The 3rd CFOSAT Science Team Meeting

# Validation of Wave Spectral Partitions from SWIM instrument on-board CFOSAT against In-situ Data


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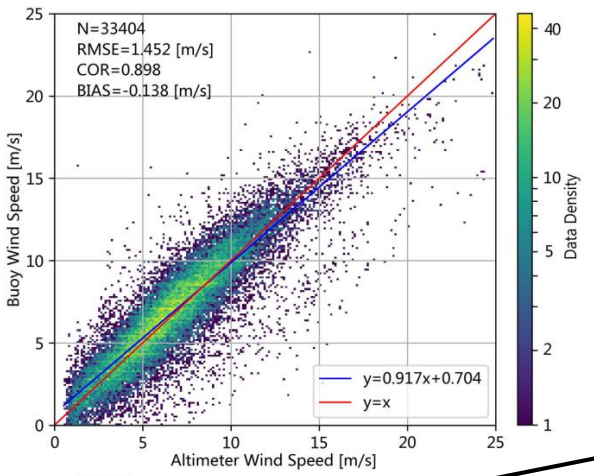
# 1. Introduction

- **Cal/Val is important for space-borne ocean remote sensors, including SWIM**
  - Understanding of uncertainties
  - Correction of systematic errors

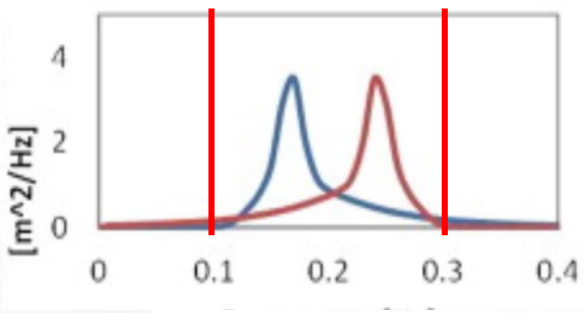
- **For integral wave parameters (SWH, MWP, MWD), Cal/Val can be simple:**



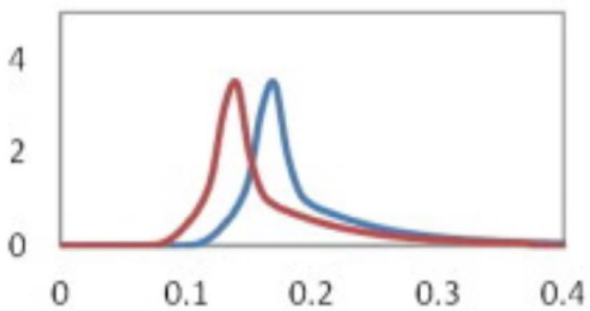
# 1. Introduction

- **Validation of remotely sensed directional wave spectra is complicated.**
- **No universal method to compare two sets of directional wave spectra**
  - Using the difference/correlation/similarity of spectral grid points or directional/frequency bands ?

1. **Different spectral shapes can have the same band-wise energy**
2. **“Bad agreement” in spectral-bins is not necessarily “that bad”**
3. **Physical meaning of spectral density is not as clear as wave parameter**




Same band-wise energy but different shape

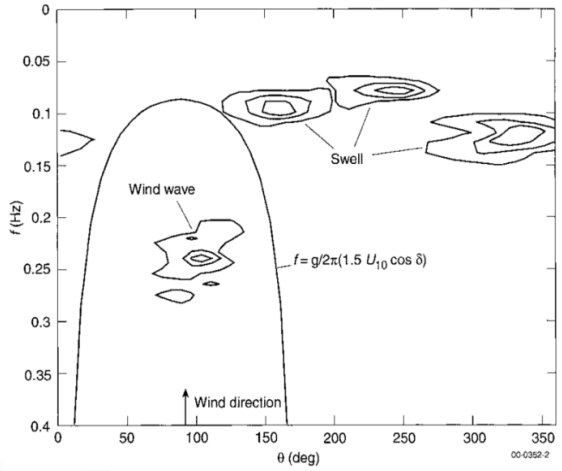


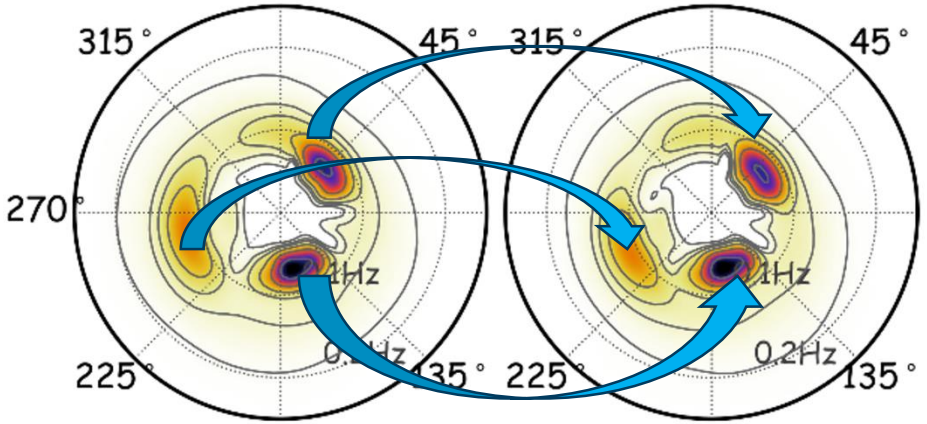

Similar spectral shape but $r = 0$

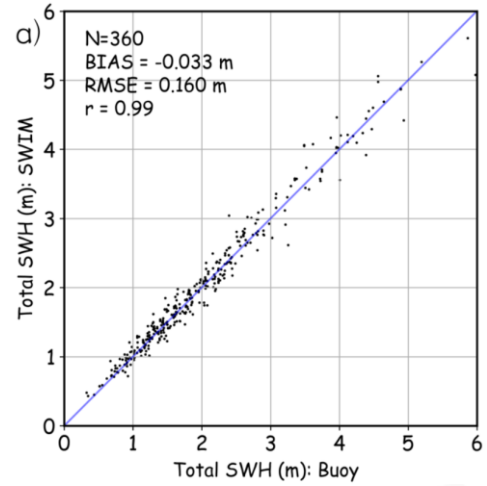
One can imagine the difference between a 4.5-m SWH and a 5-m SWH, but it is difficult to consider the difference in the wave spectra of 20 $m^2s$ and 25 $m^2s$ (*Ardhuin et al.* 2019)

# 1. Introduction

- **Comparing the partitioned integral wave parameters might be a solution**
- **Process**
  - **Partitioning:** Separating wave systems generated by different events.
  - **Cross-assignment:** Collocating the partitions from the same events in two data sets.
  - **Comparison:** Computing the error metrics between the matched-up partitions.




- **It sounds simple, but we encountered many problems when doing this**

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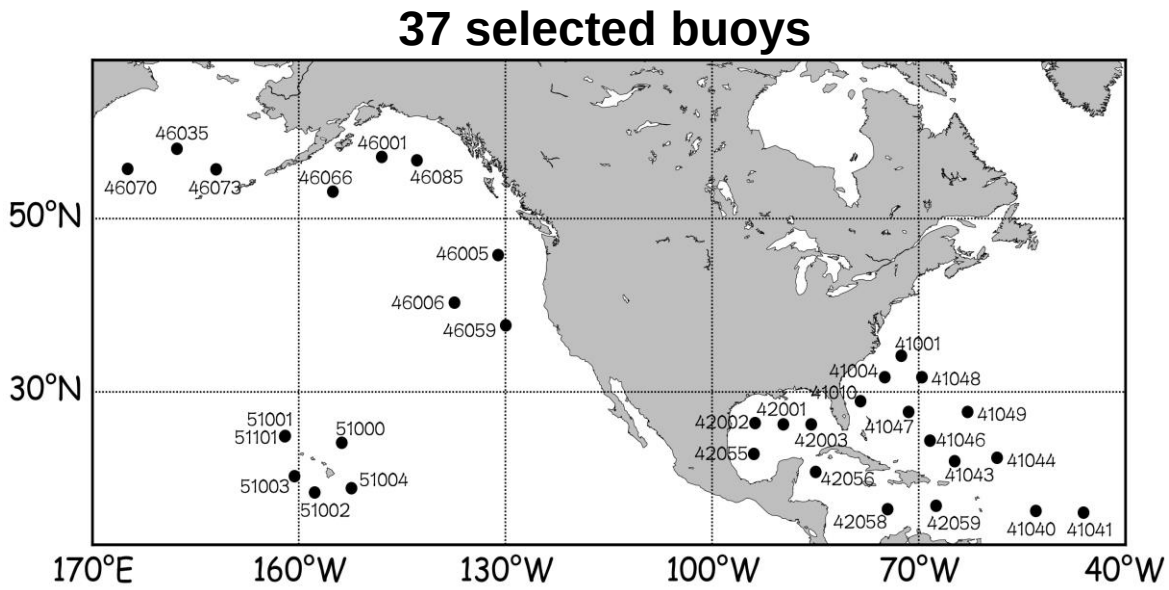
# 2. Discussion: Comparing Partitions from two Spectra

- **NDBC buoy data**
  - May 2019 ---- April 2020
  - “First-5” information available
  - Offshore distance > 150 km
  - Water depth > 200 m
  - Wave spectra reconstructed (MEM)




- Partitioned using Hanson & Phillips (2001) + Portilla et al. (2009)[Smoothing]
- Partitioned SWH, PWP, and PWD (without identifying wind-seas & swells)

# 2. Discussion: Comparing Partitions from two Spectra

- **NDBC buoy data**
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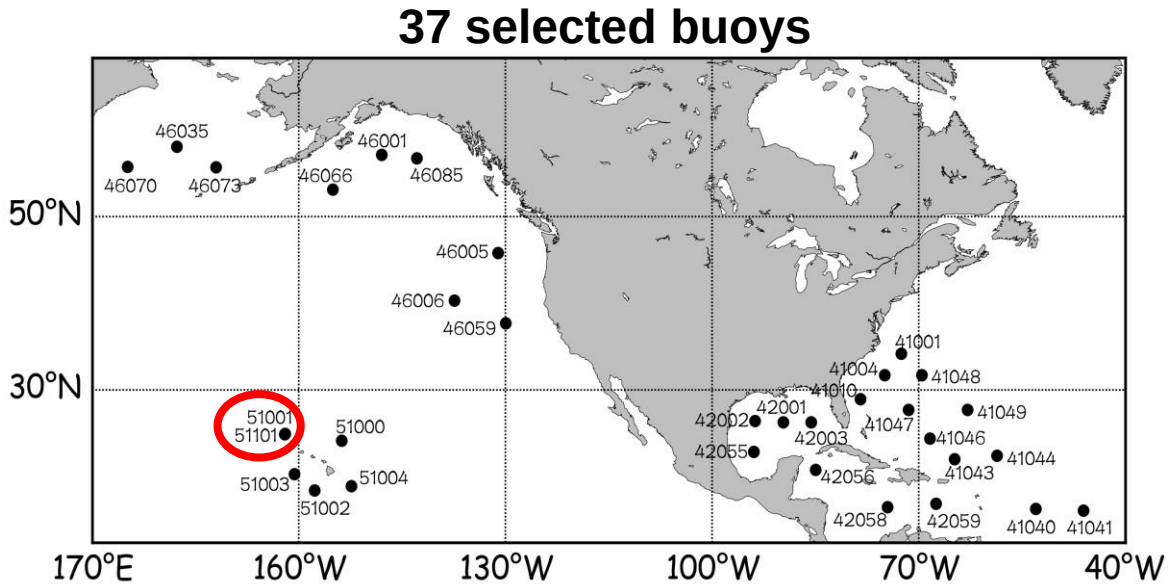
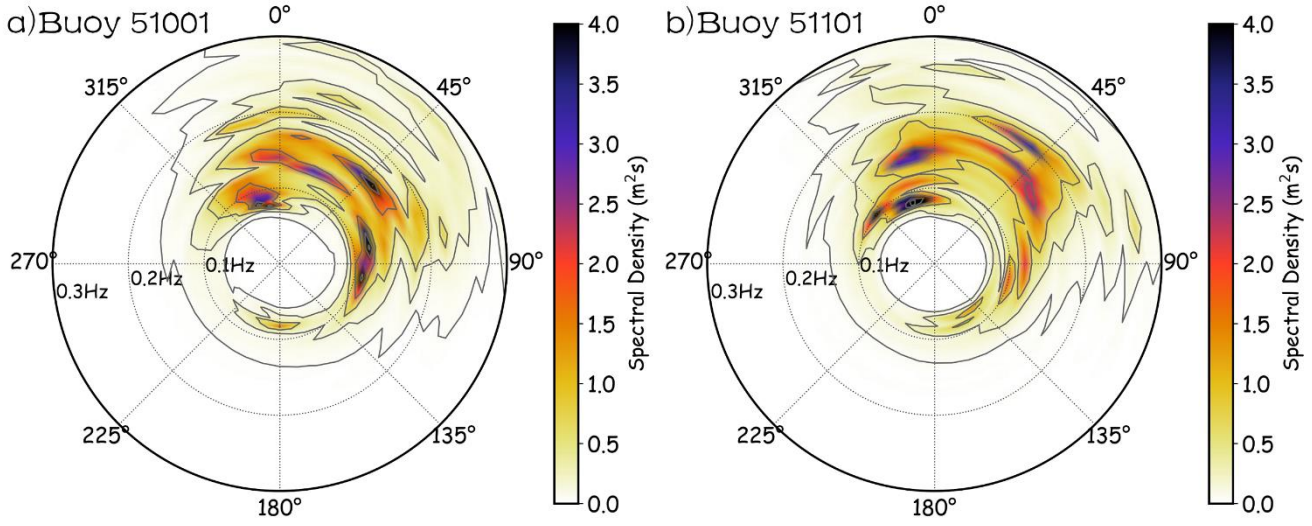



- Partitioned using Hanson & Phillips (2001) + Portilla et al (2009)[Smoothing]
- Partitioned SWH, PWP, and PWD (without identifying wind-seas & swells)

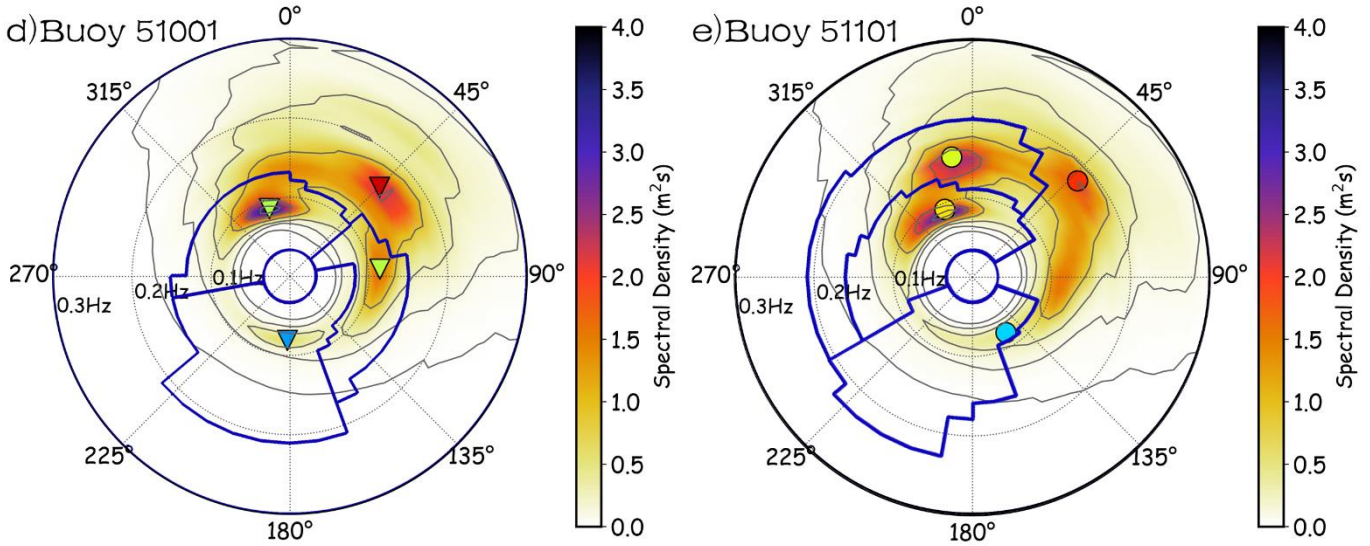
- **51001 & 51101 are only ~13 km away from each other, providing an opportunity to compare the wave spectra from two buoys**

# 2. Discussion: Comparing Partitions from two Spectra

- **The agreement between spectra from the two buoys**




**Original** Reconstructed Spectra at UTC1700 May 9, 2019
*r* between the two spectra: ~ 0.52




**Smoothed** Reconstructed Spectra at UTC1700 May 9, 2019
*r* between the two spectra: ~ 0.91

# 2. Discussion: Comparing Partitions from two Spectra

## ➢ Cross-assignment

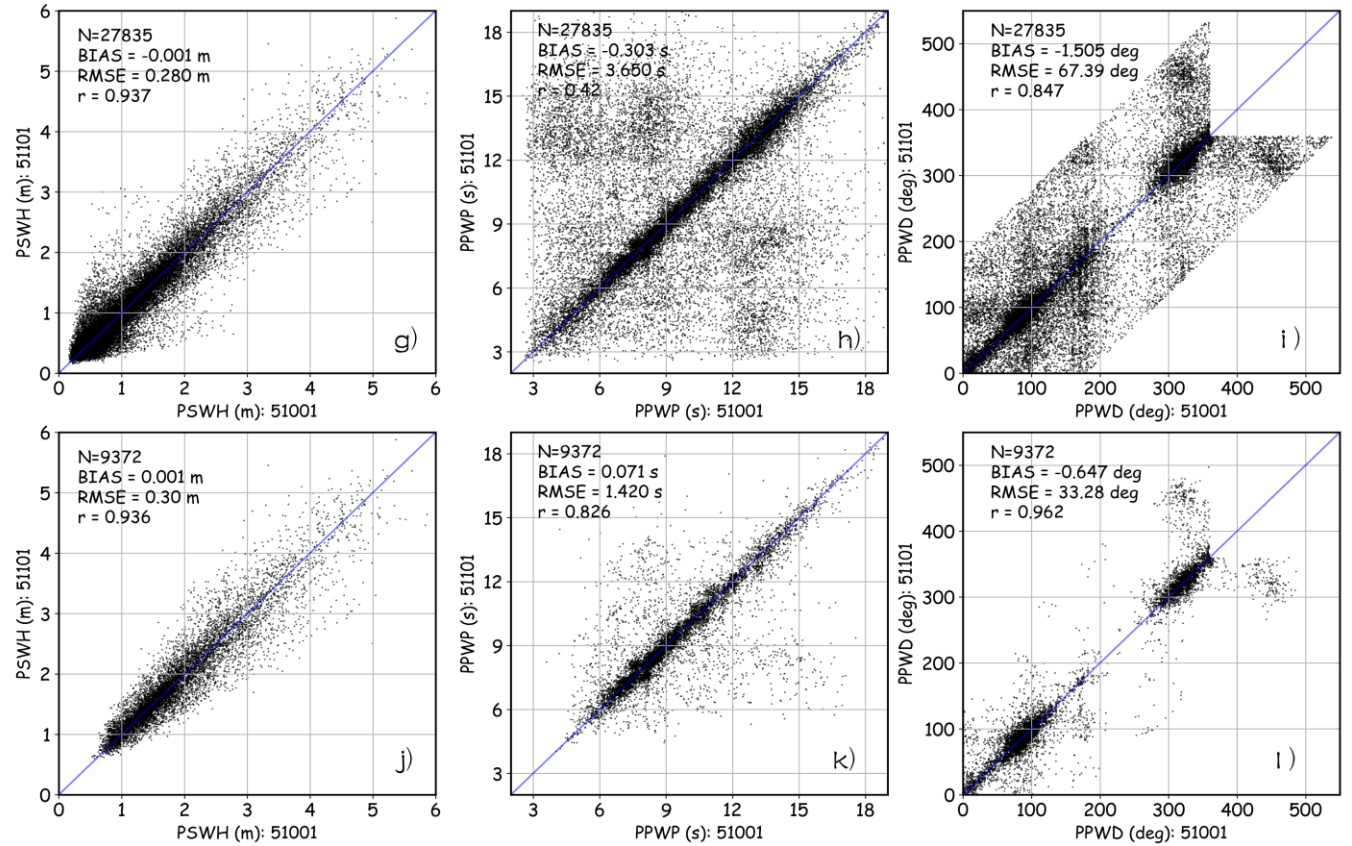
- However, again, no universal method to cross-assign partitions:

Energy ranking: Comparing the 1st/2nd/3rd partitions in two spectra accordingly

1. Missing or spurious partitions

2. Partitions with similar wave energy

**Too many outliers!**




All partitions are cross-assigned and compared

Only the most energetic (the 1st) partition at each spectrum is compared.

Comparisons of PSWH, PPWP, PPWD between the two buoys **using energy ranking method**.

# 2. Discussion: Comparing Partitions from two Spectra

- **Cross-assignment**

  Spectral Distance Method: Finding the partitions in the other spectrum with the smallest spectral distances

  Still, no universal definition of spectral distances

$$\sqrt{\left(\frac{T_a - T_b}{1\mathrm{s}}\right)^2 + \left(\frac{\theta_a - \theta_b}{\theta_{coef}}\right)^2}$$

$$\frac{1}{f_{ps}}\left[\left(f_{\mathrm{ps}}\cos\theta_{\mathrm{ps}} - f_{\mathrm{ps,lin}}\cos\theta_{\mathrm{ps,lin}}\right)^2 + \left(f_{\mathrm{ps}}\sin\theta_{\mathrm{ps}} - f_{\mathrm{ps,lin}}\sin\theta_{\mathrm{ps,lin}}\right)^2\right]^{\frac{1}{2}}$$

Distance in wavenumber ($k$) space: $|k_1 - k_2|$

$$\frac{1}{q}\left(|D_1 - D_2| \mod 360 + 2\frac{|T_1 - T_2|}{T_1 + T_2}r\right)$$

$$q = 60 \text{ and } r = 250$$

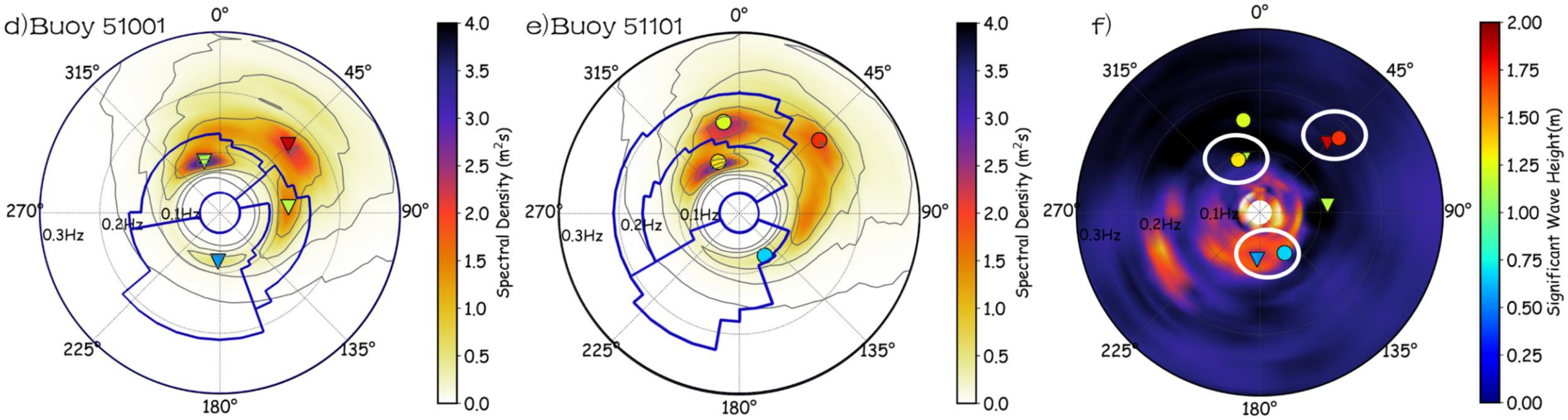
$$\sqrt{\left(\frac{a_{\mathrm{rms,peak}} - a_{\mathrm{rms,group}}}{3a_{\mathrm{rms,group}}}\right)^2 + \left(\frac{\theta_m - \theta_{\mathrm{group}}}{\pi}\right)^2 + \left(\frac{\log f_m - \log f_{\mathrm{group}}}{\frac{1}{3}}\right)^2}$$

To some extent, the selection of the definition depends only on personal taste, and on how the data will be used afterward ? (Personal opinion)

# 2. Discussion: Comparing Partitions from two Spectra

- **Cross-assignment**

  Spectral distance method sounds reasonable but…




Such conditions of wrong cross-assignment are common because missing or spurious partitions are common.

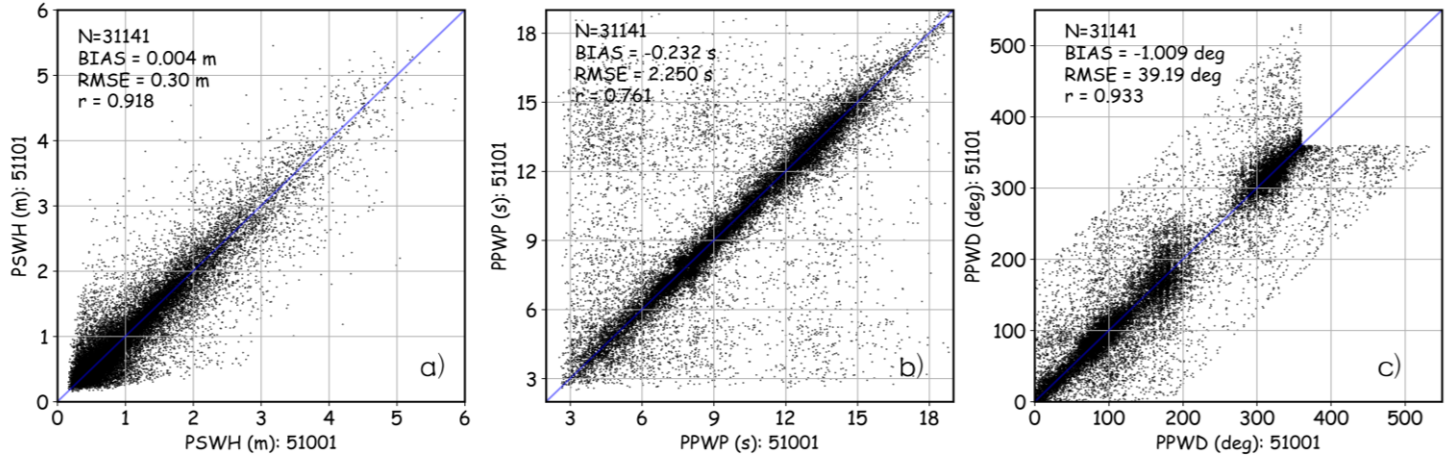
# 2. Discussion: Comparing Partitions from two Spectra

## ➢ Cross-assignment

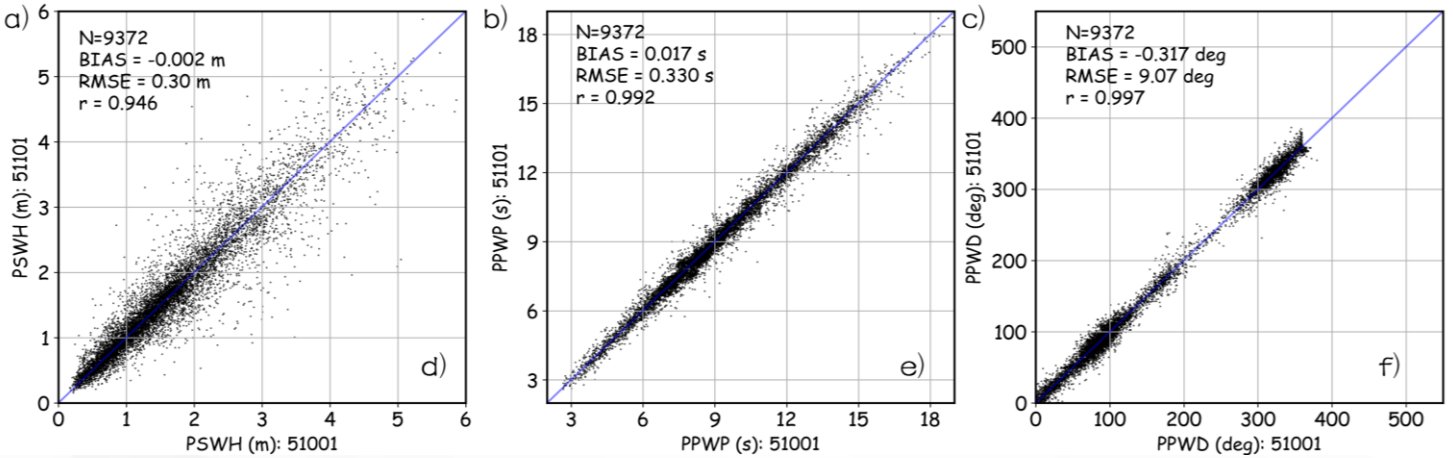
$$D = \sqrt{\left(\frac{T_a - T_b}{1\text{s}}\right)^2 + \left(\frac{\theta_a - \theta_b}{\theta_{coef}}\right)^2} \qquad \theta_{coef} = 25°$$

Wrong cross-assignments also lead to many outliers.

All partitions are cross-assigned and compared




Only partitions with the minimum spectral distance for each pair of spectra are cross-assigned




However, the “true errors” are underestimated. Only the lower limit of the error

**<Best-matching>**

Comparisons of PSWH, PPWP, PPWD between the two buoys **using spectral distance method**

# 2. Discussion: Comparing Partitions from two Spectra

## ➢ Error Evaluation <Best-matching>

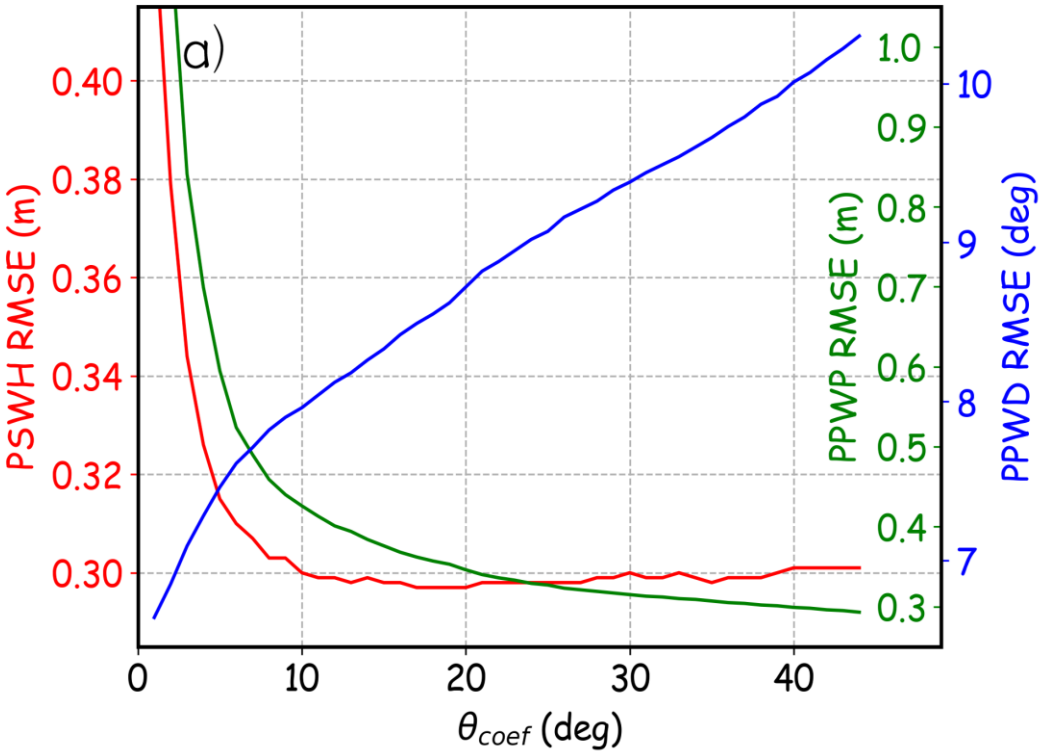
$$D = \sqrt{\left(\frac{T_a - T_b}{1\text{s}}\right)^2 + \left(\frac{\theta_a - \theta_b}{\theta_{coef}}\right)^2}$$

$\theta_{coef} = 25°$

Different values of $\theta_{coef}$ also impact the error metrics.

- The RMSE of PPWD increases with the increase of $\theta_{coef}$
- The RMSE of PPWP decreases with the increase of $\theta_{coef}$
- The RMSE of PSWH first decreases with the increase of $\theta_{coef}$ then become stable

*When* $\theta_{coef}$ = 15°~50°
PSWH RMSE: ~ 0.3 m
PPWP RMSE: 0.4~0.3 s
PPWD RMSE: 8.5~10.5 °



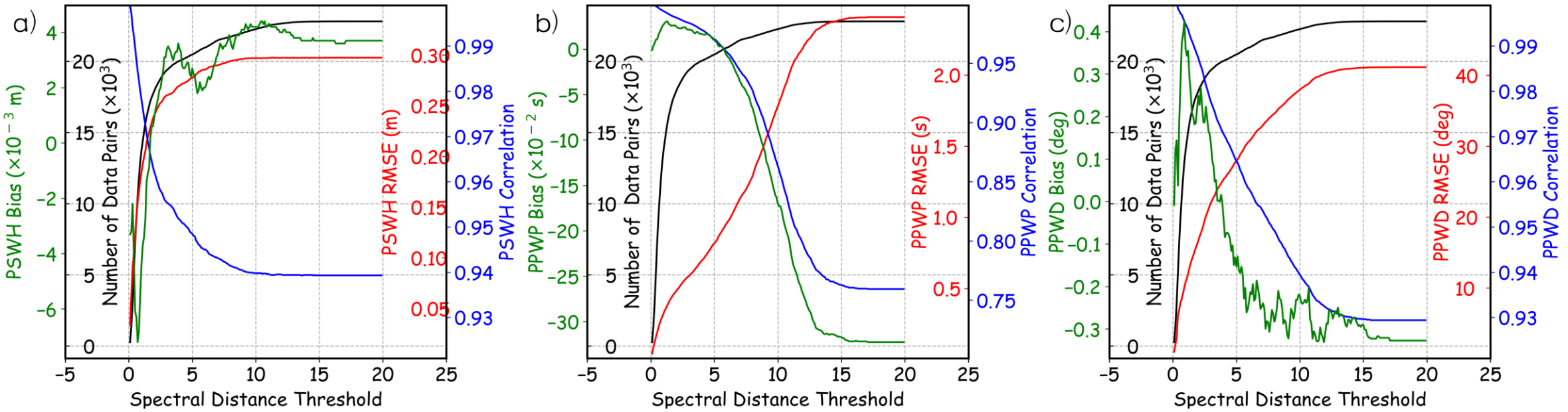

RMSEs of PSWH (red), PPWP (green), and PPWD (blue) for best-matched partitions as a function of $\theta_{coef}$

# 2. Discussion: Comparing Partitions from two Spectra

➢ **Error Evaluation** **<Changing Threshold>**

$$D = \sqrt{\left(\frac{T_a - T_b}{1\text{s}}\right)^2 + \left(\frac{\theta_a - \theta_b}{\theta_{coef}}\right)^2} \qquad \theta_{coef} = 25°$$

- Using a threshold of D during cross-assignment seems to be a feasible method for removing the outliers, but… error metrics are sensitive to the threshold.



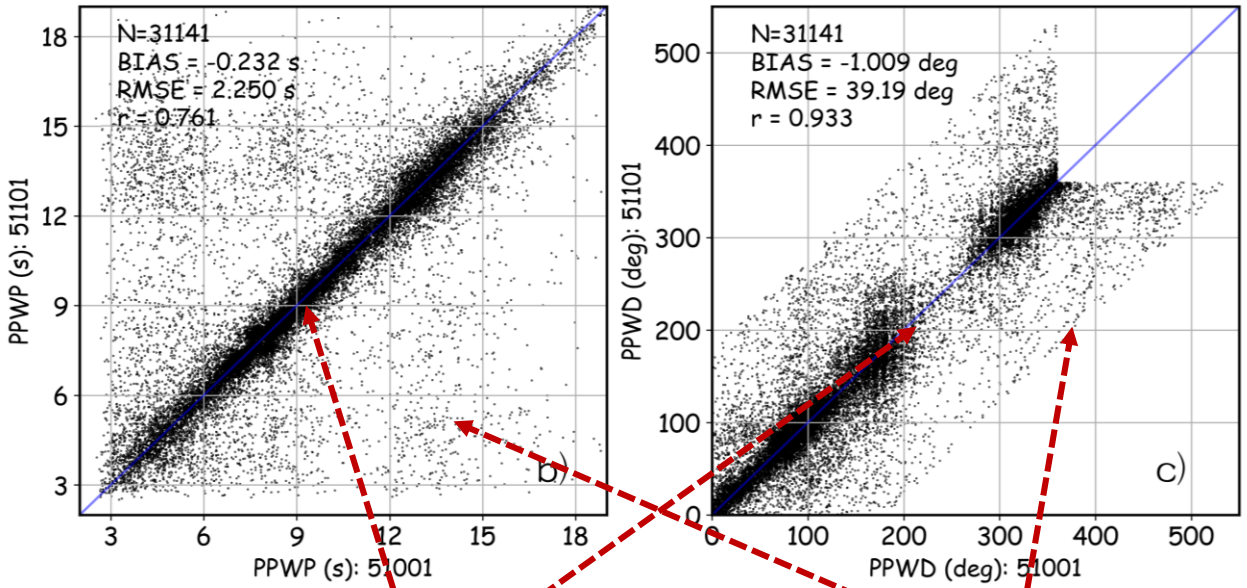

Number of cross-assigned data pairs (black), bias (green), RMSE (red), and CC (blue) of (a) PSWH, (b) PPWP, and (c) PPWD between buoy 51001 and 51101 as a function of spectral distance threshold

These curves can also serve as a tool to demonstrate the comparison between the partitions from two sets of wave spectra ?

# 2. Discussion: Comparing Partitions from two Spectra

## ➢ Error Evaluation <Maximum Likelihood>

- Another method: Assuming the distributions of differences of PPWP and PPWD are the superposition of a normal distribution $U(a, b)$ and a uniform distribution $N(\mu,\sigma^2)$

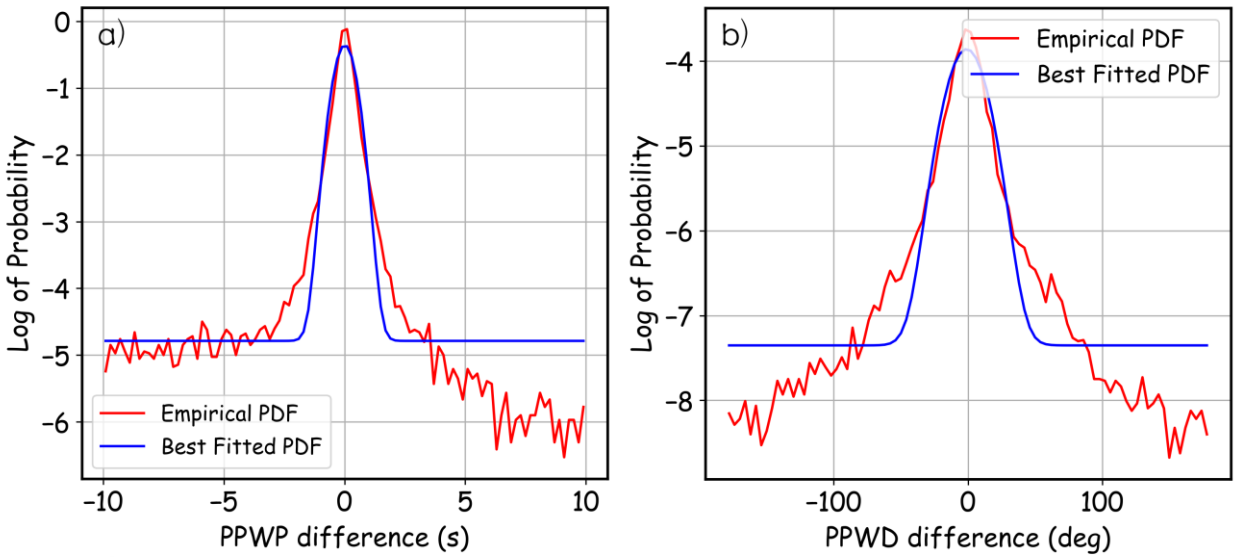



**Normal Distribution** + **Uniform Distribution**

$N(\mu,\ \sigma^2)$ $U(a, b)$

$\sigma$~0.5 s

$\sigma$ ~10°




PDFs of (a) PPWP and (b) PPWD difference between buoy 51001 and 51101

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# 3. Results: SWIM V.S. Buoy Partitions

## ➢ SWIM data

- Level-2, version 5.1.2
- May 2019 ---- April 2020
- Partitioned using Hanson & Phillips (2001) + Portilla et al (2009)[Smoothing]
- Partitioned peak wave lengths are converted to partitioned peak wave periods

## ➢ Collocation & Cross-assignment

- A 50-km-30-min window is used first
- Only ~360 collocations
- $\theta_{coef} = 25°$
- Beam 10° performs the best using all methods

Computed errors of different beams

| | Beam 6° | Beam 8° | Beam 10° | Wave Box |
|---|---|---|---|---|
| No. Collocation | 371 | 367 | 360 | 391 |
| PSWH RMSE | 0.66 m | 0.60 m | 0.61 m | 0.63 m |
| PPWP RMSE | 0.74 s | 0.62 s | 0.60 s | 0.69 s |
| PPWD RMSE | 23.2° | 20.4° | 20.4° | 21.3° |
| PSWH Bias | 0.46 m | 0.35 m | 0.36 m | 0.33 m |
| PPWP Bias | -0.16 s | -0.16 s | -0.11 s | -0.19 s |
| PPWD Bias | -2.5° | -2.9° | -3.5° | -2.7° |
| PSWH CC | 0.92 | 0.91 | 0.91 | 0.92 |
| PPWP CC | 0.96 | 0.97 | 0.97 | 0.96 |
| PPWD CC | 0.86 | 0.85 | 0.85 | 0.86 |

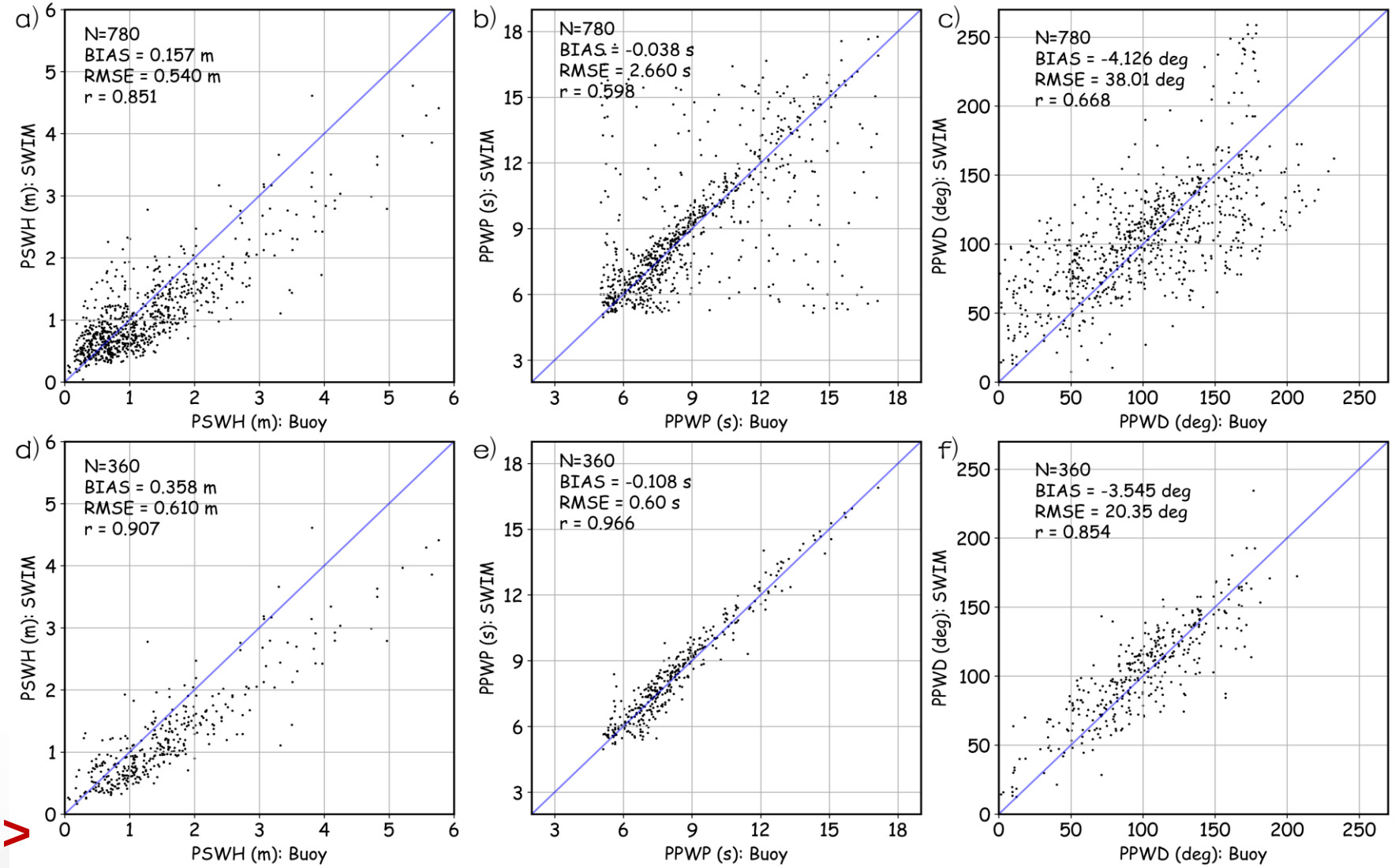
# 3. Results: SWIM V.S. Buoy Partitions

## ➢ Error estimation after cross-assignment

All partitions are cross-assigned and compared

Only partitions with the minimum spectral distance for each pair of spectra are cross-assigned

**<Best-matching>**

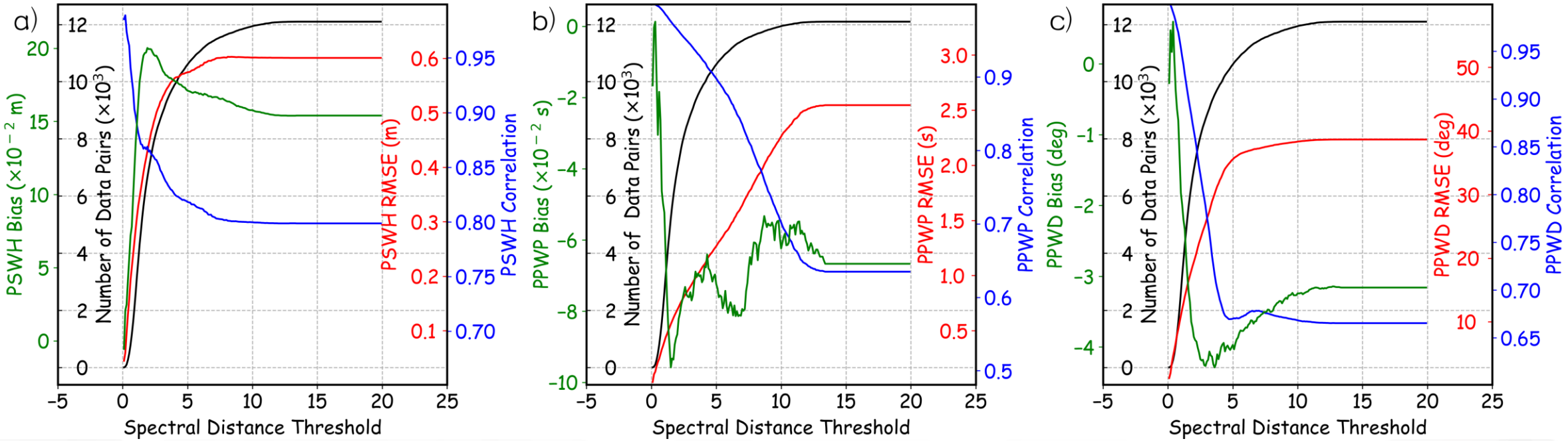


# 3. Results: SWIM V.S. Buoy Partitions

➢ **Error estimation after cross-assignment** **<Changing Threshold>**

- Increasing the spatial window to 200 km to yield more collocations.
- The spatial representativeness error can be estimated by changing the window size:

  ~0.1 m for PSWH  ~0.1 s for PPWP  ~1° for PPWD

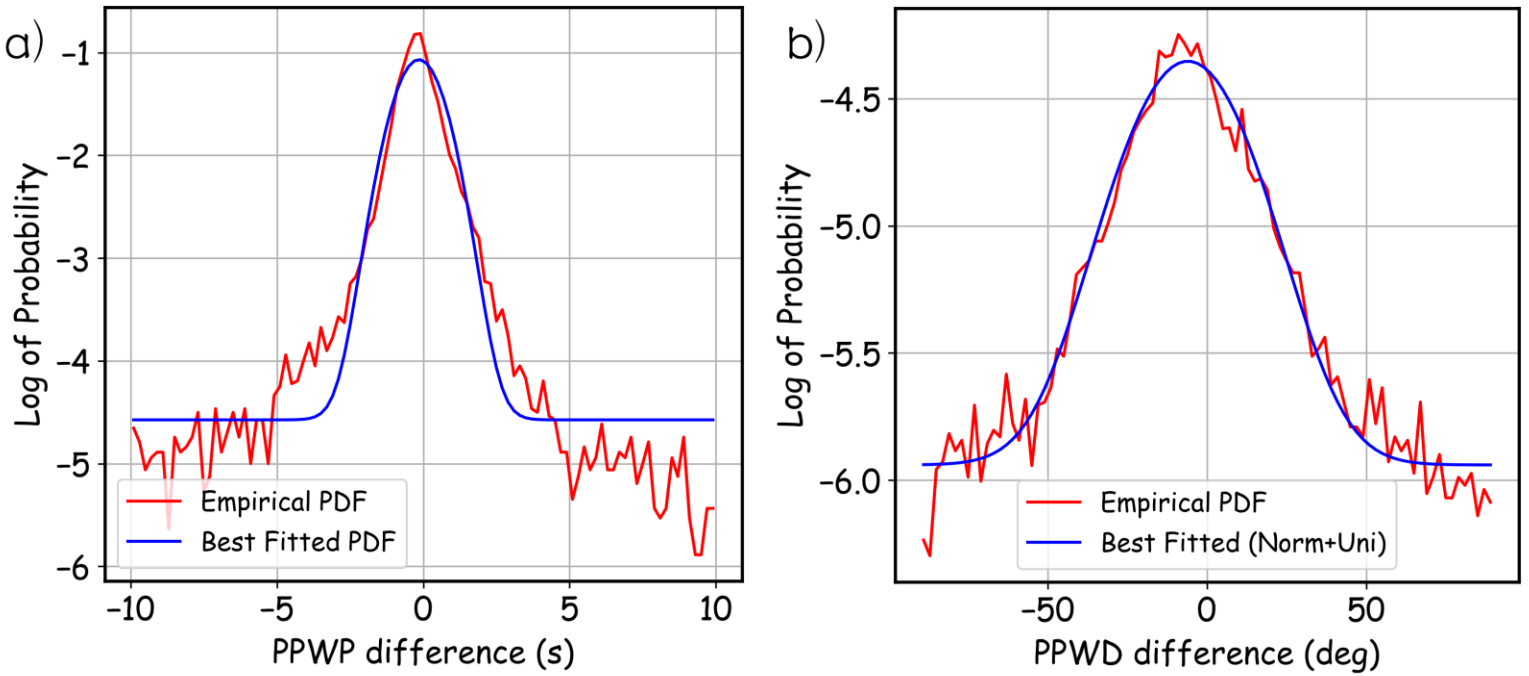



Number of cross-assigned data pairs (black), bias (green), RMSE (red), and CC (blue) of (a) PSWH, (b) PPWP, and (c) PPWD between buoy and SWIM as a function of spectral distance threshold

# 3. Results: SWIM V.S. Buoy Partitions

➢ **Error estimation after cross-assignment** **<Maximum Likelihood>**

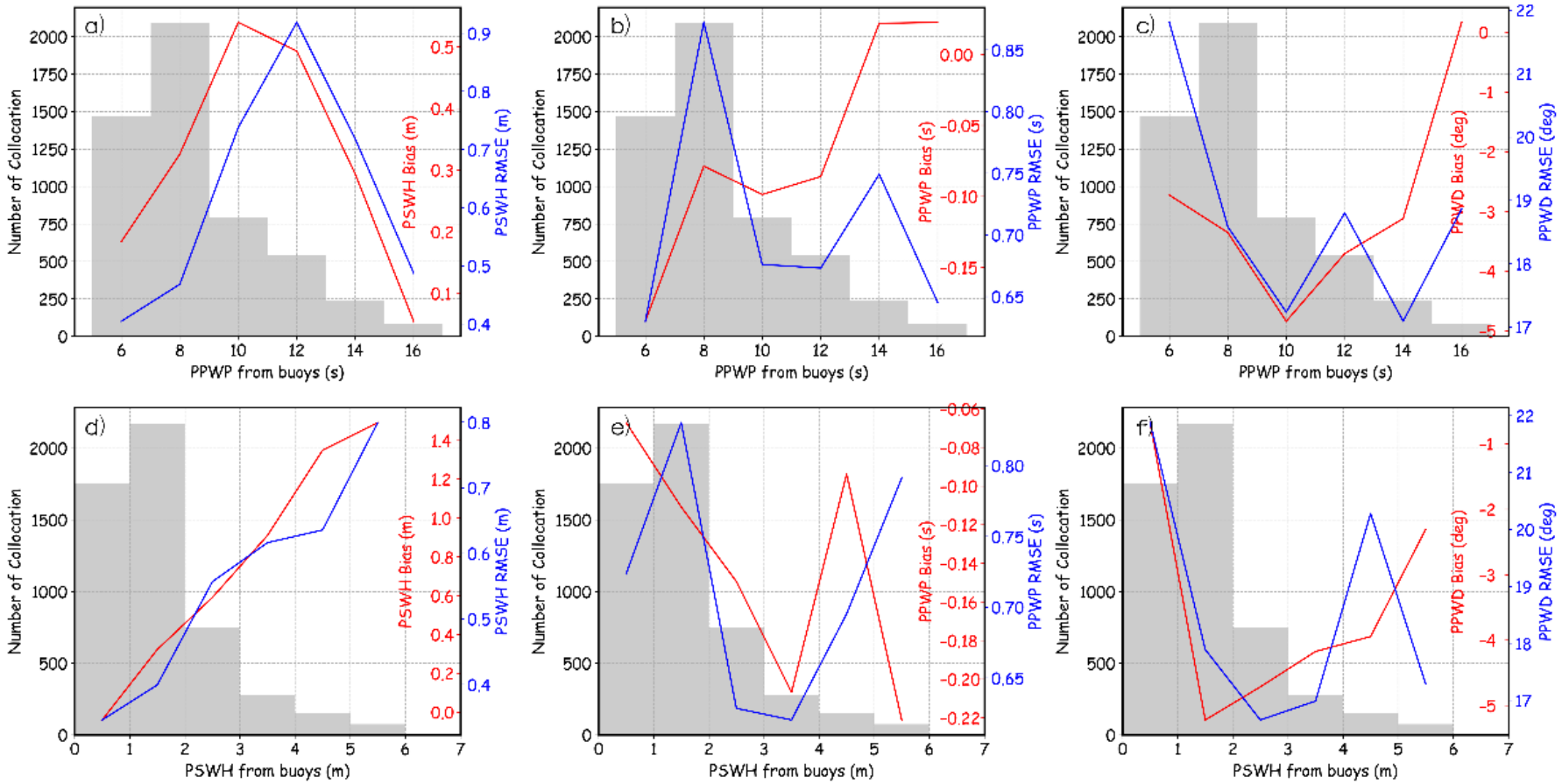
*σ~0.9 s* *σ ~20°*




PDFs of (a) PPWP and (b) PPWD difference between buoy and SWIM using a 200 km spatial window

# 3. Results: SWIM V.S. Buoy Partitions

➢ **Error estimation after cross-assignment** **<Best-matching>**




Biases (red) and RMSEs (blue) of PIWPs (left: PSWH, middle: PPWP, right: PPWD) from SWIM for each (a-c) 2-s bin of buoy PPWPs and (d-f) 1-m bin of buoy PSWH.

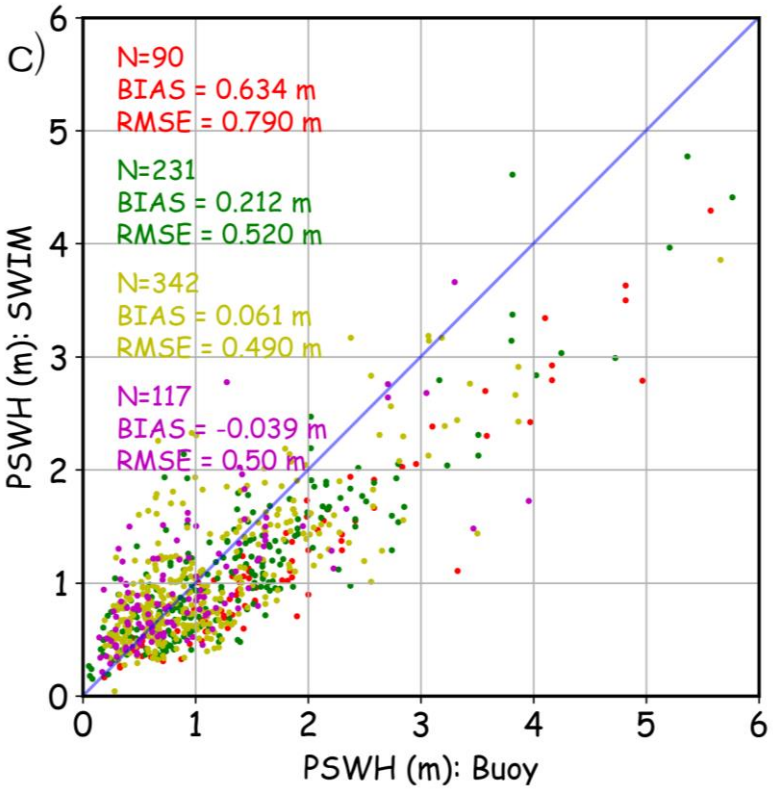
# 3. Results: SWIM V.S. Buoy Partitions

## ➢ Calibration ?

- Linear calibration is almost not helpful for the accuracy of PPWP and PPWD.
- If PSWHs are calibrated against buoy partitions, the total SWH will be overestimated!

## ➢ Potential Reasons for PSWH errors

- Bias: Less identified partitions in buoy spectra → higher mean PSWH for buoys
- RMSE: Spectral folding → More overlapping of spectral energy → Under/over-estimation of low/high energy partition.

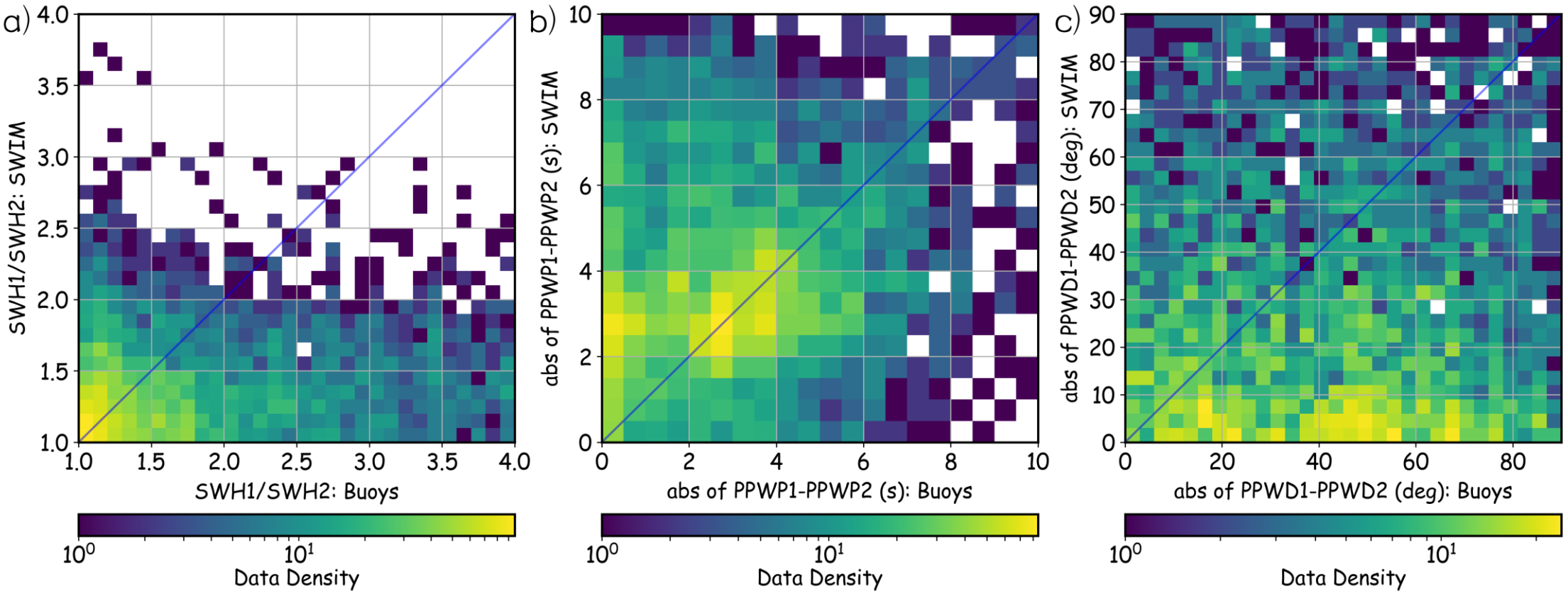



Color: Number of partitions identified in buoys

Red: 1
Green: 2
Yellow:3
Cyan: 4

# 3. Results: SWIM V.S. Buoy Partitions

## ➢ Comparing the relationship between partitions




Comparison of (a) PSWH ratio, (b) PPWP difference, and (c) PPWD difference between the 1st and 2nd partitions between buoy and SWIM spectra

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# 4. Summary

- Cross-assignment of partitions between two spectra is easily impacted by missing or spurious partitions (very common).
- Three method to partly solve the problem:
  - Best-matching method can get rid of most outliers, but the results can only be regarded as the lower limit of errors.
  - The curves of error as a function of spectral distance thresholds can be helpful to evaluate the error, but the result of this method is difficult to explain.
  - The RMSE of PPWP and PPWD can be estimated using the maximum likelihood method, but not applicable for PSWH.
- For SWIM data
  - The RMSEs of PPWP (0.9 s) and PPWD (20°) are generally small, while the performance of PSWH still needs to be improved.

**THANKS!**

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