# WGCV-55

## *Microwave Sensors Subgroup Update Report*

Xiaolong DONG, NRSCC/NSSC

Agenda Item 1.12

WGCV-55, Hyderabad, India

8th - 11th July 2025

Committee on
Earth Observation Satellites

# Contents:

1. Progresses of existing tasks
2. Proposal of new tasks: Cal/Val of GNSS-R
3. Perspectives for microwave FRMs

# Recent Focuses of MSSG

MSSG covers EO sensors operated in microwave spectrum, except SAR

MWR, SCAT, ALT, GNSS-RO/R

- Microwave Radiometers (sounders, imagers) (MWR)
- Radar Scatterometers (surface and volume) (SCAT)
- Radar Altimeters (ALT)
- GNSS-Radio occultation and reflectrometry (GNSS-RO/GNSS-R)

**With current focuses on**

- Radar Scatterometers (Active Microwave)
- Microwave Radiometers (Passive Microwave)
- *GNSS-Radio occultation and reflectrometry*

# Recent Tasks of MSSG

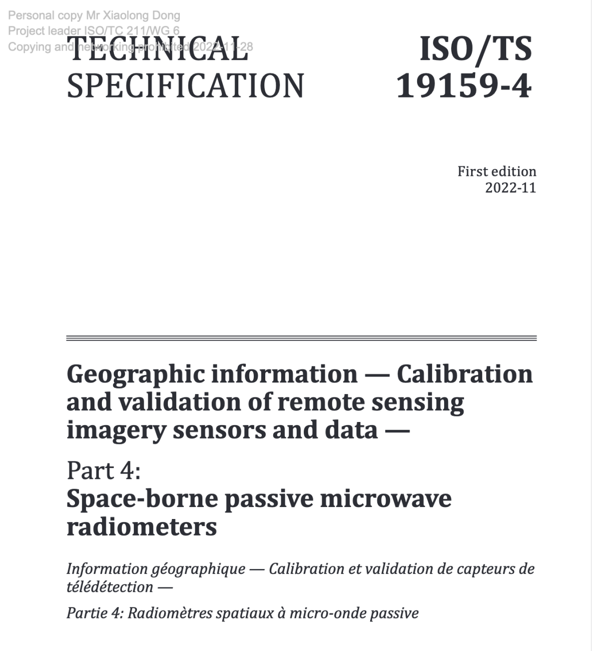
## Completed tasks:

- Radar Scatterometers (Active Microwave)

  CEOS task CV-20-05: Standards and Metrics for Scatterometers and Wind Retrievals
  (ISO-TS initiated in TC-211 plenary in May, 2023)

- Microwave Radiometers (Passive Microwave)

  ISO/TS 19159-4:2022 (published in November 2022)
  Geographic information — Calibration and validation of remote sensing imagery sensors and data — Part 4: Space-borne passive microwave radiometers (ISO TC-211 19159-series)





TECHNICAL SPECIFICATION

ISO/TS 19159-4

First edition
2022-11

**Geographic information — Calibration and validation of remote sensing imagery sensors and data —**

Part 4:
**Space-borne passive microwave radiometers**

*Information géographique — Calibration et validation de capteurs de télédétection —*

*Partie 4: Radiomètres spatiaux à micro-onde passive*

## On-going tasks:

- CV-23-05 Retrieval and validation with high winds with combined active-passive microwave measurements (2025 Q2)
- CV-23-06 Retrieval and validation of sea surface atmospheric pressure with microwave remote sensing (2025 Q2)

# Task CV-23-05

CV-23-05: Retrieval and validation with high winds with combined active-passive microwave measurements

Task lead:

Prof. Wenming Lin
Nanjing University of Information Science and Technology (NUIST)

## Motivation

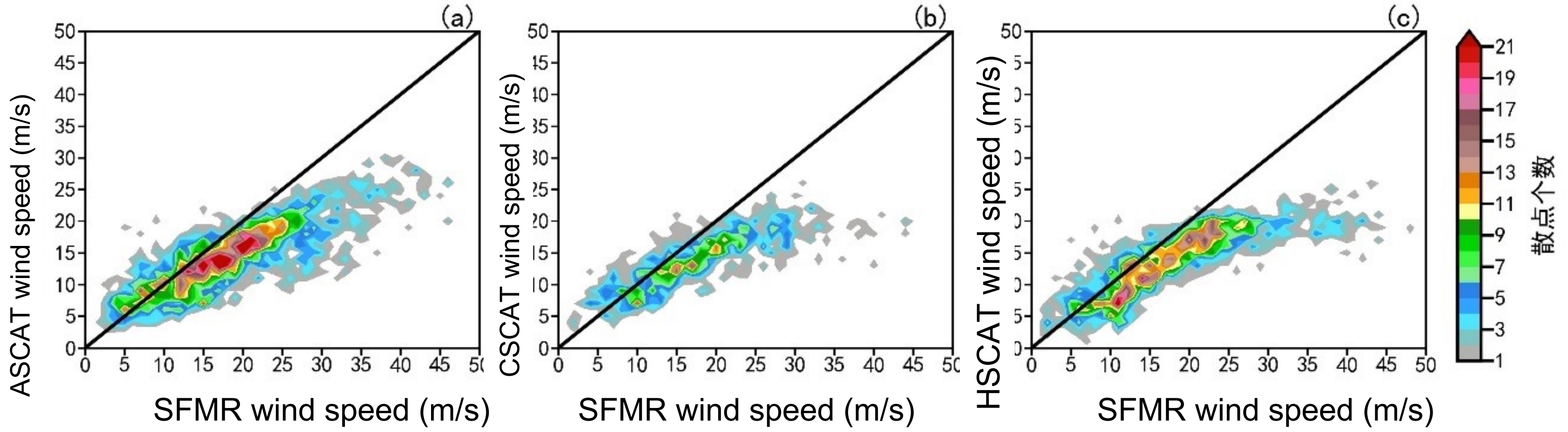
- Extreme sea surface winds (speed ≥ 32.7 m/s) may lead to storm surge, transportation disruptions, injury or death, damage to ships and coastal buildings, and etc.

- Monitoring of sea surface extreme winds using satellite-based microwave sensors is of great significance not only to the Risk Management authorities, but also the oceanic and atmospheric communities.

- The current satellite scatterometer or radiometer-derived extreme winds are far from the “truth”, due to:
  - Rain contamination for both active and passive sensors;
  - Extreme wind signal saturation for the co-polarized observations of active sensors;
  - Limited understanding the physical fundamentals of wave breaking, whitecaps, …

## Motivation

- It requires a re-calibration or re-process task in order to improve the quality of extreme winds retrieved from either satellite scatterometers or radiometers, and to achieve a consistent multi-mission extreme winds. Several approaches have been developed recently:
  - High wind calibration for satellite scatterometers (only active sensors);
  - Extreme winds from radiometers' low-frequency measurements (only passive sensors);
  - Retrieval from combined active and passive measurements.



## Task team

- Nanjing University of Information Science and Technology (NUIST); (Task lead & SAR extreme winds);
- National Space Science Center (NSSC); (Rain effect for extreme winds)
- Royal Netherlands Meteorological Institute (KNMI); (SCAT extreme winds)
- National Ocean Satellite Application Center (NSOAS); (SCAT and RAD extreme winds);
- National Satellite Meteorological Center (NSMC/CMA); (C- and Ku- combined wind)
- National Oceanic and Atmospheric Administration (NOAA); (SFMR reference winds)
- Other potential contributors

## Main contents

- To re-calibrate microwave radiometer brightness temperature, radar scatterometer and synthetic aperture radar (SAR) normalized radar cross section (NRCS, $\sigma^0$), and to derive well inter-calibrated high and extreme sea surface wind products.

- To validate the high and extreme winds using collocated NOAA hurricane hunter Stepped Frequency Microwave Radiometer (SFMR) winds as reference.

- To better understand the intrinsic characteristics (e.g., the true spatial scale of each wind source) of the satellite-derived high and extreme winds.

## Main contents

### Validation reference aspect:

- Collocations in storm-centric coordinates: improve storm center location. **(Done)**
- Spatial representativeness: Look for suitable SFMR upscaling for each SAR, scatterometer & radiometer. **(Done)**

### Satellite data aspect:

- Analyze the sensitivity of each sensor measurement under high and extreme wind conditions, improve the radiation and scattering models. **(Done)**
- Re-calibration of radiometer brightness temperature, and radar NRCS. **(Done)**
- Re-calibration and/or re-process the extreme winds from the mentioned sensors. **(Done)**
- High and extreme wind validation using the reference data. **(Done)**

# Introduction

CEOS

## Deliverables

**Data:**

1. Adjusted scatterometer extreme wind product;

- ✓ Adjusted Advanced Scatterometer (ASCAT) high wind data; *https://www.maxss.org/*
- ✓ Adjusted Haiyang-2 satellite scatterometer (HSCAT) high wind data; *https://www.maxss.org/*

2. Improved Haiyang-2 radiometer extreme wind data; *https://osdds.nsoas.org.cn/home*
3. Combined active and passive wind data. *(limited cases, upon request)*

**Tool:**

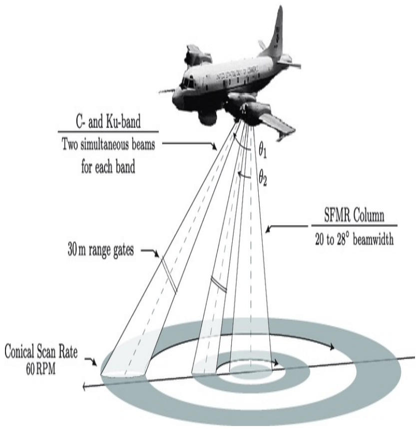
- Scatterometer wind adjustment tool;
- Wind data illustration tool;

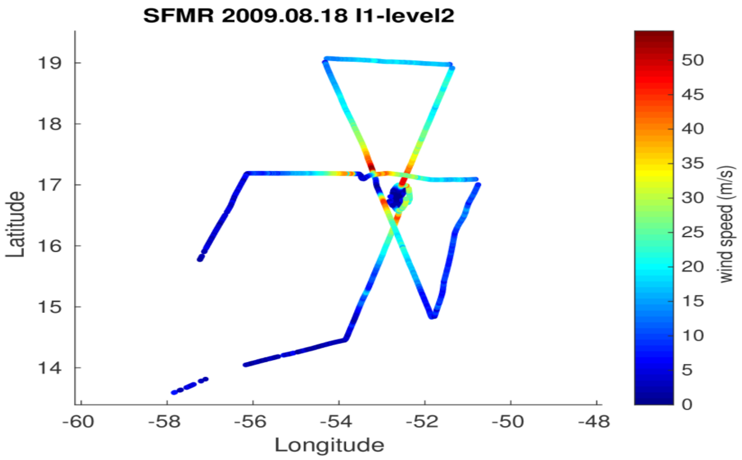
**Technical report:**

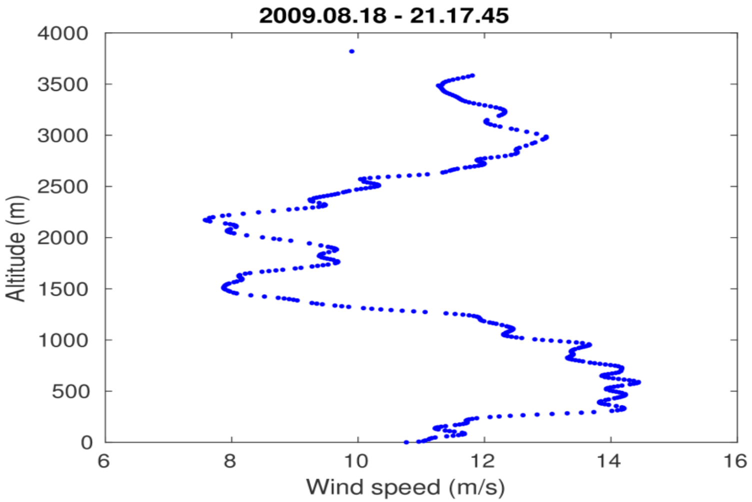
- Introduction of data and methods;
- Result validation;
- Discussion and perspectives;

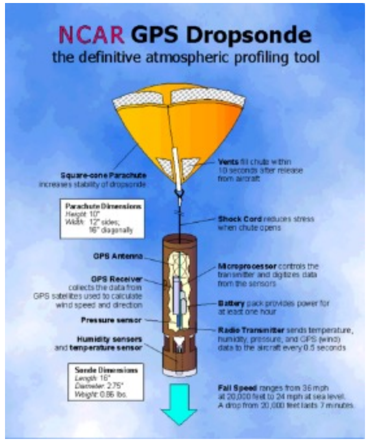
# Deliverables-1:
# Adjusted scatterometer extreme wind product

## Reference data




**Stepped Frequency Microwave Radiometer (SFMR) :**

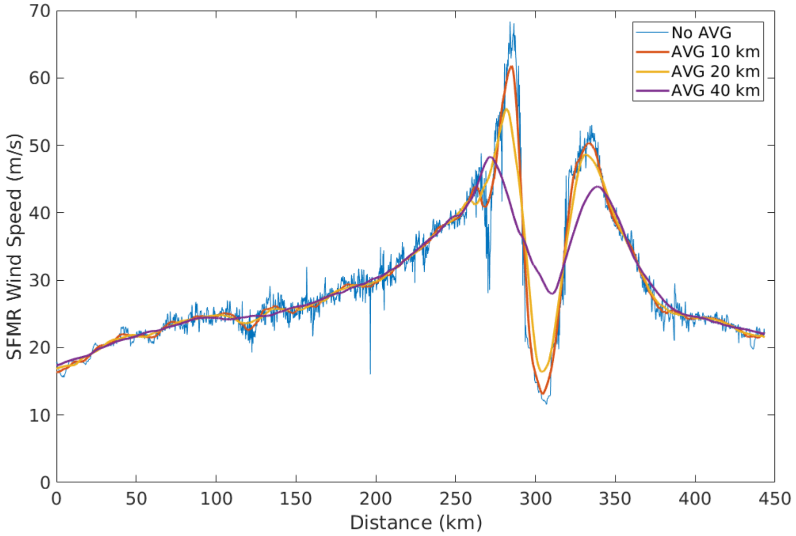
- Nadir-pointing radiometer at C-band.
- The equivalent neutral surface wind speed retrieved by inversion of a Geophysical Model Function.
- Surface wind retrieval are provided in **1-sec sampling** and the **aircraft position** is assigned to each wind retrieval.

**Dropsondes:**

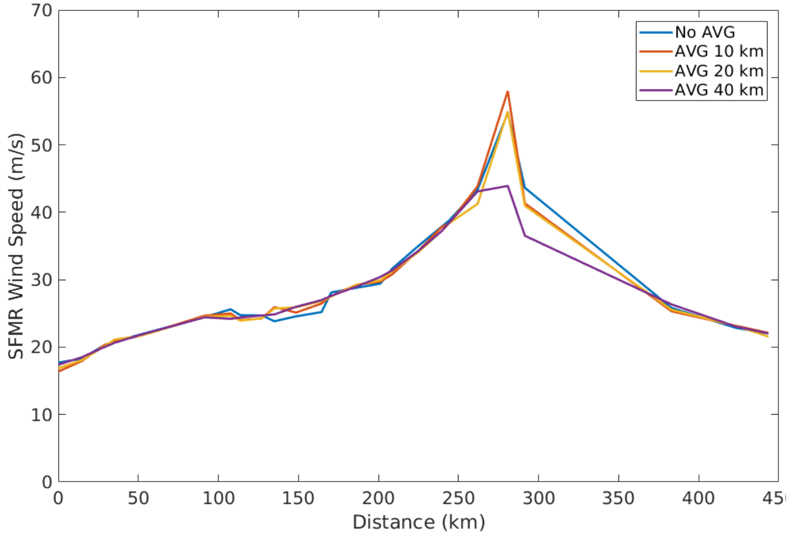
- They provide the wind profile
- The 10m equivalent neutral surface wind speed and direction *empirically derived* by the **WL150 algorithm**.
- Surface wind value consists in an **height-weighted average** of the dropsonde readings available within the lowest **150m-layer** between 10m and 350m.

# Deliverables-1:
# Adjusted scatterometer extreme wind product

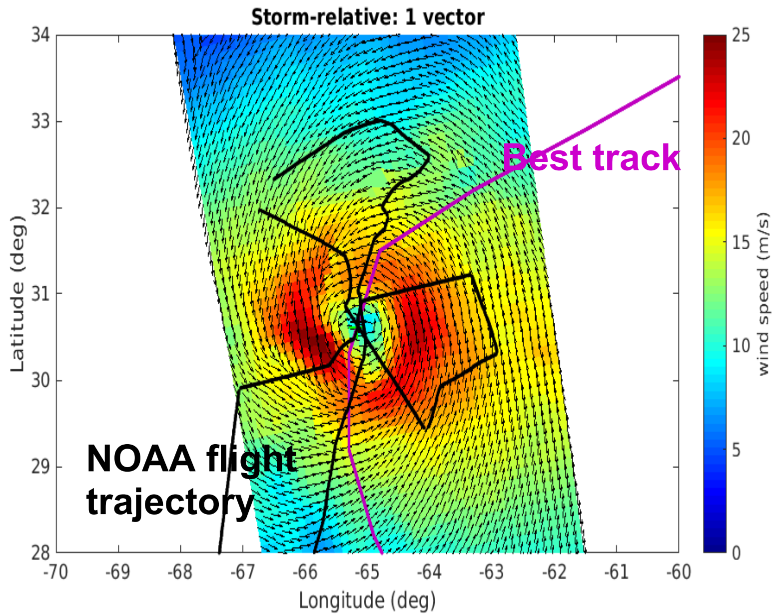
## Reference data




*SFMR upscaling effects at SFMR 1-sec sampling*




*SFMR upscaling effects at 12.5 km sampling*




ASCAT wind field over Hurricane Karl on September 23rd, 2016

- ***SFMR upscaling effects are significantly smaller at 12.5-km (ASCAT-A) sampling***
- ***SFMR 40-km averaged winds more representative of ASCAT 12.5-km (25-km resolution) winds***

# Deliverables-1:
# Adjusted scatterometer extreme wind product

CEOS

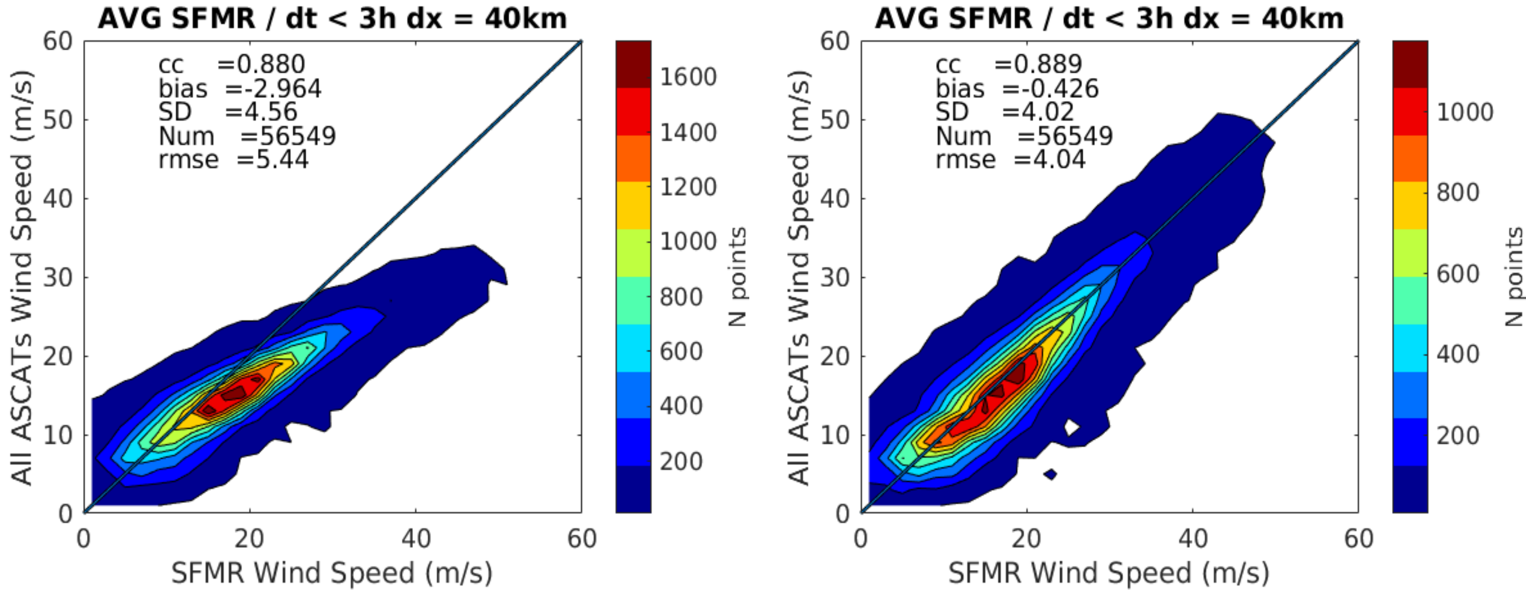
## Wind speed adjusting model & results

① Airborne SFMR winds calibrated by Dropsondes;

② ASCAT winds collocated with the airborne SFMR winds;

③ ASCAT winds calibrated using a polynomial fitting function;

④ Other scatterometer or radiometer winds calibrated by the re-calibrated ASCAT wind speed.




(Portabella et al., 2023)

$$V_c = 0.0095 \times V^2 + 1.52 \times V - 7.6$$

(Polverari et al., 2022)

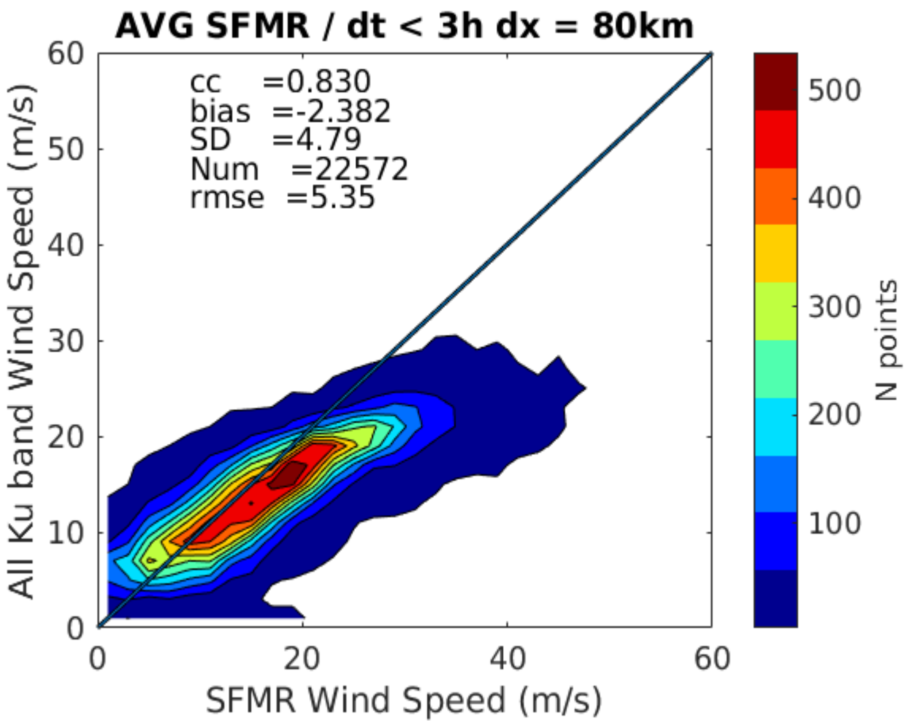
$$V_c = 0.01847 \times V^2 + 1.035 \times V - 2.9$$

(Portabella et al., 2023)

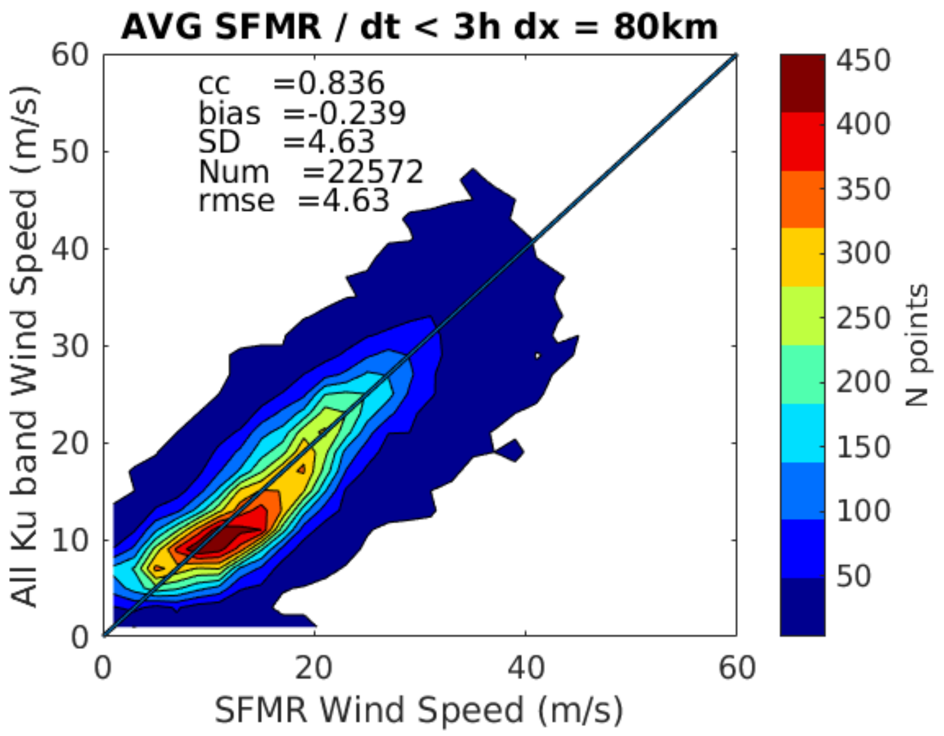
# Deliverables-1: Adjusted scatterometer extreme wind product

## Wind speed adjusting results

***Original Ku-band winds***



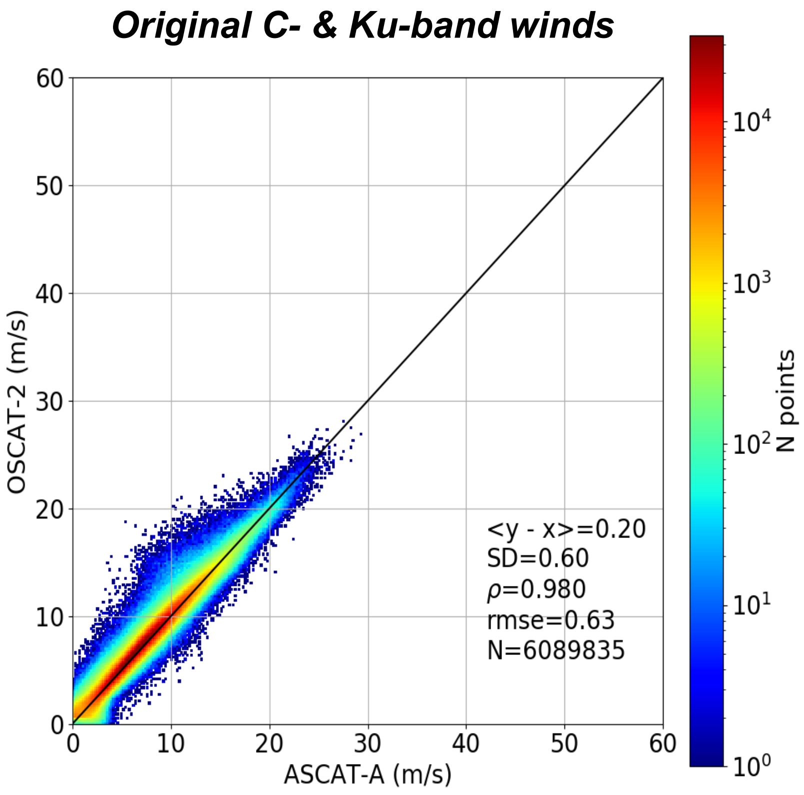

***Recalibrated Ku-band winds***

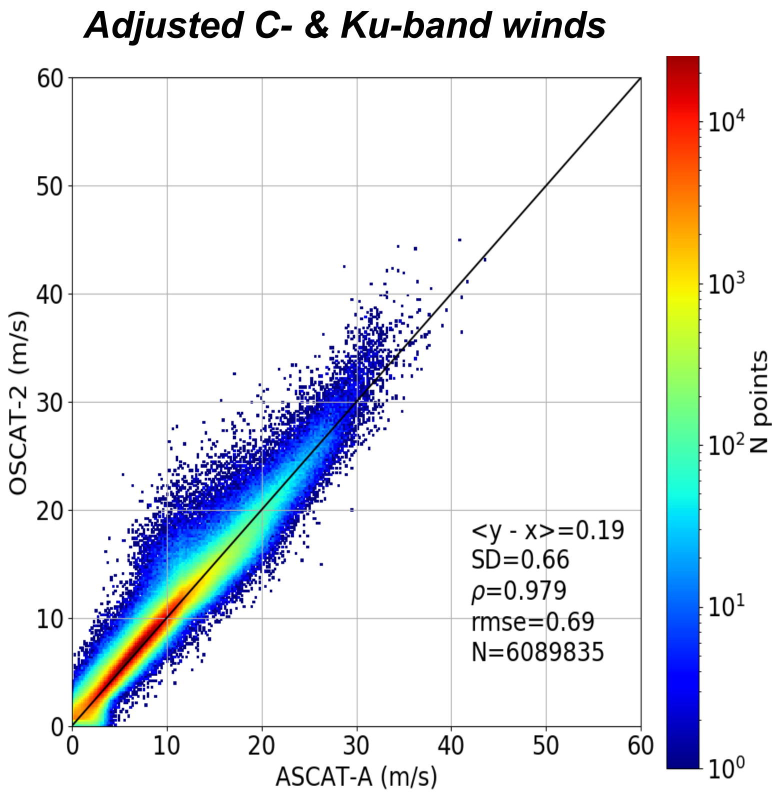



- ***Adjusted Ku-band winds consistent with SFMR winds (as expected)***

# Deliverables-1:
# Adjusted scatterometer extreme wind product

## Wind speed adjusting results

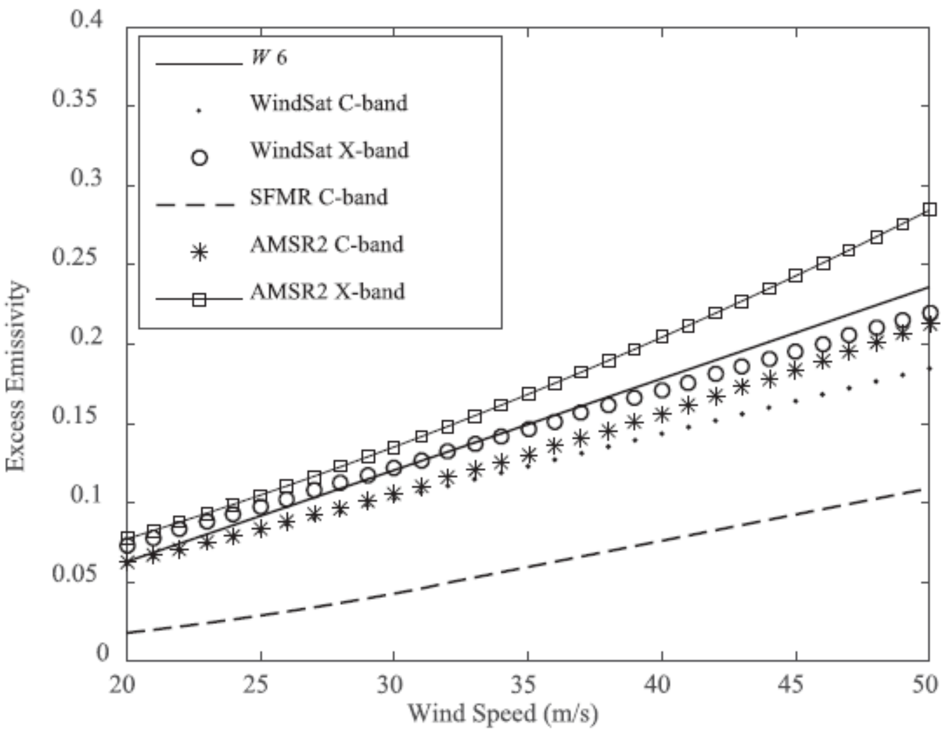


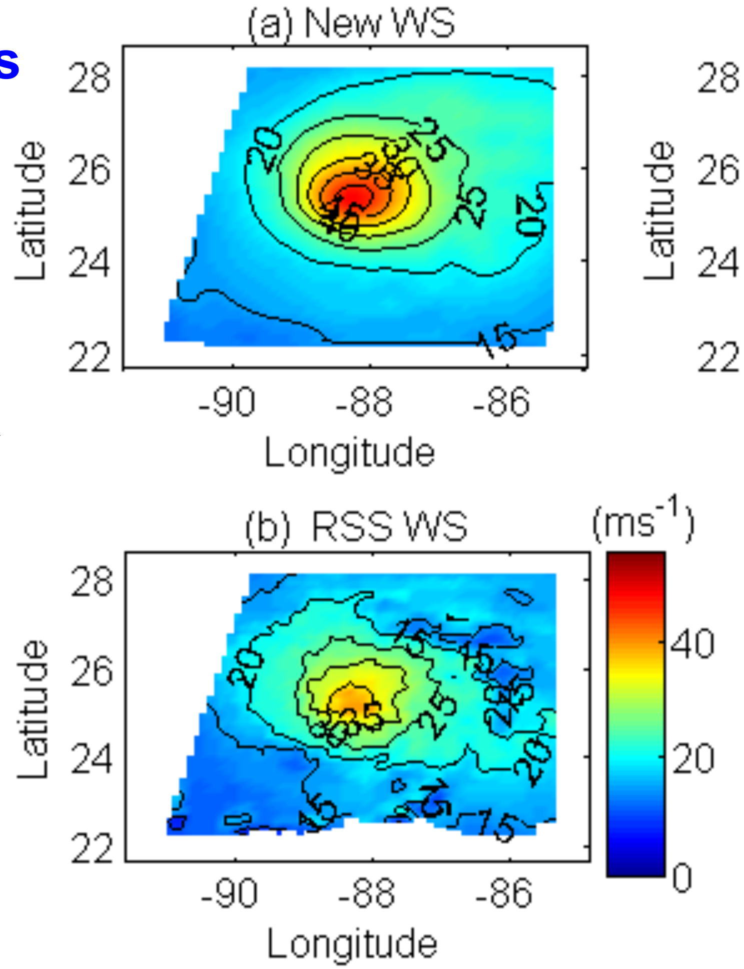

- ***Adjusted OSCAT-2 high & extreme winds inconsistent with adjusted ASCAT-A winds due to "rain fitting" of the former***

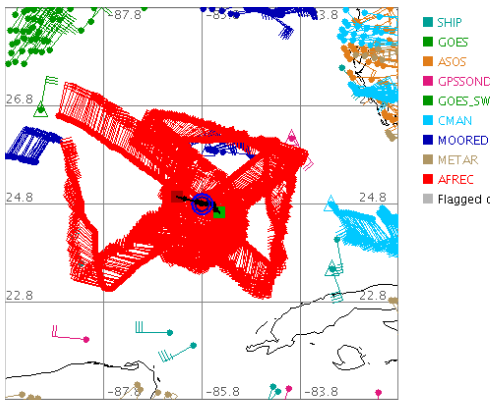
# Deliverables-2:
# Improved Haiyang-2 radiometer extreme wind data

## Improved emissivity model & wind retrieval results




Improved emissivity model (Yin et al., 2023)

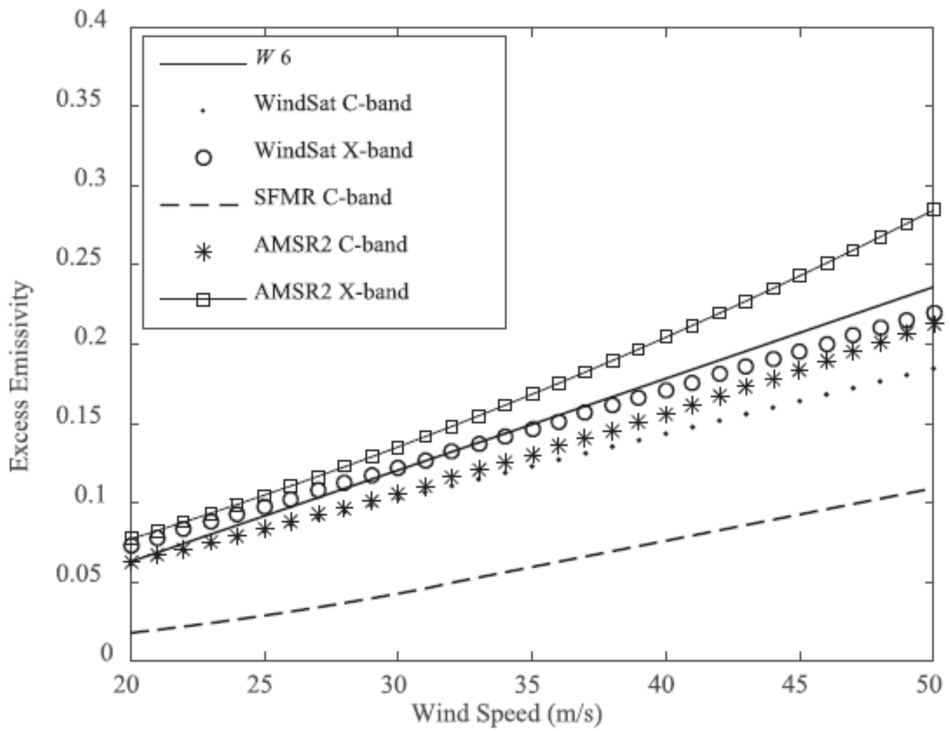


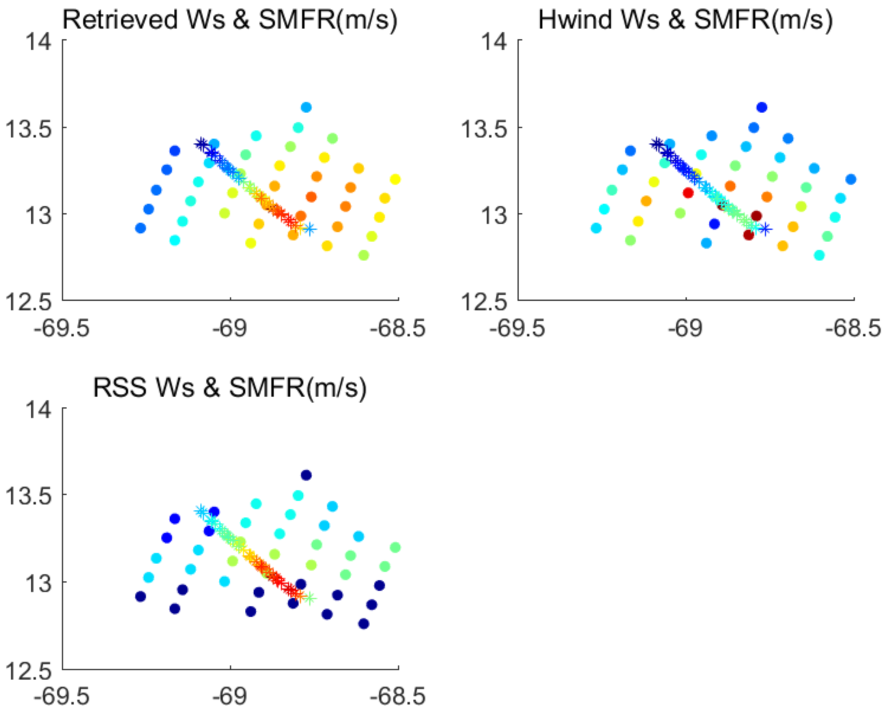

**Compared to Hwind or field measurements, extreme winds retrieved from the low-frequency (C-band/6.925 GHz) radiometers are better than the RSS all weather product**

# Deliverables-2:
# Improved Haiyang-2 radiometer extreme wind data

## Improved emissivity model & wind retrieval results




Improved emissivity model (Yin et al., 2023)




Better agreement with SFMR

**High wind retrieval using the low-frequency (C-band/6.925 GHz) radiometers**

# Deliverables-2:
# Improved Haiyang-2 radiometer extreme wind data

## Improved radiometer wind retrieval results

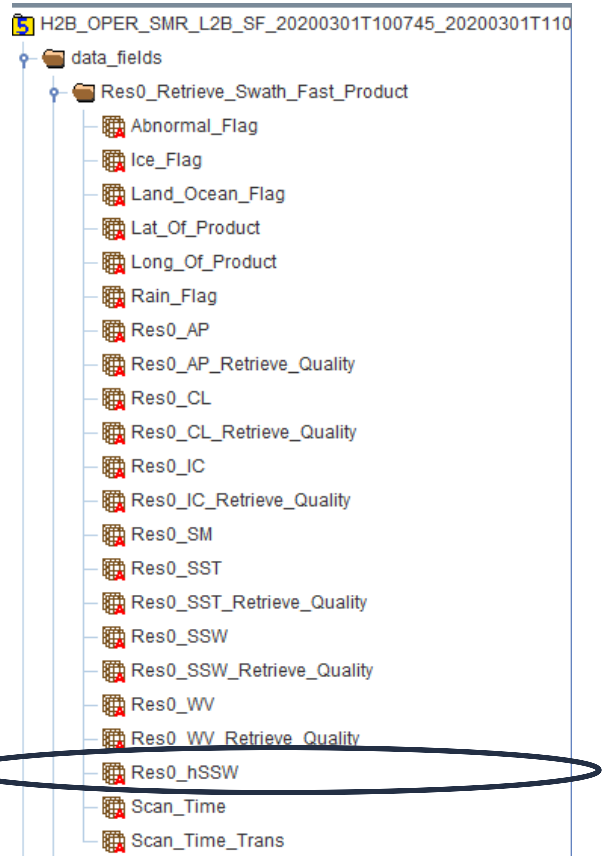
| Name | Ours | | RSS | | Matches |
|---|---|---|---|---|---|
| | std (m/s) | mean (m/s) | std (m/s) | mean (m/s) | |
| Fabian | 2.5 | 1.8 | 2.5 | -3.3 | 174 |
| Katrina | 3.3 | 1.3 | 3.6 | -5.0 | 88 |
| Felix | 2.6 | 0.3 | 3.0 | -4.0 | 40 |
| Ike | 3.3 | 0.7 | 5.4 | -5.3 | 71 |
| All | 2.8 | 1.3 | 3.2 | -4.2 | 373 |

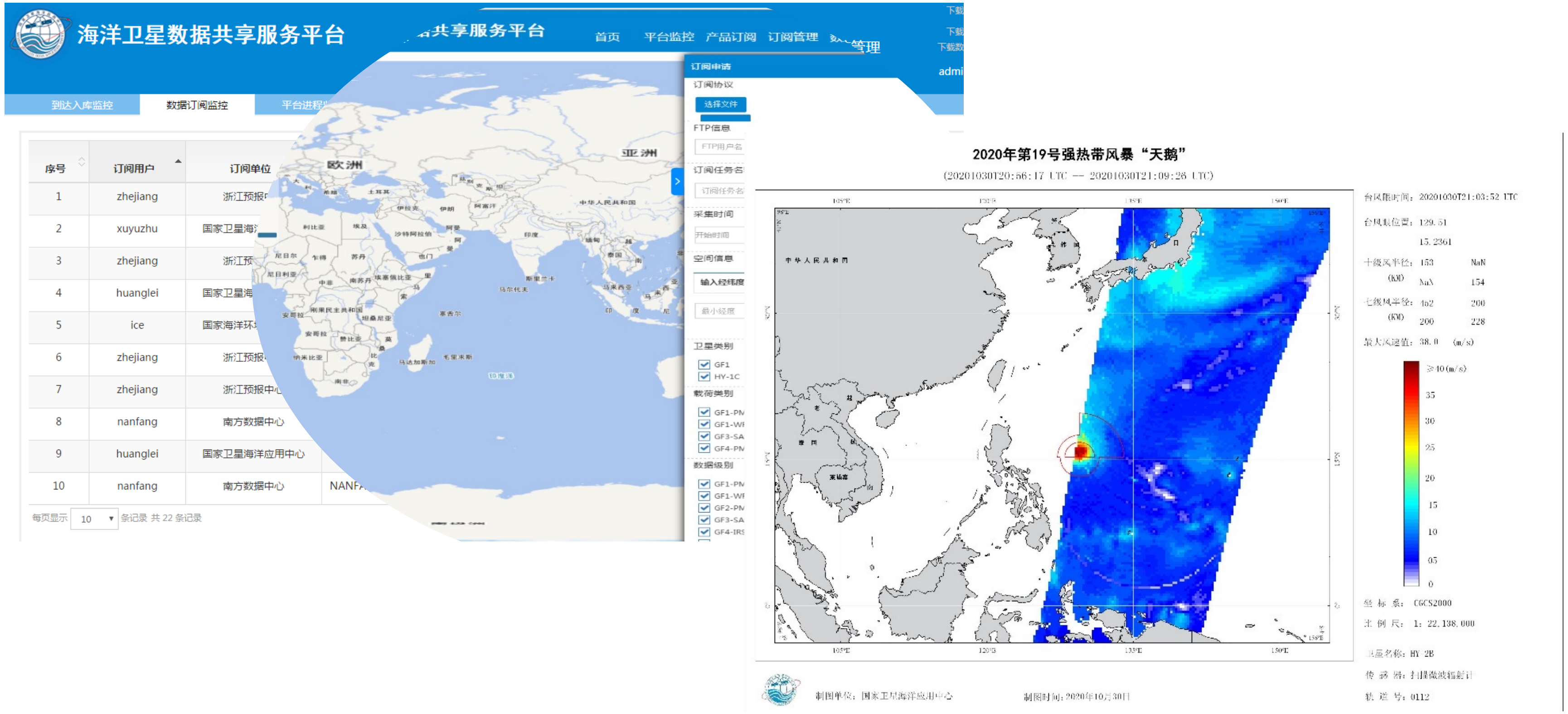
Improved low-frequency radiometer wind retrieval(Yin et al., 2023)

# Deliverables-2: Improved Haiyang-2 radiometer extreme wind data

## Improved radiometer wind product

https://osdds.nsoas.org.cn/




## Improved HY-2B radiometer winds disseminated by NSOAS

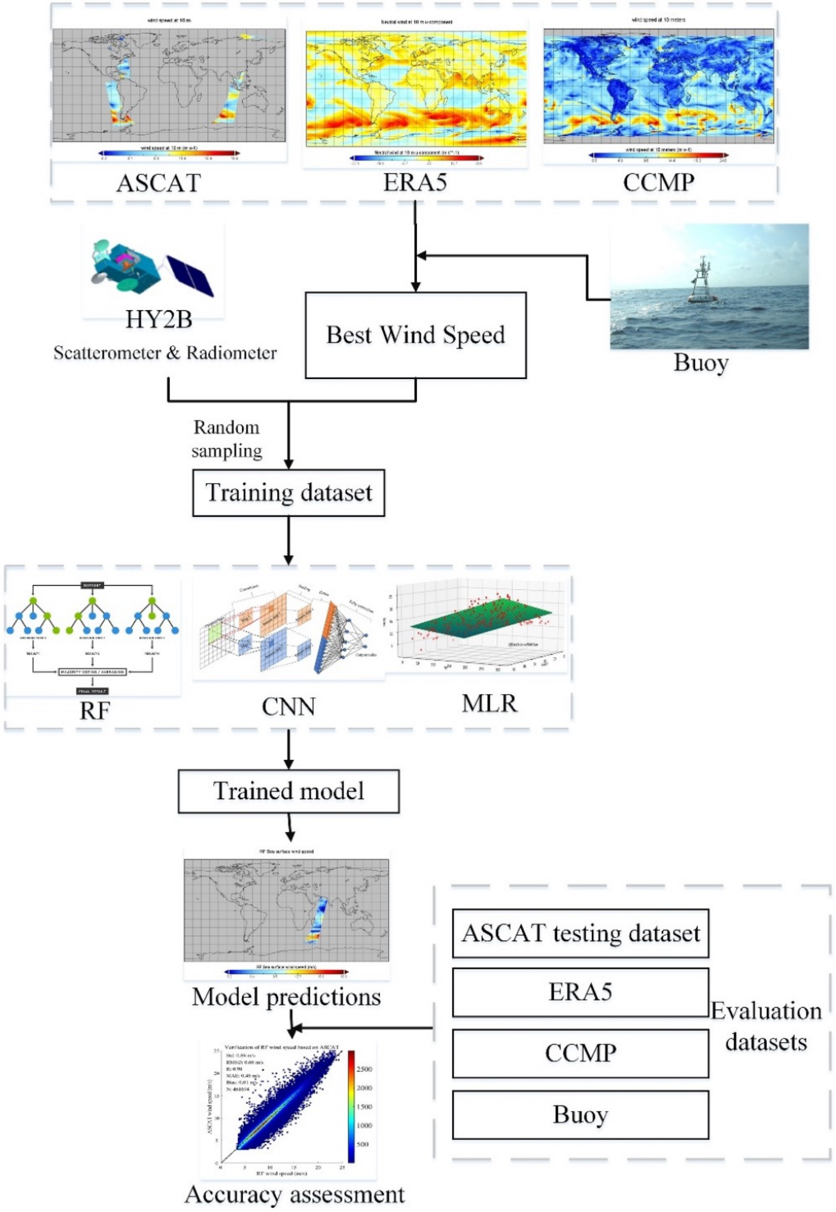
# Dilverables-3:
# Combined active and passive wind data

## Method1 – Random Forest & Convolutional Neural Networks (CNN) for general wind retrieval

**Table 1**
*The Fundamental Information for the HY-2B Microwave Scatterometer and Radiometer*

| Sensor | Frequency (GHz) | Polarization | Swath (km) | Spatial resolution (km) |
|---|---|---|---|---|
| Scatterometer | 13.256 | HH | 1,350 | 25 |
| | | VV | 1,700 | |
| Radiometer | 6.925 | V&H | 1,600 | 90 × 150 |
| | 10.7 | V&H | | 70 × 110 |
| | 18.7 | V&H | | 36 × 60 |
| | 23.8 | V | | 30 × 52 |
| | 37.0 | V&H | | 20 × 35 |

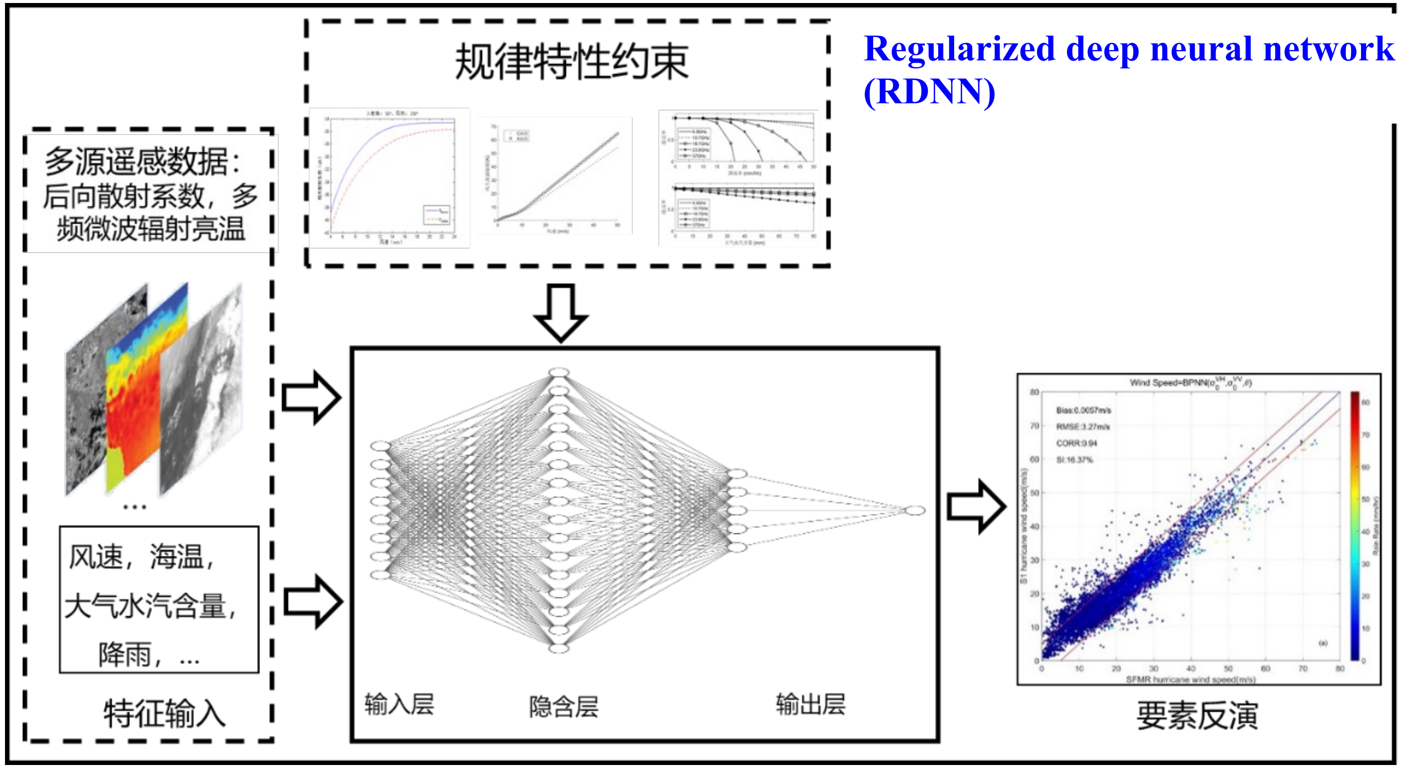
- The joint active-passive approach **(RMSE 1.16m/s),** e.g., RF and CNN models, consistently outperformed both the individual active (1.27 m/s) and passive (1.80 m/s) models.
- The accuracy assessment, conducted with buoy, ERA5, and CCMP data, confirmed the effectiveness of the integrated methodology.




**Chartflow of the combined retrieval (Xiang et al., 2024)**

# Dilverables-3:
# Combined active and passive wind data

## Method2 – Regularized deep neural network (RDNN) for extreme wind retrieval

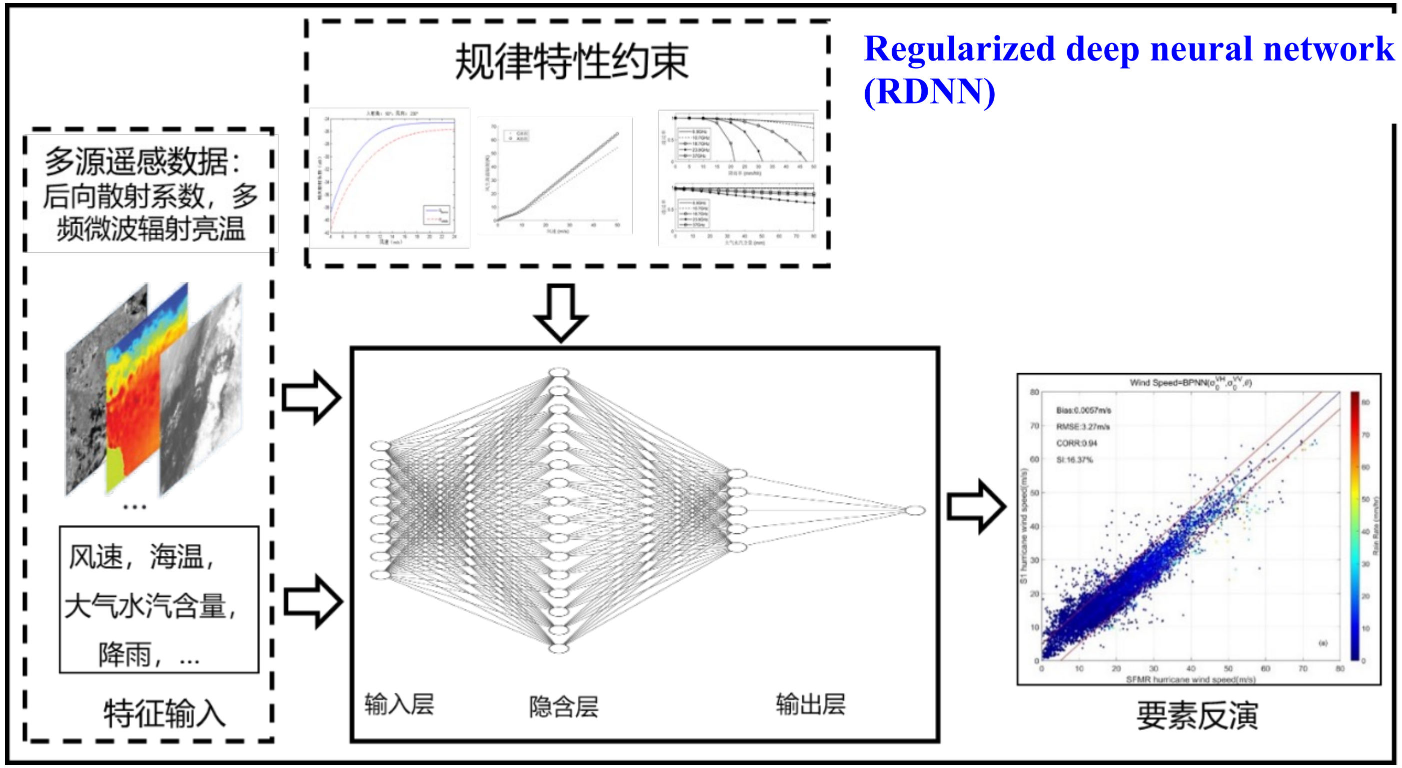


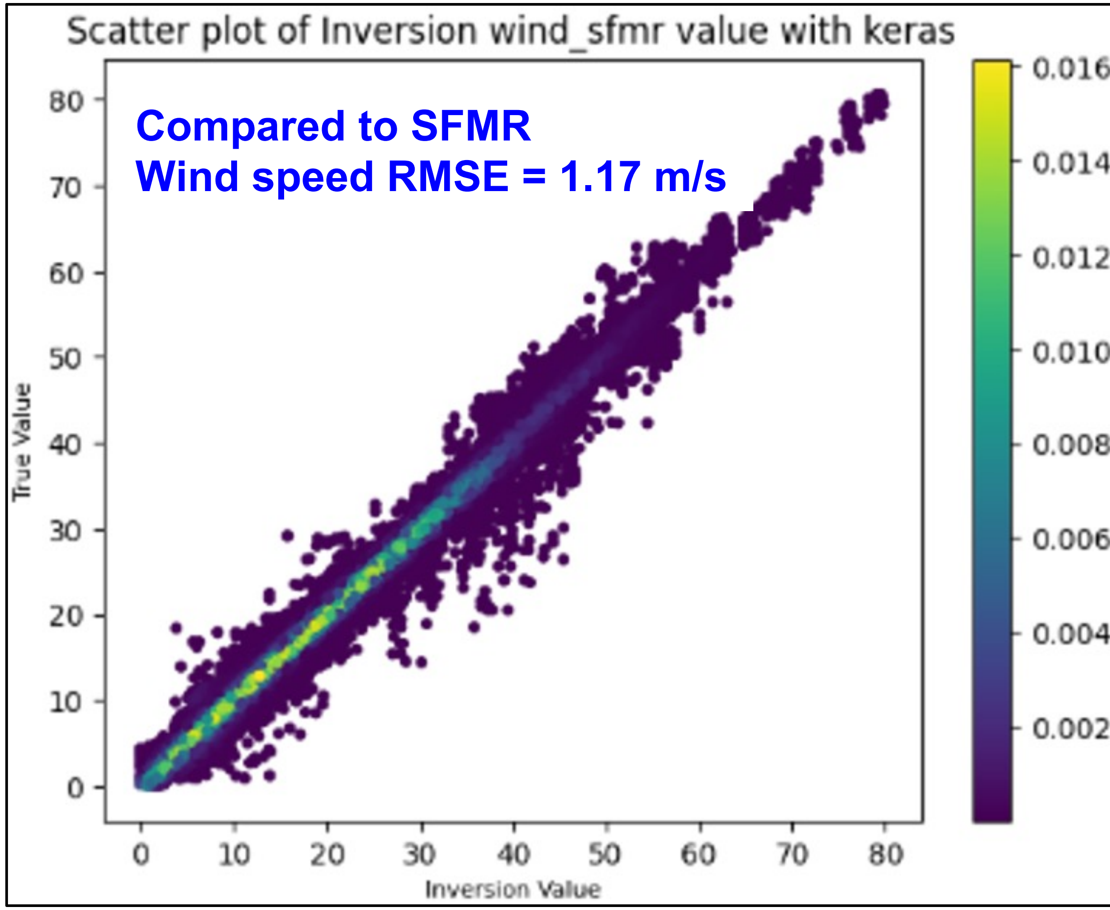

**Variables used for the model training**

| Variables | Variables |
|---|---|
| 6.925GHz TB_H | 37.0GHz TB_H |
| 6.925GHz TB_V | 37.0GHz TB_V |
| 10.7GHz TB_H | Rain rate |
| 10.7GHz TB_V | Atmospheric water vapor |
| 18.7GHz TB_H | SST |
| 18.7GHz TB_V | SCAT $\sigma^0$ |
| 23.8GHz TB_V | |

# Dilverables-3:
# Combined active and passive wind data

## Method2 – Regularized deep neural network (RDNN) for extreme wind retrieval



# Summary:

- Although the scatterometer signals saturate at extreme winds, and the high-frequency radiometer signals are affected by rain, both active and passive sensors show great potential for the retrieval of extreme sea surface winds by applying:
  - High wind calibration for scatterometers;
  - Improved emissivity model for low-frequency (C-band) brightness temperature.

- Combining active and passive measurements in the ANN model not only improves the general wind retrieval (RF&CNN), but also improves the extremes (RDNN).

- Relevant data and processing tool have been developed, and are already deliverable.

- Better understanding on the backscatter/radiation characteristics is needed, in order to optimize the configuration of active/passive channels for the remote sensing of extreme winds.

# Task CV-23-06

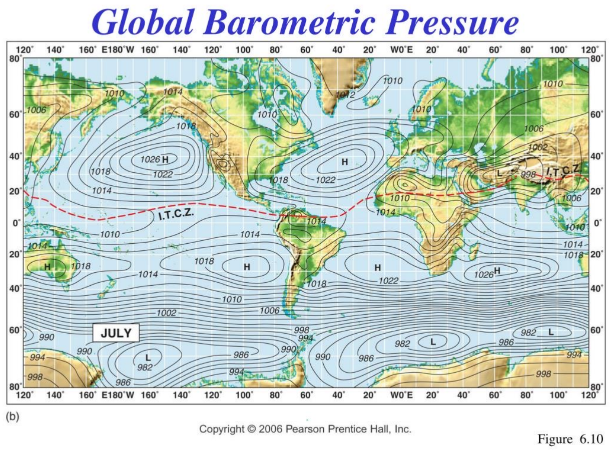
CV-23-06: Retrieval and validation of sea surface atmospheric pressure with microwave remote sensing

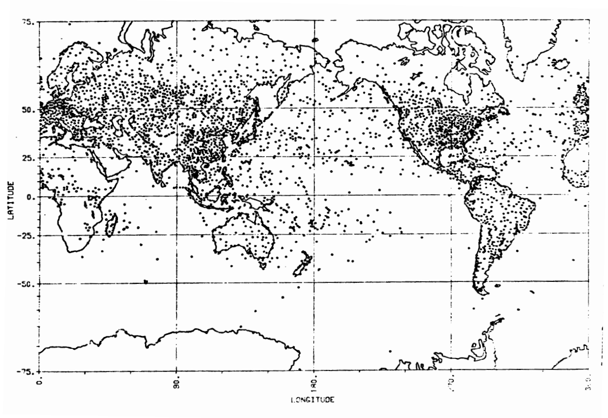
Task lead:

Dr. Zijin ZHANG
National Space Science Center, CAS

# Introduction

- Surface pressure data have important applications in **numerical weather prediction (NWP), tropical cyclone forecasting and analysis, global climate change studies.**
- Currently, ocean surface atmospheric pressure data are mainly provided by buoys and ship measurements. **The spatial coverage of in situ data for use by weather forecasters is very poor.**
- Only remote sensing techniques can obtain surface pressure data with large spatial coverage and high density sampling over oceans. **However, no on-orbit sensor is designed for ocean surface pressure observation, and there are no operational surface pressure retrieval products.**



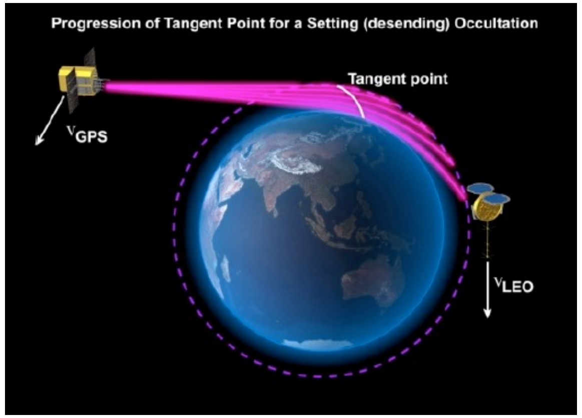




Stations reporting surface pressure

# Introduction

## Overview of Existing Techniques

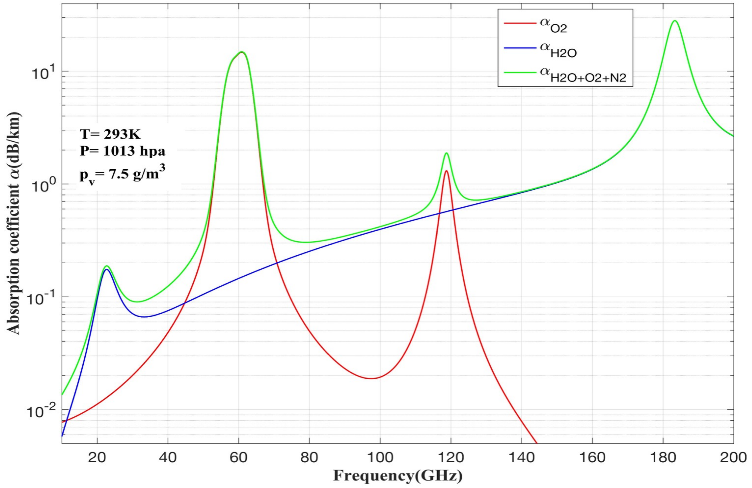
| Instrument | Frequency Band | Accuracy | Disadvantages |
|---|---|---|---|
| Grating spectrometer (Mitchell and O'Brien, 1987) | $O_2$ A band (759-771 nm) | 1~2 hPa (Clear Sky) | Only available in daytime and clear-sky |
| Global Positioning System radio occultation （Healy, 2013） | L-band<br>L1:1.57542 GHz<br>L2: 1.227 GHz | 1~2 hPa | Horizontal resolution is several hundred kilometers |
| Airborne differential absorption radar (L. Millan 2014; Lin and Hu 2005) | 50-56 GHz $O_2$ bands | 4~7 hPa | Continuous, large-scale and wide swath observations are not available |
| Microwave Scatterometer (Patoux et al., 2008; Zhang et al., 2011) | 14.6 GHz (SASS)<br>13.4 GHz (QuikSCAT) | 1~3 hPa（clear-sky、cloudy and rainy conditions)<br>~ 20 hpa (hurricanes and typhoons) | • Performance during extremely high wind conditions (wind speed >28 m/s) are not satisfactory<br>• Data cannot be obtained in real-time |

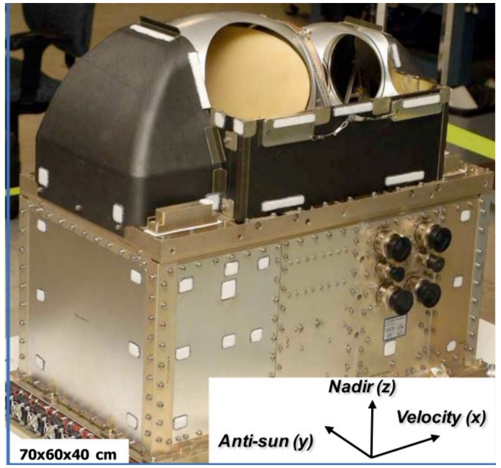



# Introduction

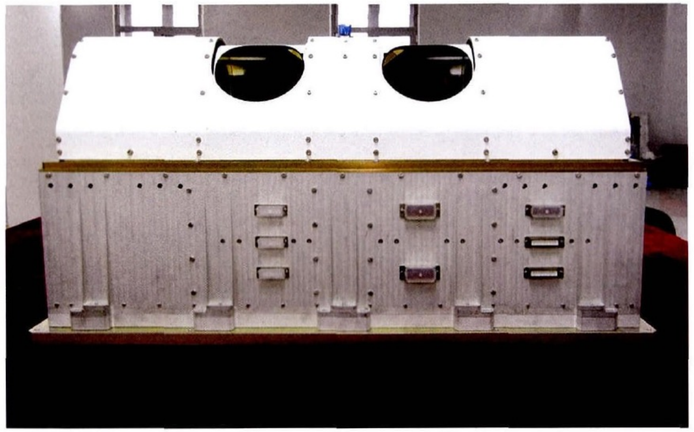
## Retrieving surface atmospheric pressure from spaceborne passive microwave observations

Surface pressure sounding is achieved by microwave radiometers due to their ability **to measure the total columnar oxygen absorption**.
In the oxygen absorption band (**50-70 GHz, 118 GHz**) , the total columnar atmospheric absorption is strongly related to column oxygen mass. Oxygen is uniformly mixed in the atmosphere; therefore, the column oxygen mass is directly proportional to the surface pressure.




SNPP/ATMS (50-60 GHz )



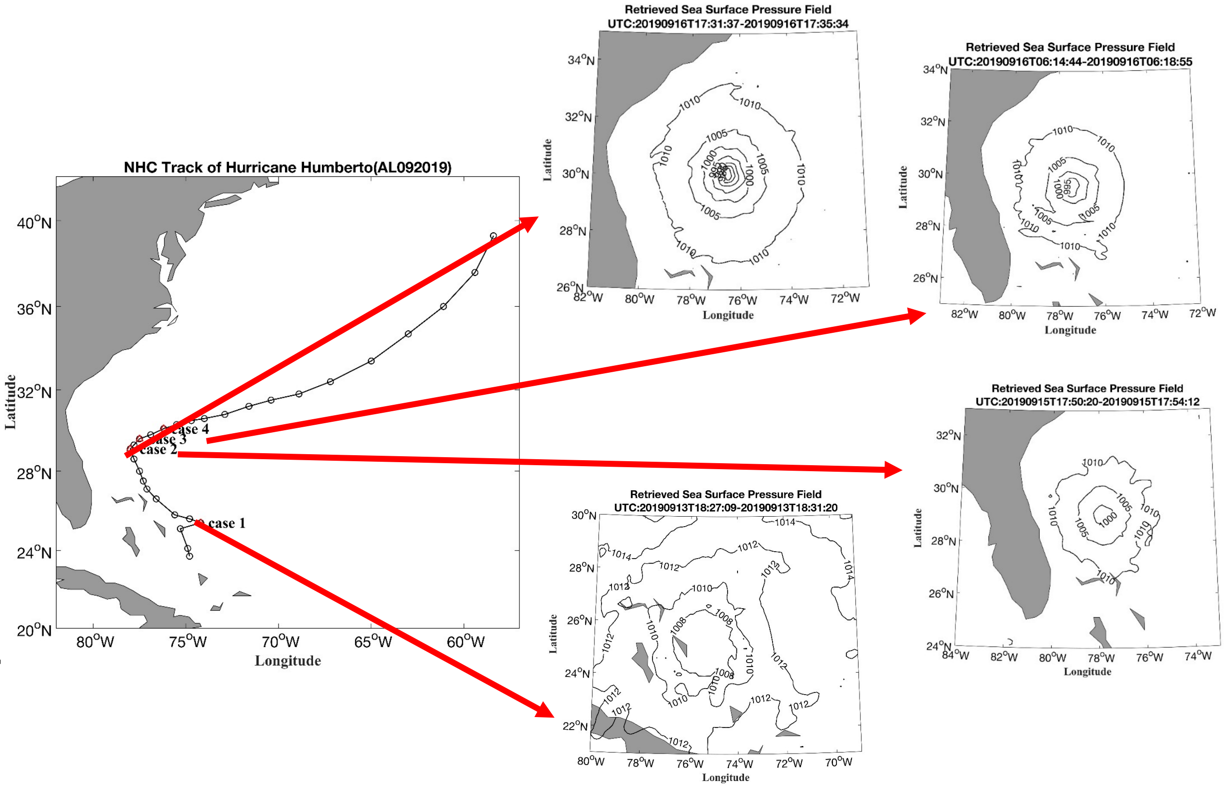
FY-3C/MWHTS(118 GHz)

# Introduction

## Advantages of the new technique

**Advantages:**

- All weather capability
- Day and night capability
- High spatiotemporal resolution (<3h, ~16km by multi-satellite joint observation)
- Wide swath observations  (several thousand km): fast, continuous and stable global observations capability




**Applications:**

- Prediction and forecasting for disasters and extrer weather;
- Numerical weather prediction (NWP);
- Global climate change studies;

# Introduction

## Task team

- National Space Science Center (NSSC); (Task lead & retrieval algorithm)
- Shanghai Typhoon Institute (TC data analysis);
- National Satellite Meteorological Center (NSMC/CMA); (MWHT/MWHT data)
- National Ocean Satellite Application Center (NSOAS); (SCAT wind data);
- Hong Kong Observatory (in situ data)

# Introduction

## Objective

- To develop and optimize the retrieval models and algorithms for sea surface pressure by passive microwave observations.
- To validate and assess the sea surface pressure data products using collocated in situ measurement data.
- To deliver the all-weather sea surface pressure data product from passive microwave observations.

**Towards all-weather quality ocean surface atmospheric pressure product**

# Introduction

## Progress summary

### Algorithm aspect:

- Develop the retrieval algorithms for sea surface pressure by passive microwave observations. **(Done)**
- Optimize the algorithm under high wind conditions using warm TB anomaly (TB minus environmental TB) observations of tropical cyclones. **(Done)**
- Analyze the surface pressure information content obtained by 60 GHz and 118 GHz radiometers, improve the algorithm using joint 60- and 118- GHz observations. **(Done)**

### Validation aspect:

- Validate the respective and joint retrieval results from 60 GHz and 118 GHz radiometers using collocated reanalysis and analysis data (ERA-interim, ERA5, and GDAS/FNL analysis). **(Done)**
- In situ validations using the collocated buoy, ship and dropsonde data. **(Done)**

# Deliverables

**Deliverable**

## Data

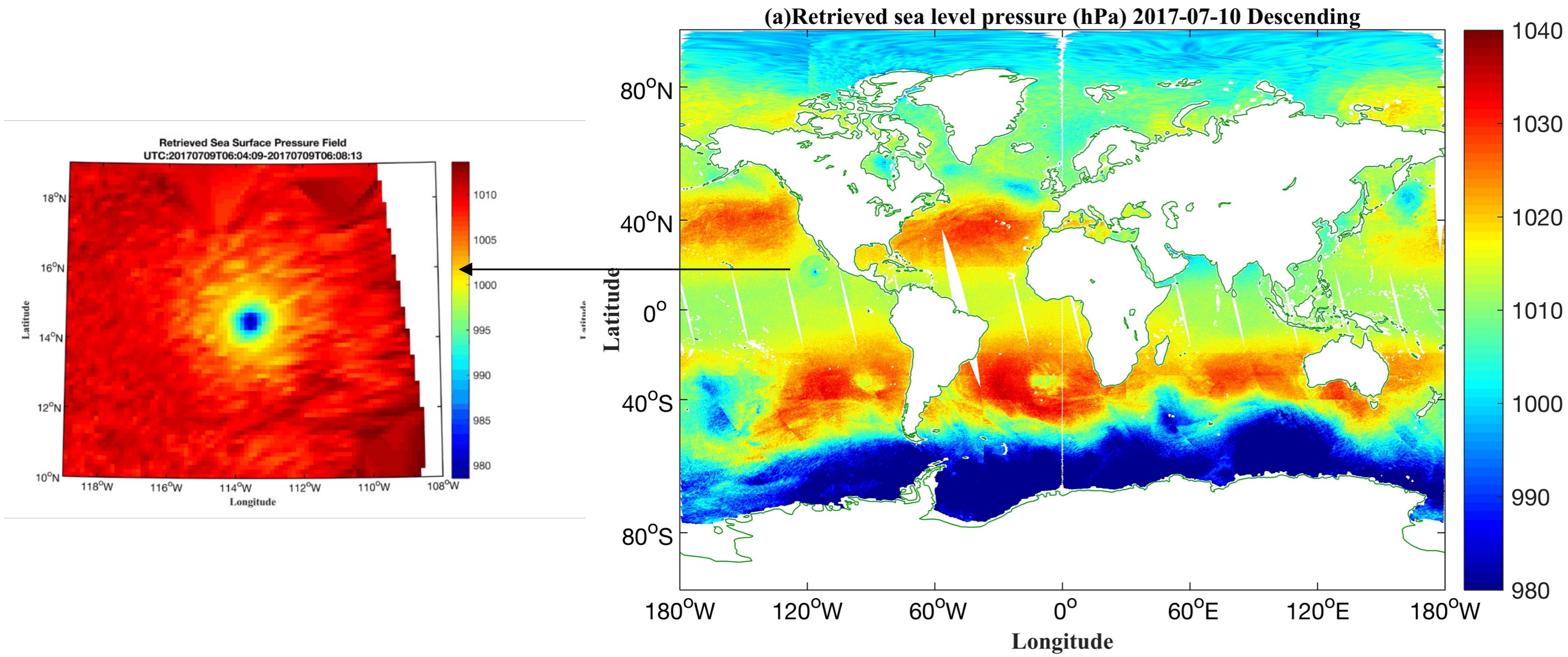
- A set of all-weather ocean surface pressure retrievals from passive microwave observations

## Technical report

- Introduction to the data and retrieval algorithm
- Validation report based on collocated reanalysis and in situ data
- Discussion and perspectives

# Deliverables-1: Data

## Data

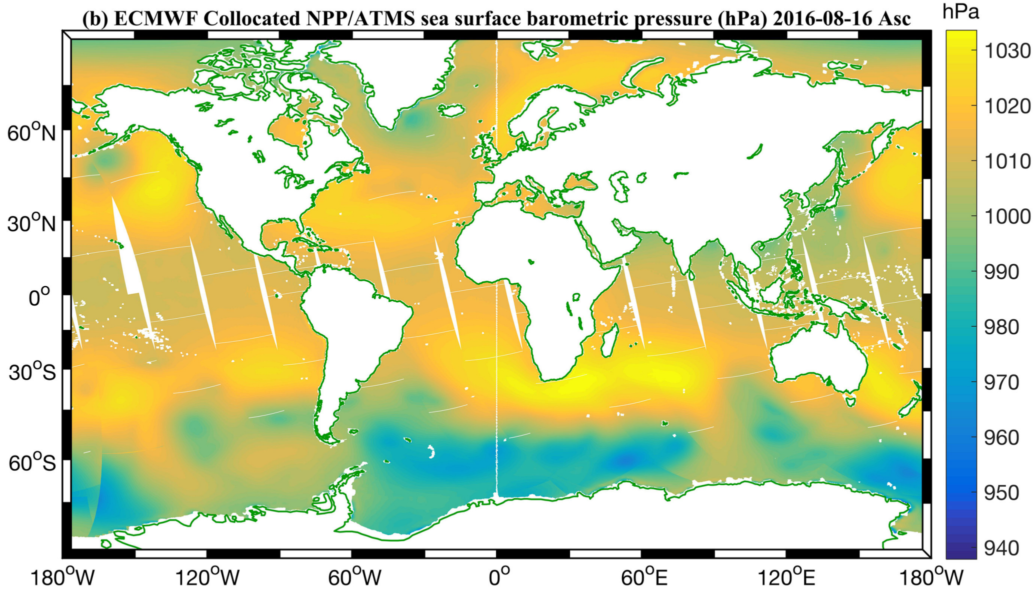



A set of all-weather (clear-sky, cloudy, rainy and high wind conditions) ocean surface pressure retrievals from joint observations of FY-3D/MWTS-II and FY-3D/MWHTS

- Spatial resolution (nadir): 32 km
- Parameters include: Lat, Lon, Time, Retrieved surface pressure value, uncertainty

# Deliverables-1: Data

## Reference data




### Reanalysis/analysis surface pressure data

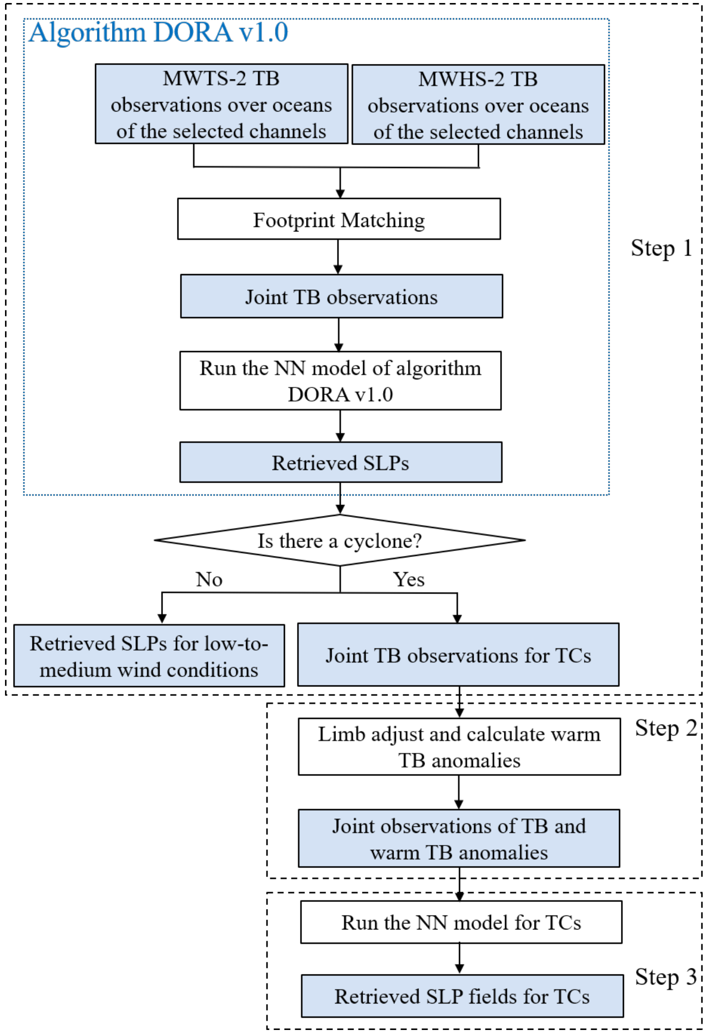
- GDAS/FNL analysis (https://rda.ucar.edu/ds083003), ERA-5 reanalysis(https://cds.climate.copernicus.eu/)
- Spatial resolution: 0.25º X 0.25º
- Temporal resolution: 6 hours


### In situ measurements

- Sea level pressure measurements from dropsonde (http://www.aoml.noaa.gov/hrd/), buoys and ships (http://www.nodc.noaa.gov/) were used
- Accuracy is better than 1 hPa.

# Deliverables-2: Algorithm

## Retrieval algorithm

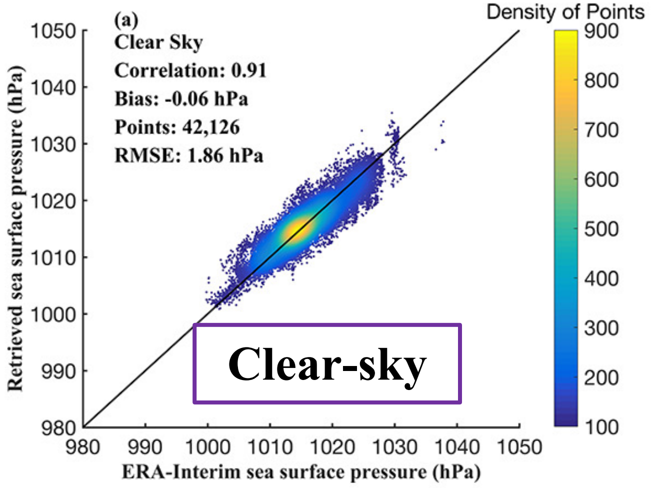


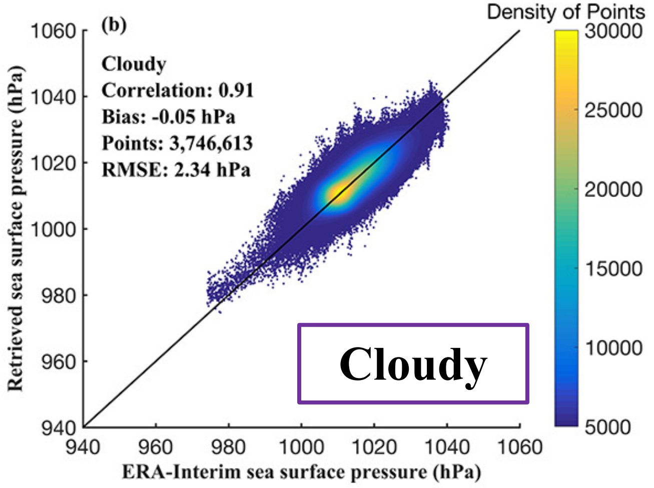

- Inputs are TB observations from MWTS-2 and MWHS-2.
- Outputs are all-weather ocean surface pressure retrievals
- The algorithm is based on backpropagation neural network (BPNN) algorithm
- Warm TB anomaly (TB minus environmental TB) observations are used to improve the performance under high wind conditions
- Joint 60- and 118- GHz observations are used to improve the performance under both low-to-medium wind conditions and high wind conditions

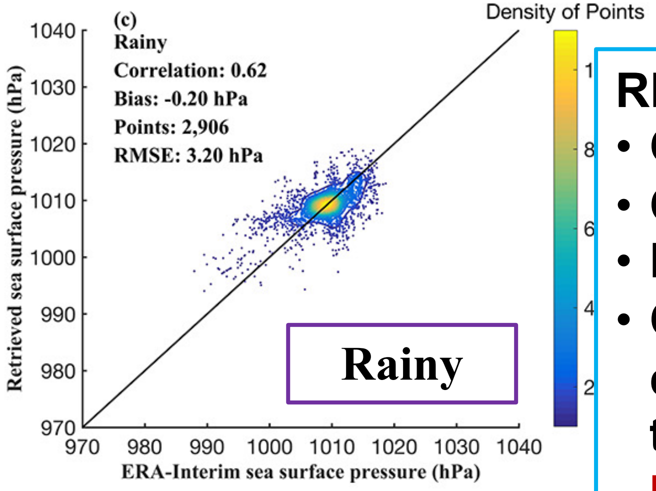
Z. Zhang *et al.*, "Retrieval of Tropical Cyclone Sea-Level Pressure Fields From the MWTS-2 and MWHS-2 Onboard the FengYun-3D Satellite," in *IEEE Transactions on Geoscience and Remote Sensing*, vol. 63, pp. 1-14, 2025, Art no. 5301814, doi: 10.1109/TGRS.2025.3574455.

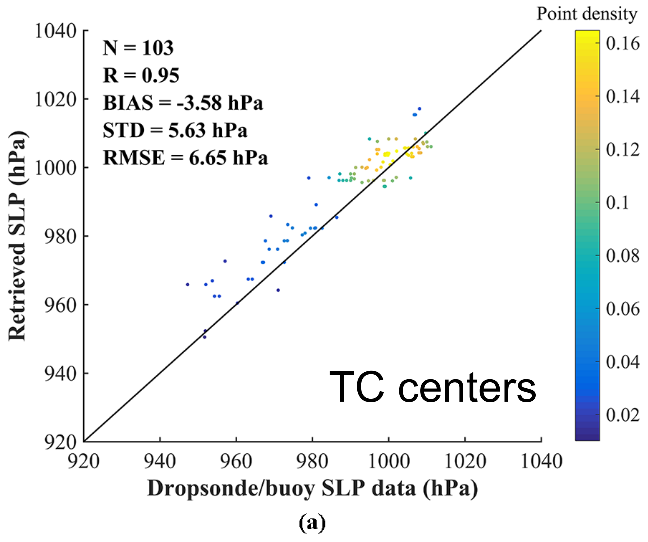
# Deliverables-2: Algorithm

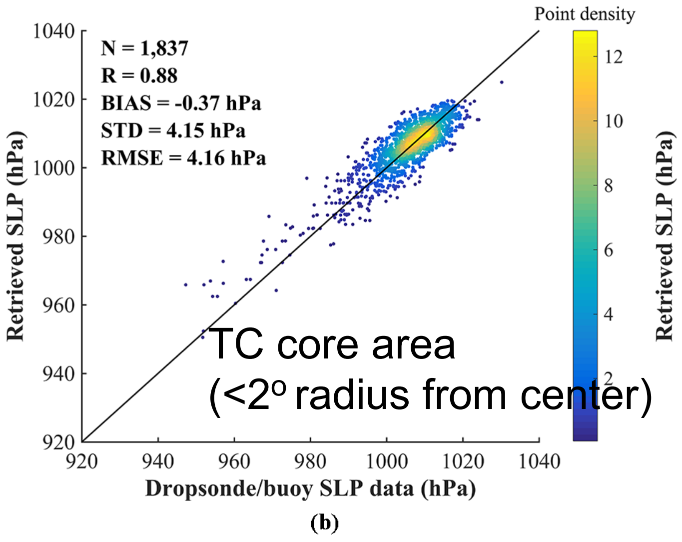
## Validation using collocated reanalysis and in situ data

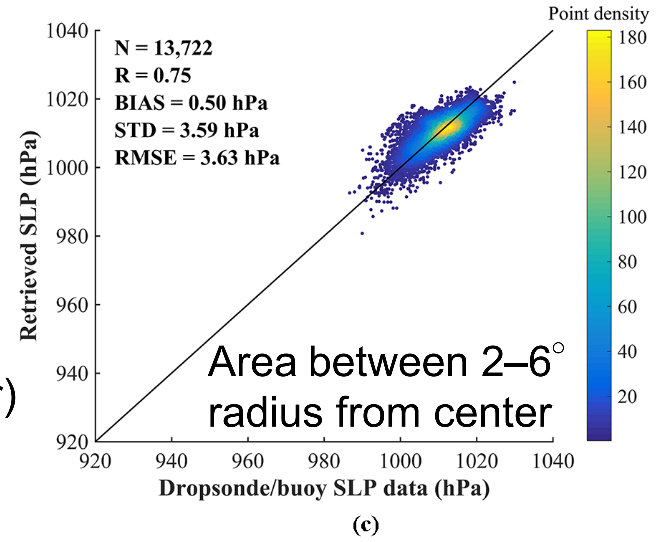


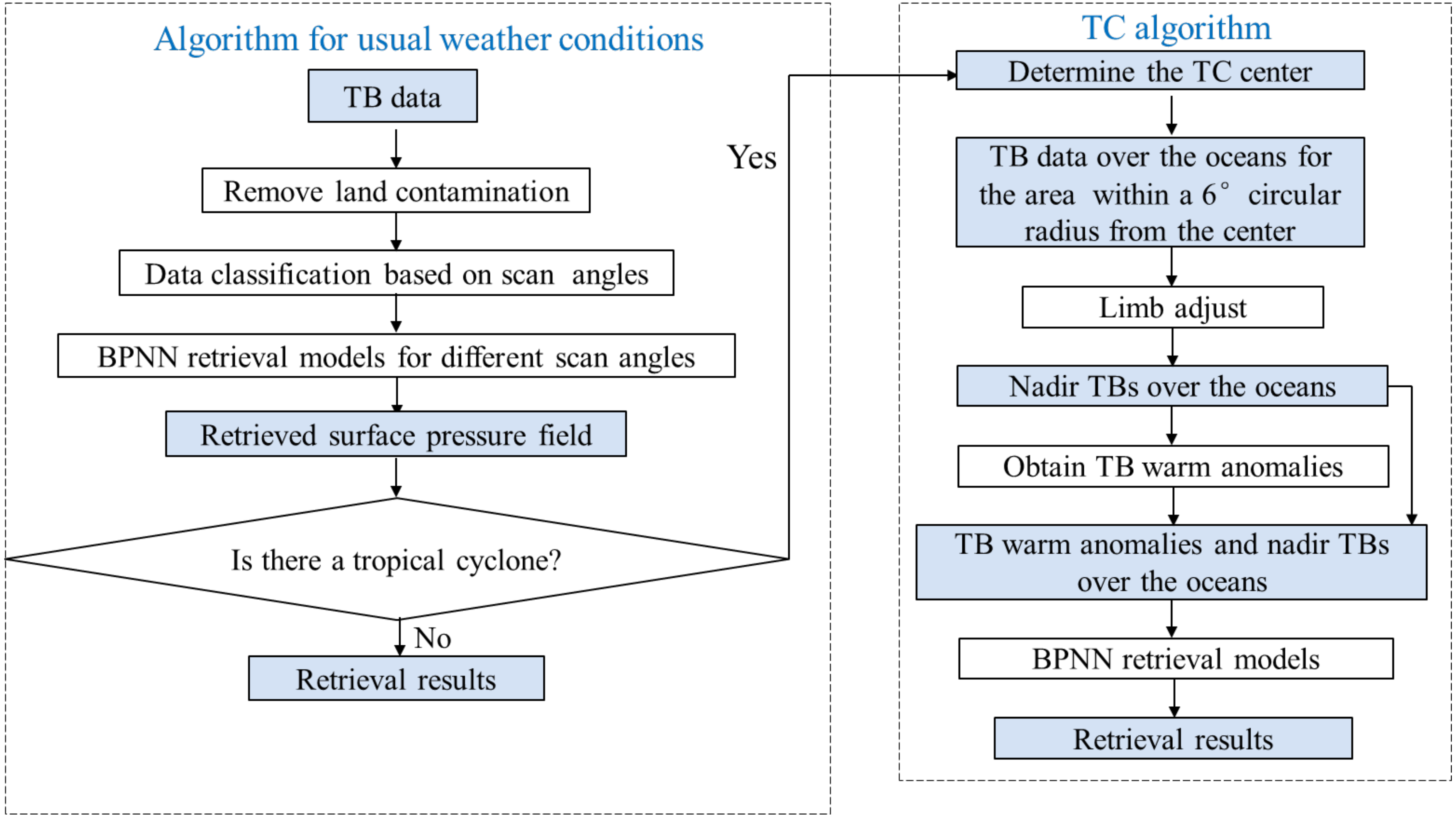

**RMSE**:

- **Clear-sky**: 1.86 hPa
- **Cloudy**: 2.34 hPa
- **Rainy**: 3.20 hPa
- **Core area of tropical depressions and tropical storms**: 2.78 hPa
- **Core area of typhoons or hurricanes**: 4.23 hPa
- **Core area of severe typhoons or major hurricanes**: 6.15 hPa

# Deliverables-2: Algorithm

## Development process of algorithm

### a) Development of Single $O_2$-band (60 GHz or 118 GHz) retrieval algorithm using machine learning

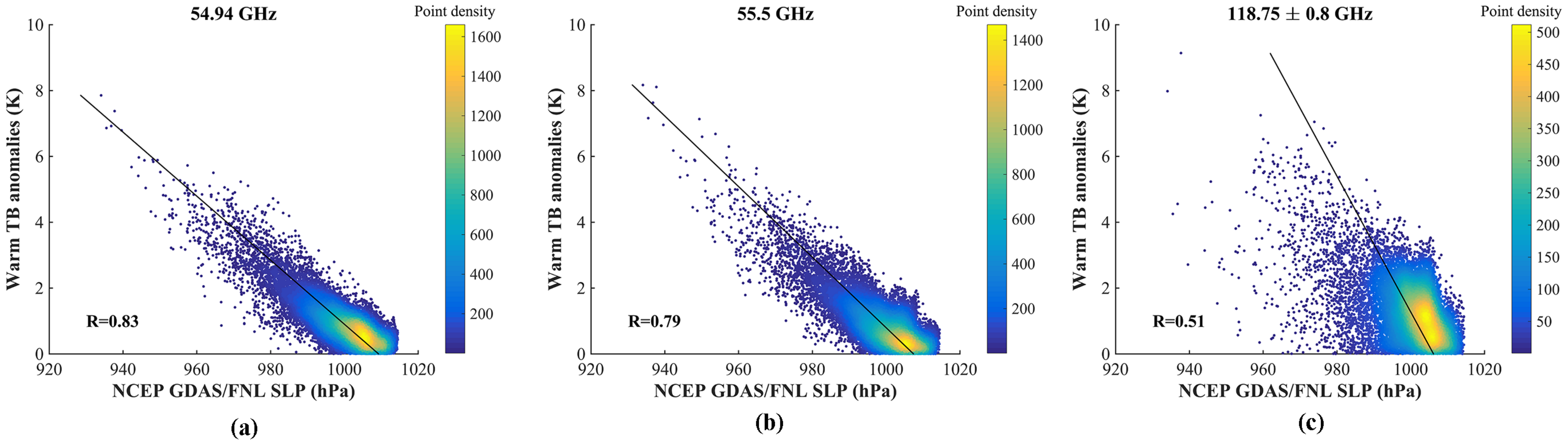



- A backpropagation neural network (BPNN) based retrieval algorithm was established and used to retrieve surface pressure from the TB data.
- **The priori information is not required** as input of the algorithm. Surface pressure data can be **rapidly and directly** retrieved from radiometric observations.

# Progress of task CV-23-06

## Development process of algorithm

**b) Optimize the algorithm under high wind conditions using warm TB anomaly observations**

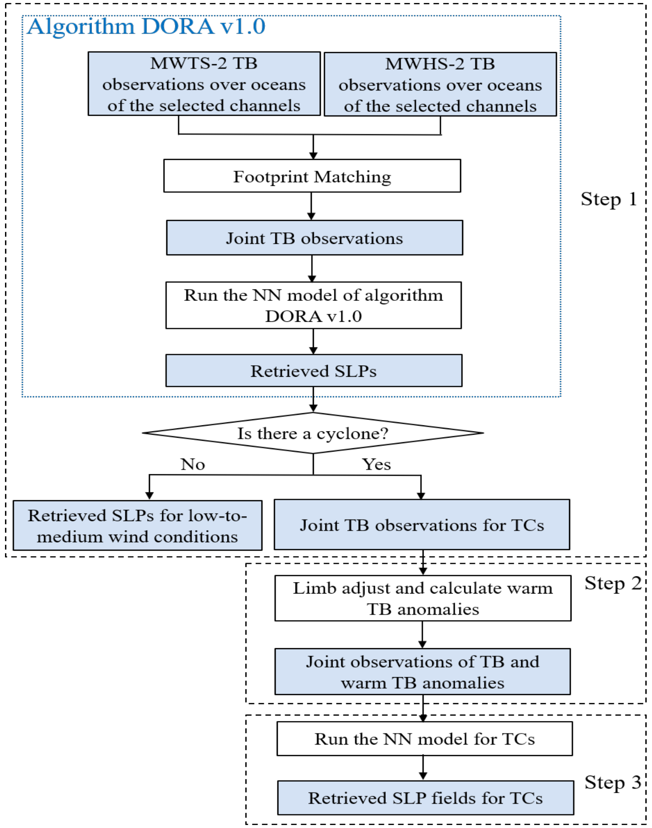



- Warm TB anomalies, defined as TBs minus environmental TBs (average TBs within a 6–8° radius from the TC centers), observed by upper-tropospheric sensitive channels are closely related with surface pressure drop around TC centers.
- Warm TB anomalies are incorporated to improve retrieval performance under high wind conditions.

# Deliverables-2: Algorithm

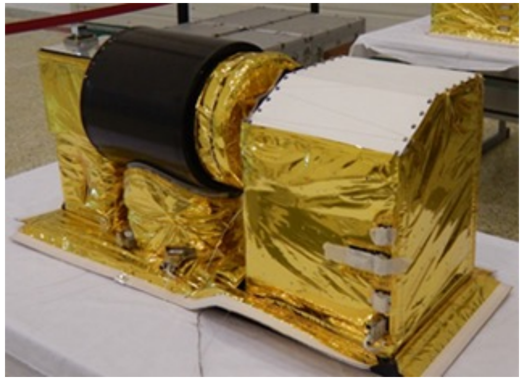
## Development process of algorithm

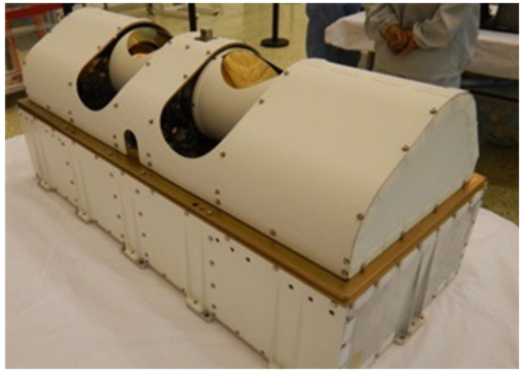
| Number | Central Frequency (GHz) | ICSC of MWTS-II and MWHTS | ICSC of MWTS-II | ICSC of MWHTS |
|---|---|---|---|---|
| 1 | 51.76 | 1.5116 | 1.5116 | — |
| 2 | 50.3 | 0.2484 | 0.2484 | — |
| 3 | 118.75±5.0 | 0.0735 | — | 0.6741 |
| 4 | 118.75±3.0 | 0.0441 | — | 0.2024 |
| 5 | 52.8 | 0.0361 | 0.0453 | — |
| 6 | 54.4 | 0.0298 | 0.0367 | — |
| 7 | 54.94 | 0.0154 | 0.0188 | — |
| 8 | 53.596 | 0.0088 | 0.0107 | — |
| 9 | 118.75±2.5 | 0.0058 | — | 0.0343 |
| 10 | 118.75±1.1 | 0.0043 | — | 0.0251 |
| 11 | 55.5 | 0.0029 | 0.0036 | — |
| 12 | 118.75±0.8 | 0.0026 | — | 0.0153 |
| 13 | 57.29±0.322±0.022 | 0.0006 | 0.0007 | — |
| 14 | 57.29±0.322±0.01 | 0.0004 | 0.0005 | — |
| 15 | 57.29±0.322±0.048 | 0.0003 | 0.0004 | — |
| 16 | 57.29±0.3222±0.005 | 0.0001 | 0.0001 | — |
| 17 | 57.29±0.217 | 0.0001 | 0.0001 | — |
| 18 | 118.75±0.3 | 0.0000 | — | 0.0003 |
| 19 | 118.75±0.08 | 0.0000 | — | 0.0001 |
| 20 | 57.29 | 0.0000 | 0.0000 | — |
| 21 | 118.75±0.2 | 0.0000 | — | 0.0000 |
| Cumulative information content | | 1.9848 | 1.8769 | 0.9517 |




The optimized retrieval algorithm used for the products development (Zhang et al., 2025)

## c) Optimize the algorithm using joint 60- and 118- GHz observations





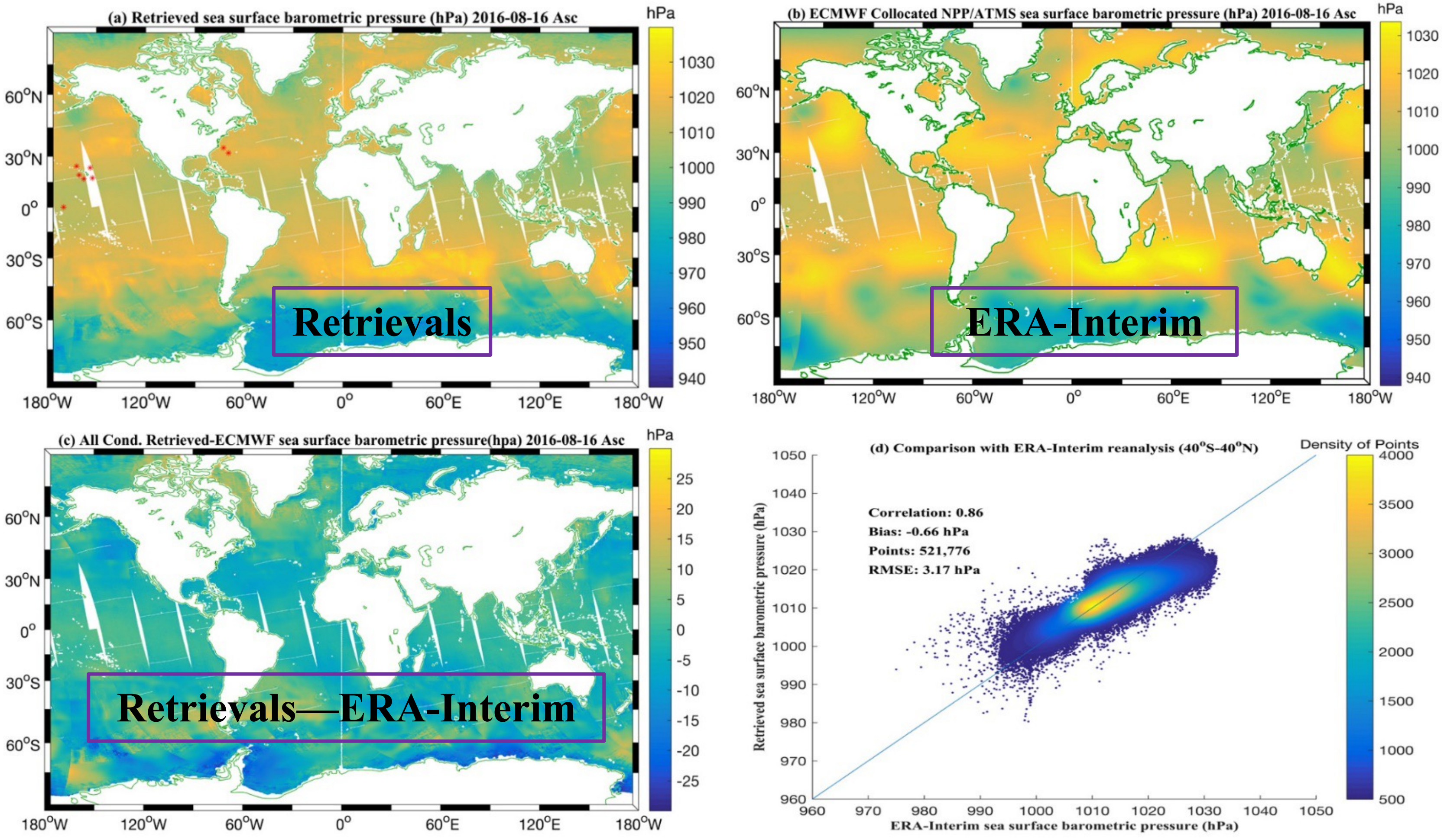
MWTS-II (50-60 GHz ) + MWHTS(118 GHz)

- Joint observations of 60 and 118 GHz provide more comprehensive surface pressure information than that observations from either band alone.
- Dual $O_2$-band (60 GHz and 118 GHz) retrieval algorithm is developed to mprove the retrieval performance.

# Deliverables-2: Algorithm

## Validation aspect

### a) Validation using reanalysis/analysis data

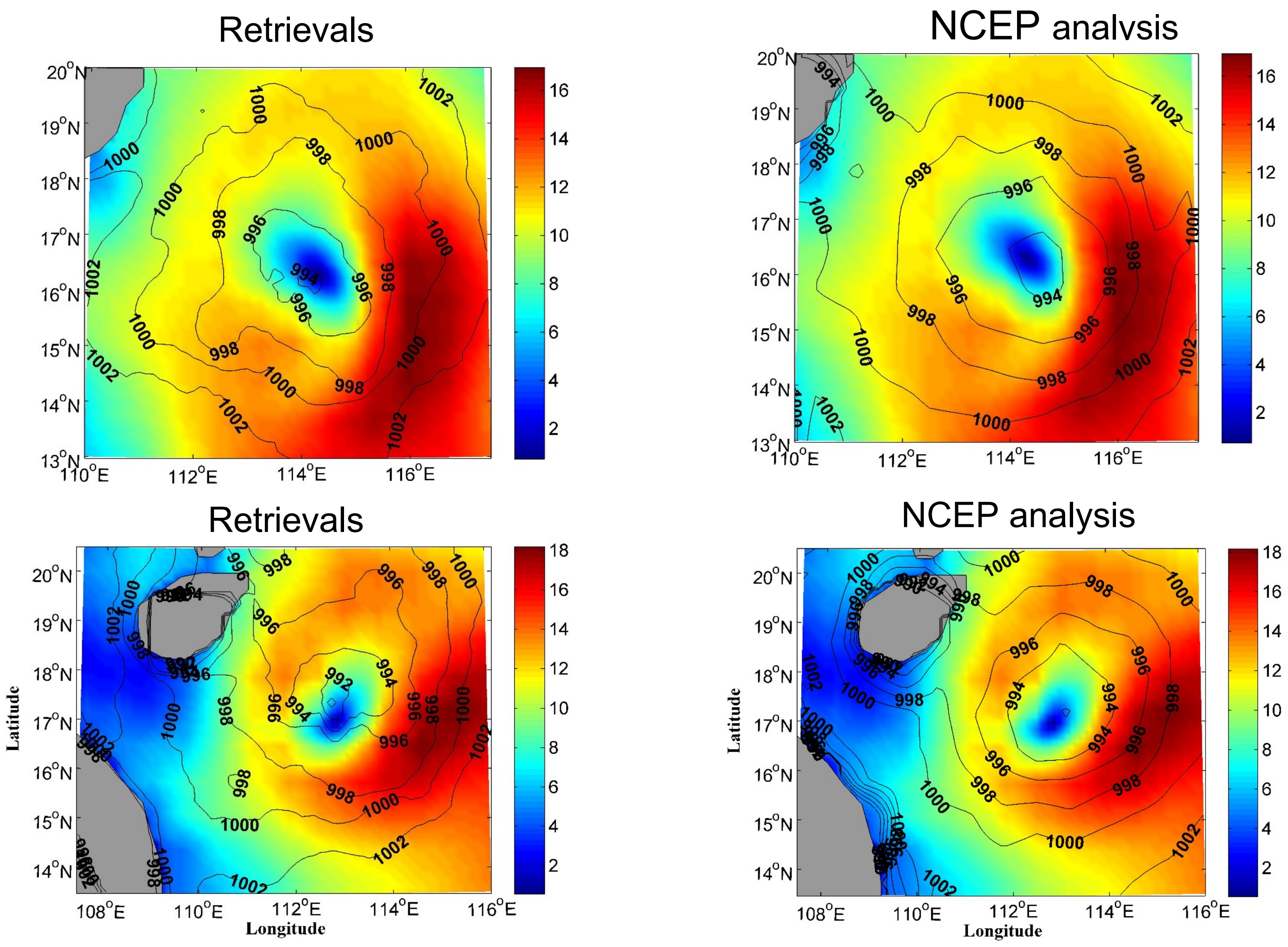



**Validate the retrievals from SNPP/ATMS using ERA-Interim reanalysis**

Retrievals from SNPP/ATMS correlate well with the ERA-Interim surface pressure reanalysis data.

Retrieval results using the SNPP/ATMS ascending data in August 16, 2016 (Zhang et al., 2018).

# Deliverables-2: Algorithm

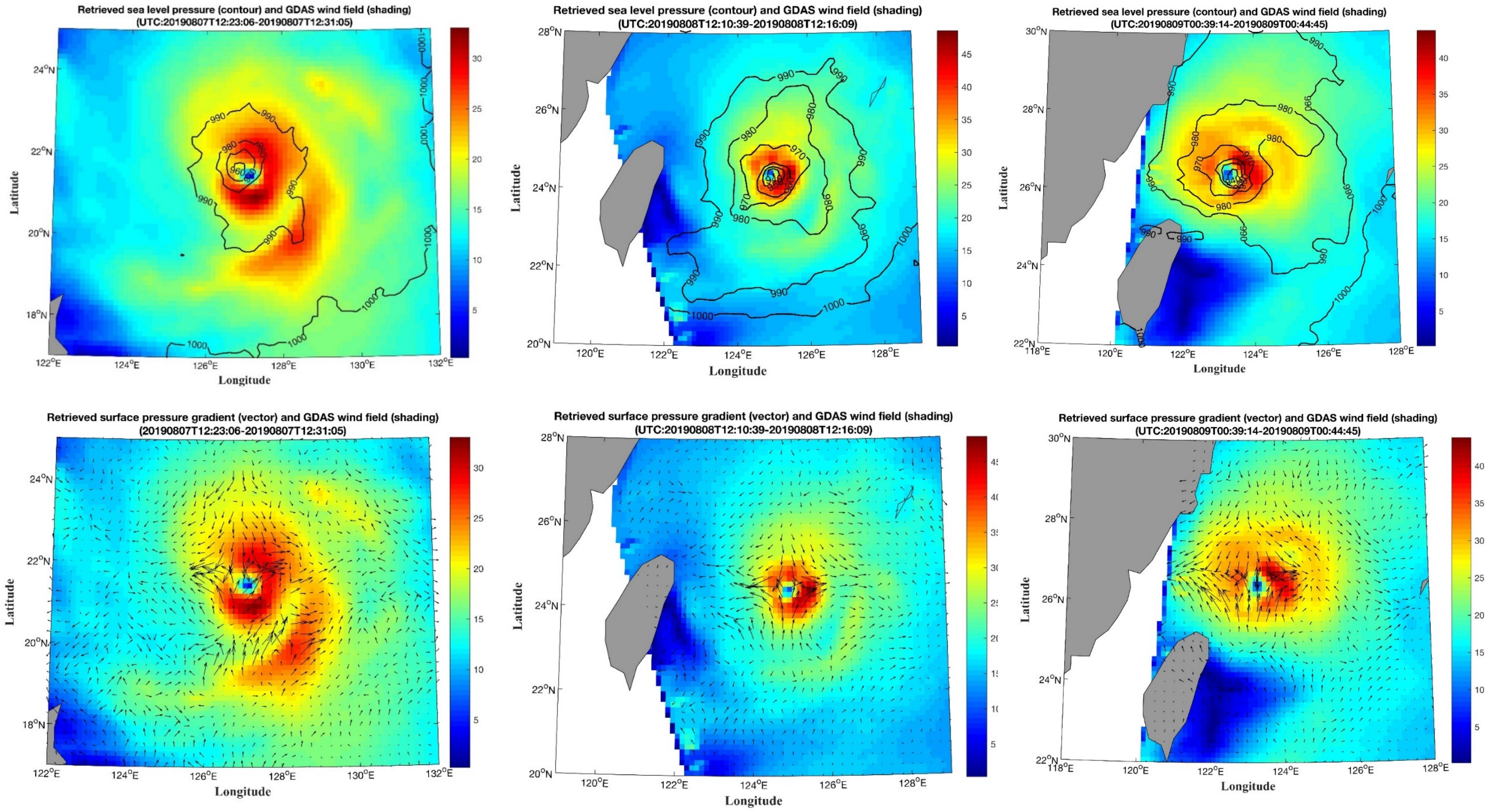



**Validate the retrievals from SNPP/ATMS using NCEP GDAS/FNL analysis**

- Retrievals correlate well with the NCEP GDAS/FNL surface pressure analysis data.
- The TC structure described by the retrievals agree well with that described by the NCEP GDAS/FNL 10m wind speeds.

Retrieved surface pressure shown using contour, and NCEP GDAS/FNL 10m wind speeds shown using shade for tropical storm Jebi at 0604 UTC (top) and 1835 UTC (bottom)1 August 2013.

# Deliverables-2: Algorithm



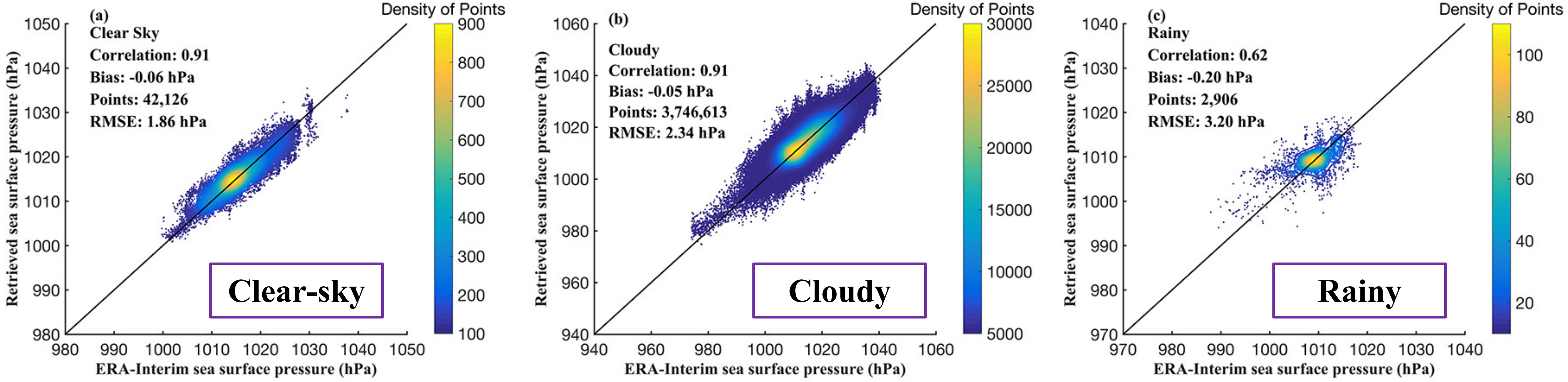

Retrieved surface pressure (top) shown using contour, surface pressure gradients (bottom) shown using vector and NCEP GDAS/FNL 10m wind speeds shown using shade for typhoon lekima (1909).

**Validate the retrievals from FY-3C/MWHTS using NCEP GDAS/FNL analysis**

- The TC structural features described by the retrievals agree well with that described by the NCEP 10m winds.
- The derived surface pressure gradients agree well with NCEP 10m winds.

# Deliverables-2: Algorithm

## Validate the retrievals from joint observations of FY-3D/MWTS-II and FY-3D/MWHTS using ERA-5 reanalysis

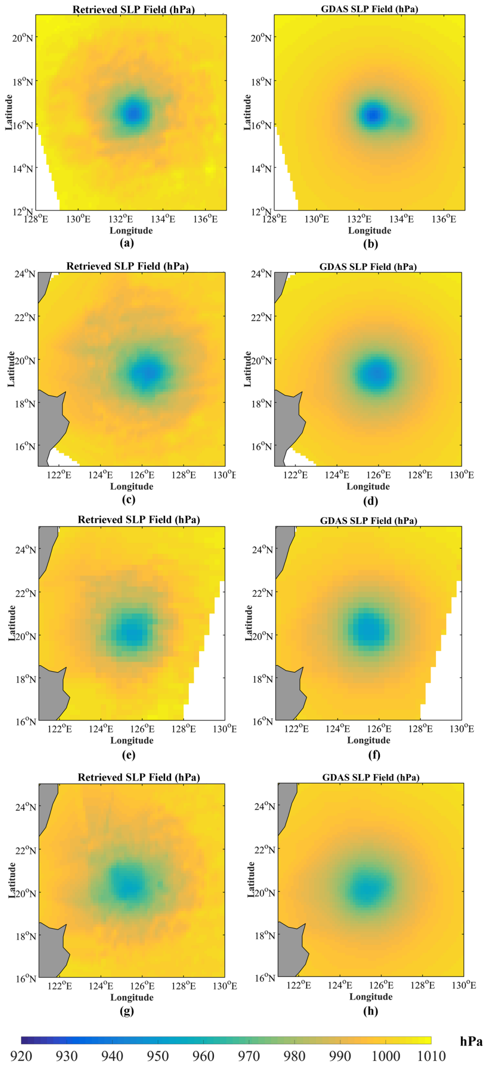



| Data source | RMSE (hPa) | | |
|---|---|---|---|
| | Clear sky | Cloudy | Rainy |
| MWTS-II | 1.95 | 2.77 | 3.47 |
| MWHTS | 1.98 | 2.91 | 3.53 |
| MWTS-II+MWHTS | 1.86 | 2.34 | 3.20 |

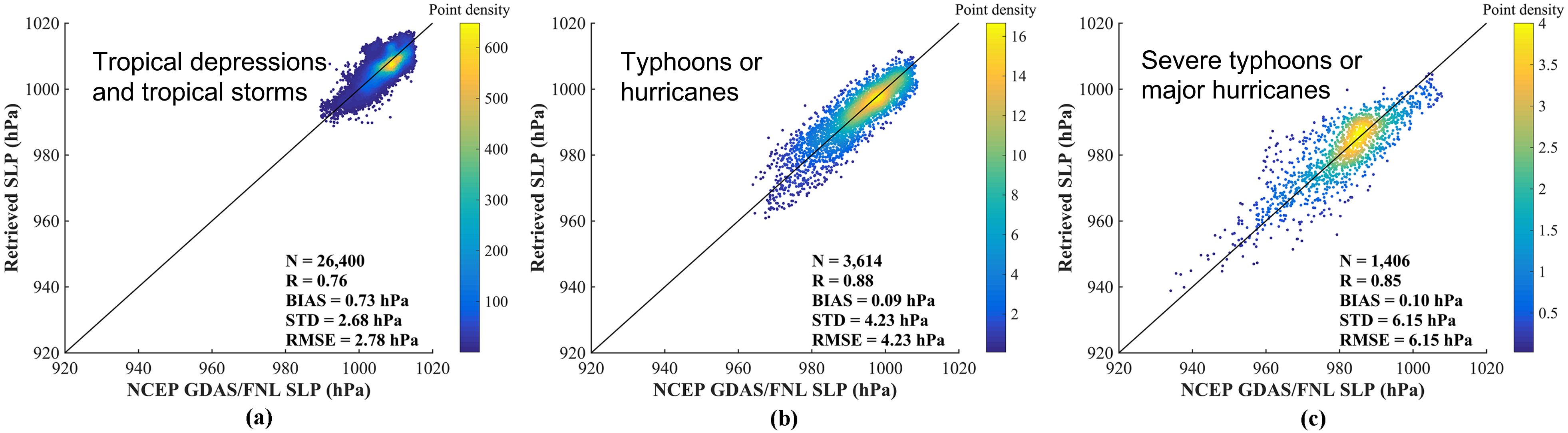
- The joint approach outperformed both the 60 and 118 GHz models under low-to-medium wind speed conditions.

# Deliverables-2: Algorithm

**Retrievals** | **GDAS/FNL**




## Validate the retrievals from joint observations of MWTS-II and MWHTS using NCEP GDAS/FNL analysis



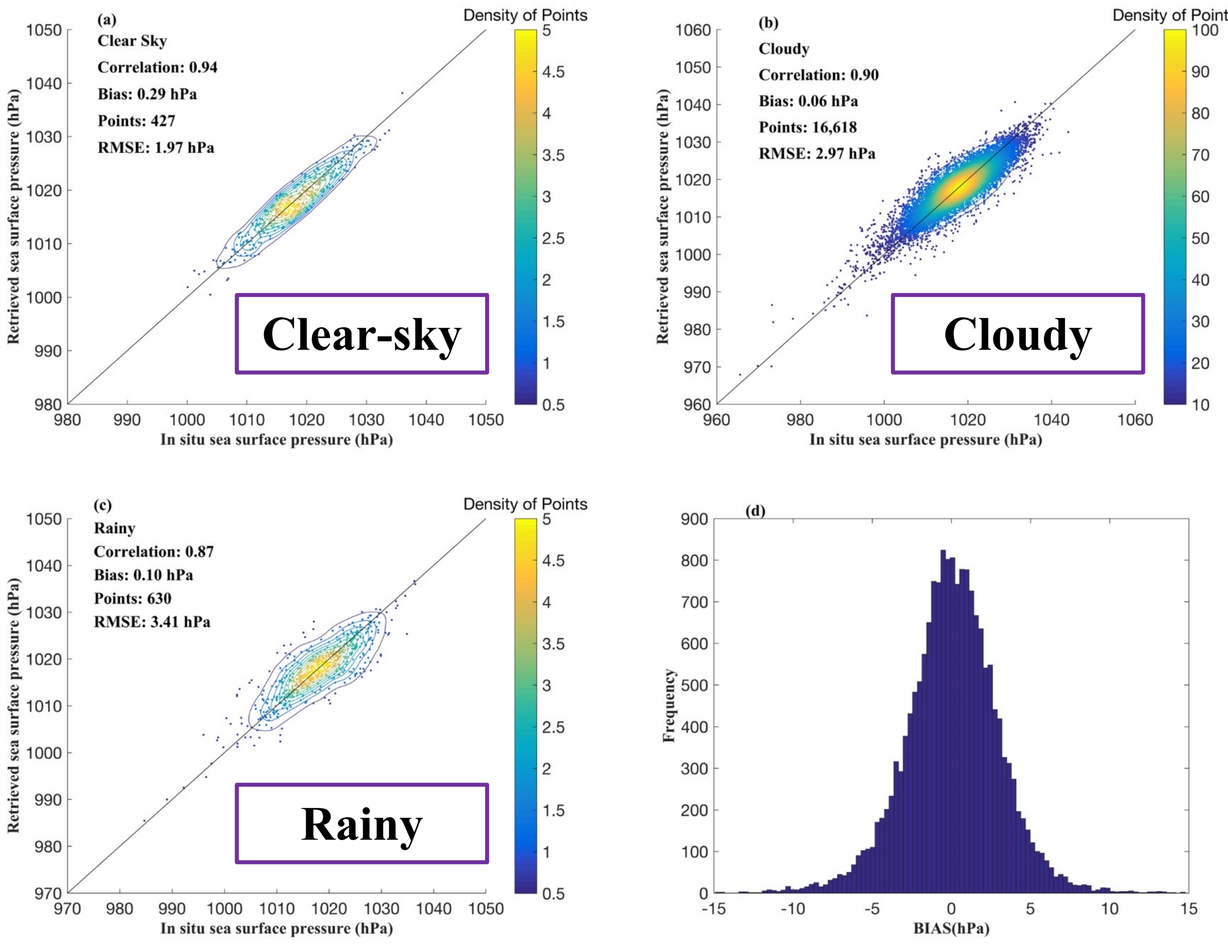

| Data source | RMSE (hPa) | | |
|---|---|---|---|
| | Tropical depressions and tropical storms | Typhoons or hurricanes | Severe typhoons or major hurricanes |
| MWTS-II | 3.03 | 4.58 | 6.66 |
| MWHTS | 3.63 | 5.33 | 8.19 |
| MWTS-II+MWHTS | 2.78 | 4.23 | 6.15 |

- The joint approach outperformed both the 60 and 118 GHz models under TC conditions.

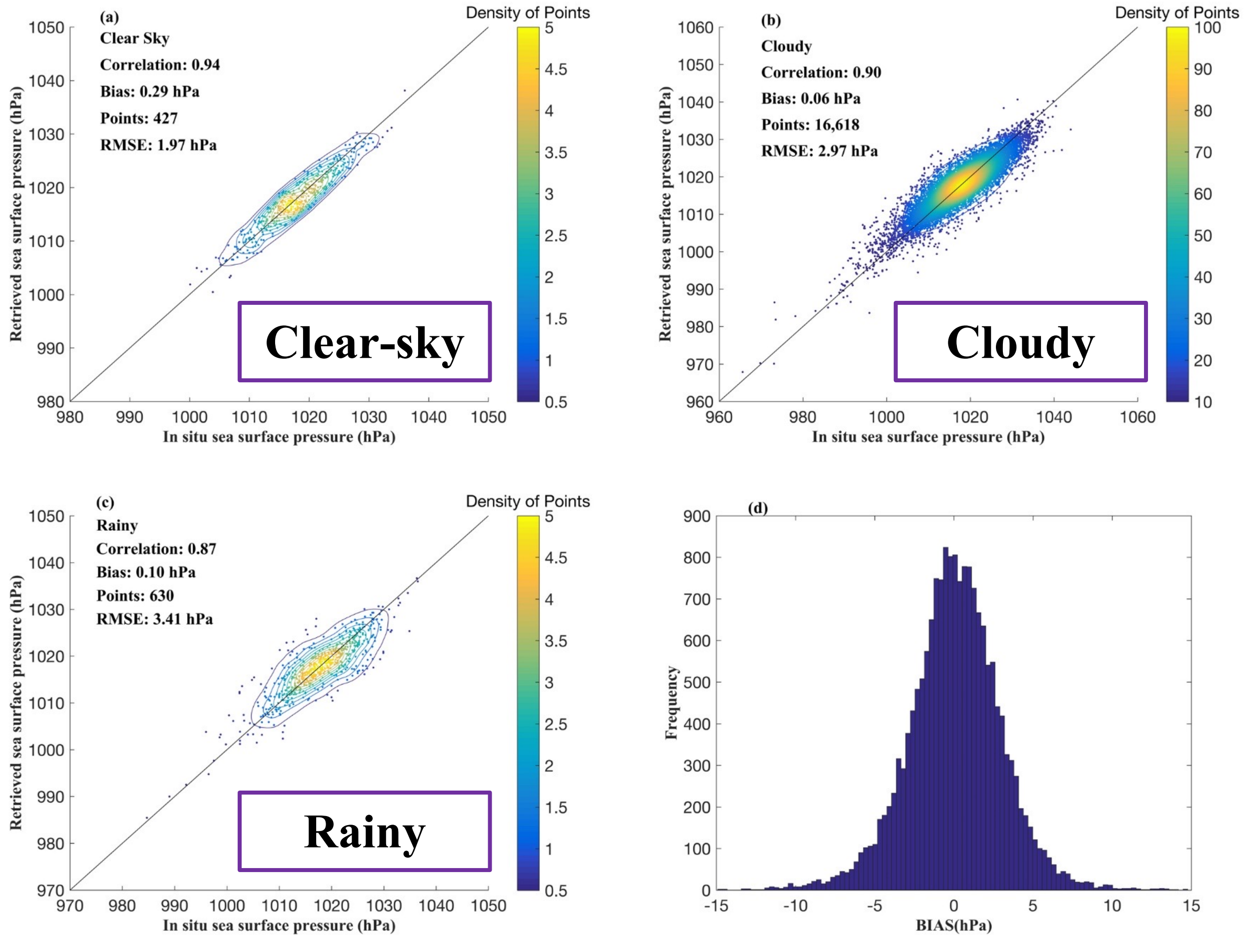
# Deliverables-2: Algorithm

## b) Validation using in situ data

**Validate the retrievals from SNPP/ATMS**

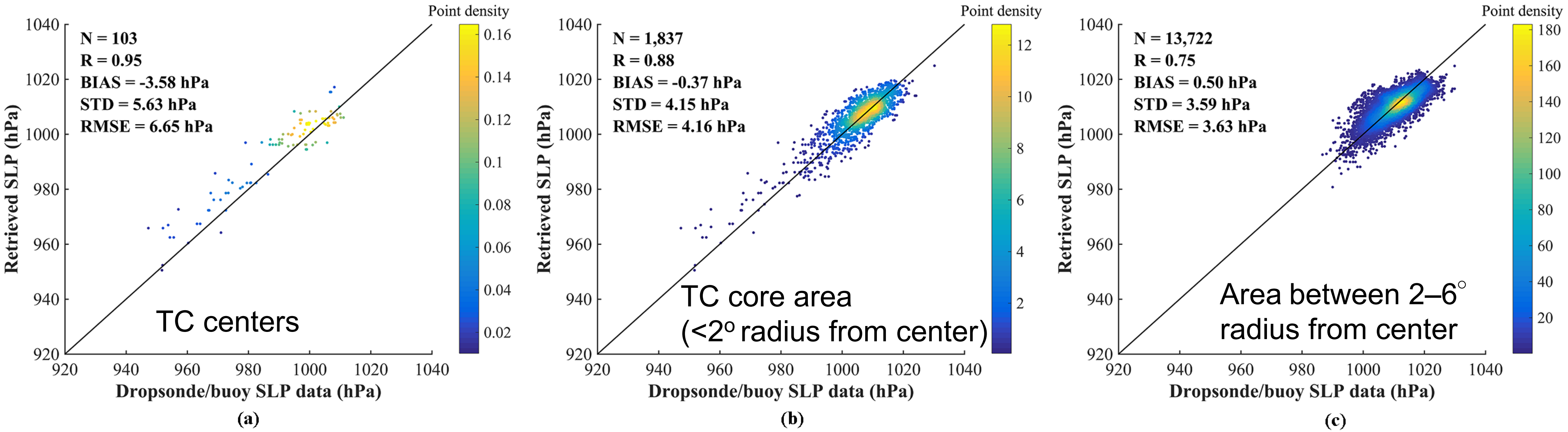



**Validate the retrievals from FY-3C/MWHTS**



# Deliverables-2: Algorithm

**Validate the retrievals from joint observations of FY-3D/MWTS-II and FY-3D/MWHTS using in situ data**




- Validations using reanalysis data and in situ data demonstrate that the retrieval accuracy of the optimized retrieval algorithm is 1.86 hPa for clear-sky, 2.34 hPa for cloudy, and 3.20 hPa for rainy, 2.78 hPa for the core area of tropical depressions and tropical storms, 4.23 hPa for the core area of typhoons or hurricanes, and 6.15 hPa for the core area of severe typhoons or major hurricanes.

# Summary:

- Sea surface atmospheric pressure data can be retrieved from observations of spaceborne microwave radiometers operating in the $O_2$-band, which relies on the radiometers' capability to measure total columnar $O_2$ absorption.
- A backpropagation neural network (BPNN)-based retrieval algorithm is developed and optimized to retrieve sea surface pressure from passive microwave observations.
- Validations using reanalysis data and in situ data demonstrate that the retrieval accuracy of the optimized retrieval algorithm is 1.86 hPa for clear-sky, 2.34 hPa for cloudy, and 3.20 hPa for rainy, 2.78 hPa for the core area of tropical depressions and tropical storms, 4.23 hPa for the core area of typhoons or hurricanes, and 6.15 hPa for the core area of severe typhoons or major hurricanes.
- Relevant methodology and data have been developed, and are already deliverable.

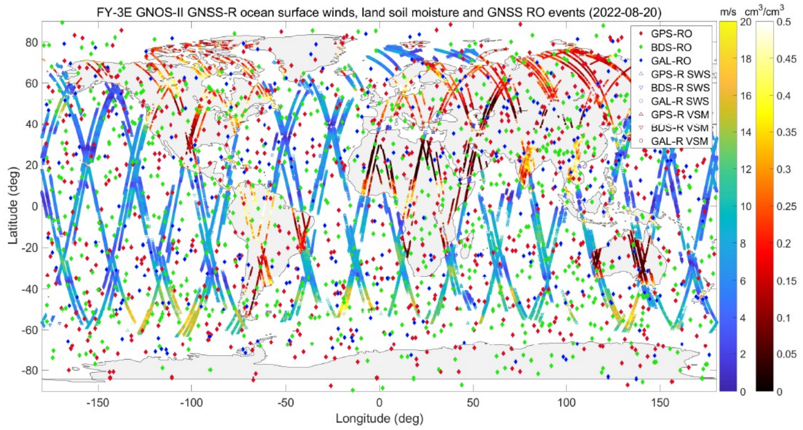
# 2. Proposal for new tasks

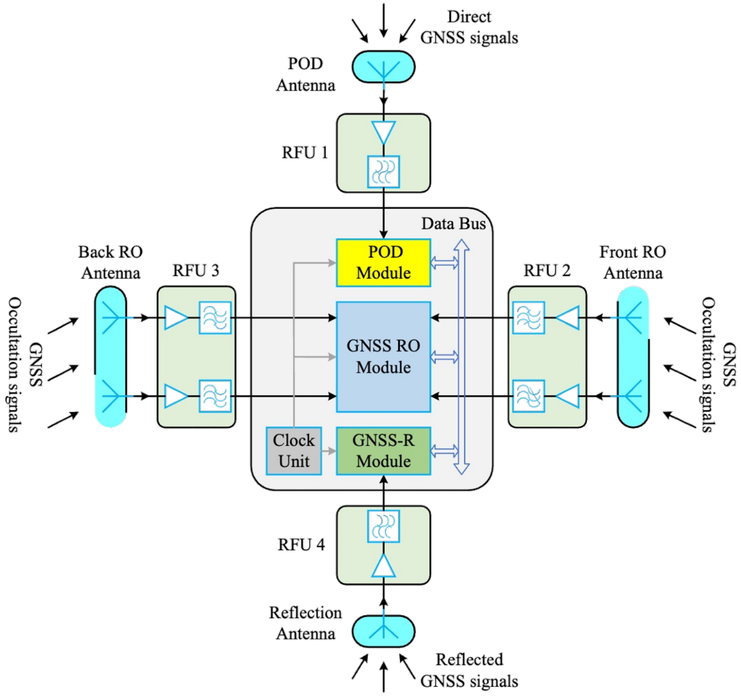
GNSS RO and GNSS-R Data
Calibration/Validation (Cal/Val)

# Introduction

- GNSS-RO and GNSS-R provide important data for atmospheric and ocean/land surface;
- GNSS-RO constellations and GNSS-R constellations ,as well as constellations, such as Chinese FengYun-3 missions (FY-3E/F/G),  with GNSS RO and GNSS-R together, have been operational for several years, which provide observations of atmospheric profiles, ionospheric profiles, ocean surface winds, land soil moisture and sea ice parameters

| | FY-3E | FY-3F | FY-3G |
|---|---|---|---|
| Launch date | 2021-07-05 | 2023-08-03 | 2023-04-16 |
| Altitude (km) | 836 | 836 | 407 |
| Inclination angle (°) | 98.5 | 98.5 | 50 |
| Descending Time | 5:40 | 10:00 | Drifting |



# Introduction: GNSS-RO and GNSS-R

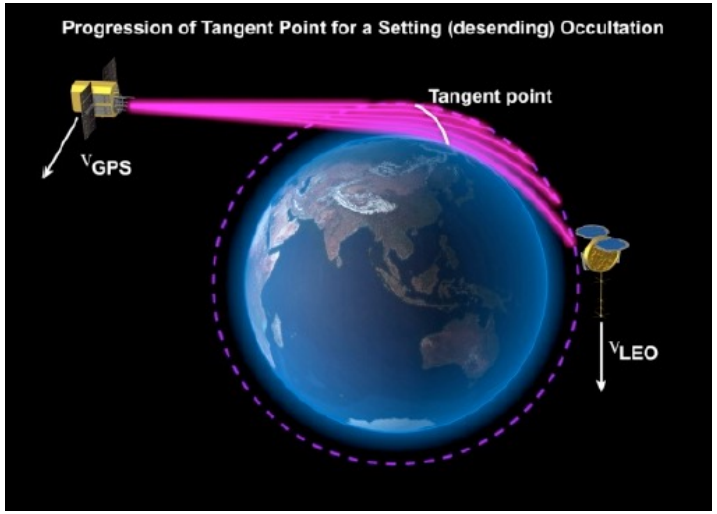
- Retrieval and validation of Global Navigation Satellite System (GNSS) radio occultation (RO) atmospheric products
- Calibration, retrieval and validation of Global Navigation Satellite System (GNSS) reflectrometry (GNSS-R) products

## Introduction of GNSS (L-band) radio occultation (RO)

**Measurements & atmospheric products:**
- Time (Carrier-wave phase)
- Excess phase
- Bending angle
- Refractivity
- Temperature
- Humidity
- Pressure

**Features:**
- Measurements traceable to SI time standard
- High vertical resolution
- High accuracy
- All-weather capability
- Global coverage
- Long-term stablility

**Applications:**
- Climate monitoring
- Numerical weather prediction (NWP)
- Meteorological disaster monitoring



# Introduction: GNSS RO

## Cal/Val tasks of GNSS-RO under CGMS/IROWG

**Coordination Group for Meteorological Satellites (CGMS):**

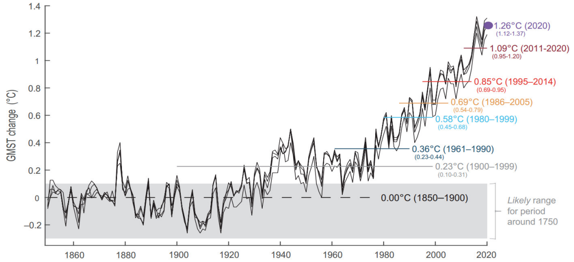
- Protection of in-orbit assets
- Contingency planning
- Data quality improvement
- Shared data access facilitation
- Satellite product application development

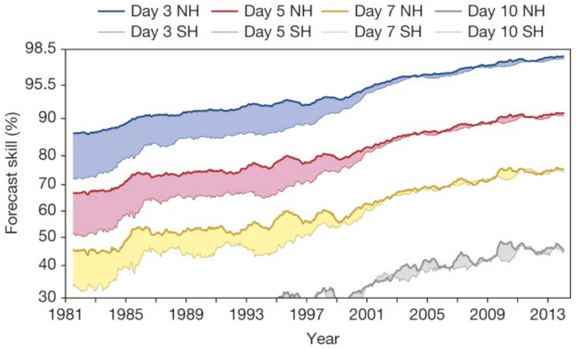
**International Radio Occultation Working Group (IROWG):**

- Established as a permanent CGMS working group at its 37th meeting (2009, South Korea)
- Co-sponsored by CGMS and WMO
- Serves as a forum for operational & research users of radio occultation data

**Cal/Val tasks:**

- rOPS for Climate monitoring application
- ROMEX for Numerical weather prediction (NWP) application




IR WG
INTERNATIONAL RADIO OCCULTATION WORKING GROUP

CGMS COORDINATION GROUP FOR METEOROLOGICAL SATELLITES
CGMS

# Introduction: GNSS RO

## Reference occultation processing system (rOPS)

**RO processing with fully traceable uncertainties:**
**rOPS approach** allows highly reversible analysis up and down the chain of all RO variables, enables SI-traceable profiling & uncertainty estimation.

**…rOPS international advisers and cooperation partners**

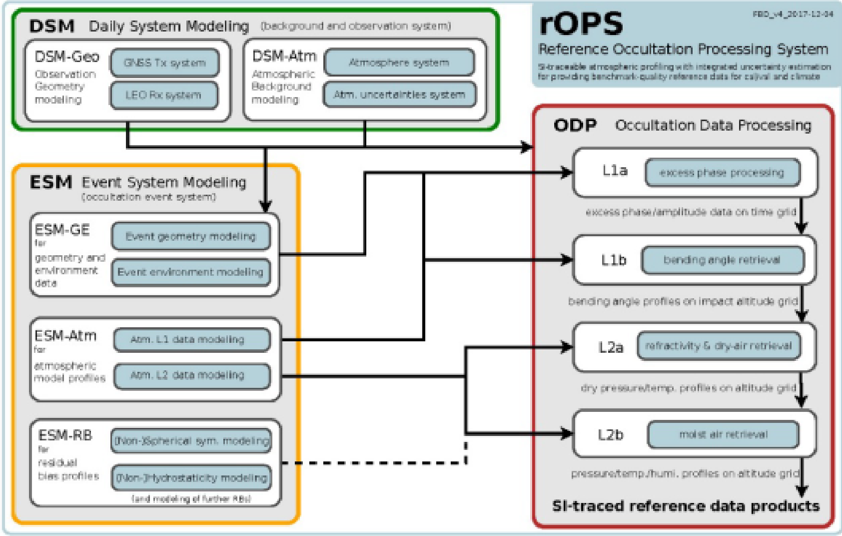
- EUMETSAT: Christian Marquardt, Yago Andres, Axel von Engeln, Riccardo Notarpietro
- EUM/ROM SAF (DMI, ECMWF): Stig Syndergaard, Joe Nielsen, Kent Lauritsen, Sean Healy
- UCAR, JPL: Bill Schreiner, Doug Hunt, Tony Mannucci, Chi Ao
- IAP, TUG: Michael Gorbunov, Torsten Mayer-Gürr
- AIUB, DLR: Adrian Jäggi, Oliver Montenbruck
- NSSC/CAS, IGG/CAS, RMIT: Congliang Liu, Ying Li, Kefei Zhang

*…and more may join as the work proceeds…thanks all!*

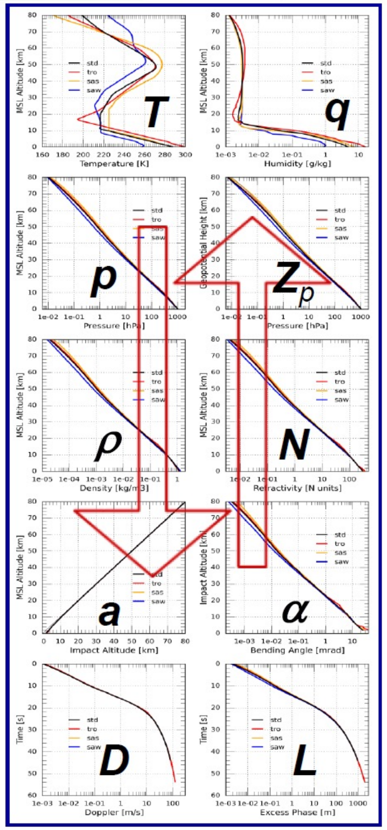
**Two main lines of cooperation:**

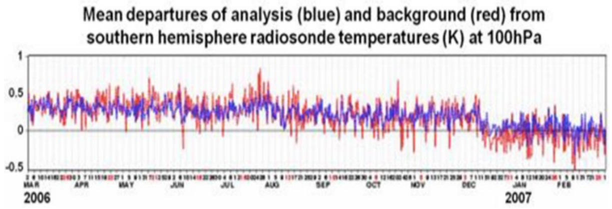
- joint papers (on specific rOPS-related key issues to be solved)
- advice & expert meetings (~1-day review/advice meetings at WEGC)

The rOPS team led by Prof. Gottfried Kirchengast from WEGC, including: EUMETSAT, DMI, ECMWF, UCAR, JPL, IAP, TUG, DLR, NSSC, RMIT, et al.

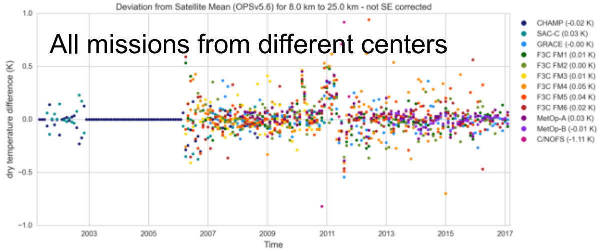


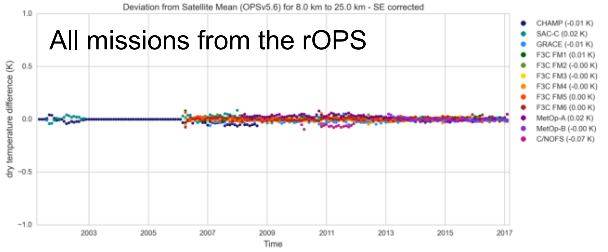

Logic of the rOPSsystem modeling and data analysis approach




Consistency after using COSMIC RO data (results from ECMWF)




**Cal/Val Conclusions for IPCC:** RO data quality validated by rOPS team and accepted by AR6 co-author, then published as benchmark dataset in IPCC AR6.

# Radio Occultation Modeling EXperiment (ROMEX)

**ROMEX IROWG-Led RO Cal/Val Task:**

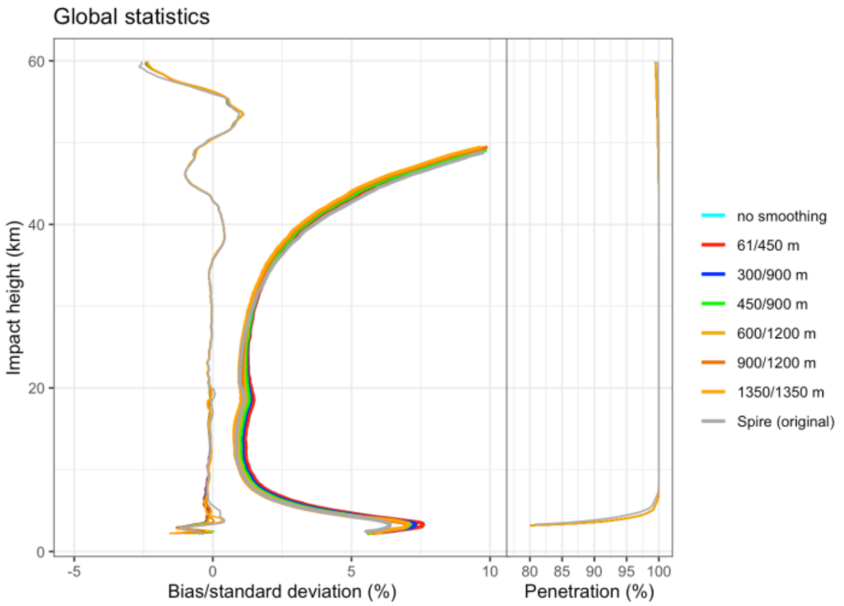
•Scope: Numerical weather prediction (NWP)

• Experimental datasets of ~35,000 daily RO profiles

•Data source: 13 missions (Sept–Nov 2022)

•**International campaign involving:**

- Data providers: COSMIC/Metop/Spire/Fengyun/TianMu/YunYao, et al.
- Processing centers: EUMETSAT/UCAR/NSSC/DMI, et al.
- Forecasting institutions: ECMWF/CMA/Met Office, et al.
- Global research & operational communities



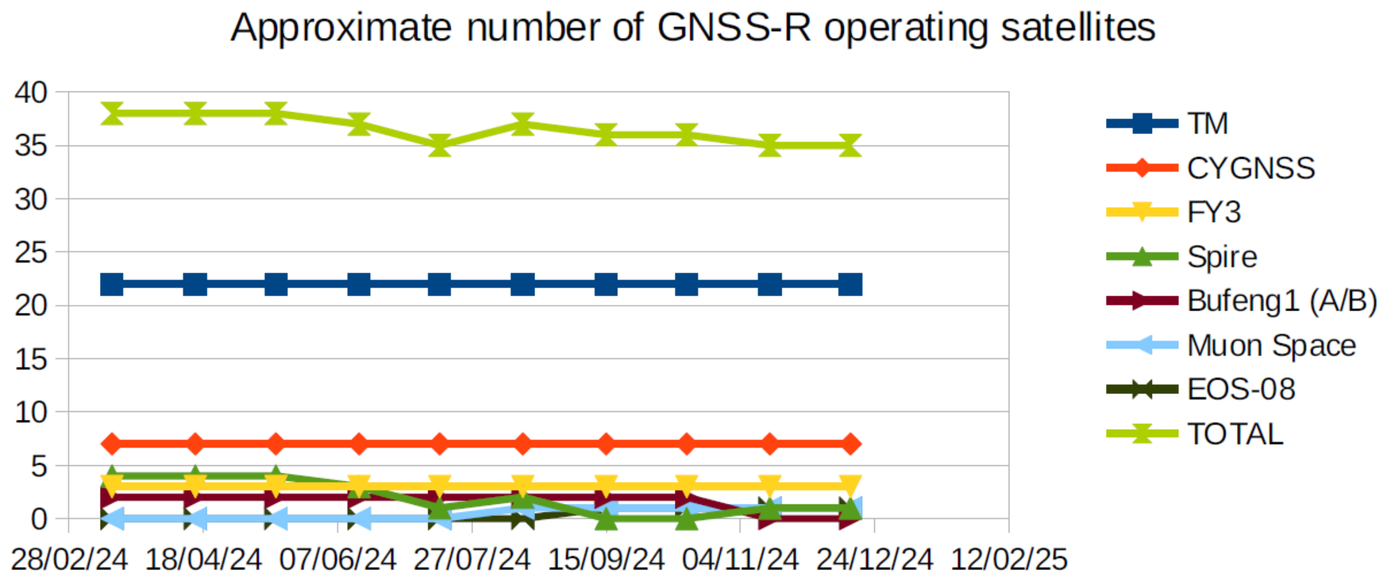

ROMEX Cal/Val results of bending angle from EUMETSAT

**Cal/Val Conclusions for CGMS:** All bending angle data sets for ROMEX exhibit similar data characteristics and are of sufficient data quality to carry out experiments required for ROMEX.

# Introduction: GNSS-R

## Demand for GNSS-R Cal/Val

- There are currently near 40 GNSS-R satellites in orbit from multiple national and commercial missions including CYGNSS, Fengyun-3, Bufeng-1, Spire, Tianmu-1, Muon, DoT-1, TRITON, EOS-8 and future missions such as HydroGNSS, Amazonia-1B, FY-3 follow-ons and FY-5.




*From Estel Cardellach et al. in IEEE GNSS+R25 in Leiden*

# Introduction: GNSS-R

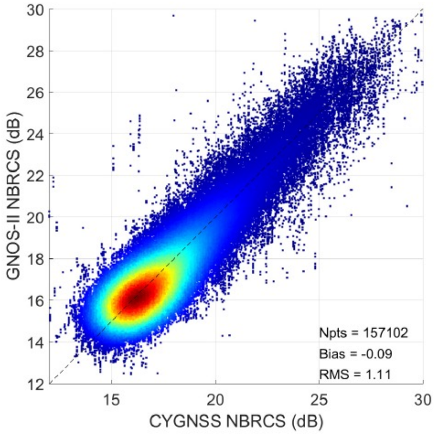
## Motivation of GNSS-R Cal/Val

- Some GNSS-R missions are extensive calibrated (such as CYGNSS and FY-3), but some others are not.
- There are significant inconsistencies in the L1 normalized bistatic radar cross section (NBRCS/sigma-0) over the ocean from different GNSS-R missions and different GNSS constellations (GPS/BeiDou/Galileo/GLONASS..)
- It is urgent to establish a benchmark for GNSS-R NBRCS over the ocean for the intercalibration of different missions.
- It will be very helpful to build an inter-calibrated virtual GNSS-R constellation of 40+ satellites (e.g. the METACONRef Project of ICE-CSIC/IEEC)

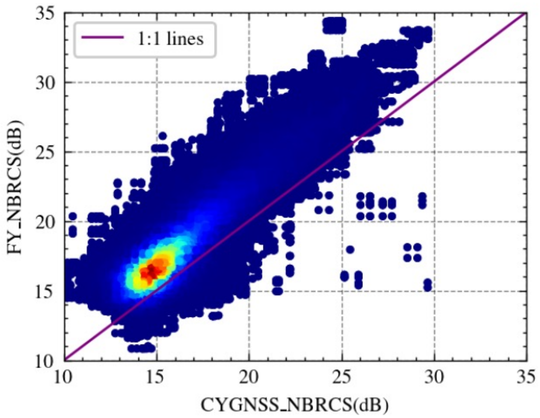
# Introduction: GNSS-R

## Motivation of GNSS-R Cal/Val

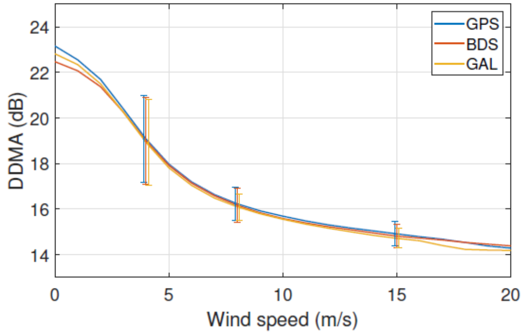
FY-3E vs. CYGNSS v3.0




FY-3E vs. CYGNSS v3.1

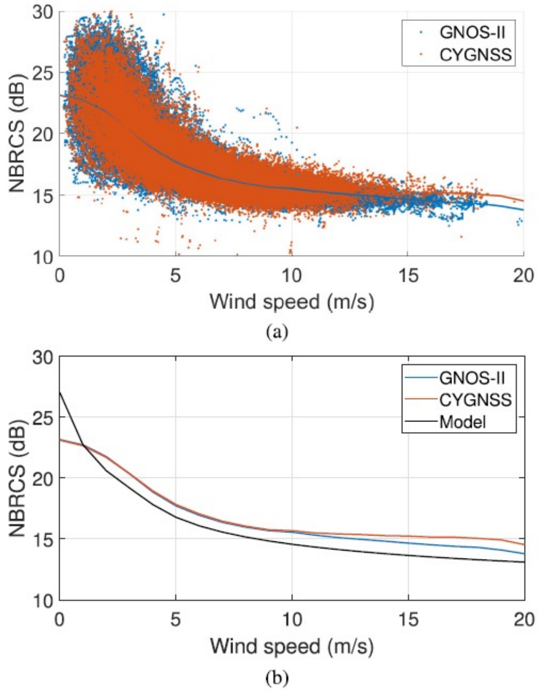



*Yang et al. 2025*



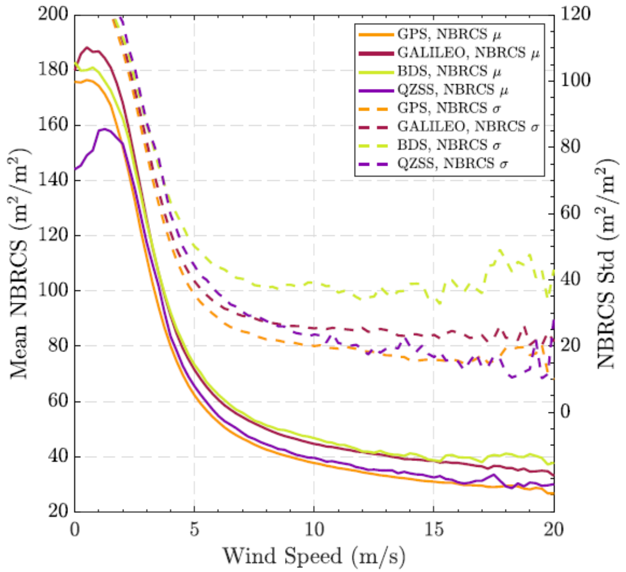

*Huang et al. 2022*

satellite observation vs. empirical model




*Huang et al. 2022*

Spire's LEMUR-2




*M. Al-Khaldi et al. 2023*

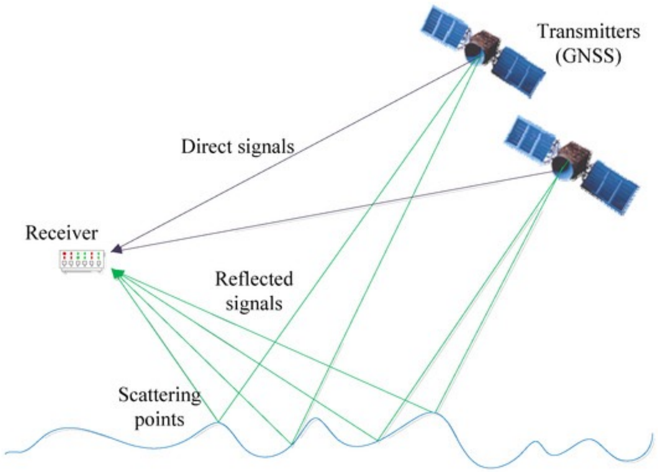
**significant inconsistencies in the GNSS-R radar cross section between different missions/GNSS systems/models**

# Proposal for GNSS-R Cal/Val

## Potential Strategy

GNSS-R is in the forward quasi-specular reflection, measuring mesoscale ocean surface roughness (>50cm) impacted by both wind wave and swell

Some strategies can be learned from the scatterometer community (all current scatterometers are well inter-calibrated)

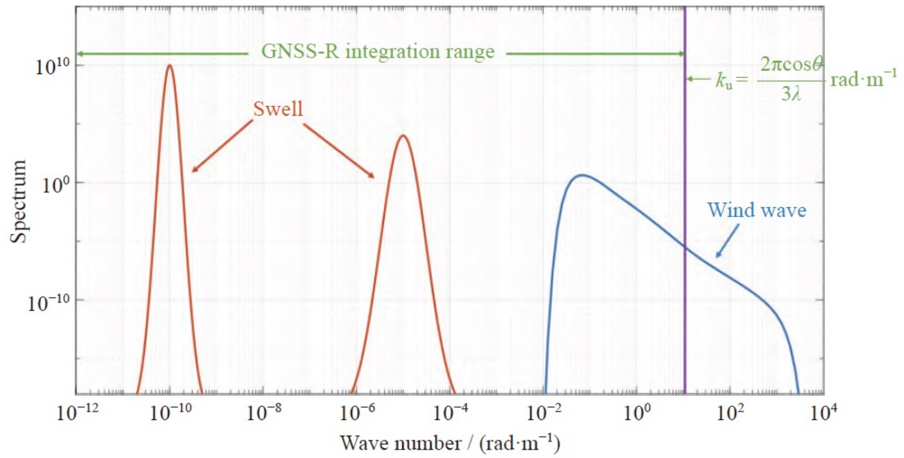



The ocean surface roughness measured by GNSS-R is represented as mean square slope (MSS) modulated by the wave spectrum and signal's wavelength

$$\sigma^0 = \frac{|\Re(\theta)|^2}{MSS}$$

$$MSS = \int_0^{k_u} k^2 S(k)dk$$

$$k_u = \frac{2\pi}{3\lambda} cos\theta$$




Can potentially use the MSS from ocean wave model (e.g. WW3) to establish a benchmark of GNSS-R NBRCS

# Proposal for GNSS-R Cal/Val

## Task Objective and expected deliverables

**(1) Establish a benchmark for GNSS-R NBRCS (sigma-0) over the ocean**

- Provide a reference model of GNSS-R ocean NBRCS in a function of wind speed and incidence angle (and potential swell height and wave age)
- A Best Practices Protocol Document for the Cal/Val of GNSS-R NBRCS

**(2) Provide a well-calibrated GNSS-R datasets for the CAL/VAL of ALL missions**

**Future goals: Data format/quality control/benchmarks of reflectivity over land and sea ice/strategy of data assimilation**

# Proposal for GNSS-R Cal/Val

## Task Team

- National Space Science Center (NSSC) (Task lead or co-lead, provide Fengyun-3 and Tianmu-1 data)
- Plan to invite members from other missions (CYGNSS, HydroGNSS, .etc)

- NSSC also has groups of scatterometer and GNSS-RO (more standardized internationally than GNSS-R) which can provide a lot of good suggestions.

- CYGNSS and FY-3 are the only two GNSS-R missions whose data are fully open to the public and well calibrated), so they are the best for us to start with.

# Perspectives of microwave FRMs

- FRM for radar altimetry
- FRM for microwave radiometer

# Fiducial Reference Measurements for High-Resolution Sea Level Profiles (FRM4SLP)

# Introduction: fully-focus synthetic aperture radar altimetry

- Radar altimeters play an indispensable role in both marine geodesy and dynamic oceanography; have provided continuous high-quality global sea level records since 1992 (Topex/Posedon Mission); keep making solid contribution to global climate study.
- Drawbacks of conventional radar altimeters and Approaches:

| Drawback | Approaches |
| --- | --- |
| **Low resolution (several kms in both along-track and across-track directions)** | **Synthetic aperture technology for along-track (Sentinel-3 &Sentinel-6)**<br>**Interference technology for across-track (Cryosat & Cristal)** |
| **Narrow swath (nadir-looking): dilemma in temporal and spatial sample pattern** | **Wide swath technology (SWOT)**<br>**IGNSS-Reflectometry** |

- The fully-focus synthetic aperture radar (FFSAR) technology introduced by Edigo et al. (2017) improves the theoretical along-track resolution of spaceborne radar altimeters to the 0.5-meter level. After necessary multi-look processing, 140Hz (corresponding to resolution of 40-50 meters) along-track sea level products have gradually become the most common choice, which can achieve a good balance between accuracy and resolution.
- High resolution sea level profiles are extremely valuable in climate-sensitive coastal altimetry, and have drawn much attention in the applications over inland waters, high sea state areas, and sea ice surfaces.

## Importance and Natural of FFSAR Altimetry Calibration

- Importance of FFSAR altimetry calibration:

① Currently, innovative FFSAR processing algorithms keep arising, most of which are immature. Different algorithm has different result, and in certain algorithm, the performance is depended on the value of the algorithm parameters. To validate and optimize the performance of the algorithms, independence and reliable sea level profile measurements should be acquired.

② FFSAR has high computation complexity, so unfocused synthetic aperture radar (UFSAR) is usually implemented over open ocean. Several studies have discovered that FFSAR and UFSAR may have relative bias. Ensuring the consistence between UFSAR (open ocean) and FFSAR (coast) further highlights the necessity of the calibration.

- Natural of FFSAR altimetry calibration:

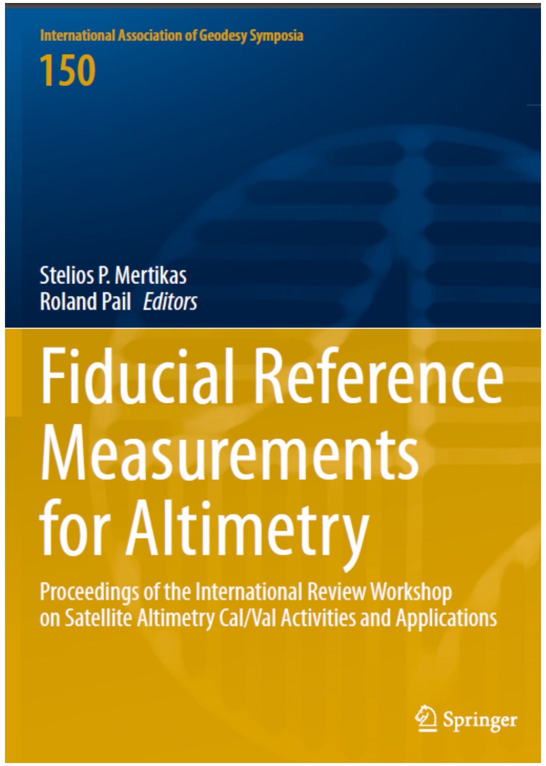
① Stringent resolution requirements (usually better than 50m, occasionally 10m).

② Loose accuracy specification: 0.8cm @ 1Hz → 10cm @ 140Hz. In-situ measurements with an accuracy of 3cm can still fulfill the high-resolution calibration task.

# Introduction

## Background: FRM4ALT

- Current altimeter calibration methods usually uses equipment (tide gauge, GNSS buoys etc.) to provide in-situ sea level observations for comparison with satellite sea surface height measurements.
- The FRM4ALT project (leaded by Prof. Mertikas from Technical University of Crete, based on the heritage of the Permanent Facility for Altimeter Calibration (PFAC) located at Gavdos, Greece) emphasized that calibration facilities must follow international metrology standards to ensure measurement results are traceable to SI units (such as the speed of light, atomic time).
- The scope of FRM4ALT lies in isolated (usually sparse) extremely-accurate in-situ instruments. Each in-situ equipment in FRM4ALT project can only provide measurement at one point.
- Besides the sea-level Cal/Val equipment, FRM4ALT also addresses transponders which can receive to microwave pulses from the satellite altimeters and retransmit them back.
- The outcomes of FRM4ALT were archived and published in a book.



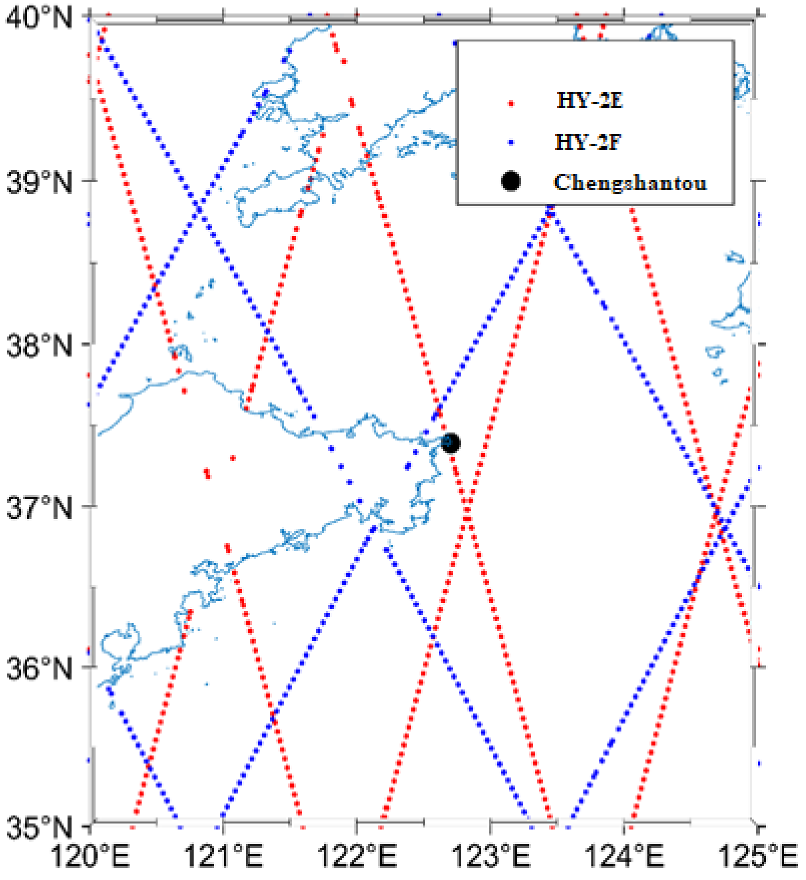
## Challenges for FFSAR Altimetry Calibration

- But the resolution of FFSAR Altimetry is very high (tens of meters), sparse in-situ FRMs cannot commit the requirements.
- An approach is to use a number of identical equipment (e.g., GNSS buoys) to form arrays, but this can hardly meet the requirements for the FFSAR altimetry.
- E.g.: according to the Nyquist sampling theorem, deploying GNSS buoys at 50m intervals within a 0-5 km offshore can acquire an effective resolution of 100m (still cannot fulfill the 40~50m requirement), but it requires 100 buoys, which is not only extremely expensive, but also impractical for actual deployment.
- It is necessary (and challenging) to establish FRM for high-resolution along-track sea level profile, which is beyond the scope of FRM4ALT.

# FRM for High-Resolution Sea Level Profiles

## UAV Calibration: Preliminary Calibration Site

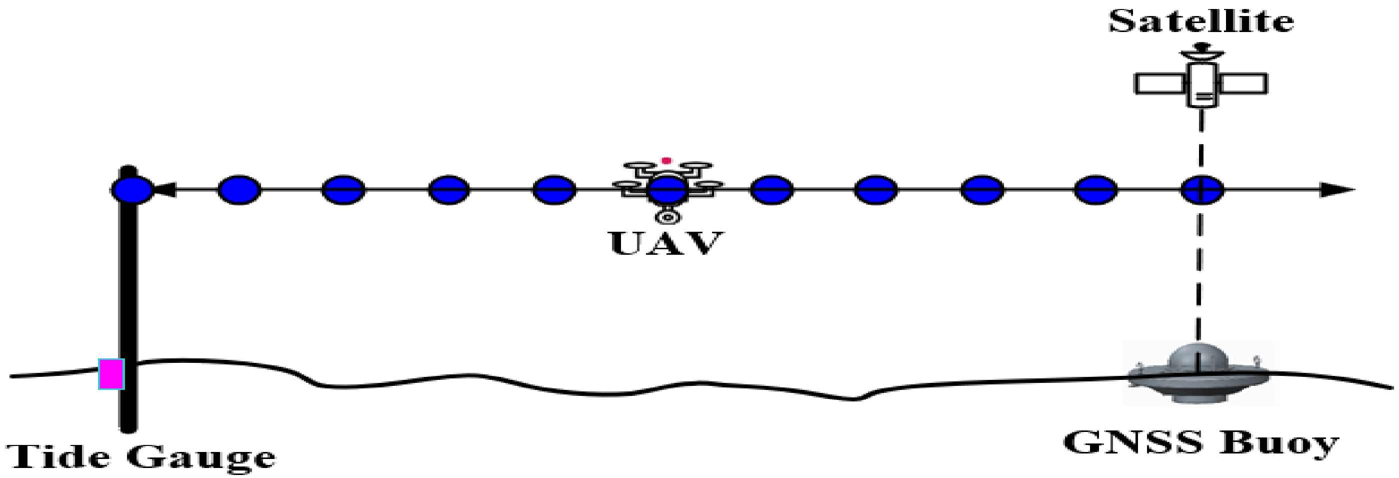
- With the rapid improvement of UAV (Unmanned Aerial Vehicle) technology in recent years, advanced UAVs have integrated RTK positioning modules, and low-cost and lightweight water-level gauges (both lidar and radar types) have become off-the-shelf products.
- Using UAV-mounted water-level gauges to carry out high-resolution sea surface height calibration campaigns before and after satellite overpasses, measuring fine along-track sea level profiles, can explore beneficial calibration for high-resolution sea level products of FFSAR altimeters.
- Through prior coordination with local experts in Chengshantou located at the easternmost end of the Shandong Peninsula, we find it is a highly feasible site for test. An operational permanent tide station located very close to the ground track of China's HY-2E satellite, have collected sea level records for years.



# FRM for High-Resolution Sea Level Profiles

## UAV Calibration: Preliminary Calibration Approach

- Firstly, the systemic bias of the UAV sea level measurements must be compensated for: hovering overhead  the nearby tide gauge for ≥ 5 minutes at the beginning and ending of each campaign.
- UAV Navigates ≥  5km along the satellite's ground track (within ±1 hour of the overhead time) in a "stop-and-go" mode, hovering occasionally for ≥ 1 minute (to form accurate virtual control points).
- Preferably, a GNSS buoy or seabed-mounted pressure gauge can be deployed  at the far end of the UAV route to provide an accurate sea-level FRM.



## UAV Calibration: Key Technologies

- **Precise Positioning Technology for High-Dynamic UAV Platforms**

① Using UAVs integrated with geodetic multi-mode GNSS (GPS / Galileo / Beidou-2 / Beidou-3) receivers and INS

② Stop-and-go strategy (increasing integration time at the virtual control points)

③ Multi-epoch adaptive filtering algorithm (e. g., Kalman)

④ Traceability to SI realized by Kinematic Position with respect to the GNSS reference station (with known coordinates in ITRF) in the calibration field.

- **Data-driven Adaptive Spatiotemporal Matching Technology**

① Mismatch error due to difference sampling pattern: instantaneous measurement with a large footprint for satellite altimeter, a  profile (for each epoch, with far smaller  footprints).

② Assuming the sea surface is an ergodic stationary random process, the average of the spatial footprint is equivalent to the average of a single point over a time period (the duration is related to parameters such as wave height). The UAV measures a profile with accurate virtual control points, making the equivalence more complex.

③ Adaptively design spatiotemporal matching window parameters and perform adaptive filtering on the UAV's original water level sequence, so as to obtain in-situ sea level data with the strongest correlation.

④ Correction of the differences in ocean tides, solid tides, etc., caused by the inconsistency in time and space between the UAV's nadir and the satellite’s nadir.

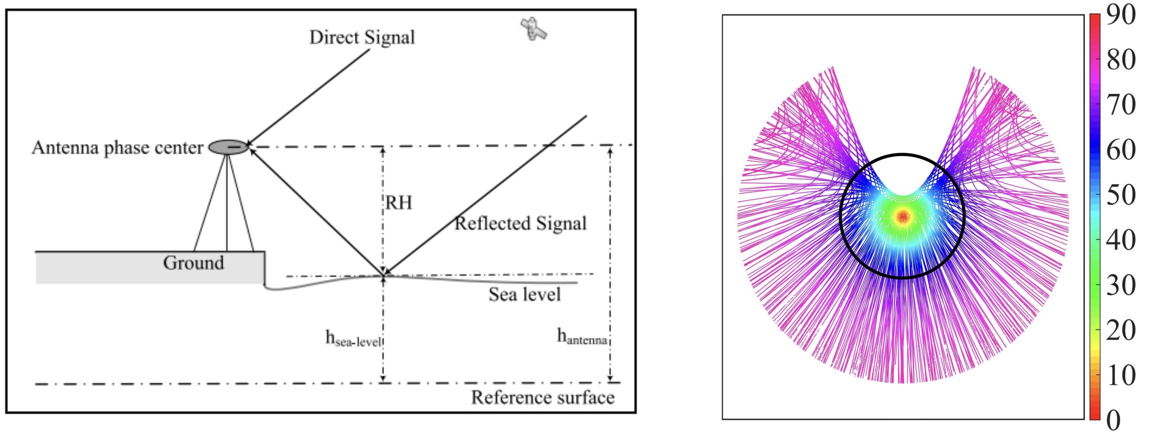
# FRM for Altimeter with GNSS-MR

## GNSS-MR Calibration: Concept and Advantages

- Global Navigation Satellite System Multipath Reflectometry (GNSS-MR), utilizing the direct and reflected multipath GNSS signals are received simultaneously and interfere with each other to form a composite signal.
- Operational range: ~100m (dependent on the height of the GNSS-MR deployment).
- Accuracy: 1~2cm.
- Advantages:

① It can provide long-term sea-level data absolutely coordinates linked to ITRF; not susceptible to crustal vertical displacement (outperforming tide gauge in this sense);

② Low-cost and easy to maintain.




Scheme of ground-based GNSS-MR sea-level estimation. The distribution of 48-hour specular reflection points are drawn and the color varies with the incident angle as the right legend.

# FRM for Altimeter with GNSS-MR

## GNSS-MR Calibration: Key Technologies

(1) Precise ephemeris downloaded from IGS are used to calculate the satellite elevation angle and azimuth at each station.
(2) Based on the elevation and azimuth mask of each station, signal strength indicator(SSI) arcs from different GNSS signals were extracted from GNSS RINEX files.
(3) To isolate the multipath signals and remove the direct signals in SSI observations, a third-order polynomial fitting is applied to each SSI arc, creating dSSI arcs.
(4) After analyzing the dSSI arcs for each satellite arc by using Lomb–Scargle periodograms (LSPs) to identify the signal frequency, H time series for each signal can be obtained.
(5) Quality-control measures were imposed to obtain valid static reflector heights (H).
(6) After quality control, H time series of each GNSS signal is used to simultaneously calculate h using a sliding window and least squares method.

CEOS

# Prospective: Wide Swath (2D) Altimeter Calibration

- Since the launch of the SWOT (Surface Water and Ocean Topography) satellite in 2022, wide-swath imaging altimeters have become the most intriguing technology in the oceanography and hydrology. In addition to effectively capturing mesoscale ocean phenomena, their standard in inland water level product resolution is 50 meters (comparable to the FFSAR along-track resolution), which greatly improves the detection capability for small lakes and narrow rivers.
- For wide swath altimeter calibration, the along-track profiles are not enough, 2D grid in-situ sea level measurements must be acquired.
- Arrays of GNSS buoys (or coastal GNSS-MR instruments) evenly distributed (spacing ~10km) in the across-track direction can provide accurate control points, and the gap between neighboring instruments can be filled by dense UAV measurements.
- The “array + UAV” strategy will be very helpful in compensating the troublesome sea surface height errors due to satellite roll angle and baseline-length variation, both show clear pattern with respect to the across-tack distance to nadir.

# FRM for microwave radiometer

Space Microwave Radiometric Standard and Traceability

# Status and Existing Problems

◆Due to the absence of a unified reference standard for space microwave radiometry, uncertainties in radiation traceability and standard transfer will introduce errors in observations. This makes it difficult to provide continuous observations with highly accuracy, stability and consistency that will ultimately affect the accuracy of climate research.

◆Space microwave radiometry is a critical method for acquiring Essential Climate Variables (ECVs). Achieving high-precision, highly stable, traceable space detection capabilities and long-term data accumulation requires significant breakthroughs in improving the radiometric accuracy of microwave remote sensing and the consistency across different satellites.

◆The internationally established "Global Space-based Inter-Calibration System" (GSICS) provides high-quality and comparable data from satellites in orbit. However, it doesn't resolve problems related to high-accuracy standard transfer and consistent traceability within the space radiometry.

◆For example, Fengyun (FY) satellites have established a constellation of four satellites operating in three orbital planes (dawn, morning, and afternoon), providing valuable atmospheric detection datafor weather forecasting six times per day. Nevertheless, achieving high-precision, long-term stable observations from remote sensing satellites is still an increasing problem.

# Development for Space Radiometry Traceability

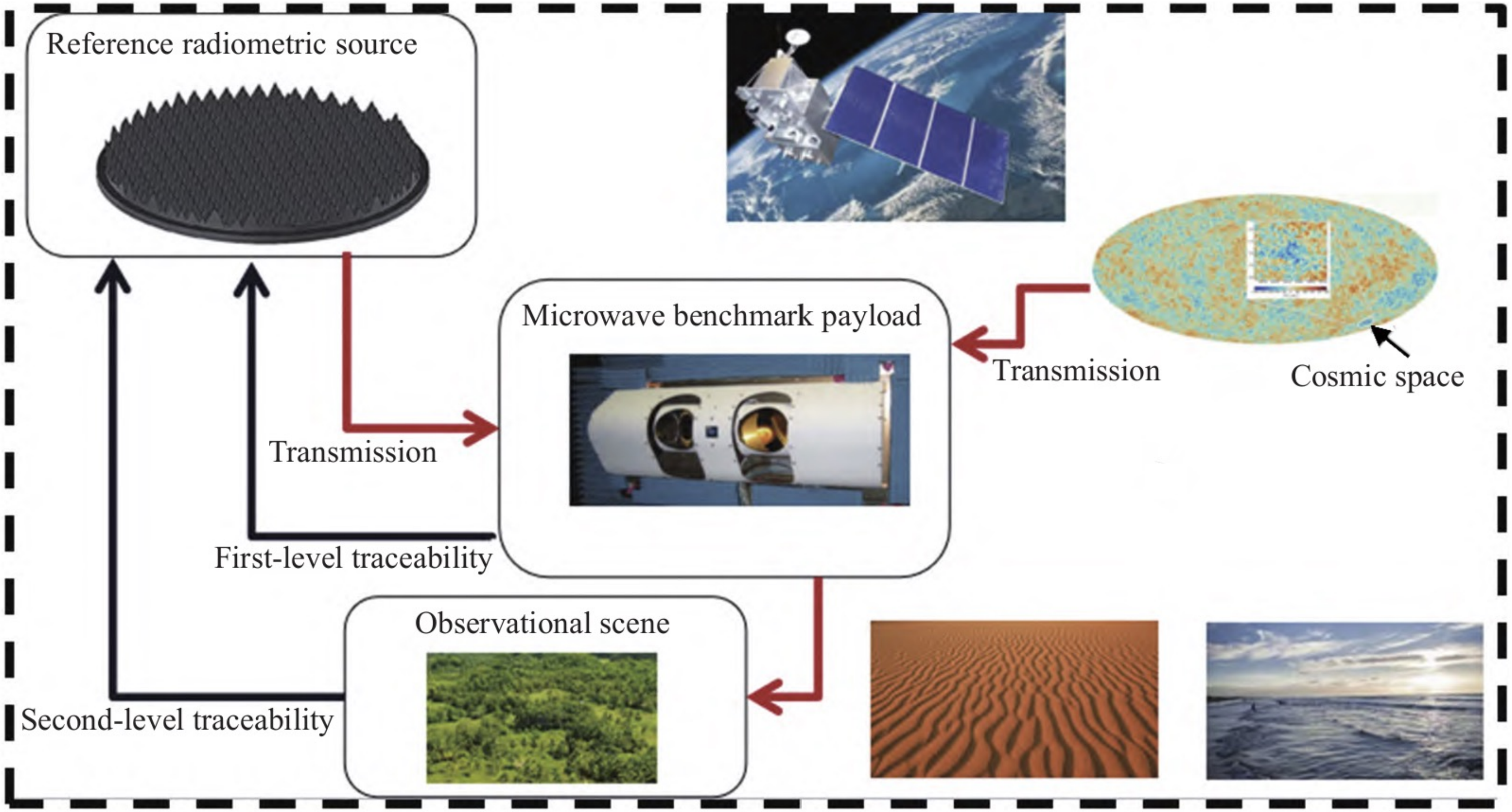
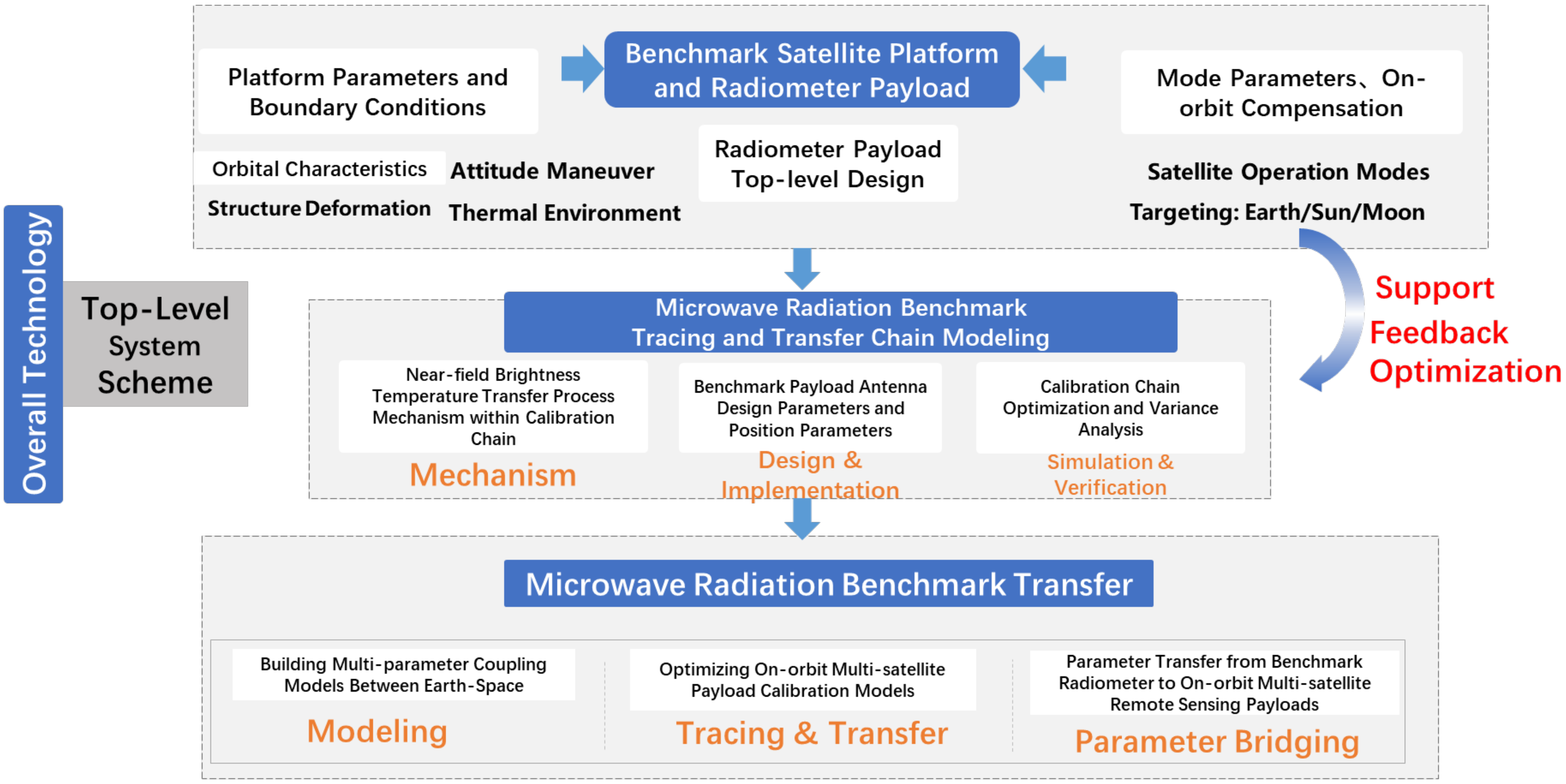



图 4　微波辐射溯源传递流程

Fig. 4　Flow chart of microwave radiometric benchmark transmission and traceability

# Space microwave radiometry Implementation Approach

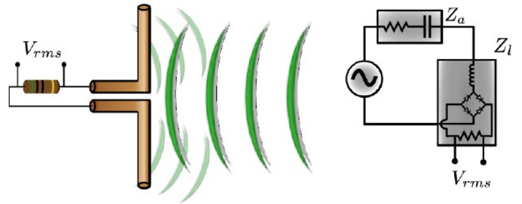


# SI Traceability Option

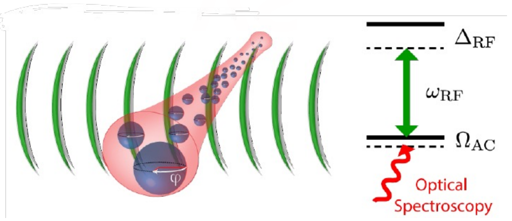
## Space Microwave Radiometric Quantum Standard and Traceability

◆**The lack of a unified and effective radiometric standard across global microwave remote sensing systems leads to accuracy, consistency, and traceability problems of scientific data across instruments, generations of satellites, and long time series.**

◆**Theoretical research on a quantum-based microwave radiometric standard and spaceborne traceability. This approach aims to establish measurements traceable to fundamental atomic constants, thereby eliminating the drift inherent in physical artifact standards. By reconstructing the measurement at the fundamental physical level, it could provide an accurate, interference-resistant, and long-term stable radiometric reference.**

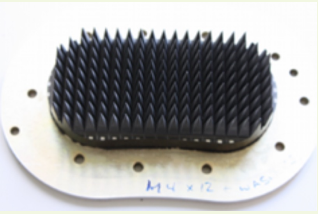



Electronics **VS** Quantum




### Traceable to Blackbody

- Individual calibration blackbodies per radiometer
- Accuracy depends on blackbody emissivity and temperature.

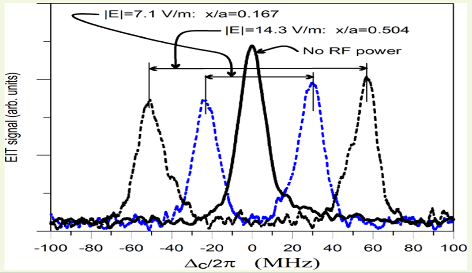


$$|E| = \sigma T^4$$

Emissivity Temperature

### Quantum Microwave Detection & Traceability

- Utilizes Rydberg atoms interacting with EM fields to generate quantum effects for microwave signal measurement




$$|E| = 2\pi \frac{\hbar}{\wp} \Delta f_m$$

Quantum Constent Spectral Split