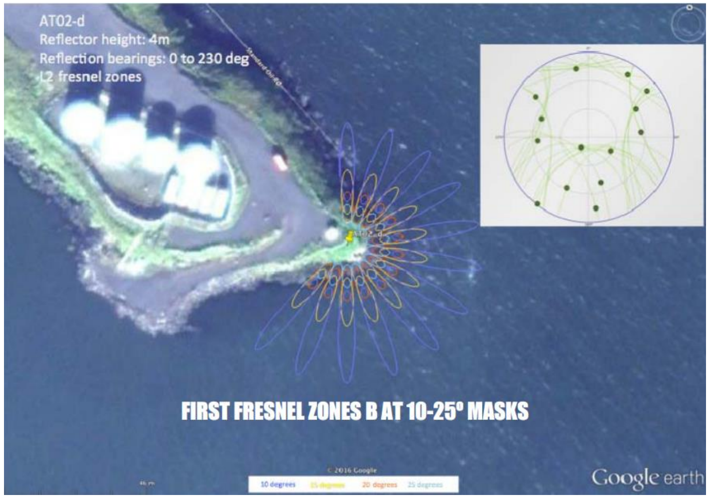
- PBO station in Alaska
  - Station ID: AT01
  - Location: St. Michael, Alaska
  - Installation date: 05/26/2018
  - Equipment
    - Trimble 159800 Chioke Ring
    - POLARX5
- Nearby NOAA tide gauges
  - 9468132 St. Michael, AK (about 1.5 km from AT01)
    - The closest tide gauge, but *no actual observation* available.
    - Still provides tide predictions and harmonic constituents
  - 9468333 Unalakleet, AK (about 74 km from AT01)
    - provides the actual observations as well as harmonic constituents
    - but too far from the AT01 to be a ground truth

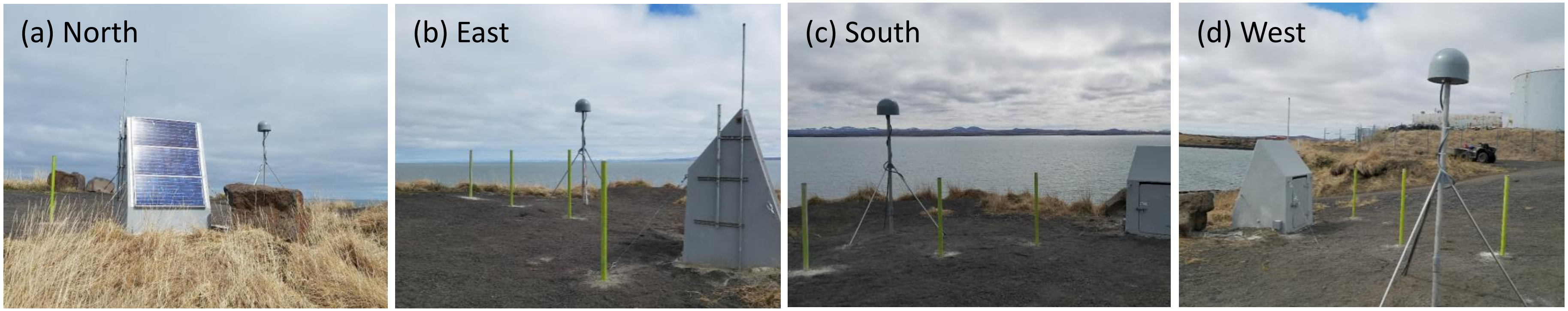
https://www.aoos.org/alaska-water-level-watch/alaska-water-level-meeting-2018/

https://www.aoos.org/alaska-water-level-watch/alaska-water-level-meeting-2018/

# Water level monitoring in St. Michael, AK

- PBO station in AK
  - AT01 in St. Michael, Alaska
  - Installation date: 05/26/2018
  - Specially designed for GNSS-R purpose
    - Azimuth mask 230 ° - 360°
    - Elevation mask 0 ° - 10 ° and 25 ° - 90 °
  - Equipment
    - Antenna: Trimble 159800 Chioke Ring
    - Receiver: Septentrio PolaRx5



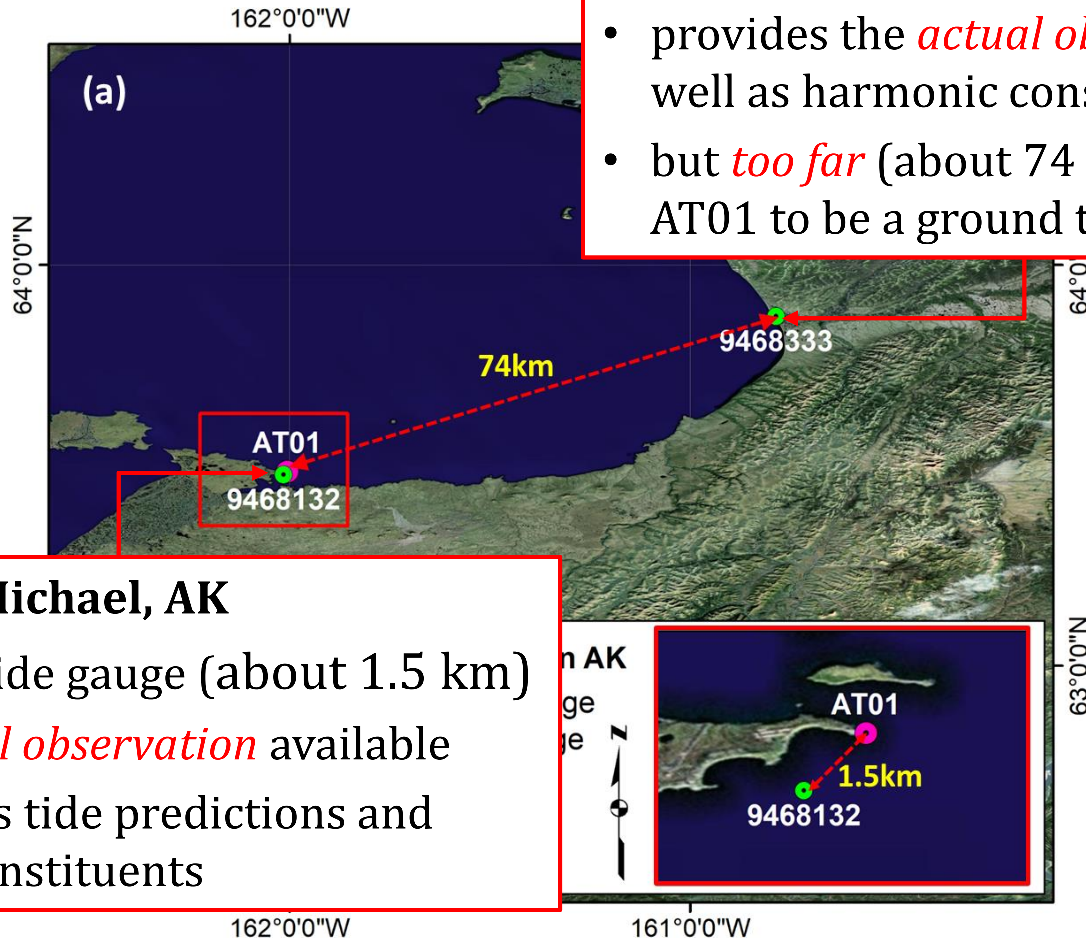



# Water level monitoring in St. Michael, AK – cont.

- Nearby NOAA tide gauges

**9468333 Unalakleet, AK**

- provides the *actual observations* as well as harmonic constituents
- but *too far* (about 74 km) from the AT01 to be a ground truth

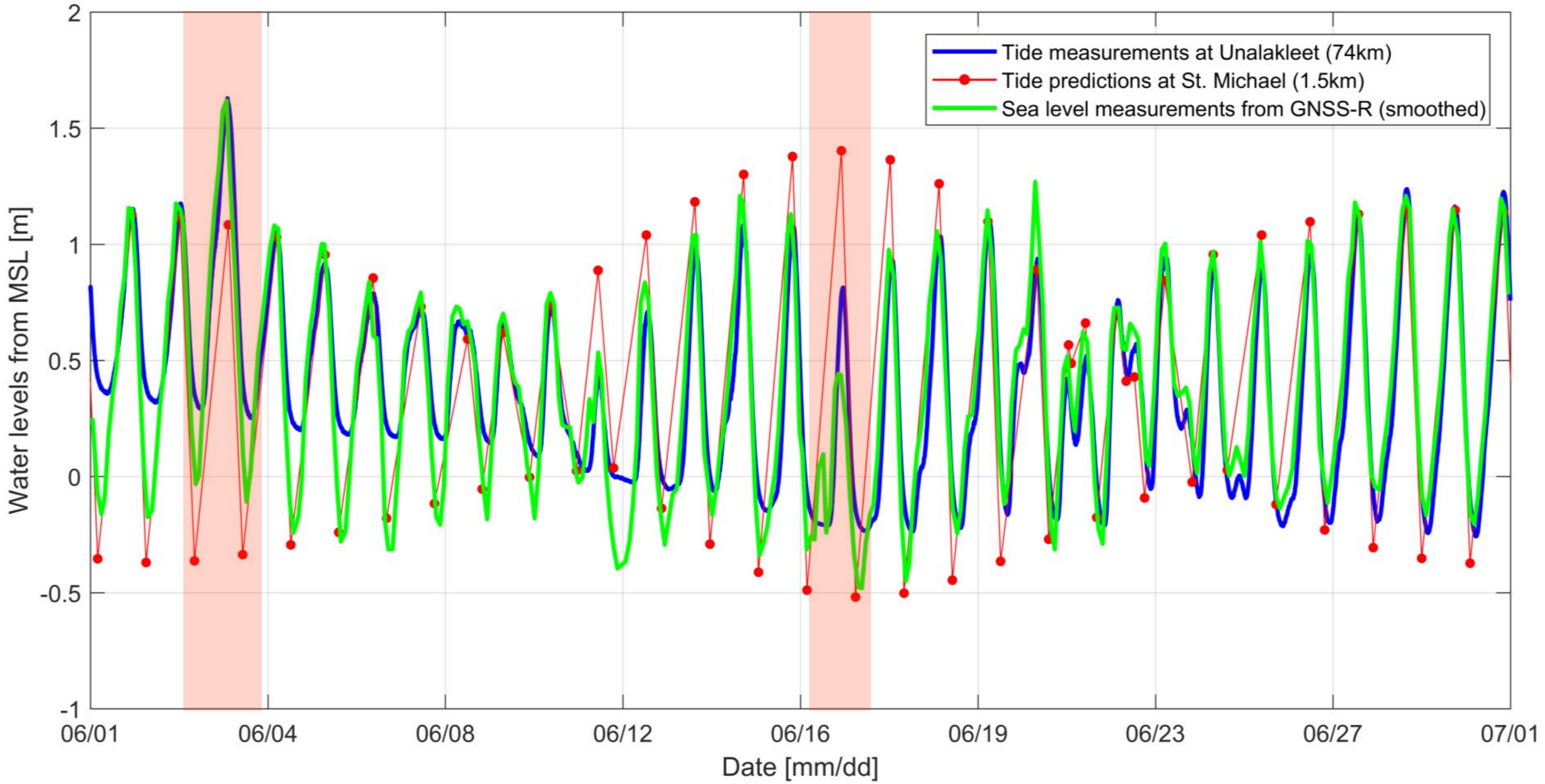



**9468132 St. Michael, AK**

- The *closest* tide gauge (about 1.5 km)
- but *no actual observation* available
- Still provides tide predictions and harmonic constituents

https://www.aoos.org/alaska-water-level-watch/alaska-water-level-meeting-2018/

# Water levels at AT01 GNSS-R TG



# Statistical analysis of the sea levels (GPS and Galileo)

Accuracy of the sea levels

| | GPS | Galileo | GPS and Galileo |
|---|---|---|---|
| Number of sea level measurements | 4928 | 3962 | 8890 |
| Mean of the differences [m] | 0.11 | 0.11 | 0.11 |
| Max of the differences [m] | 0.44 | 0.48 | 0.48 |
| RMS of the differences [m] | 0.14 | 0.13 | 0.14 |

Temporal resolution of the GNSS-R based tide gauge

| | GPS | Galileo | GPS and Galileo |
|---|---|---|---|
| Mean [min] | 19.78 | 48.97 | 14.10 |
| Max [min] | 186.50 | 271.13 | 94.50 |
| Min [min] | 0.13 | 0.13 | 0.13 |

# Summary and future direction

- can be applied to the near-real time estimation of the water level
- Works for an extreme changes (e.g., storm surges)
- Provide measurements with up to 5 min temporal resolution
- Cost effective and sustainable in extreme climate and weather events
- Can be excellent complementary equipment for monitoring WL

Civil & Construction Engineering

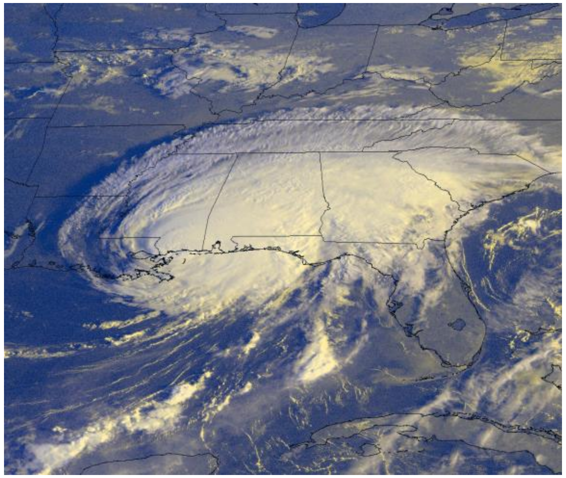
COLLEGE OF ENGINEERING

# GNSS based hurricane tracking model

Hoda Tahami
(PhD candidate of Geomatics, OSU)

- Water vapor is one of the most important components to form clouds and precipitation, and an ingredient in most major weather events.
- Precipitable water vapor (PWV) is difficult to measure with adequate spatial and time resolution under all weather conditions.
- Largest errors in Numerical Weather Prediction (NWP) come from limitations of having accurate water vapor variability in time and space and it is one of the major error sources in short-term forecasts of precipitation



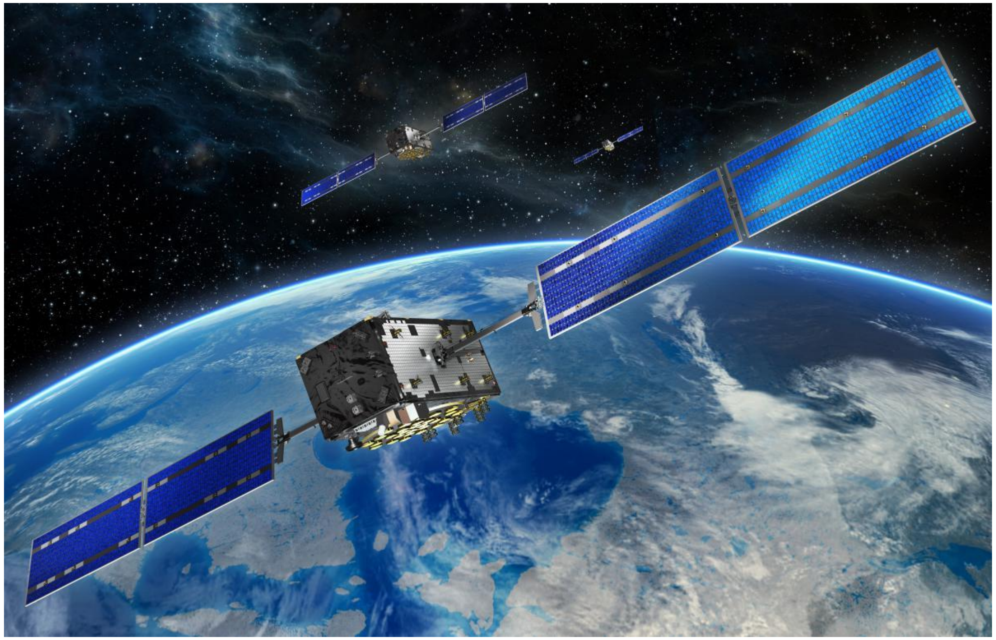


# Monitoring and Forecasting Severe Weather Events

- Radiosonde
  - low temporal and horizontal resolution; high cost
- Ground-based microware radiometers
  - Accurate in clear-sky; NOT all weather; high cost
- Satellite based instrument - e.g., SSM/I (special sensor microwave/imager) and AMSU (advanced microwave sounding unit)
  - Successful in retrieving information over ocean surfaces
  - Satellite retrievals of tropospheric water vapor may be problematic when the study of water and energy cycles is based on fields from forecast or climate models
- Satellite Imageries
  - The vertical distribution of the PWV is rarely obtained by the satellite image data
  - Presence of clouds
- Radar
  - High cost ; Difficult to apply to a wide range observations of water vapor.

# Water vapor measurements with GNSS

- ✓ high temporal and spatial resolution
- ✓ under all weather conditions, including thick cloud cover and precipitation
- ✓ without the need for external calibration.
- ✓ cost effectiveness



# GNSS Meteorology

- Refractivity associated with changes in temperature (T), Pressure (P), and water vapor in neutral atmosphere.
- Wet and Dry components

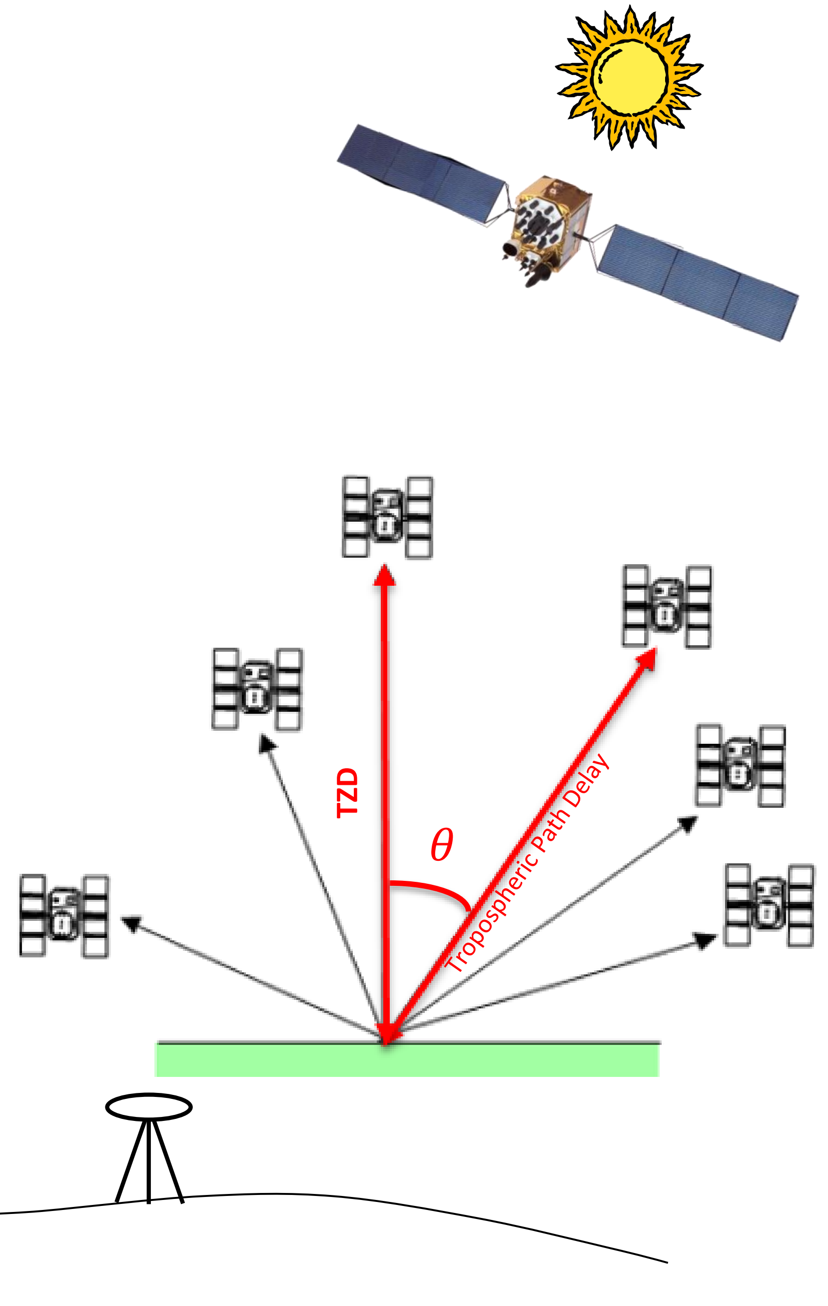
$$TD = 10^{-6}\int N_{dry} ds + 10^{-6}\int N_{wet} ds$$

N is total refractivity along the propagation path, s.

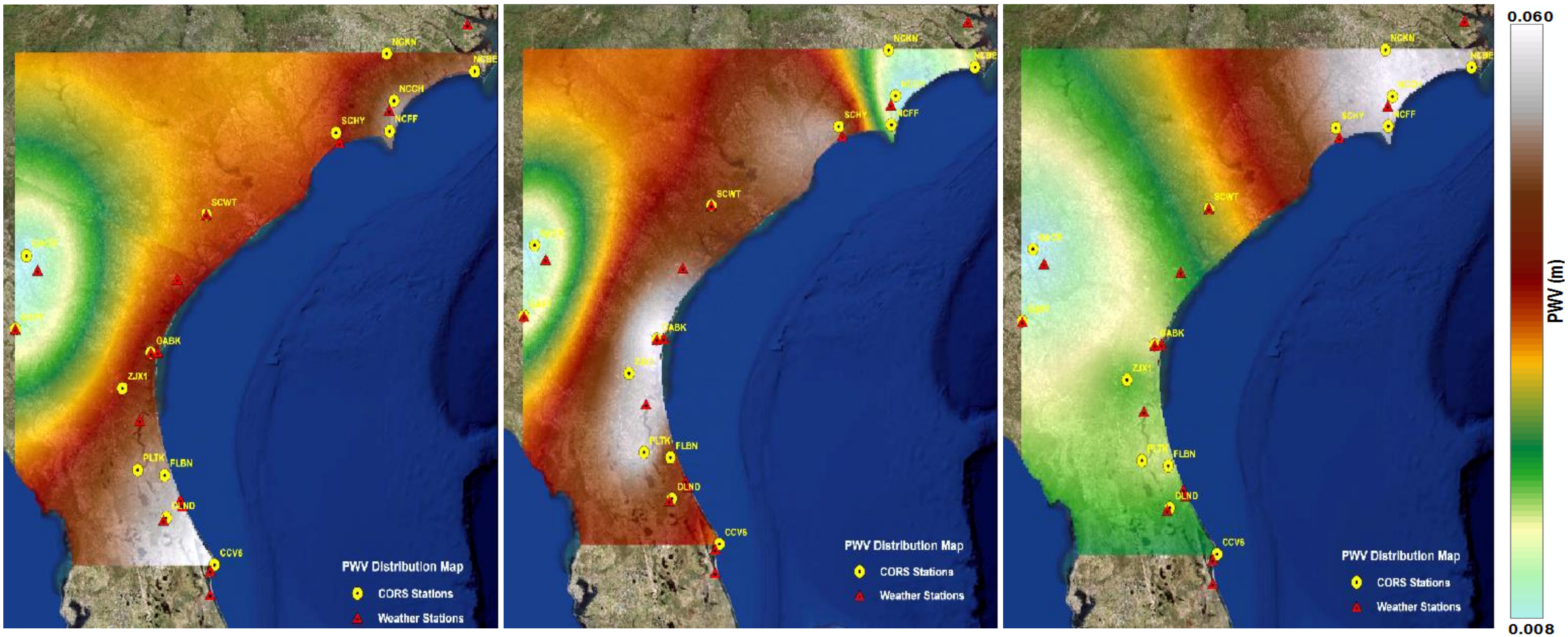
$$TD = \mathrm{ZHD} \times m_h(\theta) + \mathrm{ZWD} \times m_w(\theta)$$

$$\boldsymbol{PWV} = ZWD \times \Pi$$

$$\Pi^{-1} = 10^{-6} \times \rho \times R_v\left(\frac{(3.739 \pm 0.012)10^5}{T_m} + (22.1 \pm 2.2)\right)$$



# PWV Variation During Event Period

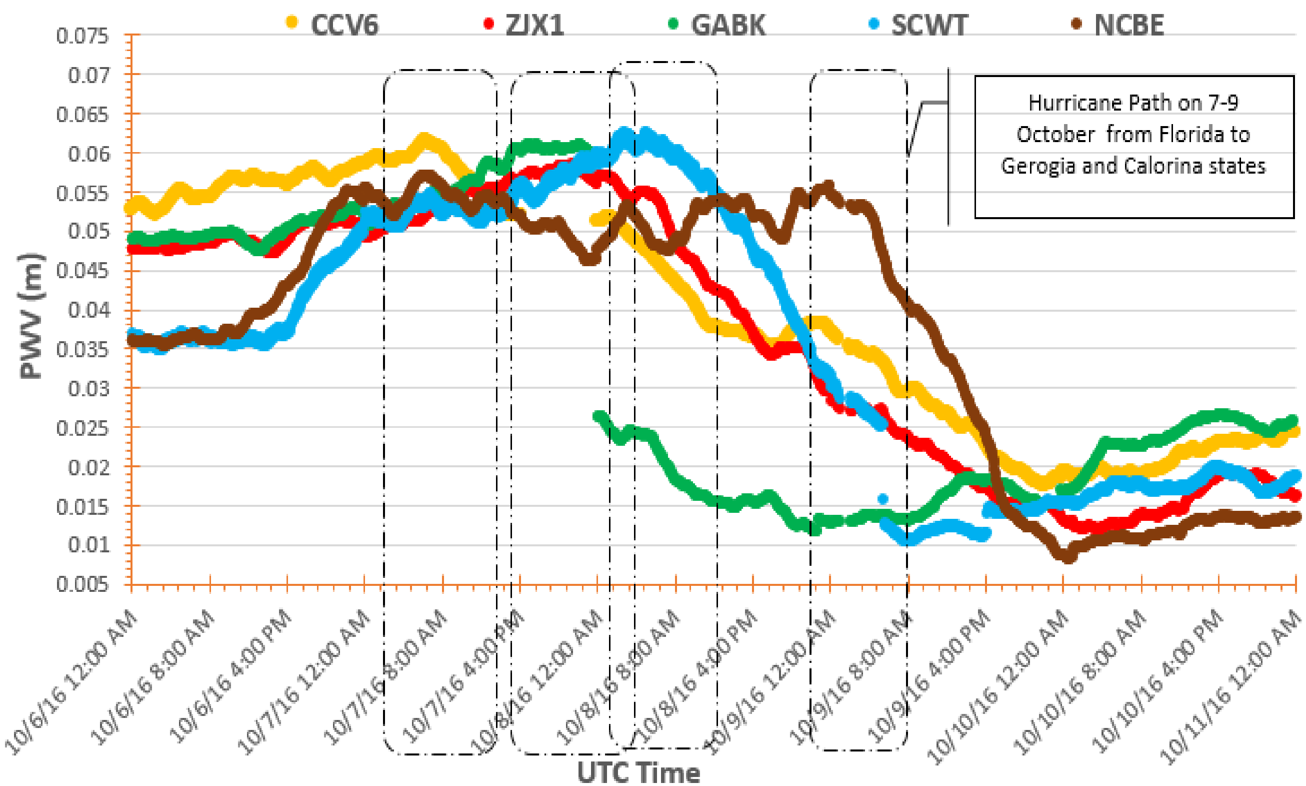


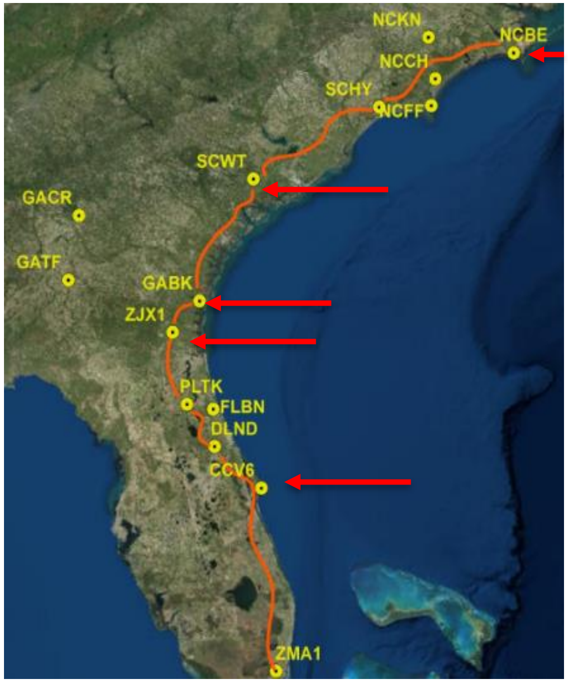

10/6/16 12:00 PM UTC

10/7/16 12:00 PM UTC

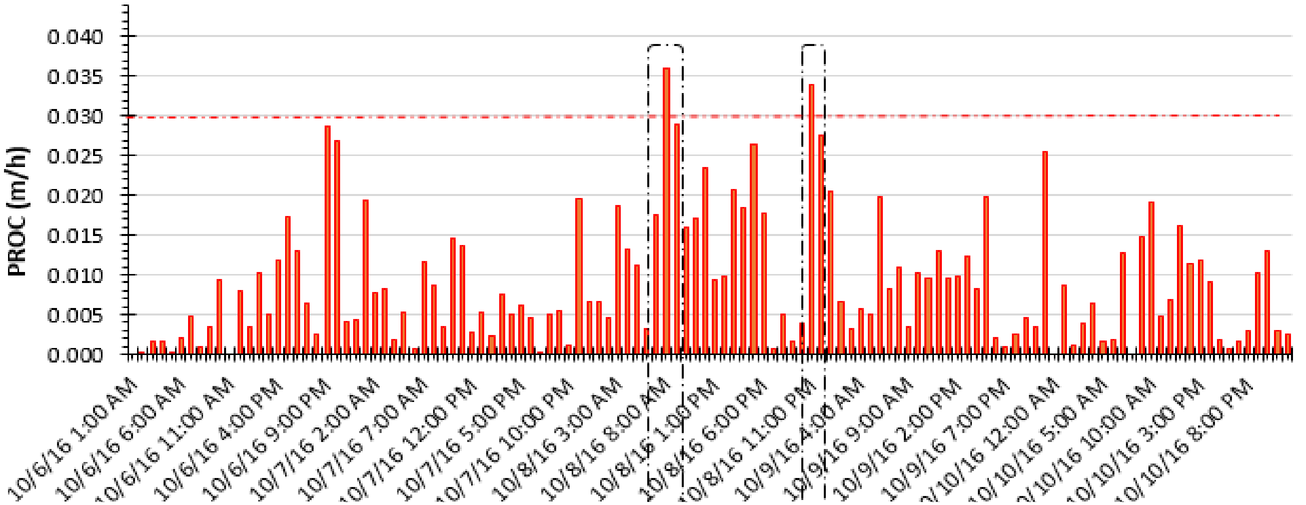
10/8/16 12:00 PM UTC

# PWV Variation During Hurricane Matthew

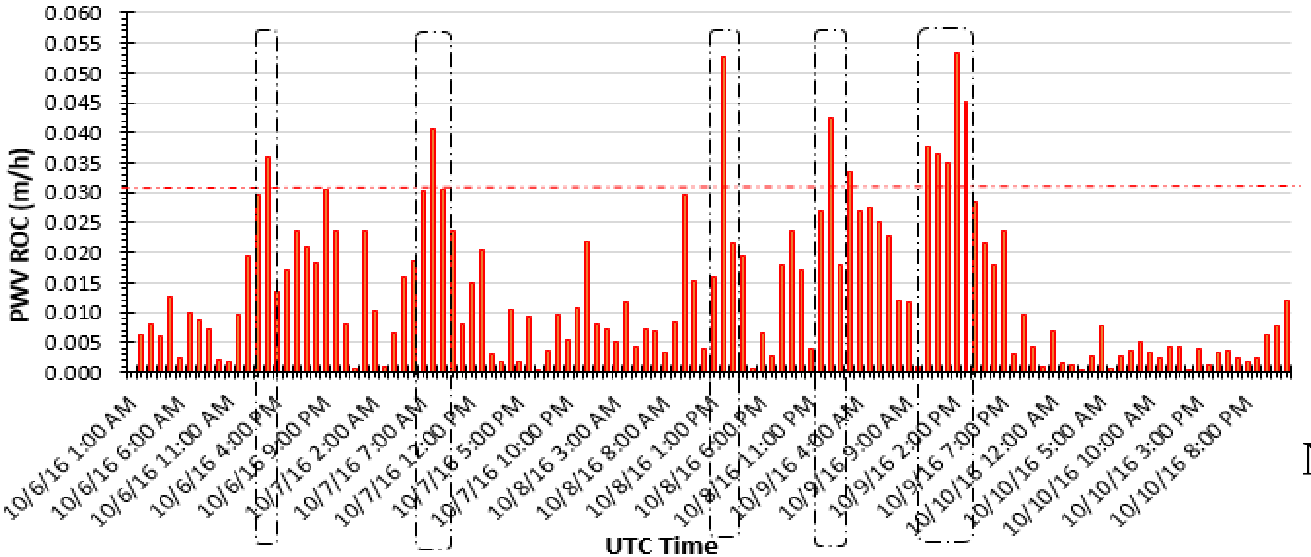


# PWV Rate of Change

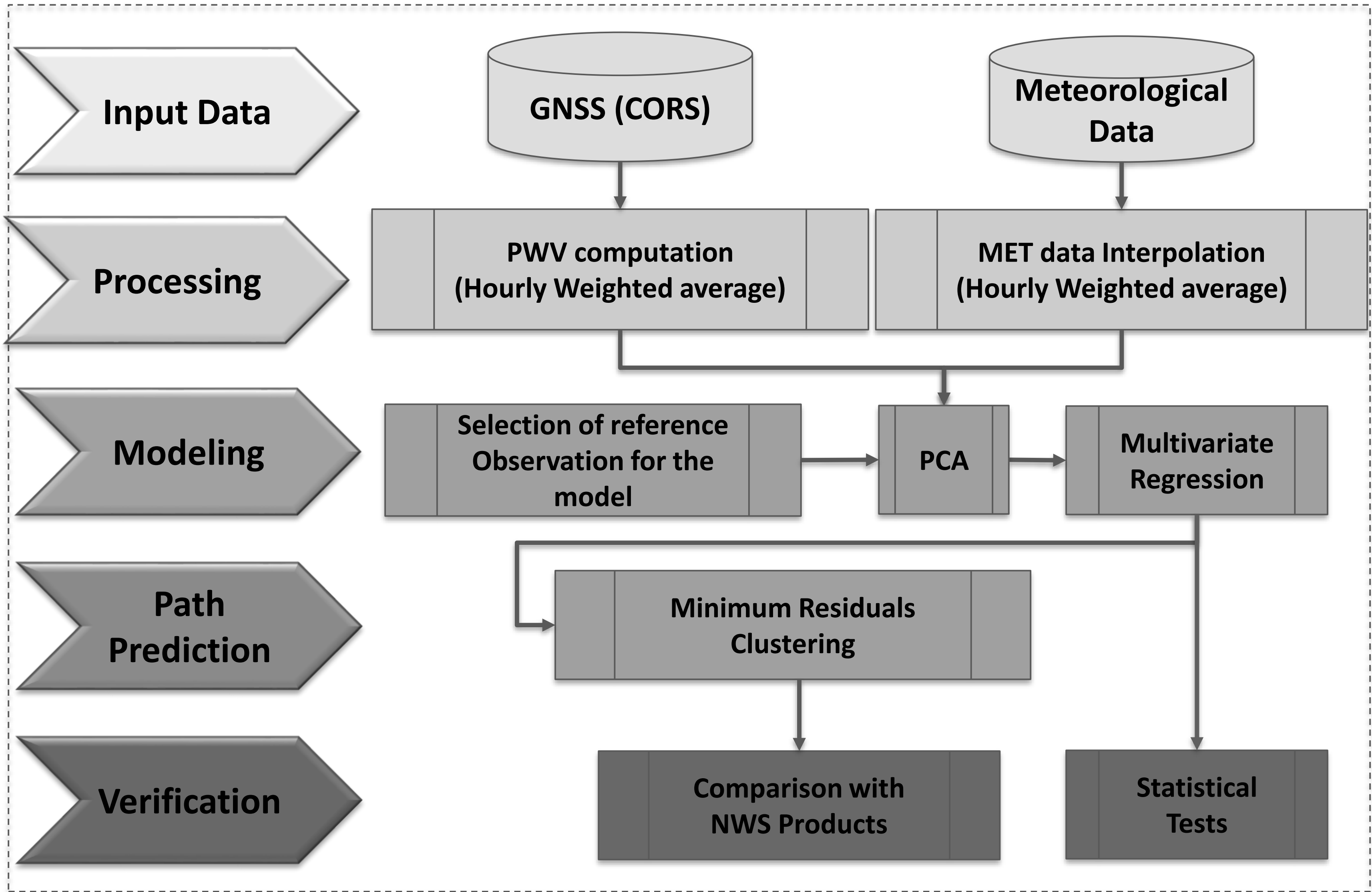



ZJX1 (Florida)




NCFF (North Carolina)

# Work flow


Input Data
GNSS (CORS)
Meteorological Data
Processing
PWV computation (Hourly Weighted average)
MET data Interpolation (Hourly Weighted average)
Modeling
Selection of reference Observation for the model
PCA
Multivariate Regression
Path Prediction
Minimum Residuals Clustering
Verification
Comparison with NWS Products
Statistical Tests

# PWV Using Multiple Regression Analysis

- Estimation of PWV based on meteorological factors

$$(PWV_{t+1}) = \overline{PWV_t} + c_1\left(PWV_t - \overline{PWV_t}\right) + c_1\left(P_t - \overline{P_t}\right) + c_3\left(T_t - \overline{T_t}\right) + c_4\left(RH_t - \overline{RH_t}\right) + e$$

$$(\Delta \mathbf{PWV_{t+1}}) = \mathbf{c_i}[\Delta \mathbf{PWV_t},\ \Delta \mathbf{P_t},\ \Delta \mathbf{T_t},\ \Delta \mathbf{RH_t}] + \mathbf{e}$$

Where

T is temperature; P is pressure; RH is relative humidity; PWV is precipitable water vapor and t is time.

- For each prediction time window, the model estimates the prediction of PWV using the hourly PWV ROC and the derivatives of P, T, and RH.

- In this study, a model with 1h, 6h, 12h and 24h lead time is applied to forecast PWV that is resulted to predict the hurricane path for 1h, 6h, 12h, and 24h forecast.

# Principle Component Regression (PCR)

- New variables obtained as a linear combinations of the original explanatory variables → Principle Components (PC)
- The principle component regression approach combats multicollinearity by using less number of PC

| Variables | $F_1$ | $F_2$ | $F_3$ | $F_4$ |
|---|---|---|---|---|
| $\Delta PWV_t$ | 0.588 | 0.236 | 0.354 | 0.088 |
| $\Delta P_t$ | -0.575 | 0.004 | 0.815 | 0.071 |
| $\Delta T_t$ | 0.342 | 0.921 | 0.030 | -0.082 |
| $\Delta RH$ | 0.568 | -0.309 | 0.235 | -0.013 |

Eigenvalues explain most variability in data

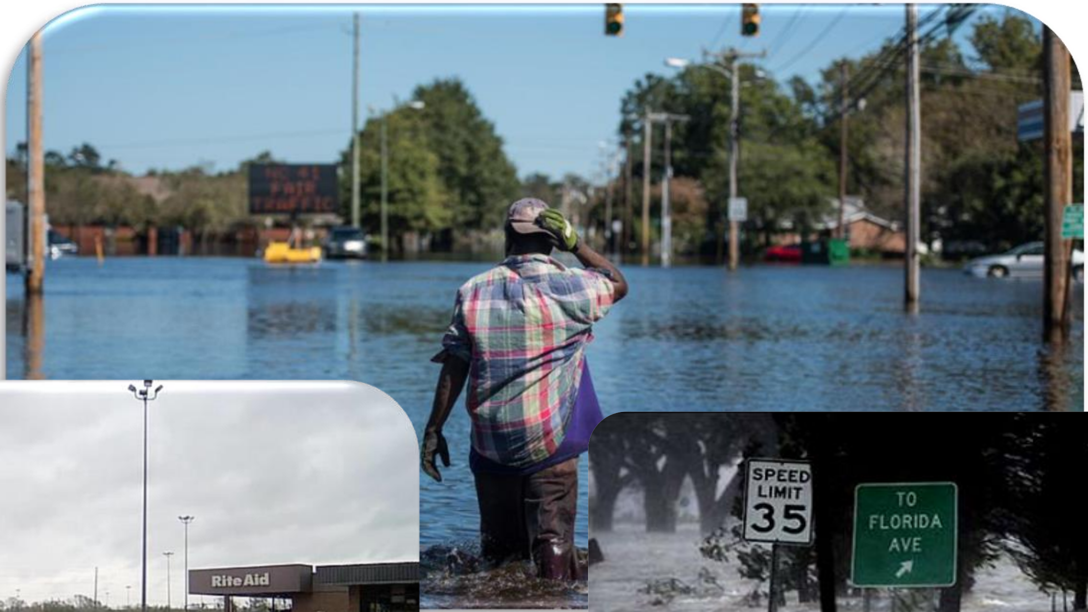
| | $F_1$ | $F_2$ | $F_3$ | $F_4$ |
|---|---|---|---|---|
| Eigenvalue | 2.491 | 1.157 | 0.266 | 0.085 |
| Variability (%) | 62.28 | 28.93 | 6.66 | 2.12 |
| Cumulative % | 62.28 | 91.25 | 97.88 | 100.00 |

# PCR models for hurricanes

- Four conditions of PWV ROC w.r.t. PWV, T, P are defined:
  - 1) Normal condition, 2) Right Before 3)During, and 4) right after a hurricane
  - As a preliminary study, pre-defined parameters are used for each condition → readjusted from sample obs.
- Randomly selected sample stations' observations were used for calculating coefficients of each PCR based statistical model
- We focus on "*right before*" model to predict the path of hurricane

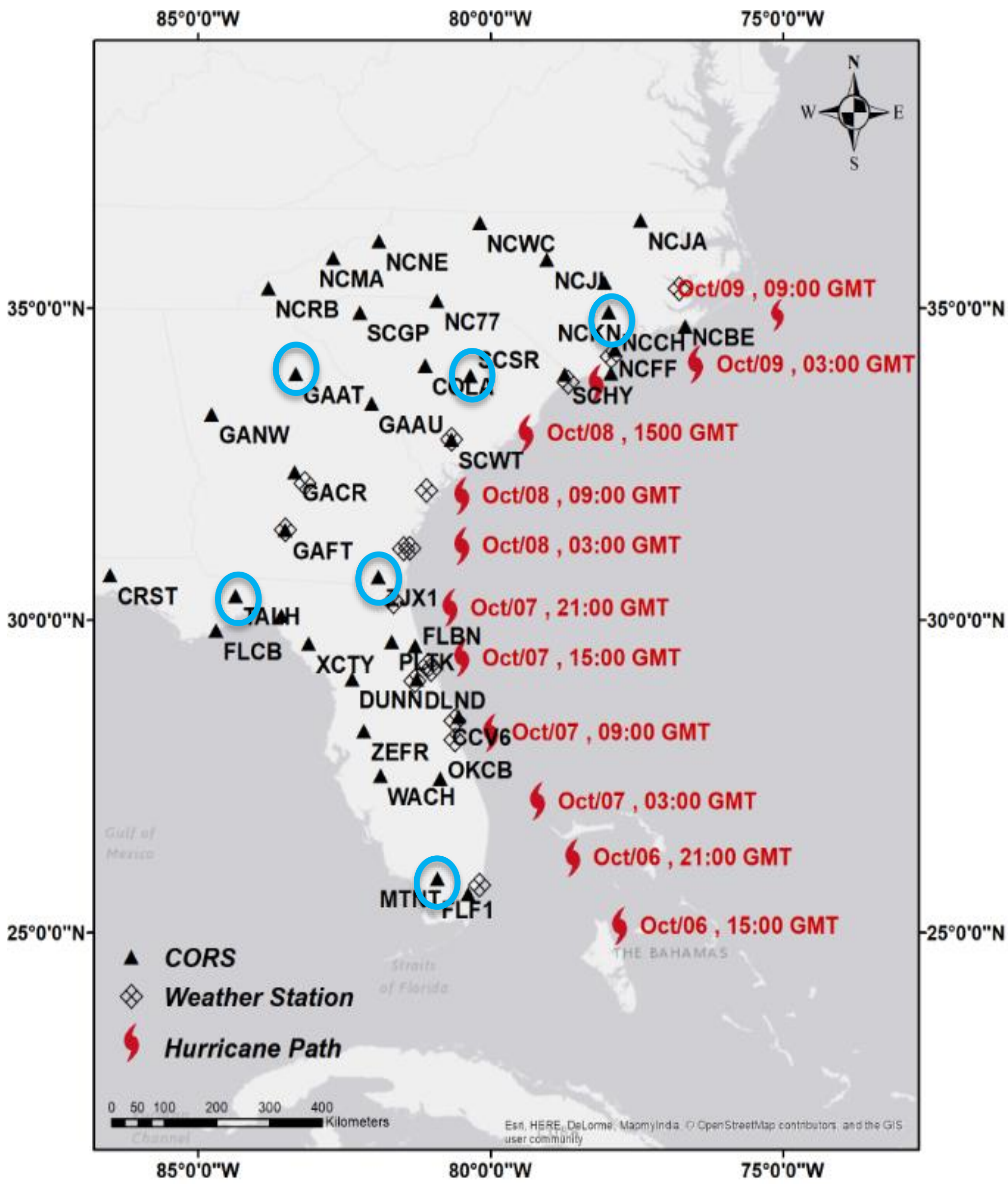
# Hurricane Matthew in 2016

- A total of 603 deaths (34 in the United States)
- Could cause ~ $10 billion in damage estimates



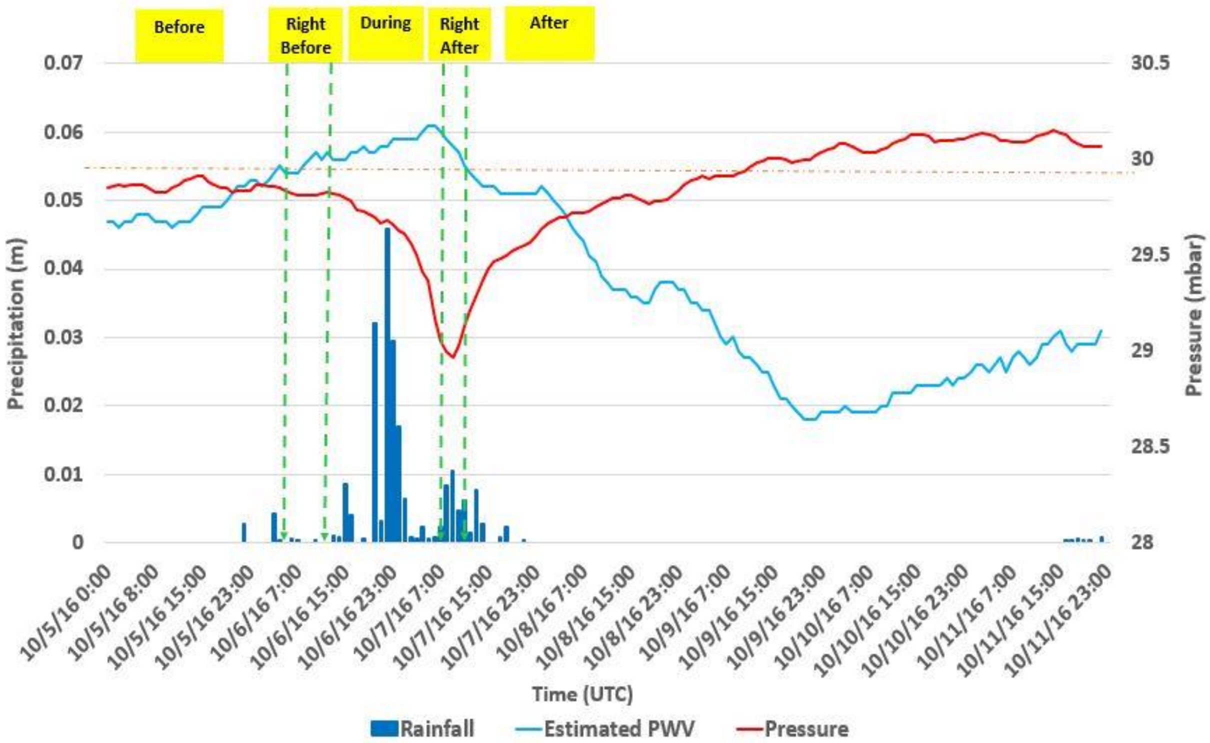

- Observations:
  - 5-11 October 2016
  - 38 CORS stations
  - 14 weather stations

- Temporal Resolution:
  - 5 minutes for CORS
  - 60 minutes for weather data



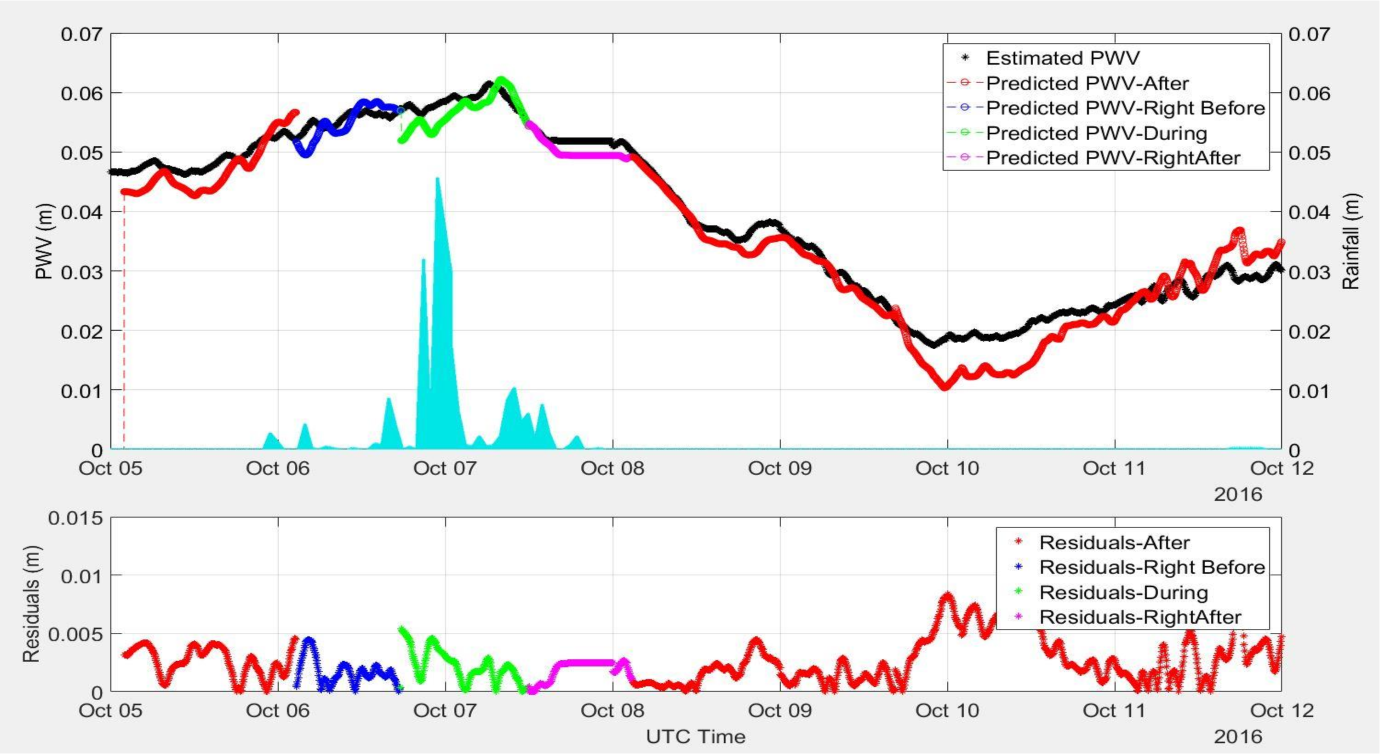
# Implementation of Prediction Models

- The PROC and other atmospheric parameters behave differently at the different stage of hurricane.
- The principle regression model should be tailored to each stage in the hurricane lifetime.



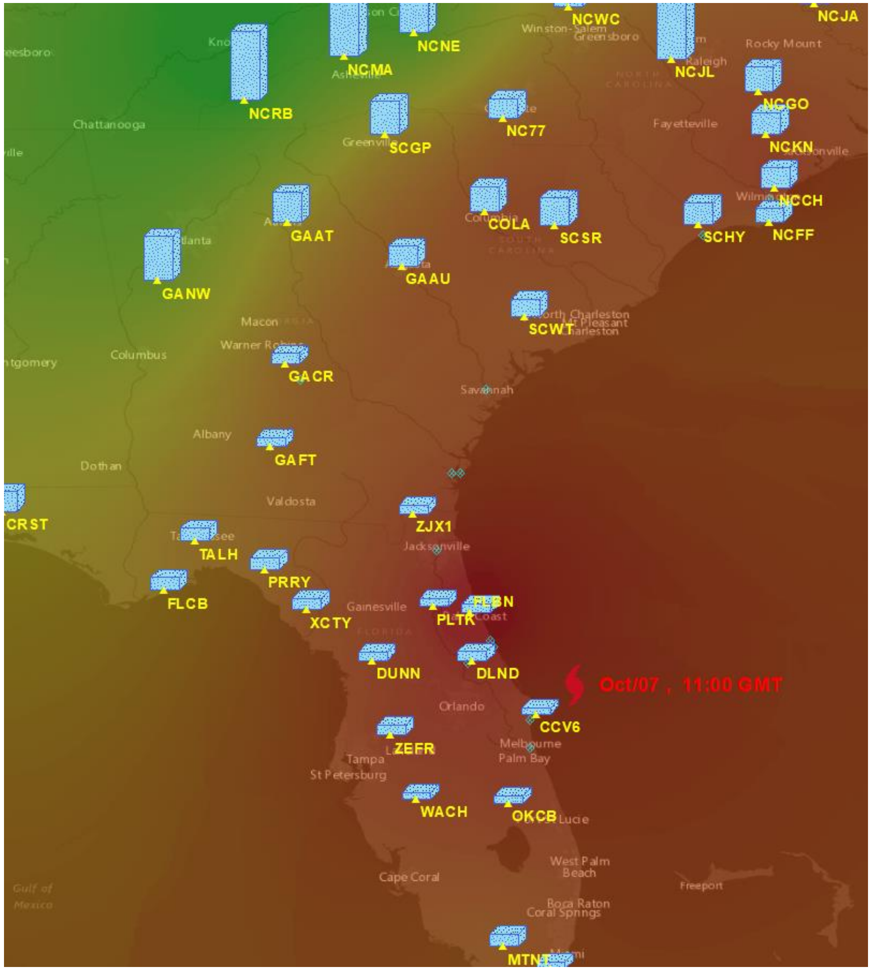
# Implementation of Prediction Models

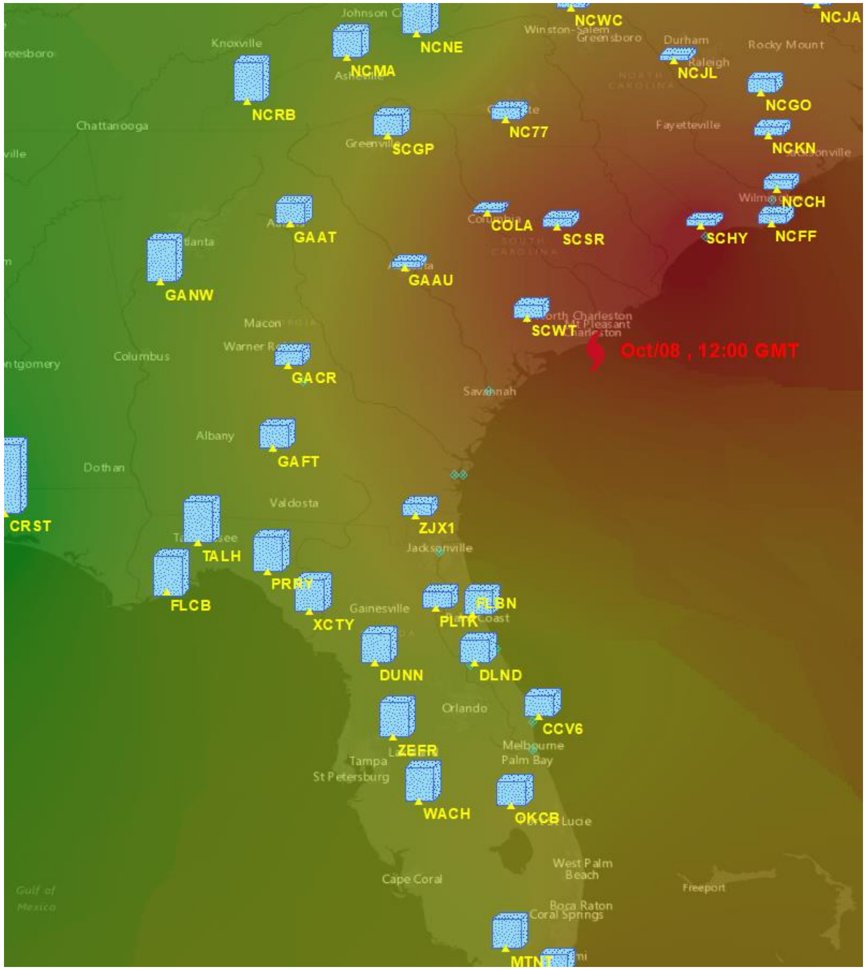
- Among all CORS stations in the test site, six stations are selected for determining the coefficients of the prediction model.
- The remaining stations are used for validating the results.



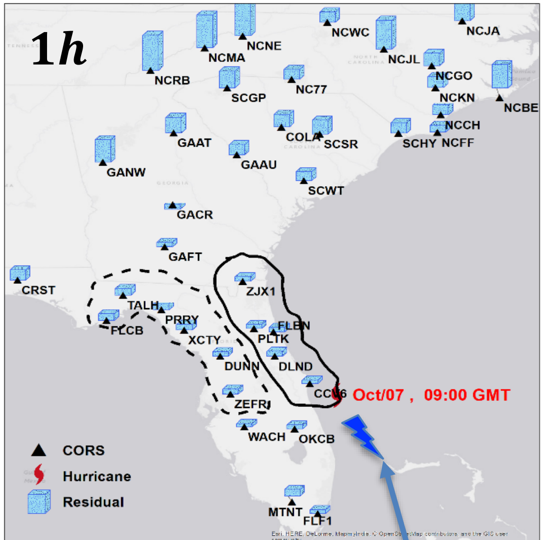

Prediction models and the corresponding residuals for CCV6 during 5-12 Oct, 2016; The top panel shows the models in different colors that are mapped over the actual PWV time series (Black line) and the blue bars represent the recorded actual rainfall on the station for the mentioned period.; the bottom panel shows the residuals of observations with respect to each model.

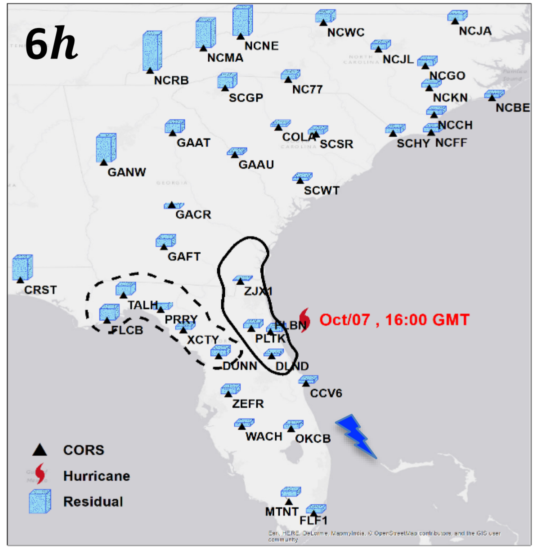
# Model's Residuals Over Hurricane Phases:

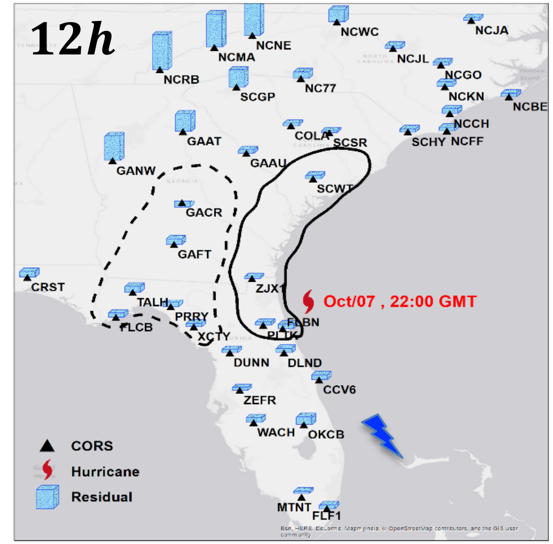


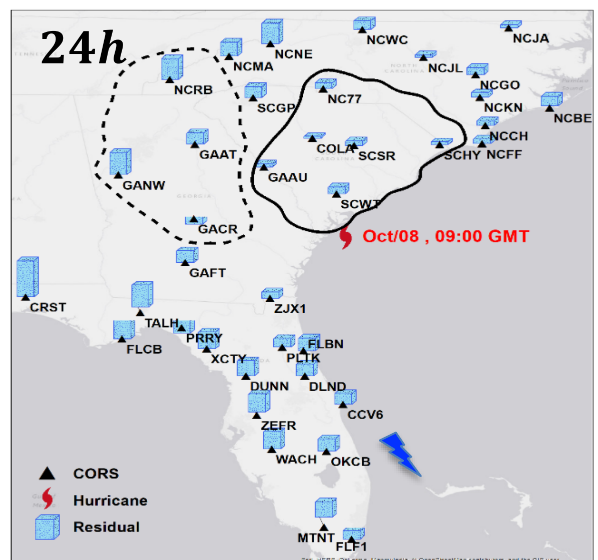
# Numerical Comparison of Right before Model




Oct07 8:00 GMT




| | 1$h$ | 6$h$ | 12$h$ | 24$h$ |
|---|---|---|---|---|
| solid | 0.002 | 0.003 | 0.003 | 0.003 |
| dashed | 0.005 | 0.006 | 0.009 | 0.028 |

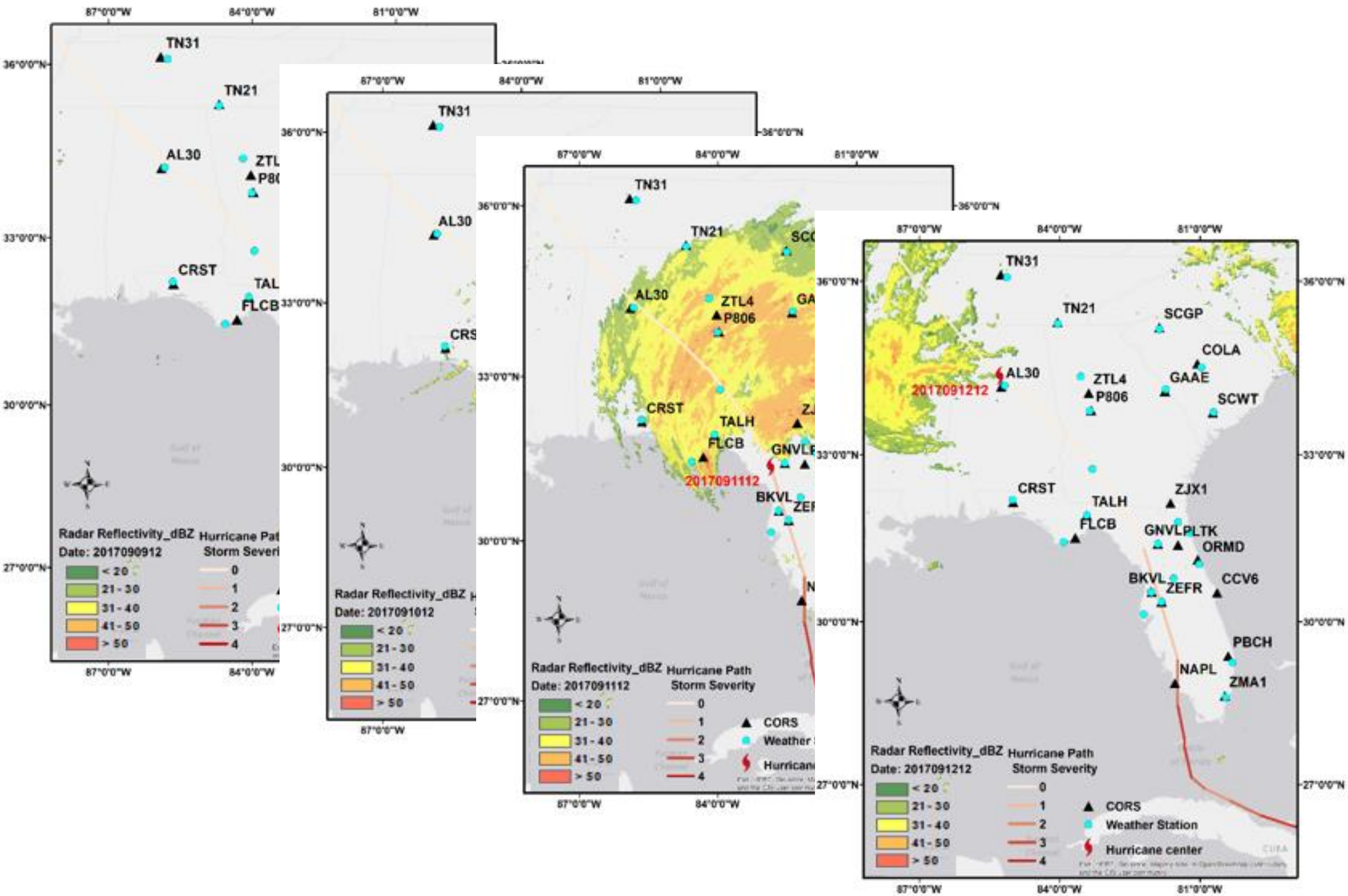
**Residuals of PWV ROC at stations within two clusters [mm]**

# More Case studies:

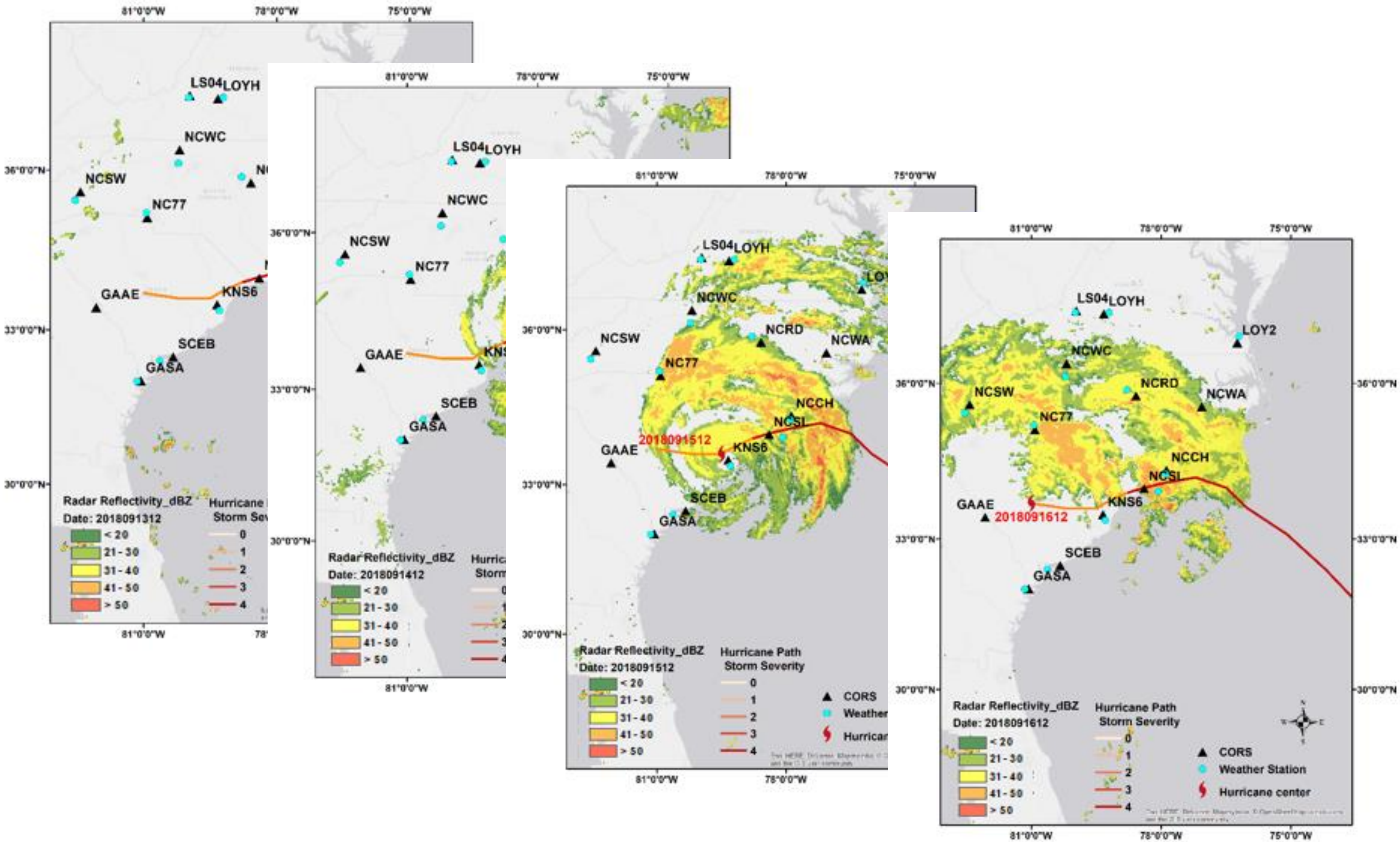
- Evaluation of the GNSS-based prediction model’s performance in **different types of hurricanes**;

- Determination of **optimal spatial and temporal resolution** for the proposed model.

# Case Study: Hurricane Irma 2017



# Case Study: Hurricane Florence 2018



# Thank you

Questions?!