全球定位系統反射觀測 (GNSS-R)原理與產品

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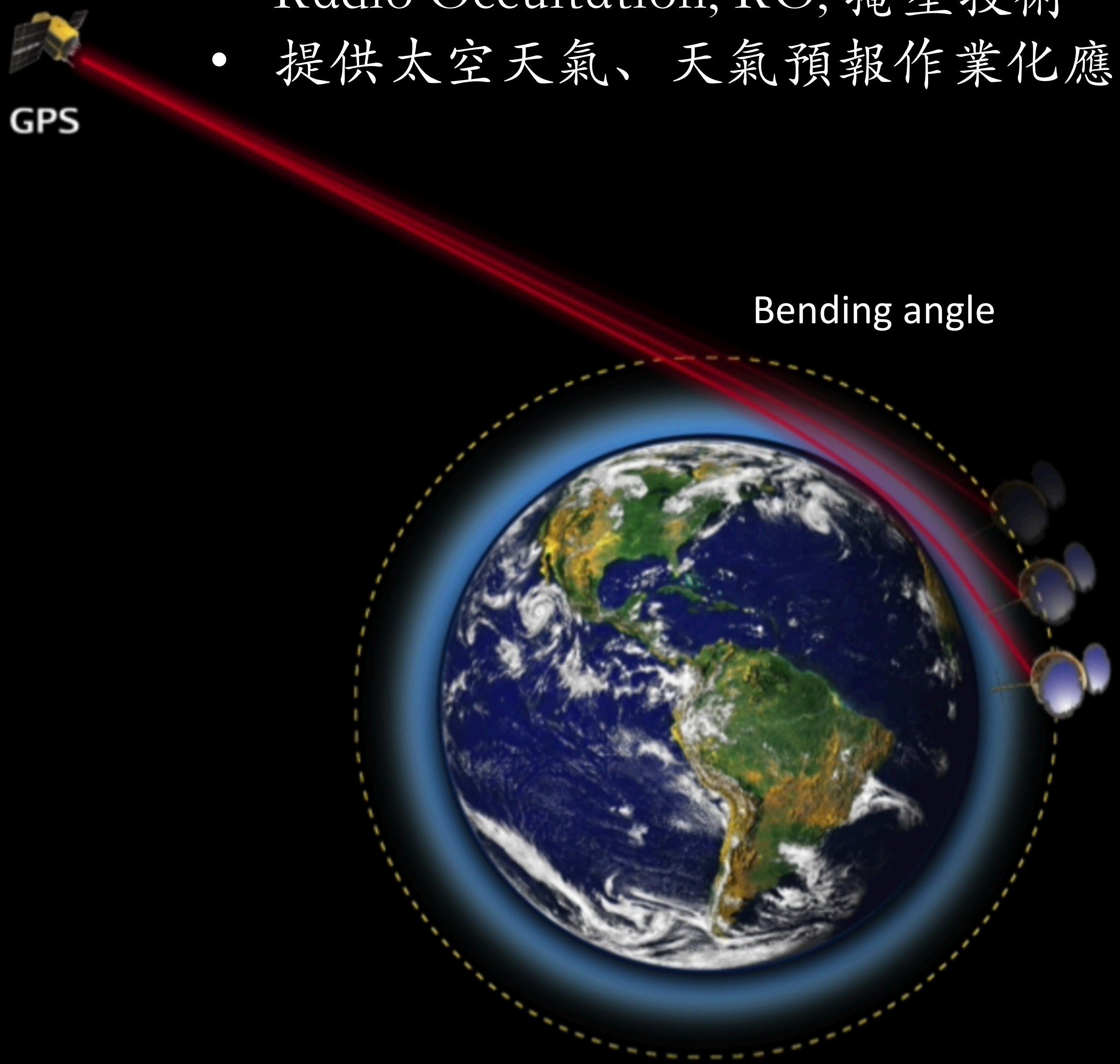
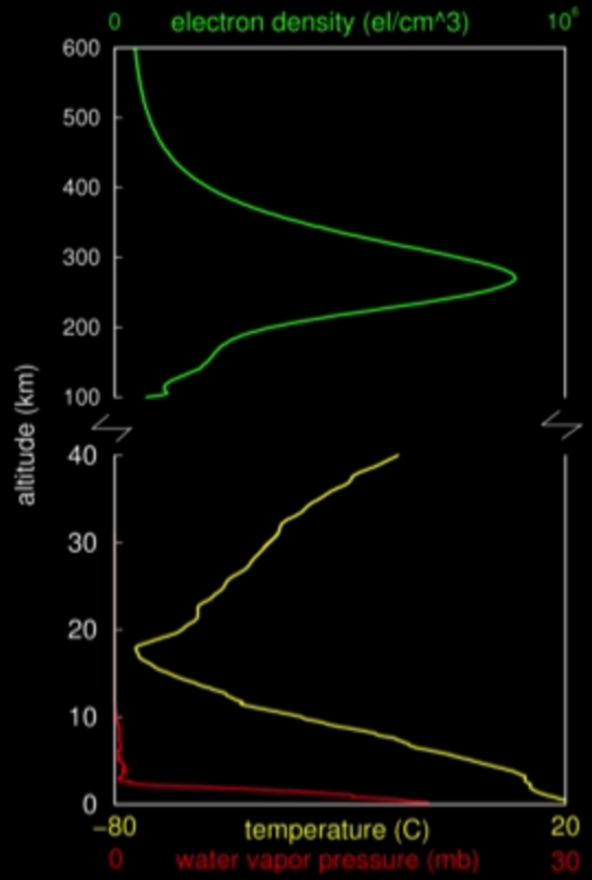
福衛七：

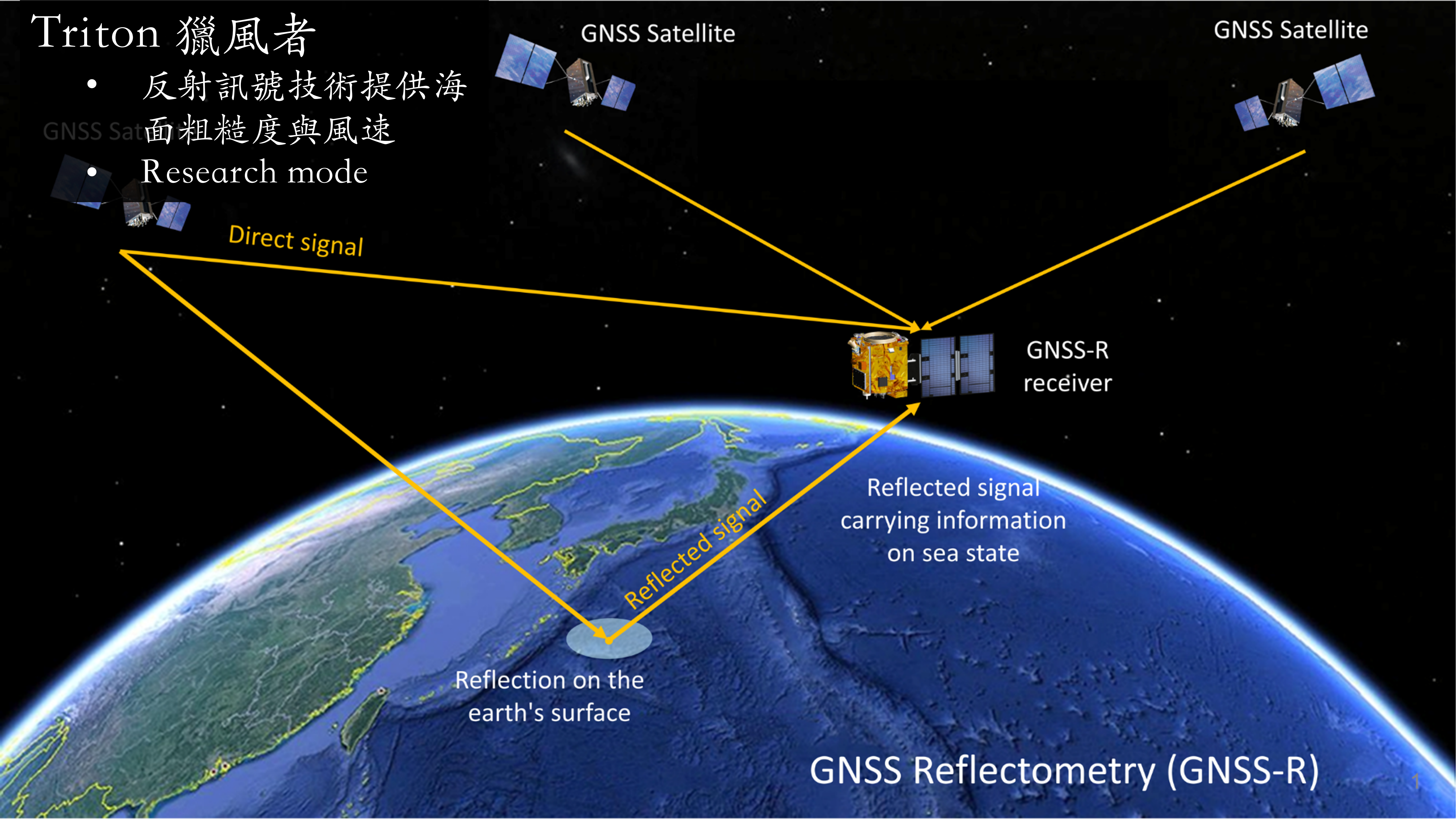
- Radio Occultation, RO, 掩星技術
- 提供太空天氣、天氣預報作業化應用





Triton 獵風者

- 反射訊號技術提供海面粗糙度與風速
- Research mode

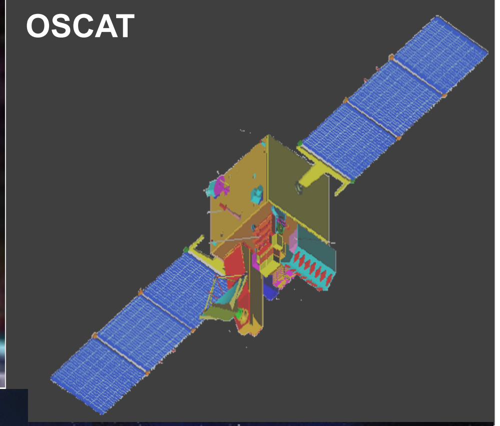


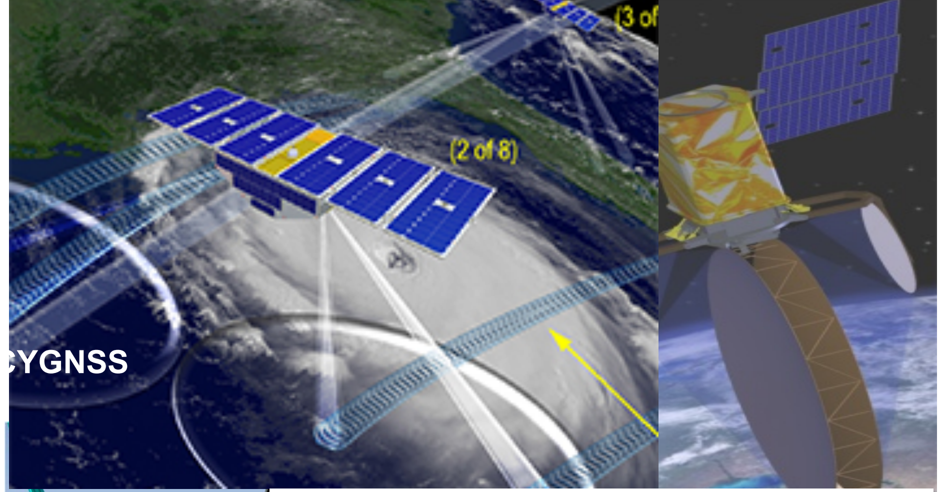
福衛七號 RO 大氣應用

- 優勢：
  - 應用RO資料同化技術於精進天氣預報服務之成效，氣象局與學界已分別針對全球模式、區域模式預報完成充分量化評估：福七資料可帶來預報準確性全面性的提升，特別是提升氣旋生成可預報度，對颱風預報而言：路徑預報改善15.5%、強度預報(36~120hr)改善9.61%。目前全球模式RO資料同化已經作業化上線運行。
  - 台灣作為全球最重要的RO資料提供者之一，其貢獻將逐步提高相關領域國際影響力。
- 挑戰：
  - 精進低空資料反演，特別是海洋邊界層(Marine Boundary Layer)參數。
- 策略：
  - 資料同化是產品加值關鍵技術，持續精進技術、培育人才。
  - 因無後續長期計畫規劃，針對對技術團隊之培養、維持與發展，參考它國以商業模式民間經營運轉提供RO資料，深入評估作為國家未來賡續發展規劃依據

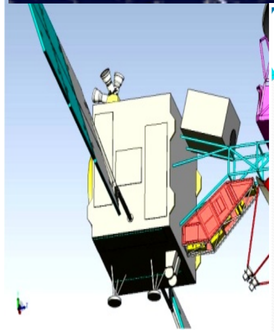
獵風者研究與應用

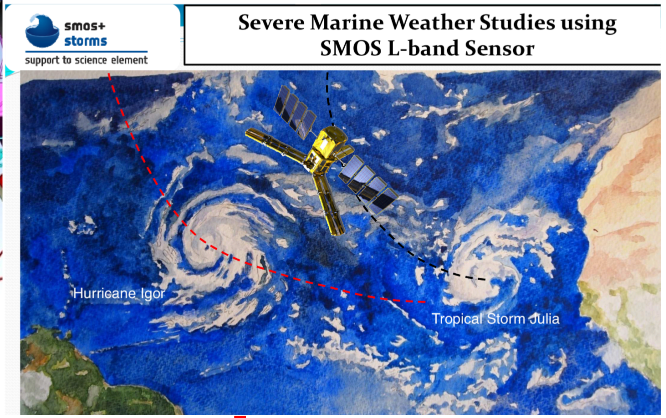
- 優勢
  - 操控系統、科學酬載、感測器、資料反演核心模組全由國人自行研製。完成科學儀器飛測，運作穩定正常。
  - 關鍵感測器DDMI解析度較國際上其他團隊高四倍。
- 挑戰
  - GNSS-R尚在Research mode：目前在軌服役僅有美國CYGNSS(2017-2023)與中國捕風者(2019-2021)，可供研究發展借鏡之資料與實務經驗少
  - 風向資料反演技術有待開發
  - 高風速資料反演正確性有賴於海氣交互作用過程機制的理解，微觀尺度Process-based大氣海洋現象之基礎科學進展很重要
  - 星系規劃單一衛星，需要資料同化技術增加資料應用價值
- 策略與建議
  - 強化國際連結與交流：持續追蹤、評估、效仿既有技術，並同時進行自主創新；
  - 上下游整合：跨域結合大氣、海洋與資工學門，以基礎研究成果加速反演技術開發，促進資料同化技術精進
  - 橫向擴大研究團隊：鼓勵多方參與、獨立發展，增加產品應用面向（土壤含水量、水文循環、海冰）
  - 自主海上實測能量建置(Capacity building)：以滿足獵風者及福七需求為目標，強化國內海洋大範圍、惡劣天候條件之Sea-truth資料觀測技術與團隊能量



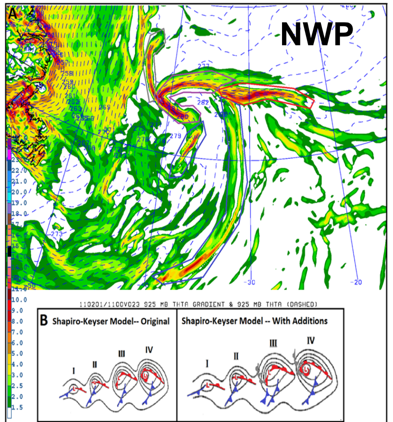


For Extreme wind measurement, new instrument design for future satellite instruments is needed to improve current scatterometer and radiometer satellite measurements



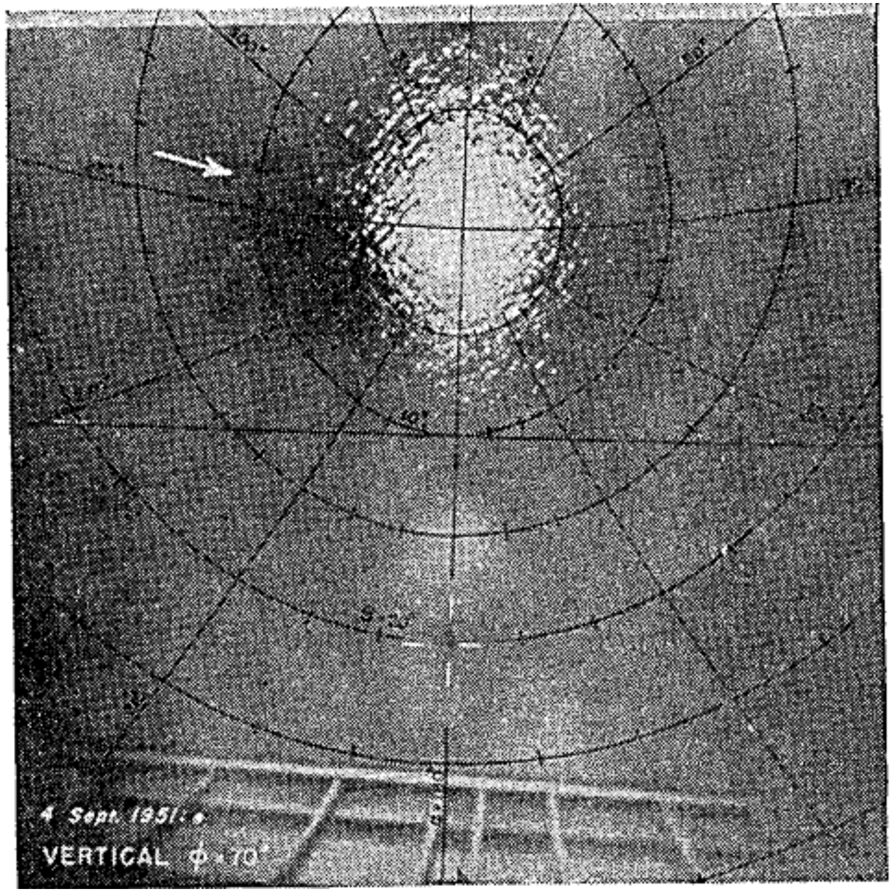


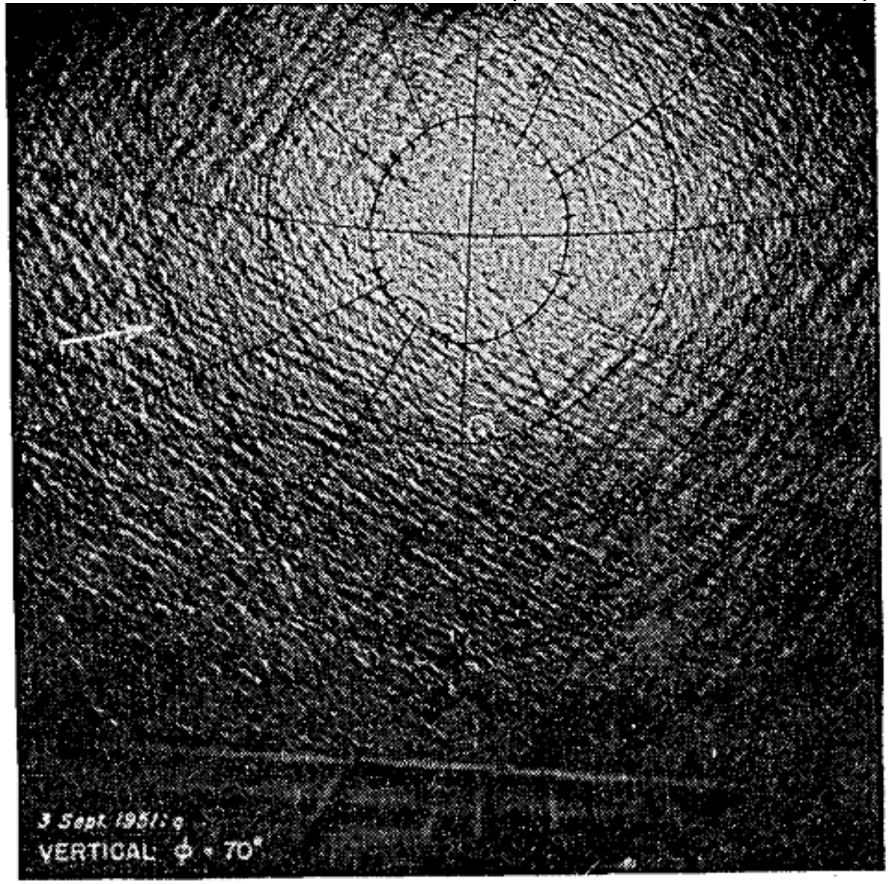
Bring new insights into physics of hurricane force winds within tropical storms



海面耀斑強度呈現二維高斯空間分布，反應海表粗糙度特徵

(Cox and Munk, 1954)





- The pattern of the NRCS (averaged return strength from each gridded area) is a function of the pdfs of (MSS_{up}, MSS_{cr})
- pdf of (MSS_{up}, MSS_{cr}) are functions of (Wave Direction, Directional Spreading, Roughness)
- Sea surface roughness
  - Low-wavenumber: Gravity waves
  - High-wavenumber: Capillary waves

MSS vs. Wind Speed

- Cox and Munk (1954):

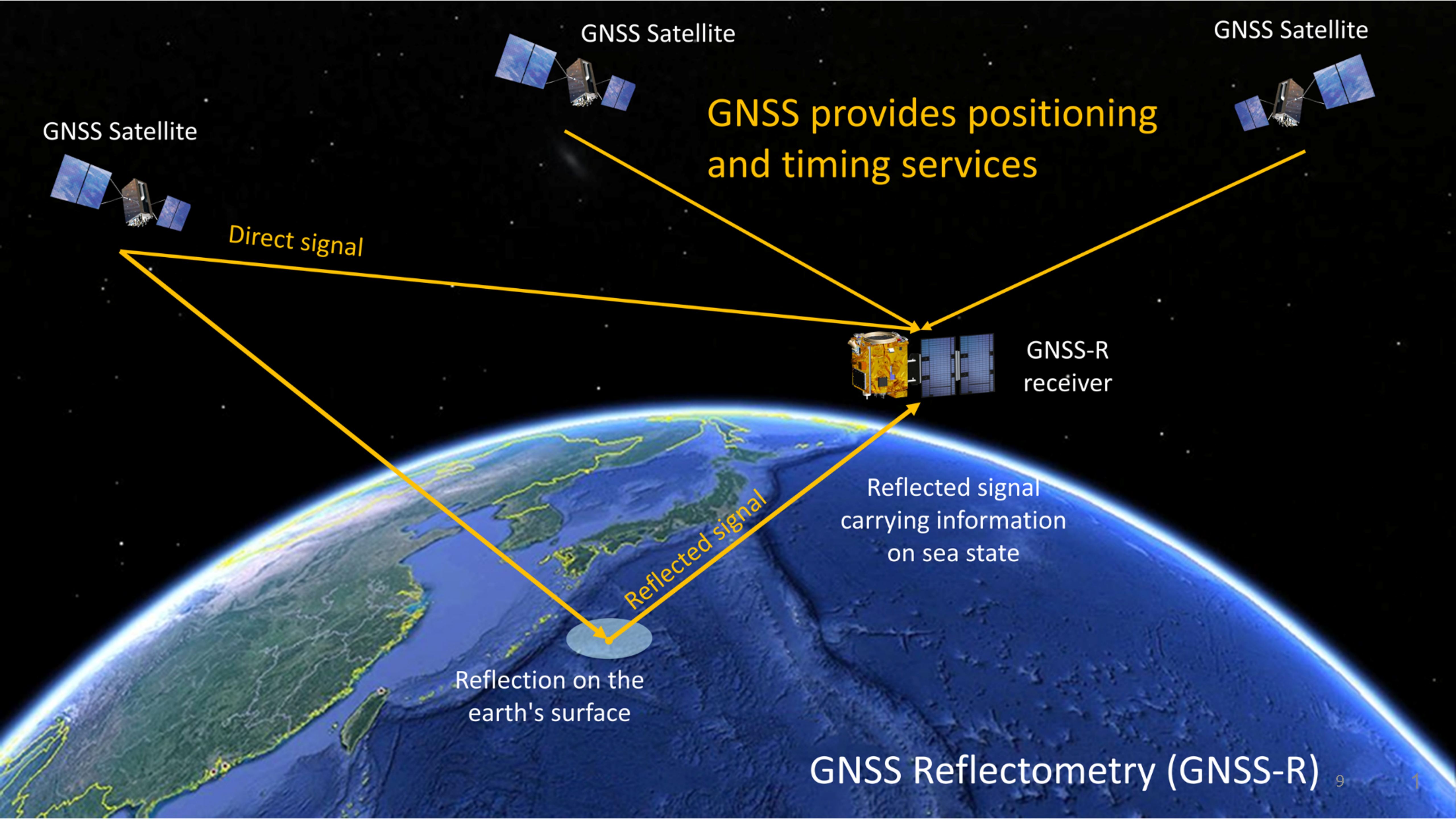
$$\begin{cases} cleansurface: MSS = 0.003 + 5.12 \times 10^{-3} U \pm 0.004\ with\ r = 0.986 \\ slicksurface: MSS = 0.008 + 1.56 \times 10^{-3} U \pm 0.004\ with\ r = 0.77 \end{cases}$$

- Wu (1972):

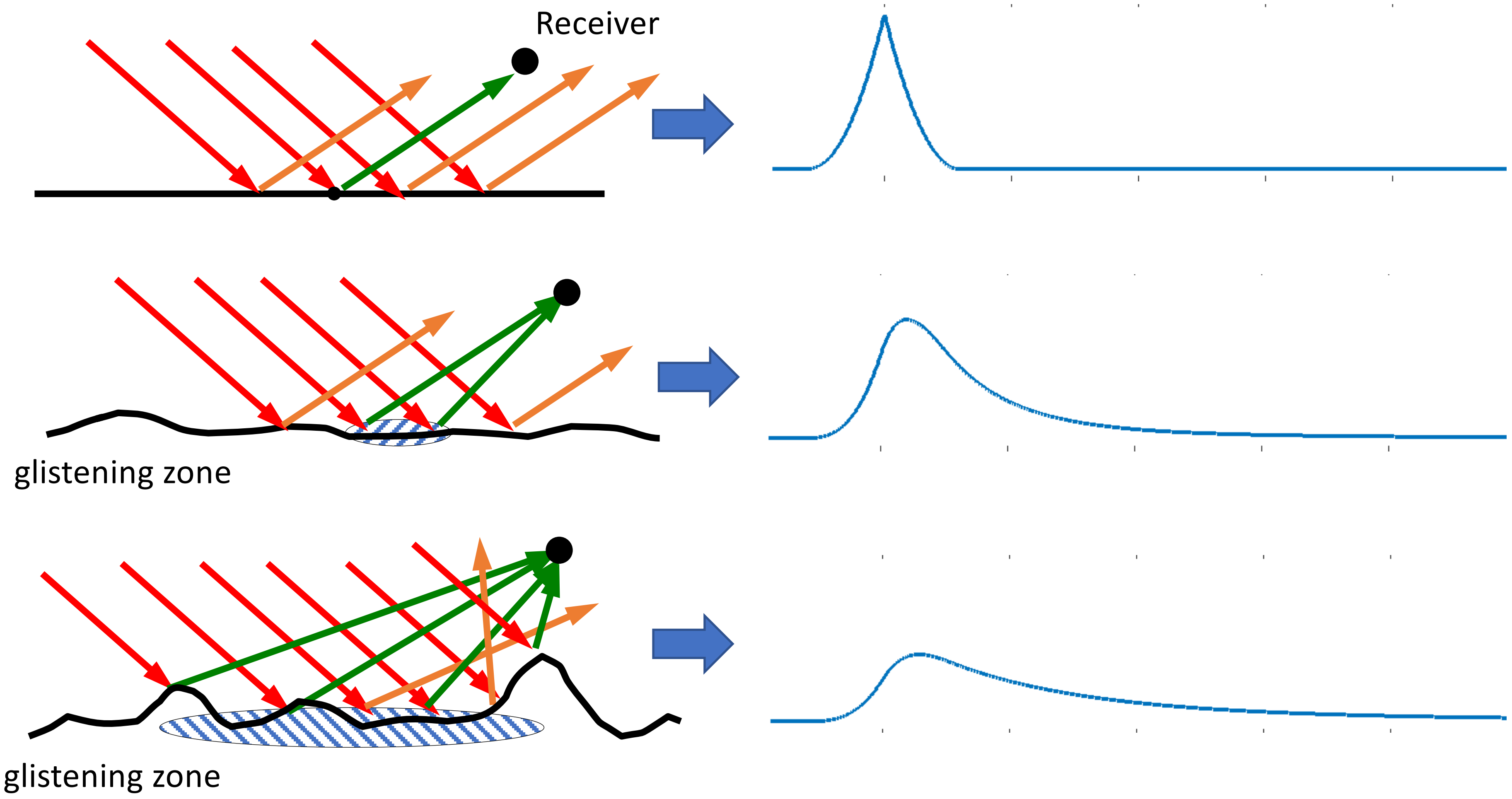
$$\begin{cases} MSS = (lnU_{10} + 1.2) \times 10^{-2}\ with\ U_{10} < 7m/s \\ MSS = (0.85 lnU_{10} - 1.45) \times 10^{-2} with\ U_{10} \geq 7m/s \end{cases}$$

- Hwang and Wang (2000):

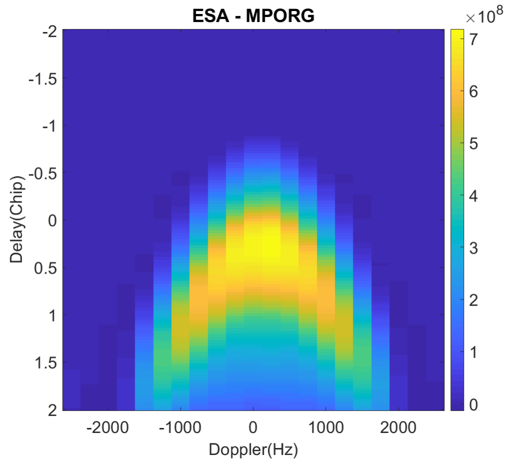
$$s^2 = MSS = 5.12 \times 10^{-3} U_{10} + 1.25 \times 10^{-3}$$

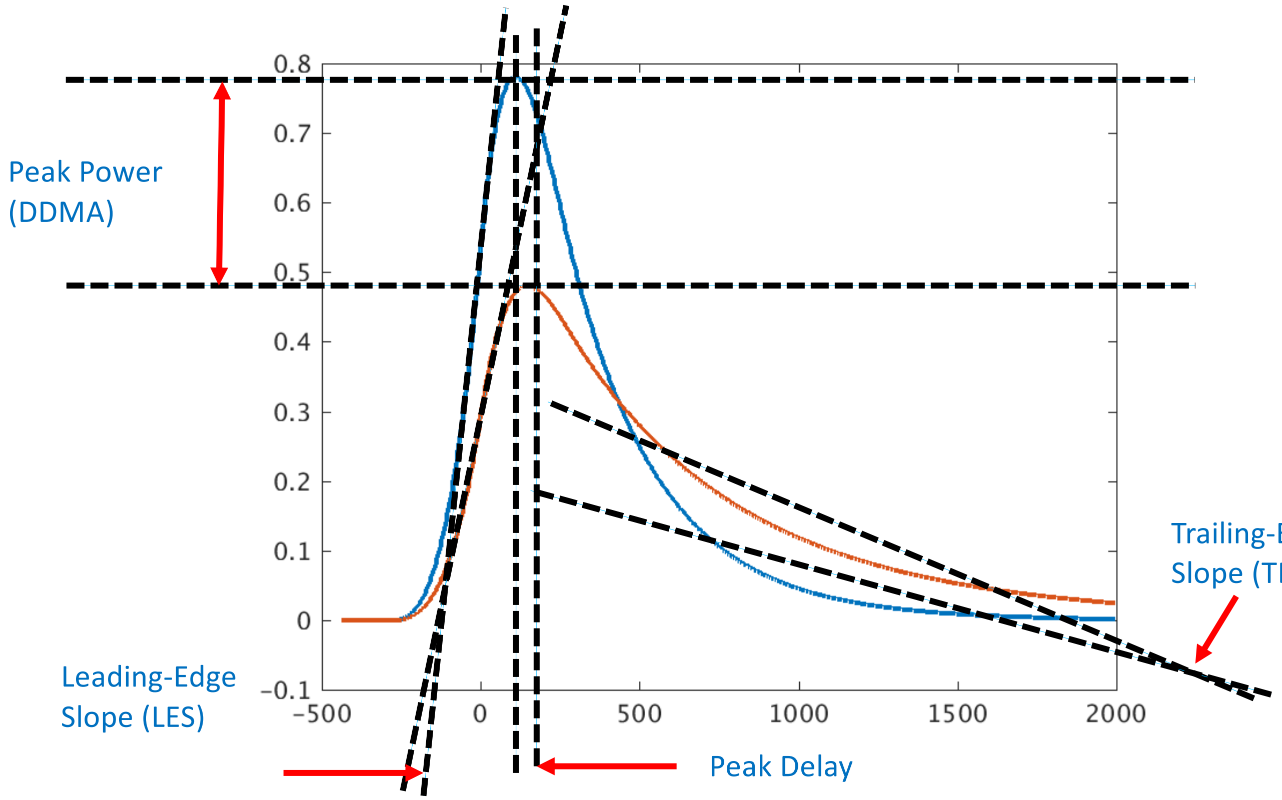

GNSS Satellite
GNSS Satellite
GNSS Satellite
GNSS provides positioning and timing services
Direct signal
GNSS-R receiver
Reflected signal
Reflected signal carrying information on sea state
Reflection on the earth's surface
GNSS Reflectometry (GNSS-R)

GNSS-R Basic Principles

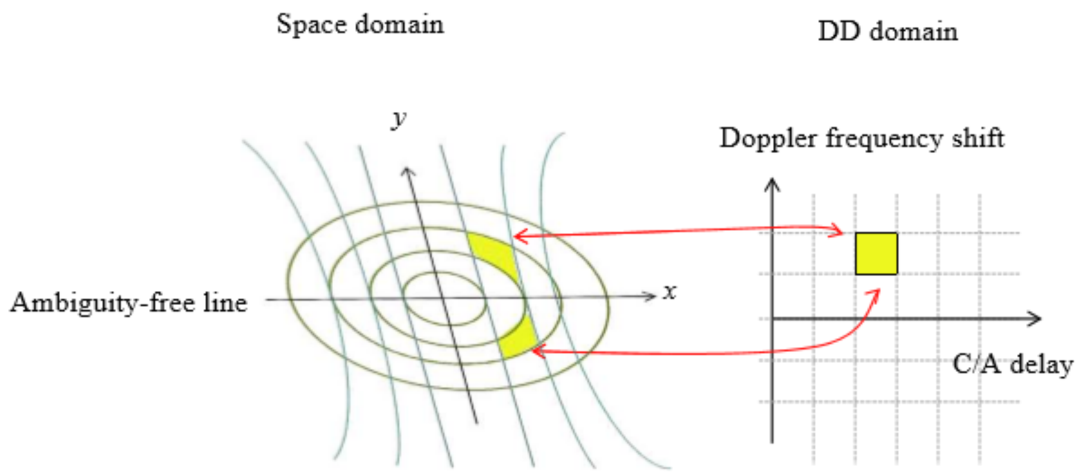


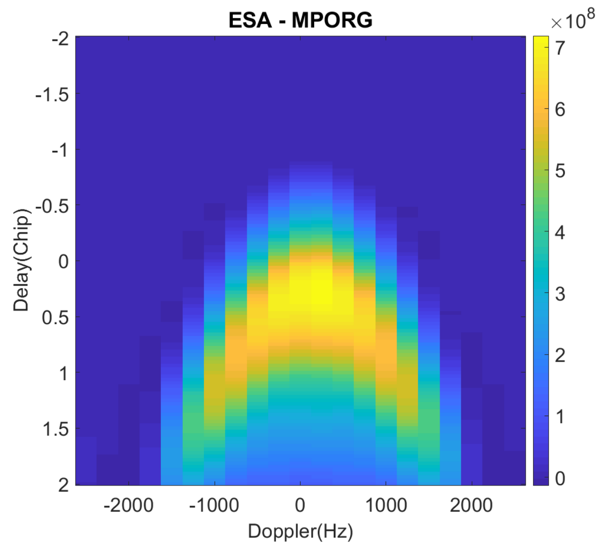
Two DDM observables



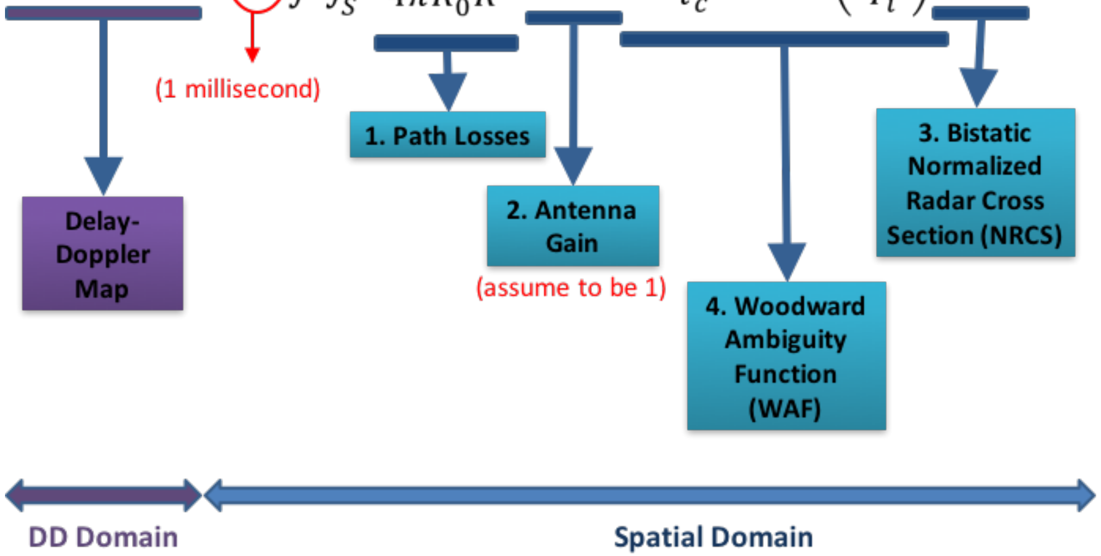


反射訊號空間分佈由Delay-Doppler Map轉換





$$\langle P(\tau, f_D)\rangle = T_i^2 \int\int_S \frac{1}{4\pi R_0^2 R^2} D^2(\mathbf{r})\Lambda^2\left(\frac{\delta\tau}{\tau_c}\right) sinc^2\left(\frac{\delta f_D}{T_i}\right)\sigma_o(\mathbf{r})d^2r$$



- The Delay Doppler Maps (DDM) show the shaped characteristics of GNSS-R correlated power over ocean
- The resolution is 128 bins in delay, and 64 bins in Doppler frequency in 16 bits resolution

$\text{PSA}(\tau, f_d) = \iint dxdy\, d\tau\, df_d$

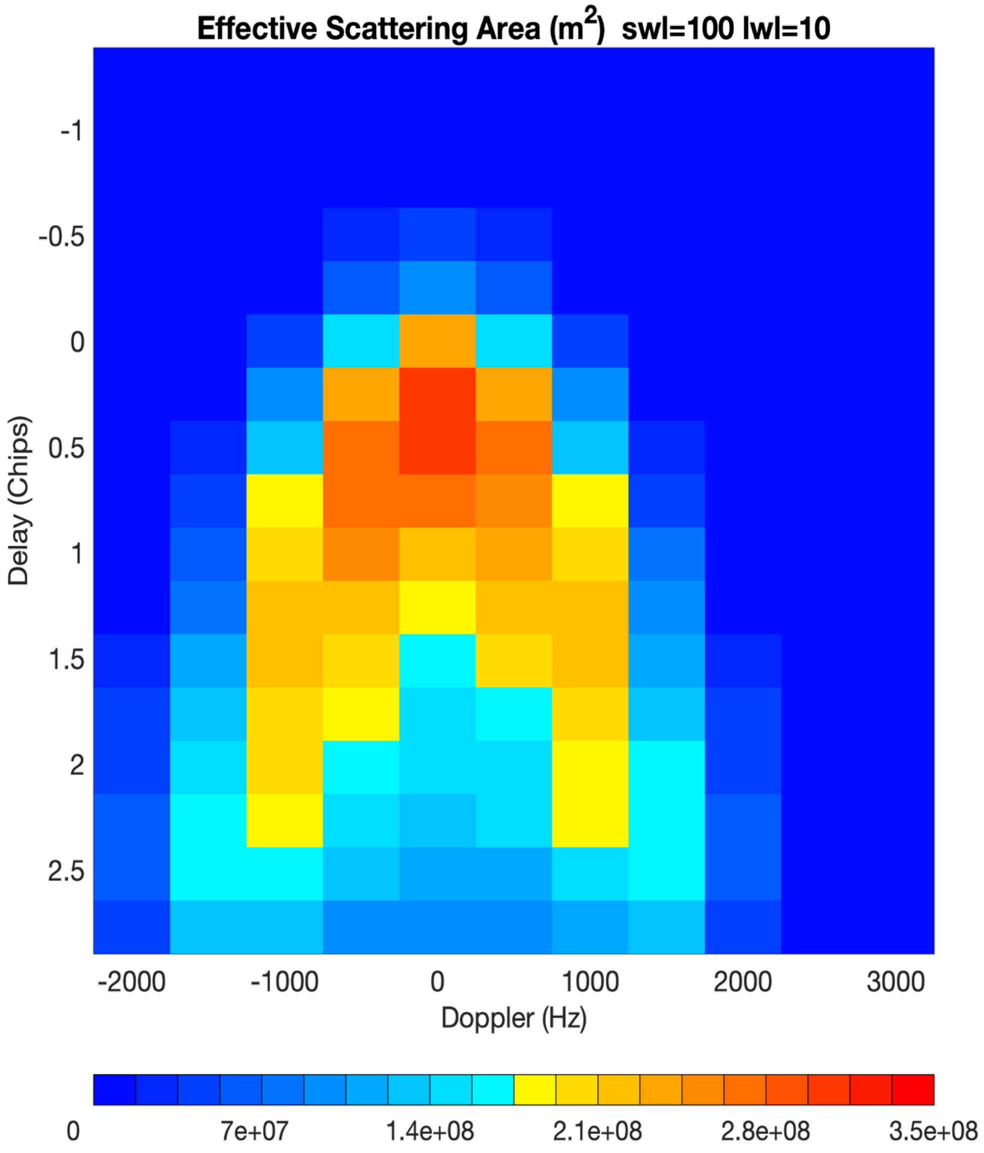
Apply sinc function on $\text{PSA}(\tau, f_d)$->esasinc (window length: 20 grid points)

```
sfunc2=(sinc(Ti.*dfreq).*abs(exp(-pi.*i.*dfreq.*Ti))).^2;
value=sfunc2*psa(bin_start:bin_end,jj);
esasinc(ii,jj)=value;
```

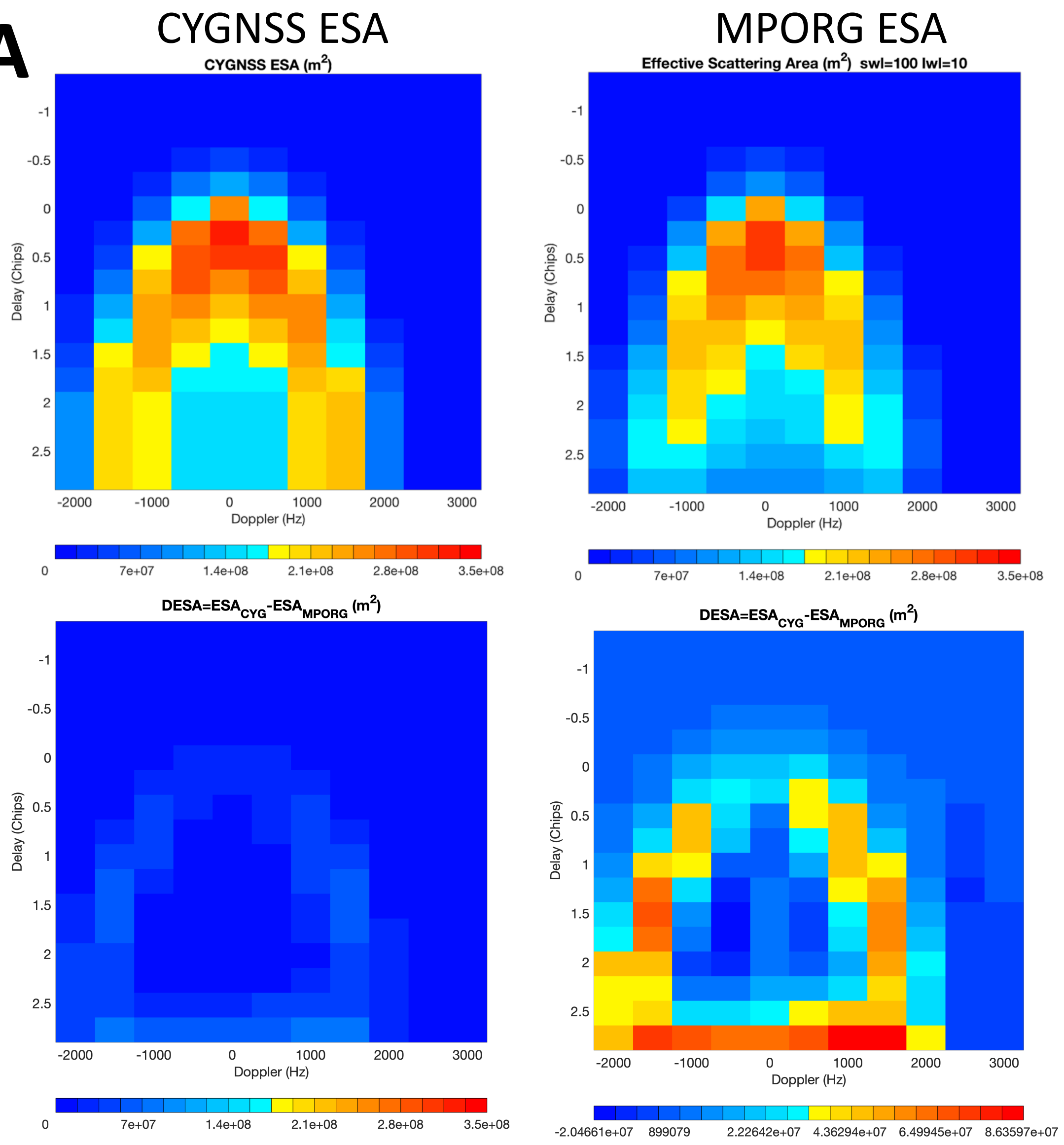
Apply lambda function on esasinc(τ, f_d)->ESA (window length: 10 grid points)

```
    lamda_waf=1-abs(dtau);%./tauc;
lamda_waf(abs(dtau)>1)=0;%follows from maximal length codes used in GPS
%2. s-fucntion:frequency response of the GNSS signal
%       sfunc2=(sinc(Ti.*dfreq).*abs(exp(-pi.*i.*dfreq.*Ti))).^2;
lamda_waf2=lamda_waf.^2;
 value2=lamda_waf2*esasinc(jj,chip_start:chip_end)';
esa(jj,ii)=value2;
```

Results: Effective Scattering Area (ESA)

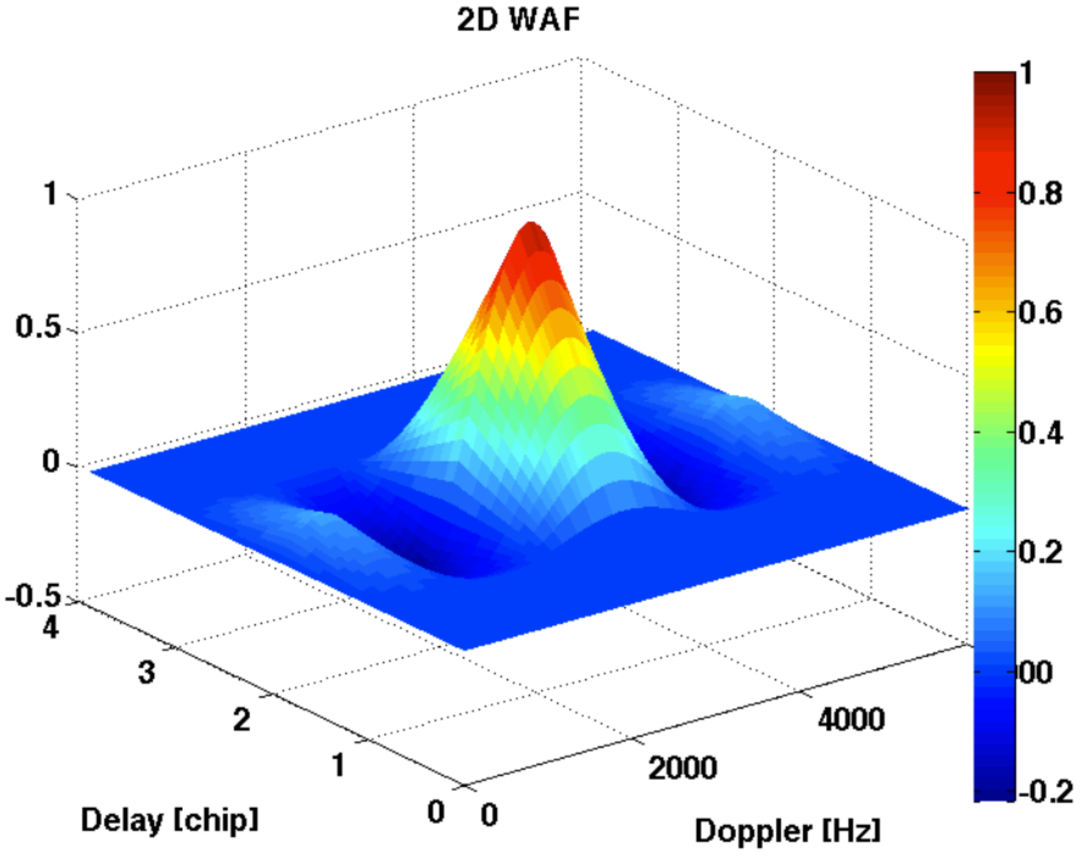


Validation: ESA

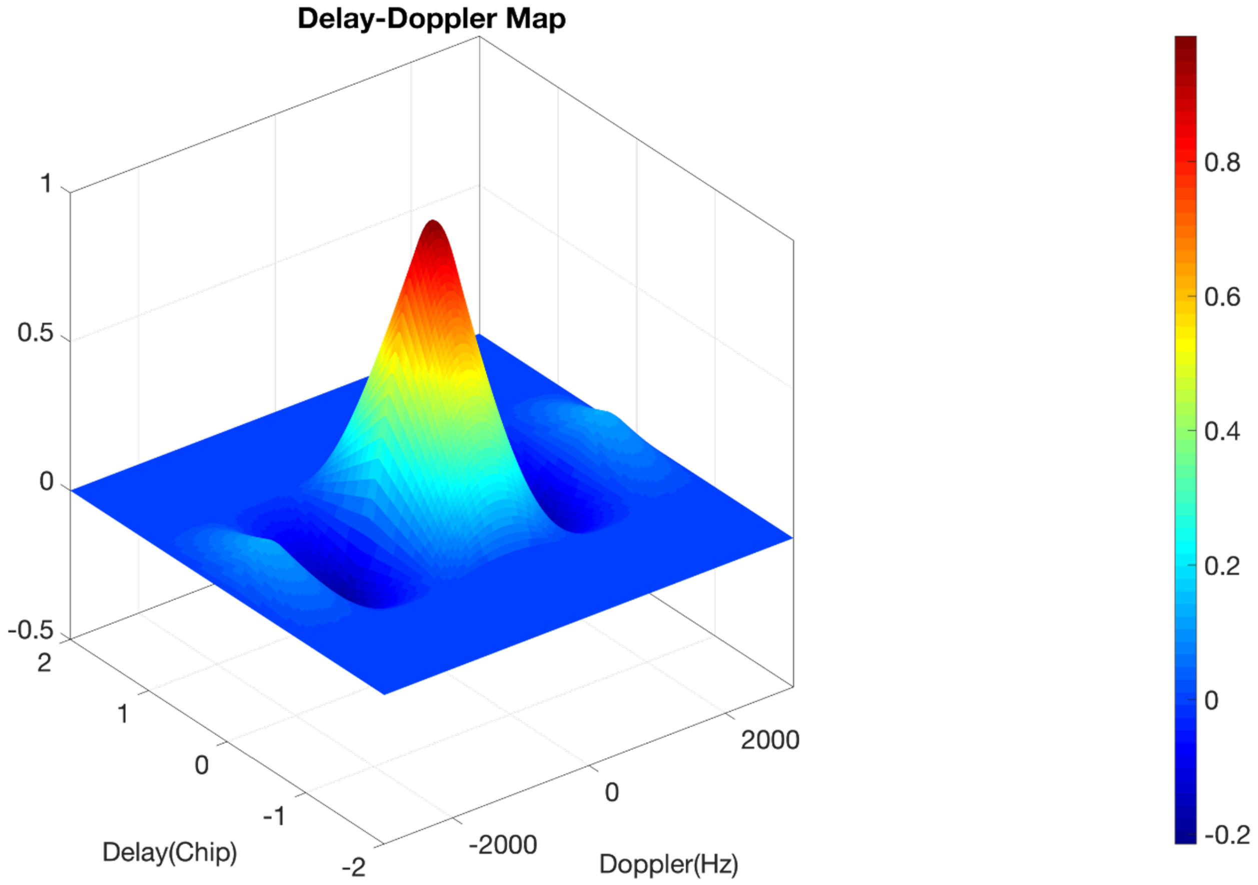


Effective scattering area comparison. CYGNSS ESA (upper left), MPORG ESA (upper right), ESA difference plotted in CYGNSS ESA value range (lower left), and ESA difference in the difference value range (lower right)

WAF



(Clarizia, 2012)



(Mporg, v01)

GNSS-R反演技術挑戰

- 風速條件反演品質
  - Scatterometer wind RMSE ~ 2.0 m/s (U10 ranges 4~24 m/S)
  - 原因：海上實測資料永遠不夠
- 風向呢？
  - 主動旋轉天線 vs. 被動式DDMI天線
- 相對於散度計，為什麼GNSS-R可能具有較佳高風速資料反演的潛力？
  - Bistatic scattering in Geometric Optics Model vs. Monostatic Bragg back-scattering
  - L band vs. Ku Band & C band

Build up U_{10} ground truth database near Taiwan using miniature buoy

Wind Speed=GMF(DDM observables, Incidence angle, Sea state)

Present

Separate by wind speed (20m/s) (CYGNSS)

Fully developed sea (ECMWWF)

Young Sea Limited Fetch (SFMR, buoy, drop sound)

Plan

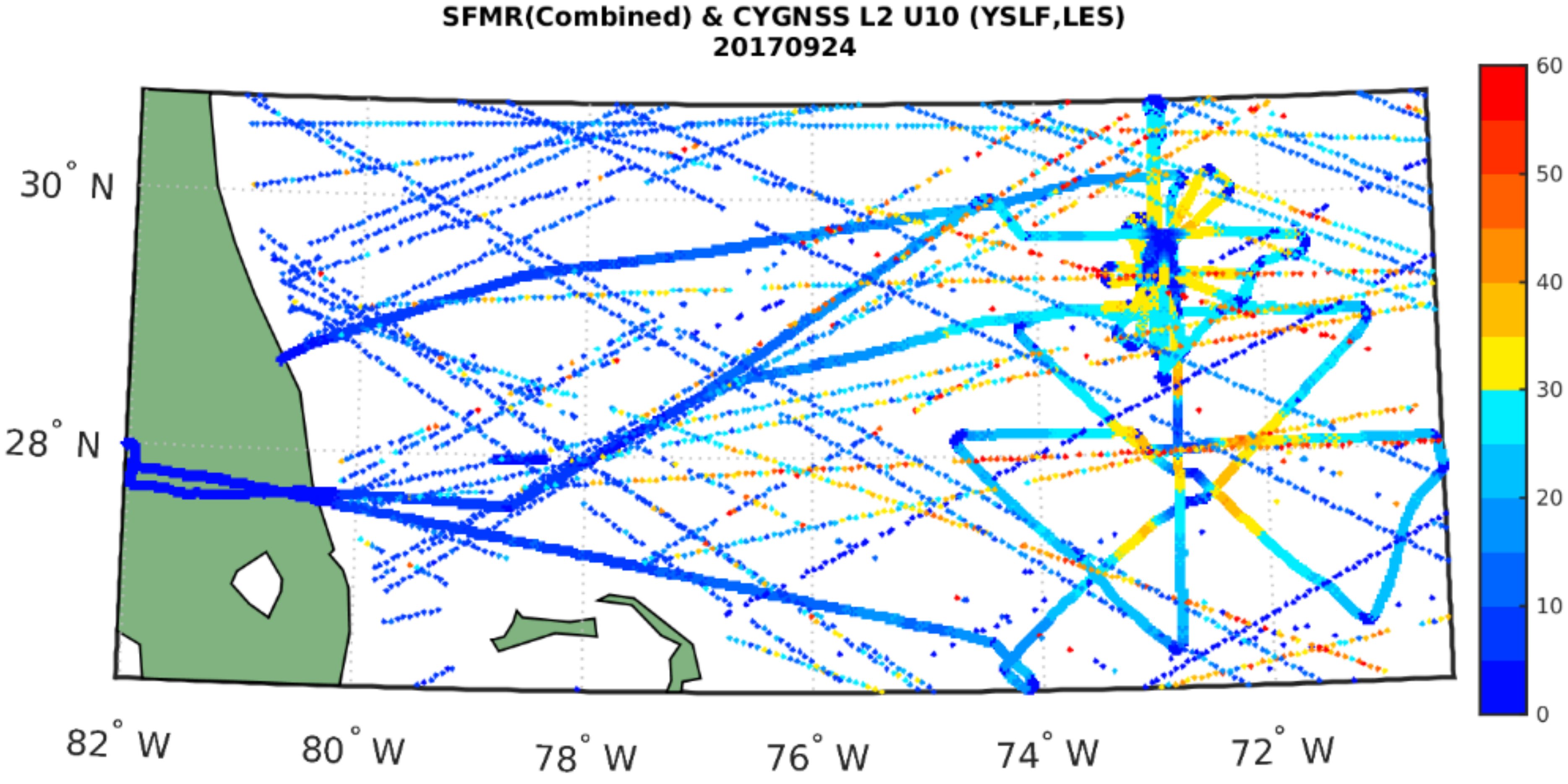
Separate by wave parameters (Hs, $T_{1/3}$,,wave age,Rb)

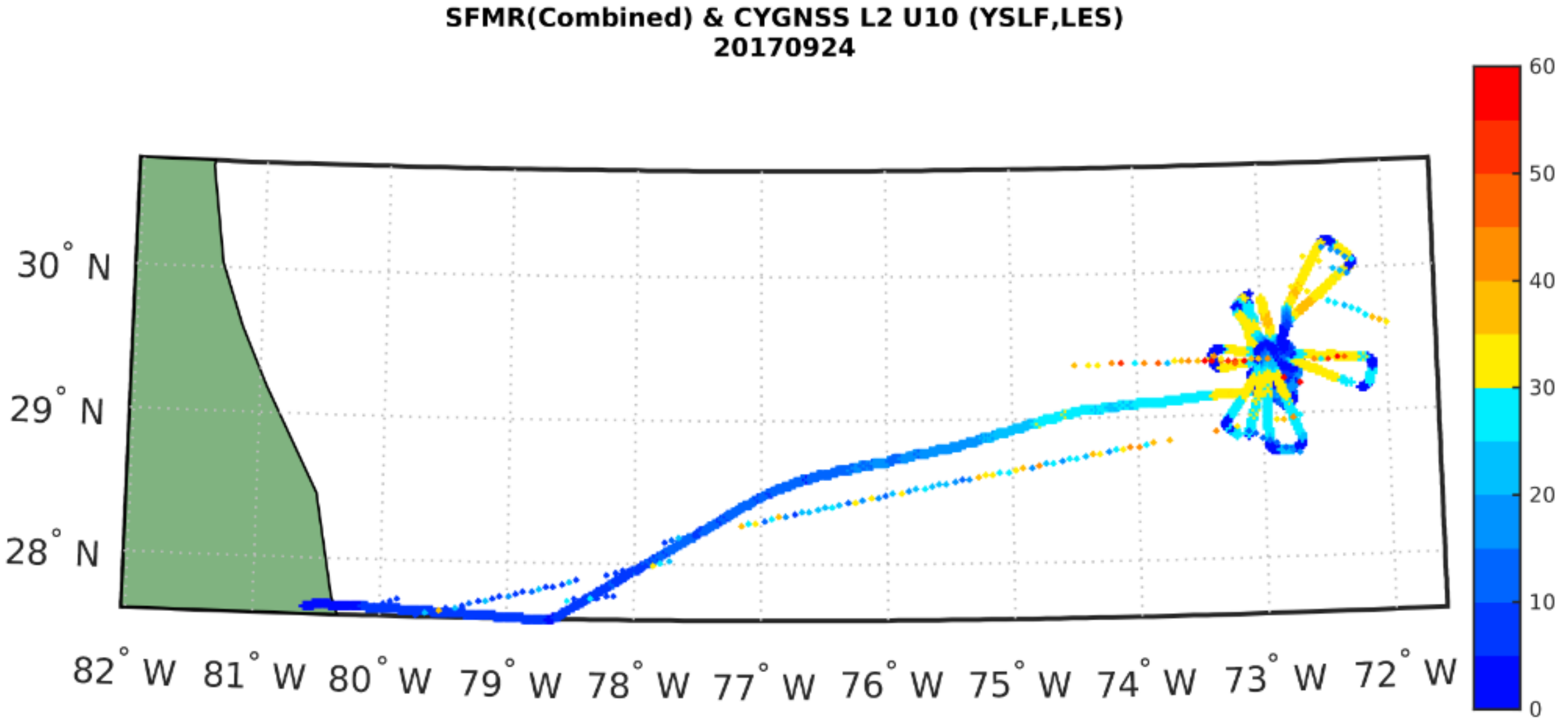
Fully developed sea

Young Sea Limited Fetch

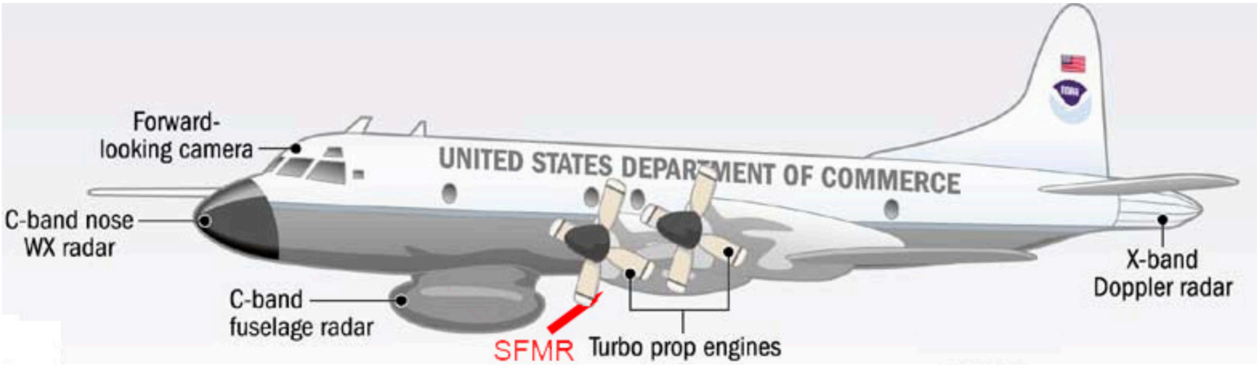
(**MSS retrieved wind measured by miniature buoy**)

NASA CYGNSS builds GMF using SFMR wind

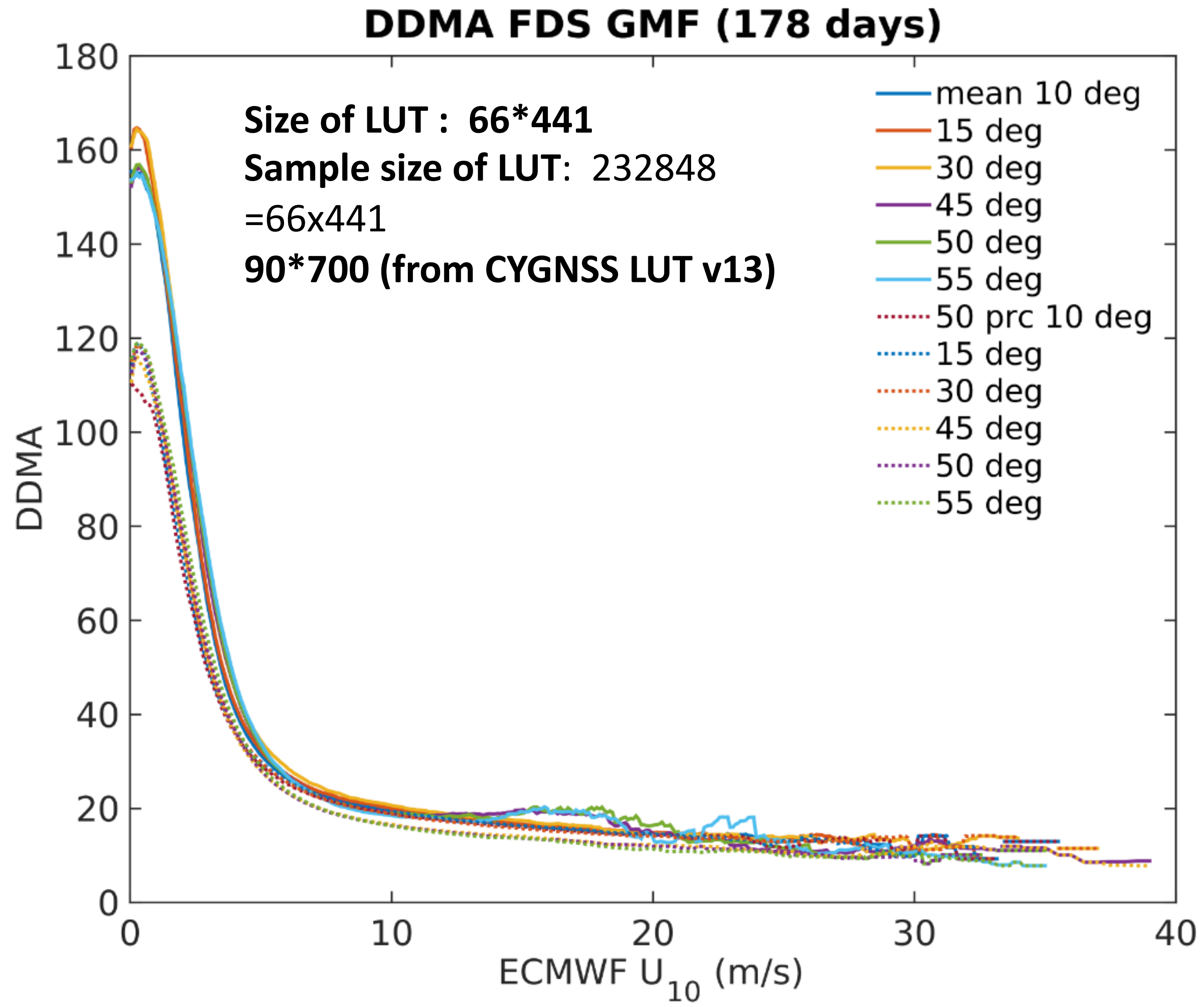


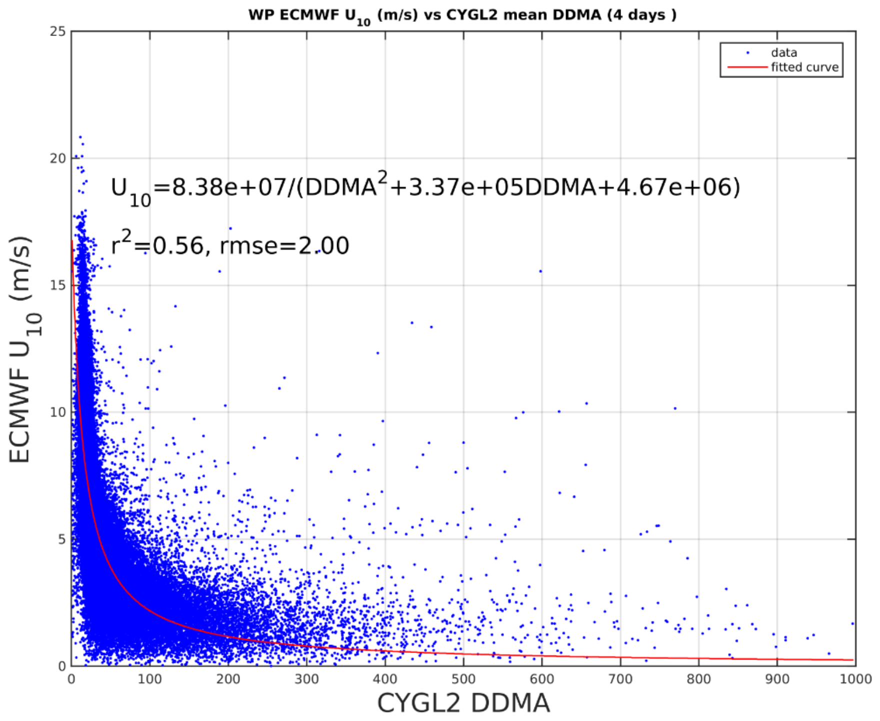


The difference
in space is within
0.5 degree, and
50 mins in time.

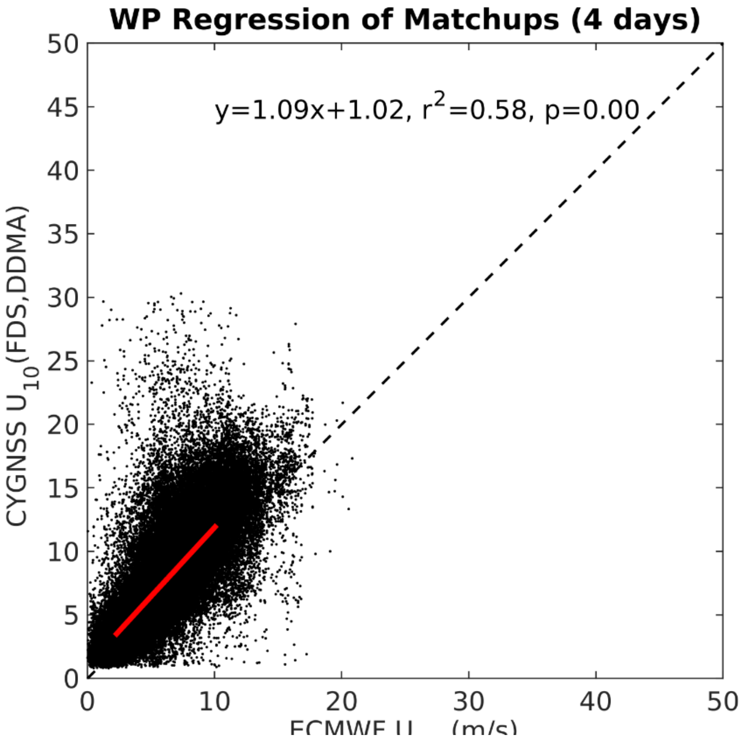


Example
Geophysical Model Function, GMF, U10-DDMA

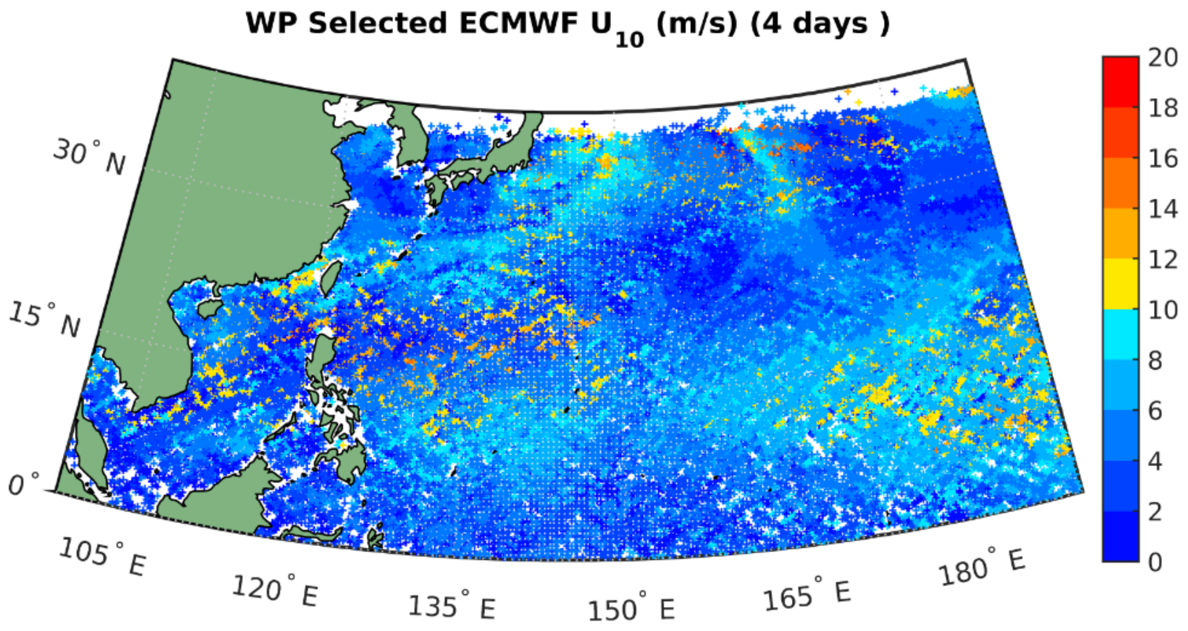




WP ECMWF U10 (m/s) vs CYGL2 mean DDMA (4 days)
data
fitted curve
U10=8.38e+07/(DDMA2+3.37e+05DDMA+4.67e+06)
r2=0.56, rmse=2.00
ECMWF U10 (m/s)
CYGL2 DDMA

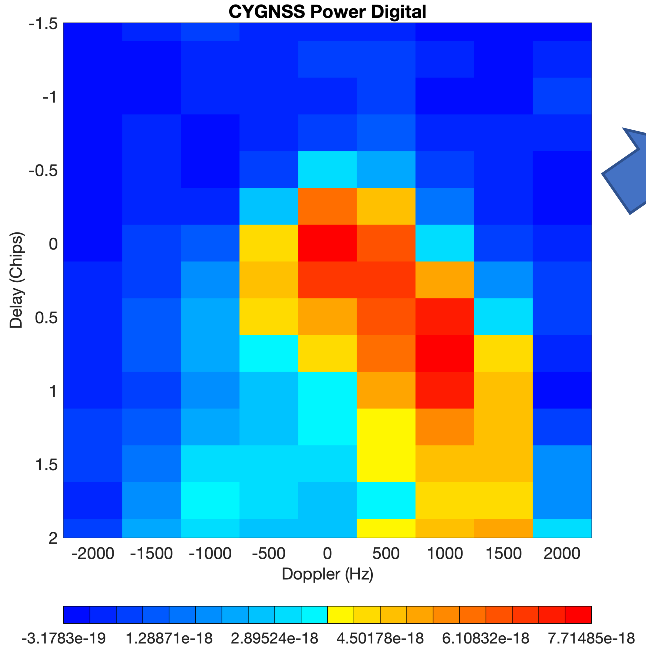


WP Regression of Matchups (4 days)
y=1.09x+1.02, r2=0.58, p=0.00
CYGNSS U10(FDS,DDMA)

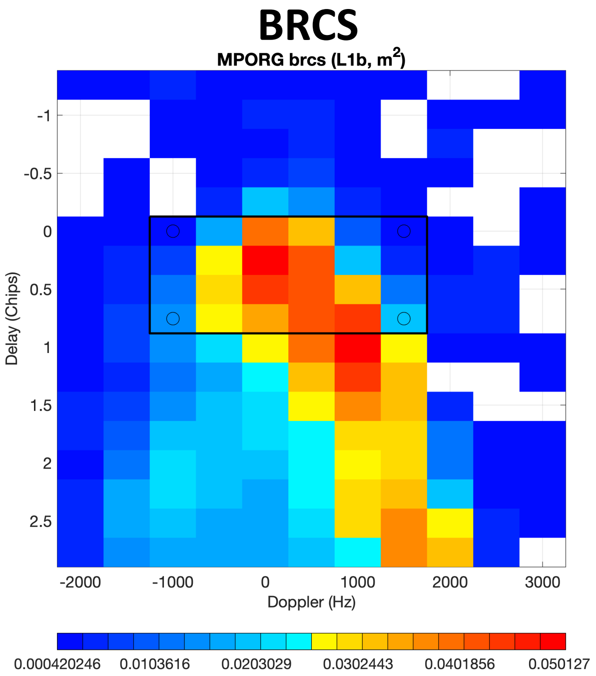


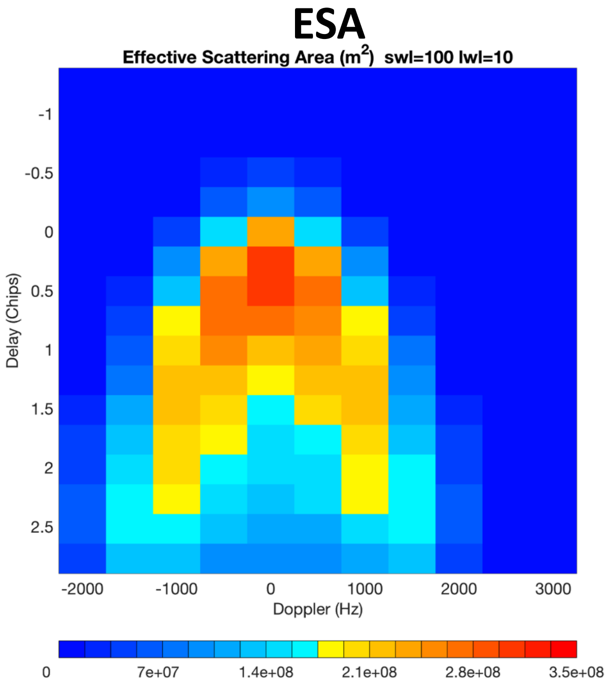
WP Selected ECMWF U10 (m/s) (4 days)
30° N
15° N
0°
105° E
120° E
135° E
150° E
165° E
180° E

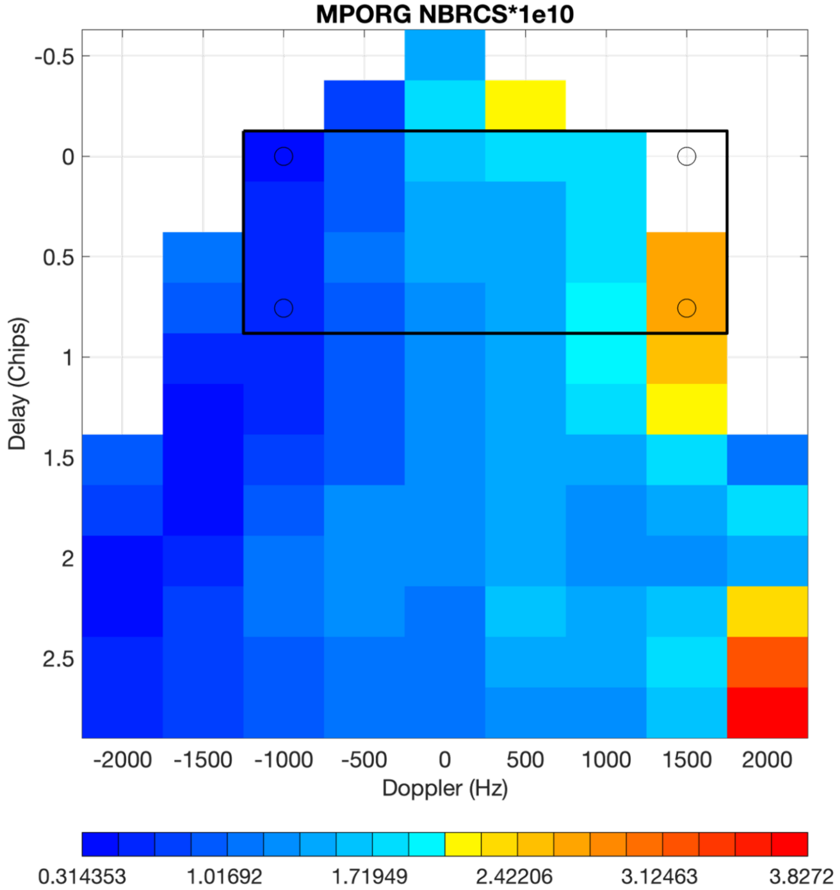
Level 1b計算NBRCS流程



L1a Output: Power on DDM







L1b Output:
DDM Observables, DDMA & LES

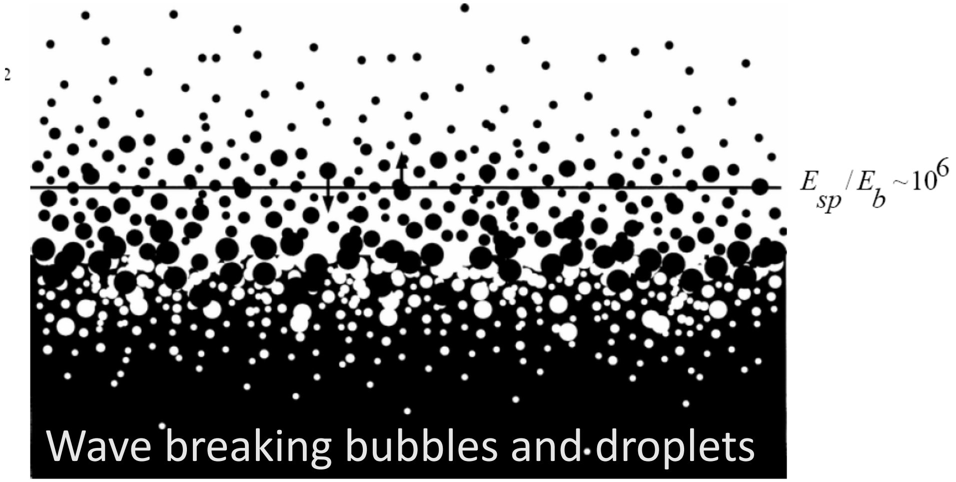
改善反演產品的挑戰 就是 科學議題
（海面白沫與粗糙度是海洋大氣交互作用關鍵）

NBRCS是Fresnel Reflectance與MSS綜合效應:

$$\sigma_0 = \pi |R|^2 \left(\frac{q}{q_z}\right)^4 P\left(-\frac{q_\perp}{q_z}\right) \qquad (1)$$

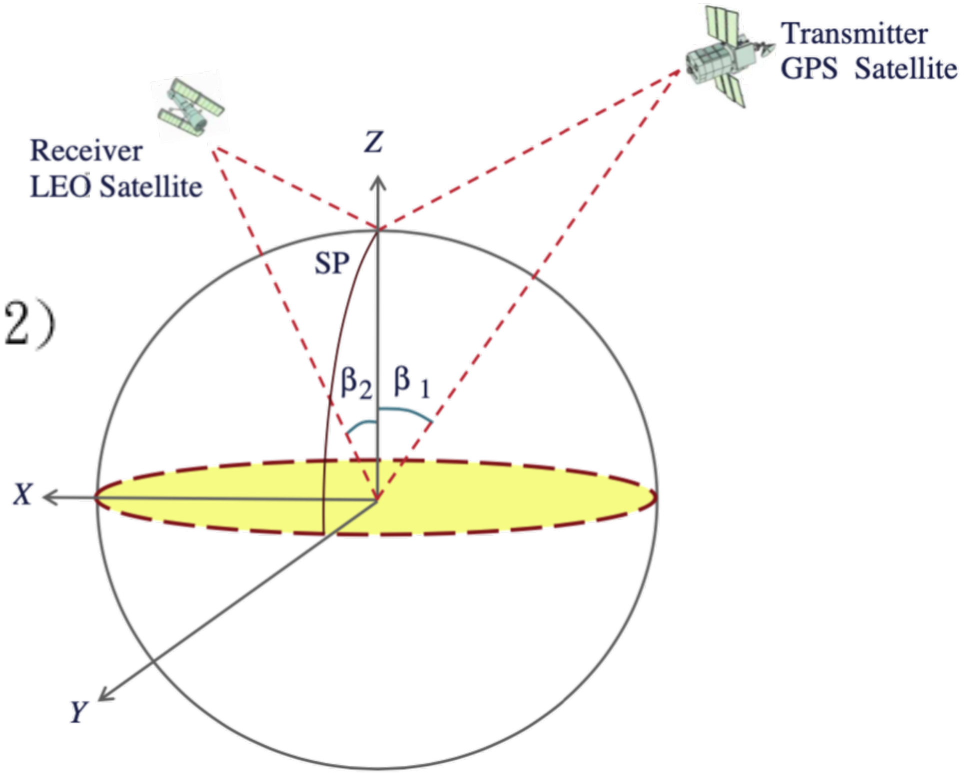
R: Fresnel reflectance by wavy sea surface (whitecap free)

$$\mathrm{R} = \frac{1}{2}\left(\frac{\varepsilon\cos\theta - \sqrt{\varepsilon - \sin^2\theta}}{\varepsilon\cos\theta + \sqrt{\varepsilon - \sin^2\theta}} - \frac{\cos\theta - \sqrt{\varepsilon - \sin^2\theta}}{\cos\theta + \sqrt{\varepsilon - \sin^2\theta}}\right)$$



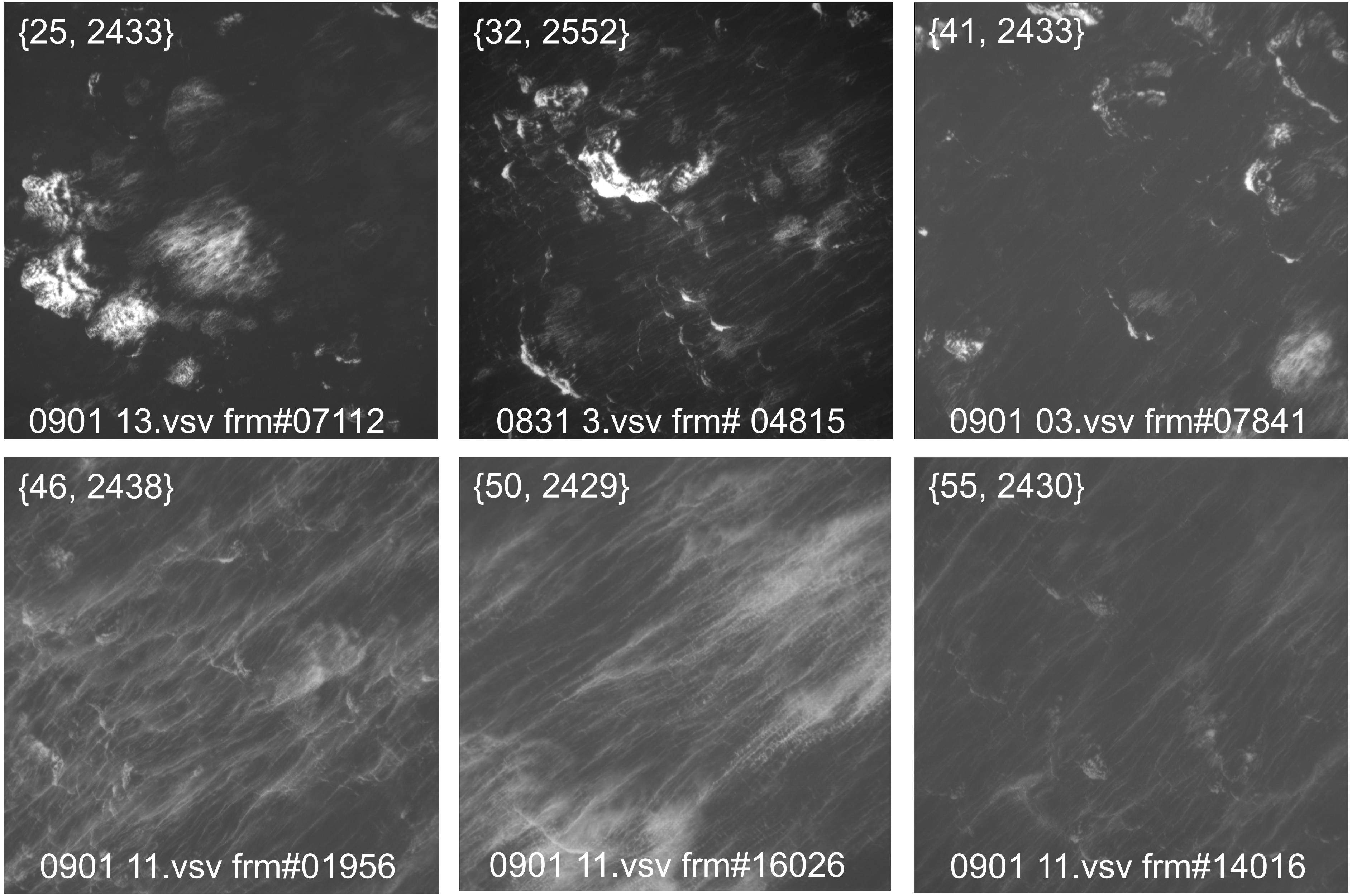
Wave breaking bubbles and droplets

(2)

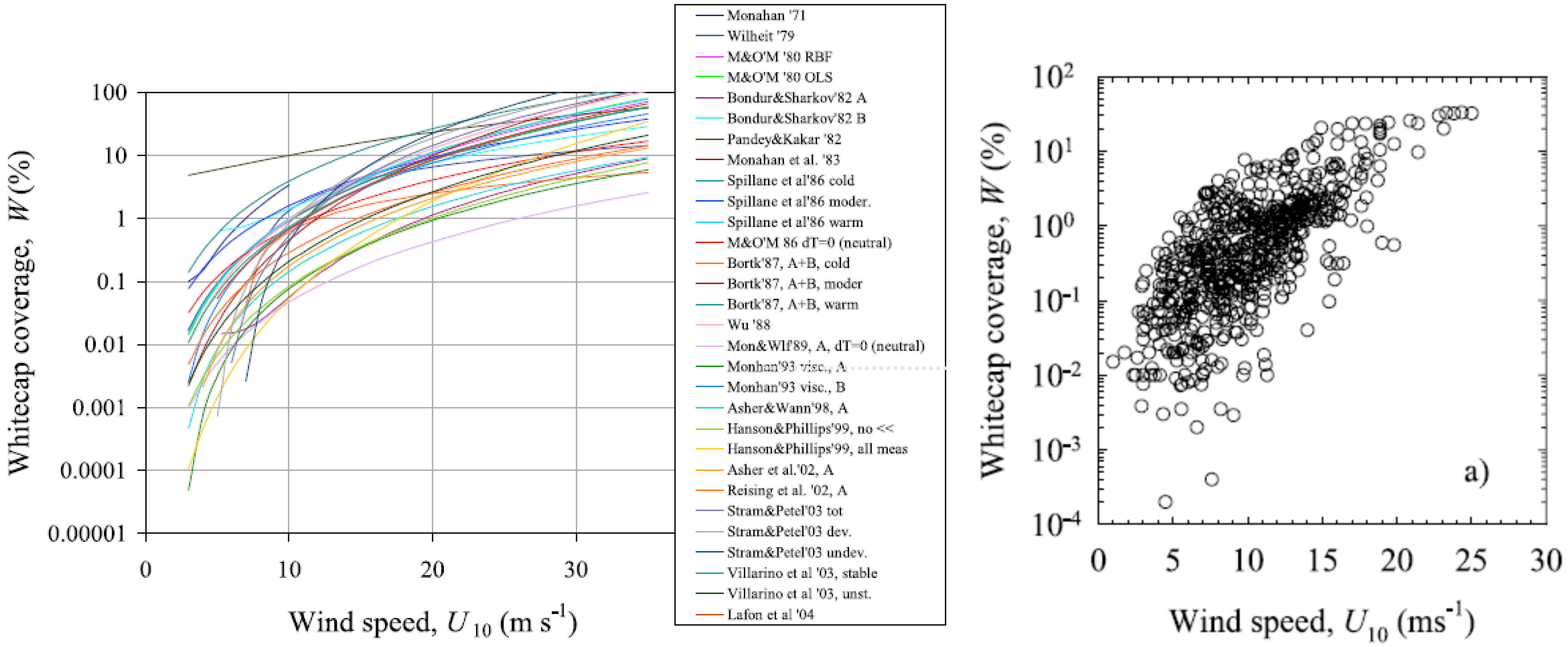


Whitecapping in extreme wind conditions

{U10 (m/s), Alt (m)}:



Whitecapping Coverage (WCC) vs. U10



(Anguelova, Magdalena D. Anguelova & F. Webster, 2006, JGR Vol.111 C03017)

Question

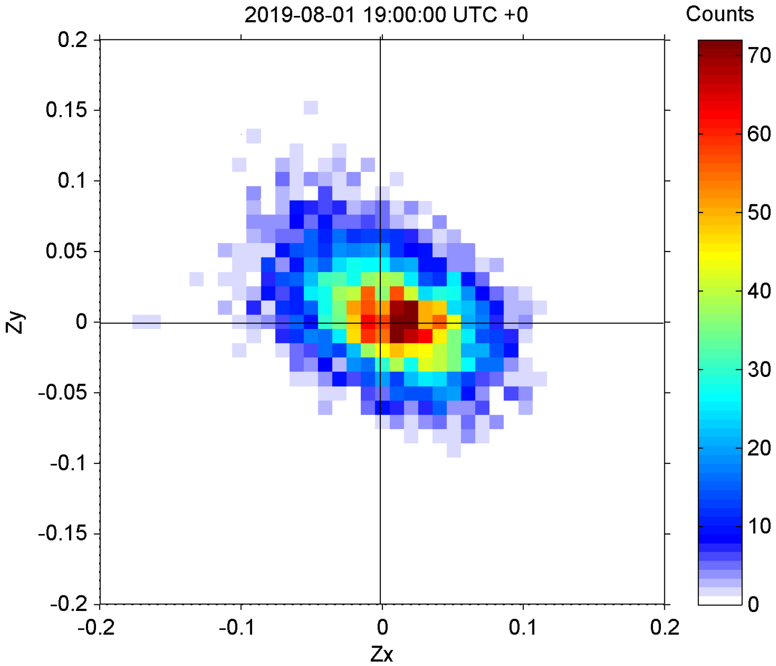
- **What happens of the foam coverage on the sea surface between moderate and high winds?**

海面粗糙度 MSS, Cd是海氣熱量、水氣交換、二氧化碳等氣體交換的重要描述參數，但高風速下所知甚少

When wind is directed along one of two axes (4.10) can be re-written in more common fashion:

$$P(\vec{s}) = \frac{1}{2\pi\sqrt{mss_x mss_y(1-b_{x,y}^2)}} \exp\left[-\frac{1}{2(1-b_{x,y}^2)}\left(\frac{s_x^2}{mss_x} - 2b_{x,y}\frac{s_x s_y}{\sqrt{mss_x mss_y}} + \frac{s_y^2}{mss_y}\right)\right] \quad (4.12)$$

where mss_x and mss_y are mean-square slopes of the sea surface for two orthogonal components; $b_{x,y}$ is the correlation coefficient between two slope components:



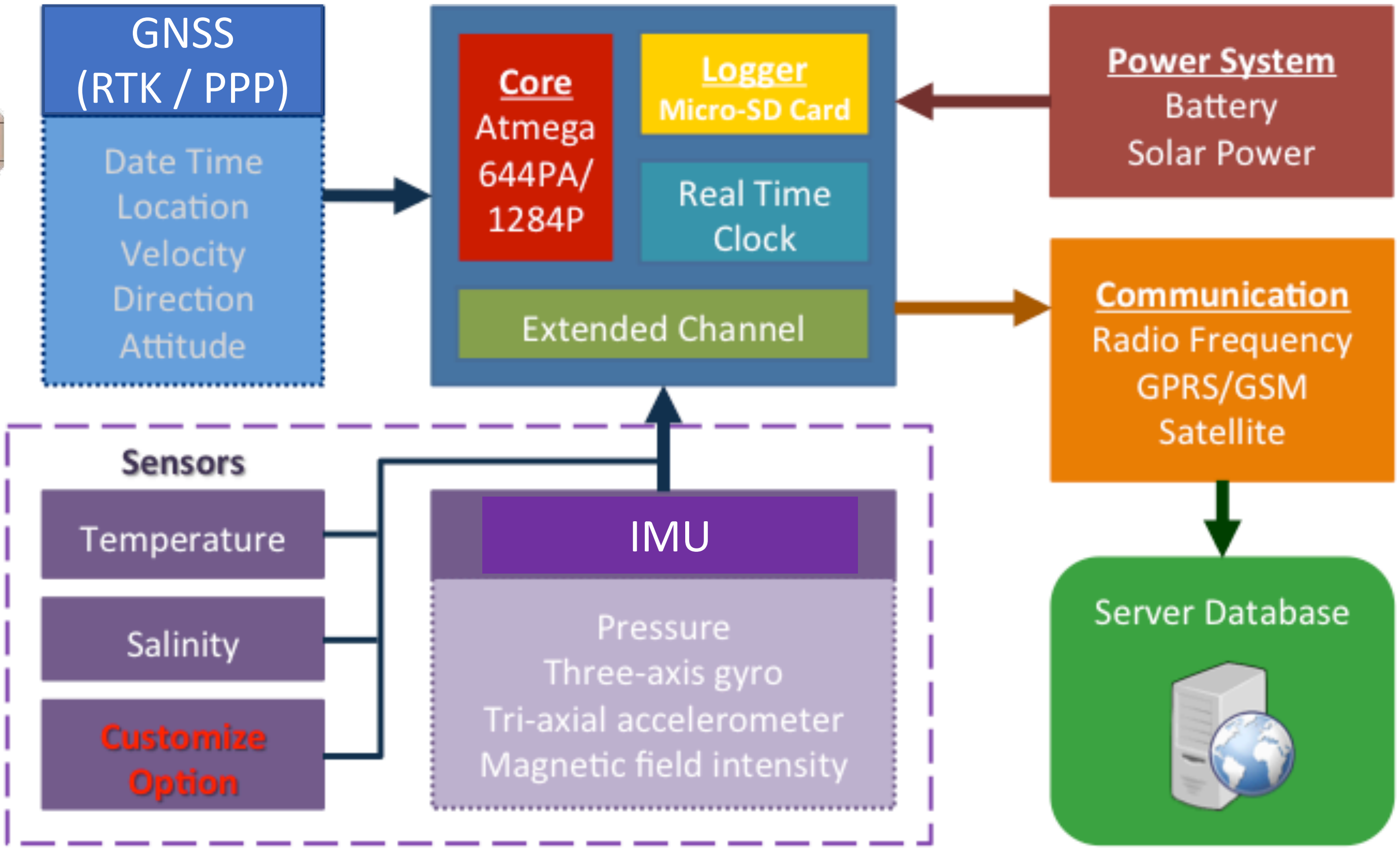
$$mss_{x,y} = \langle s_{x,y}^2 \rangle = \iint_{\kappa<\kappa_*} \kappa_{x,y}^2 \Psi(\vec{\kappa}) d^2\kappa \quad (4.13)$$

$$b_{x,y} = \langle s_x s_y \rangle / \sqrt{mss_x mss_y} \quad (4.14)$$

$$\langle s_x s_y \rangle = \iint_{\kappa<\kappa_*} \kappa_x \kappa_y \Psi(\vec{\kappa}) d^2\kappa \quad (4.15)$$

(ATBD L2, 2018)

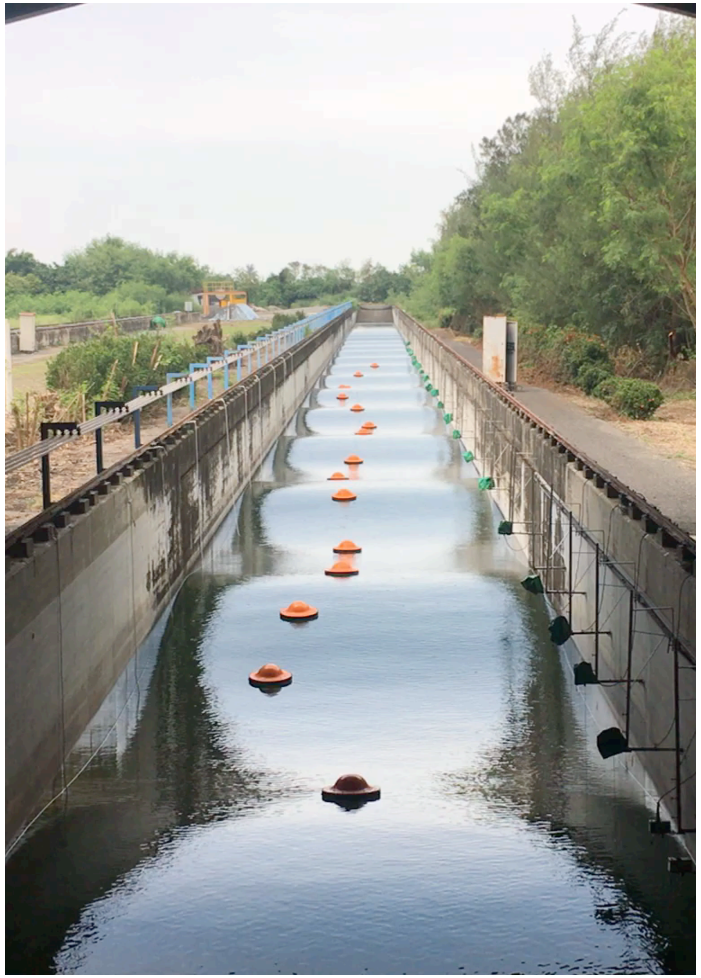
Miniature Buoy
for MSS, wave, SSS, SST, surface current real-time monitoring



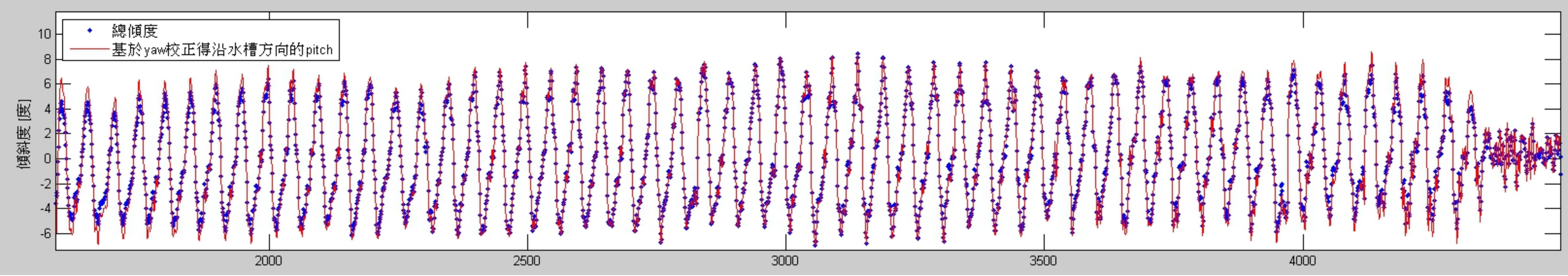
System architecture

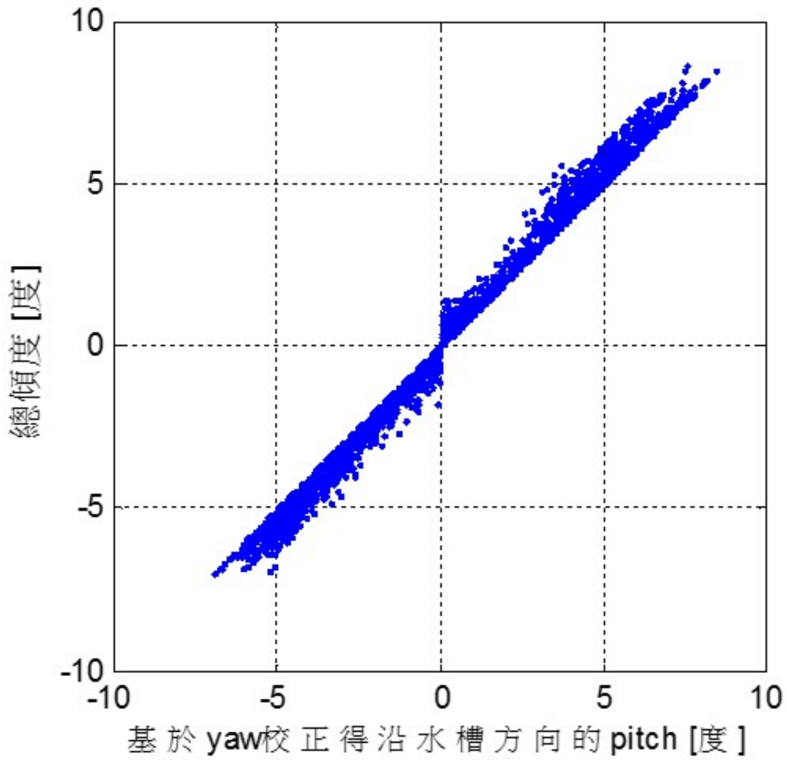
Buoy validation and calibration using super wave tank

-- to ensure the data consistency

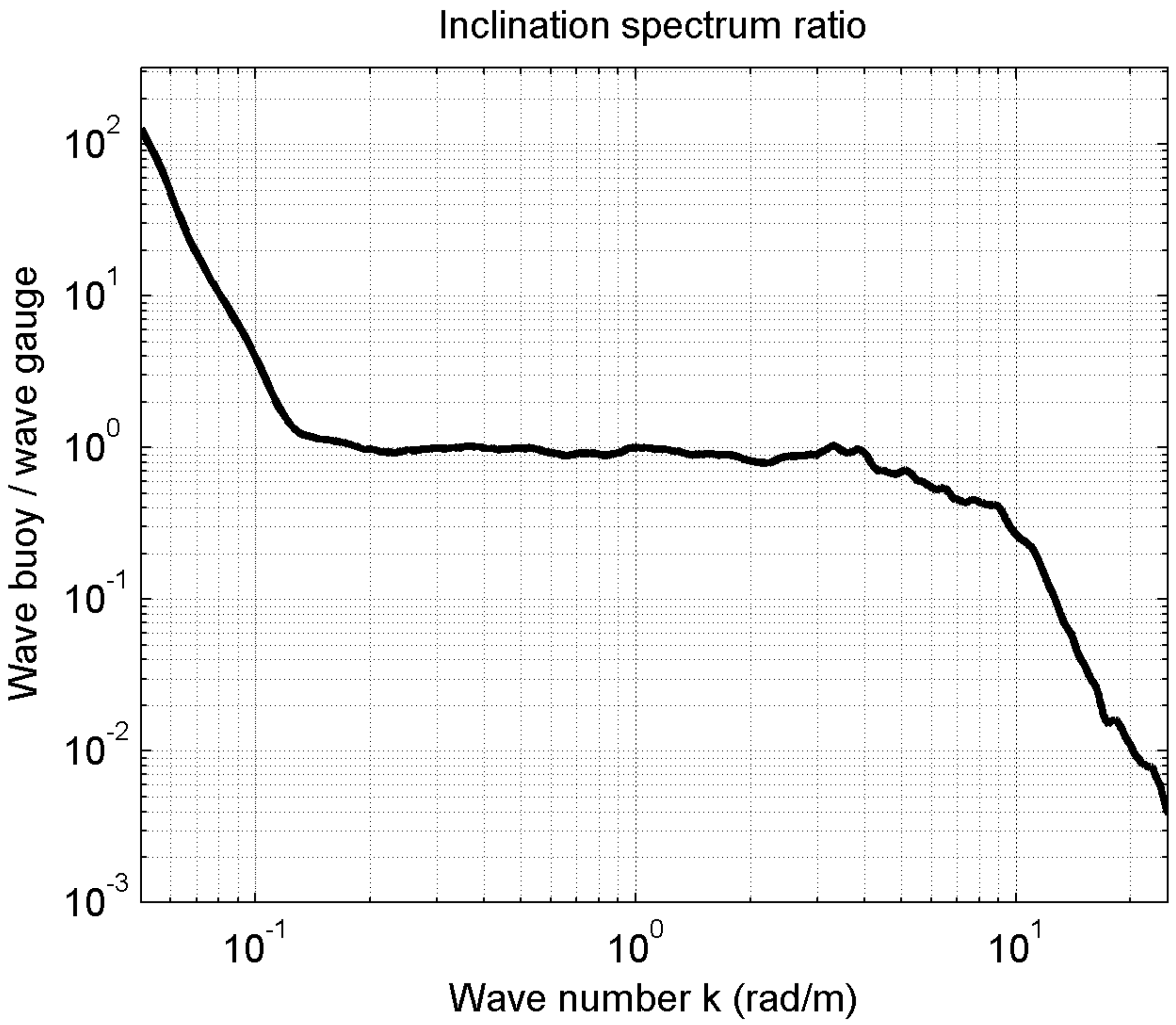


Regular wave ($H_{1/3}$:80cm, T_p:3sec)


總傾度
基於yaw校正得沿水槽方向的pitch
傾斜度 [度]
10
8
6
4
2
0
-2
-4
-6
2000
2500
3000
3500
4000


總傾度 [度]
基於 yaw校 正 得 沿 水 槽 方 向 的 pitch [度]
10
5
0
-5
-10

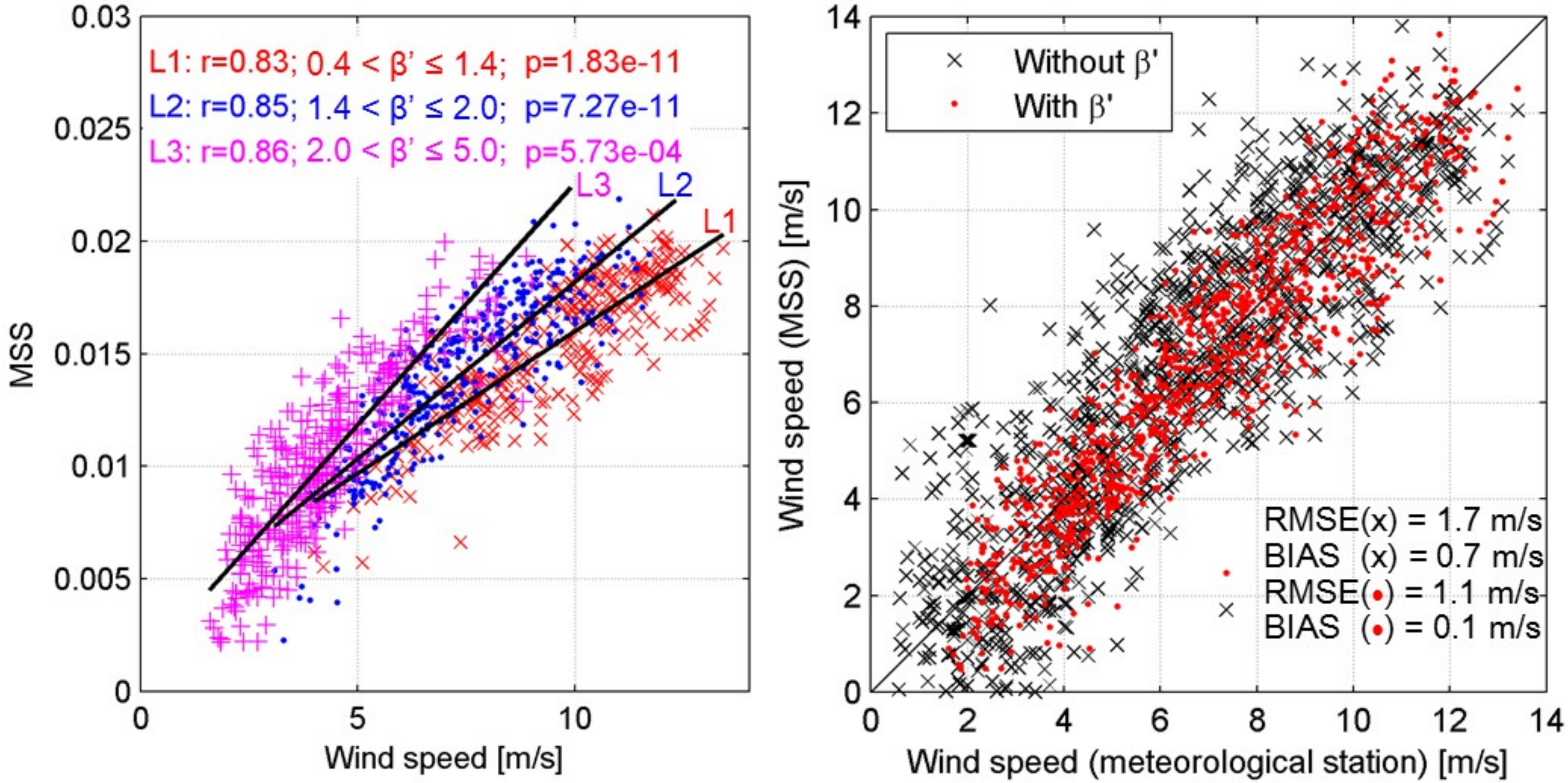
Frequency Response of hull motion



$$mss_{x,y} = \left\langle s_{x,y}^2 \right\rangle = \iint_{\kappa<\kappa_*} \kappa_{x,y}^2 \Psi(\vec{\kappa}) d^2\kappa$$

$$b_{x,y} = \left\langle s_x s_y \right\rangle / \sqrt{mss_x mss_y}$$

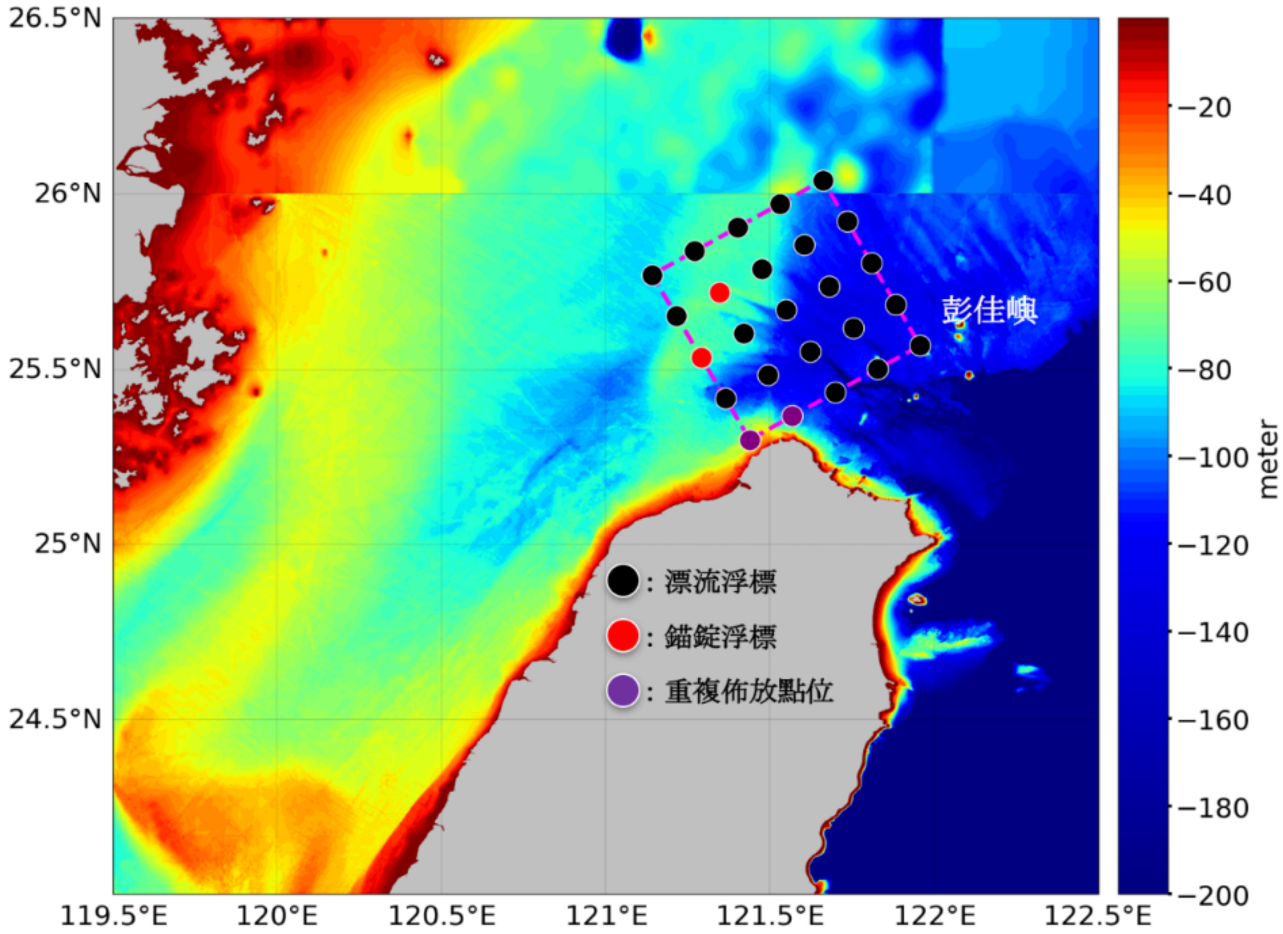
$$\left\langle s_x s_y \right\rangle = \iint_{\kappa<\kappa_*} \kappa_x \kappa_y \Psi(\vec{\kappa}) d^2\kappa$$



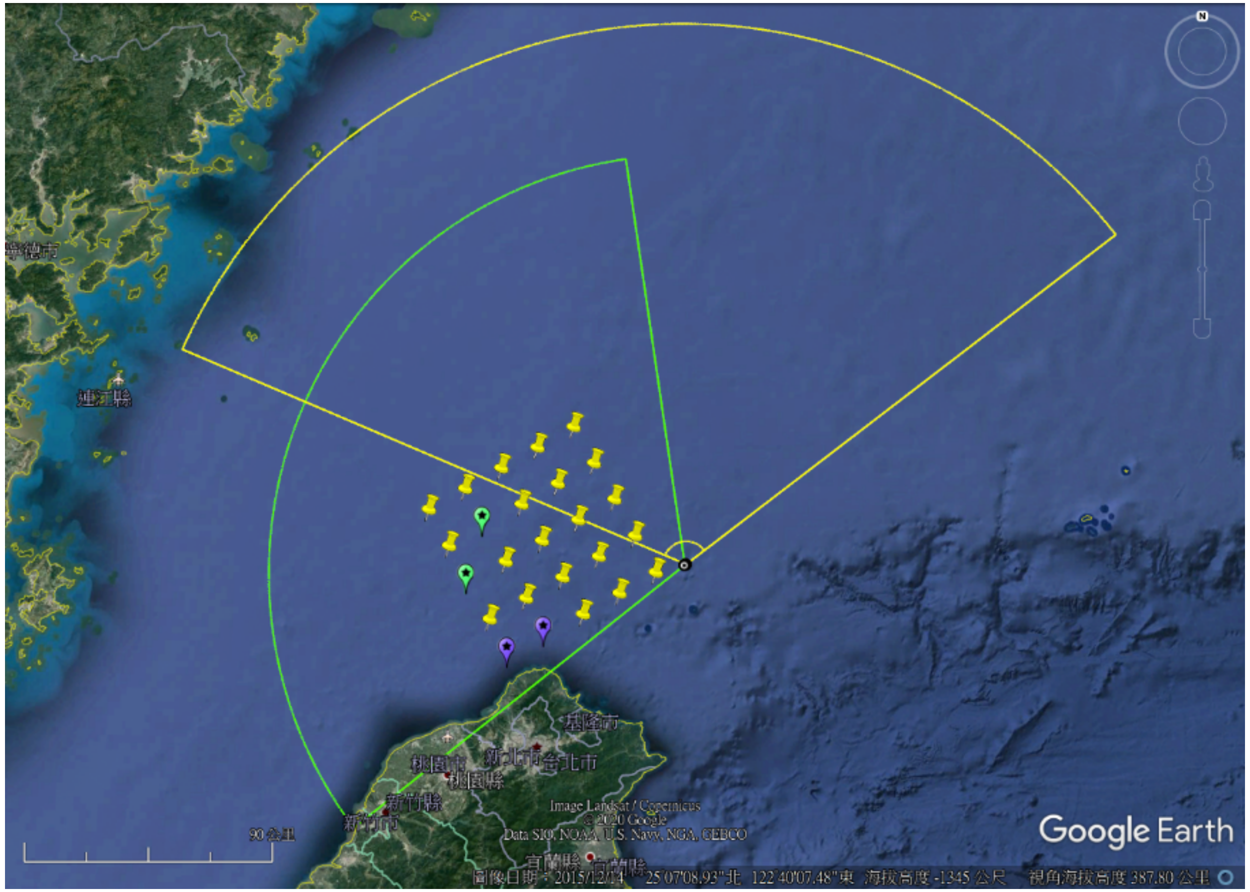
L1: r=0.83; 0.4 < β' ≤ 1.4; p=1.83e-11
L2: r=0.85; 1.4 < β' ≤ 2.0; p=7.27e-11
L3: r=0.86; 2.0 < β' ≤ 5.0; p=5.73e-04
L3
L2
L1
MSS
Wind speed [m/s]
Without β'
With β'
RMSE(x) = 1.7 m/s
BIAS (x) = 0.7 m/s
RMSE(•) = 1.1 m/s
BIAS (•) = 0.1 m/s
Wind speed (MSS) [m/s]
Wind speed (meteorological station) [m/s]

2020東海密集陣列觀測實驗測試

觀測實驗	IOP2
地點	東海(臺灣北部海域) ([121.17°N~121.96°E],[25.31°N~26.08°N])
起訖時間	2020/08/30~2020/09/09
浮標個數	43個(19個重複佈放，2個錨碇)
觀測項目	流速、流向、波高、週期、尖峰週期、波向、風速、MSS(Mean Square Slope)
浮球觀測採樣頻率	Internal : 10Hz、每三十分鐘觀測一次
天氣系統	颱風梅莎於8/28形成，並在8/31~9/1號期間接近觀測海域
衛星最大風速	颱風接近期間最大風速於9月1日0時達12.14[m/s]
觀測面積	$3600km^2$
搭配衛星風場資料	ERA5 hourly data

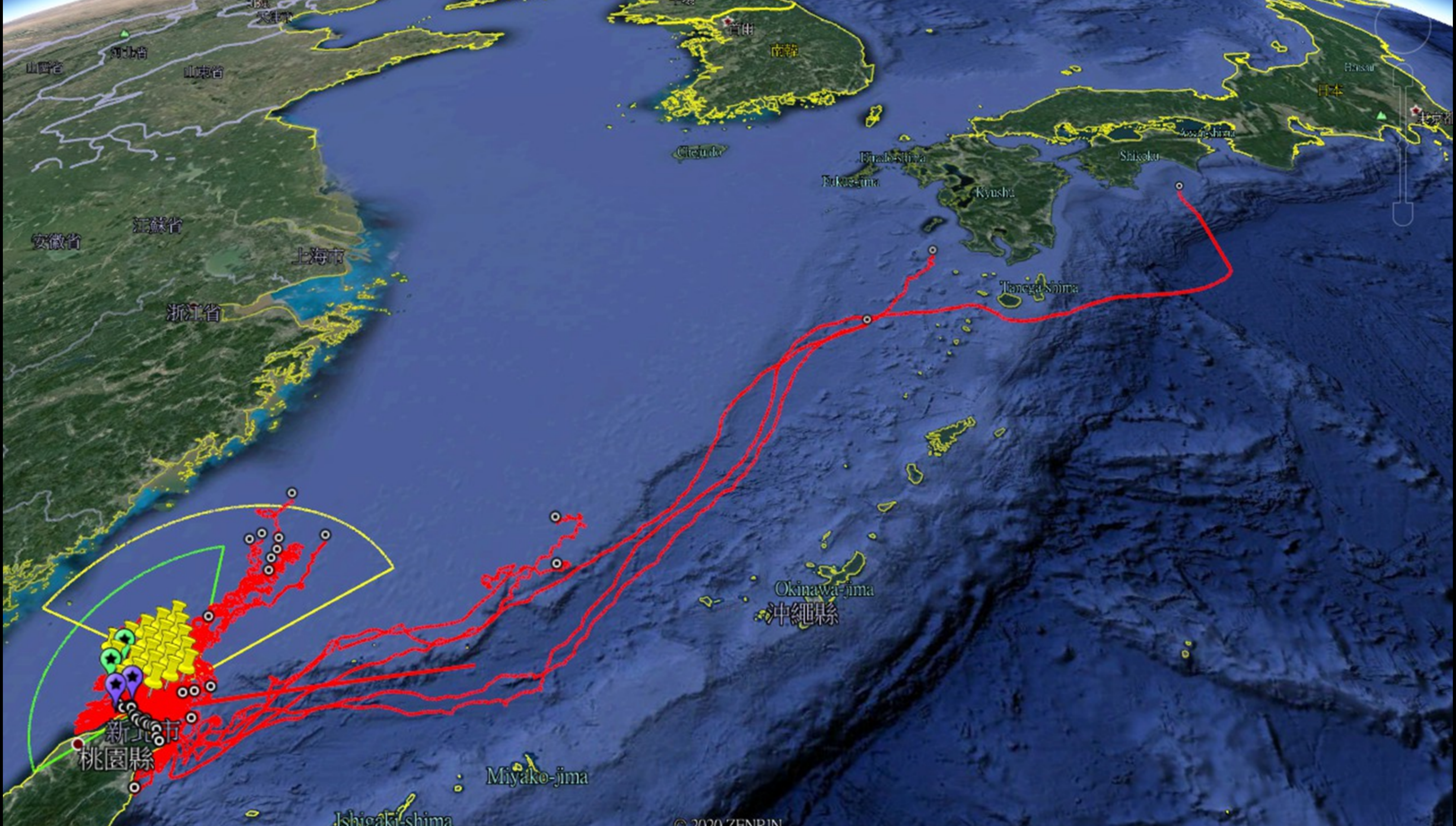


浮標位置

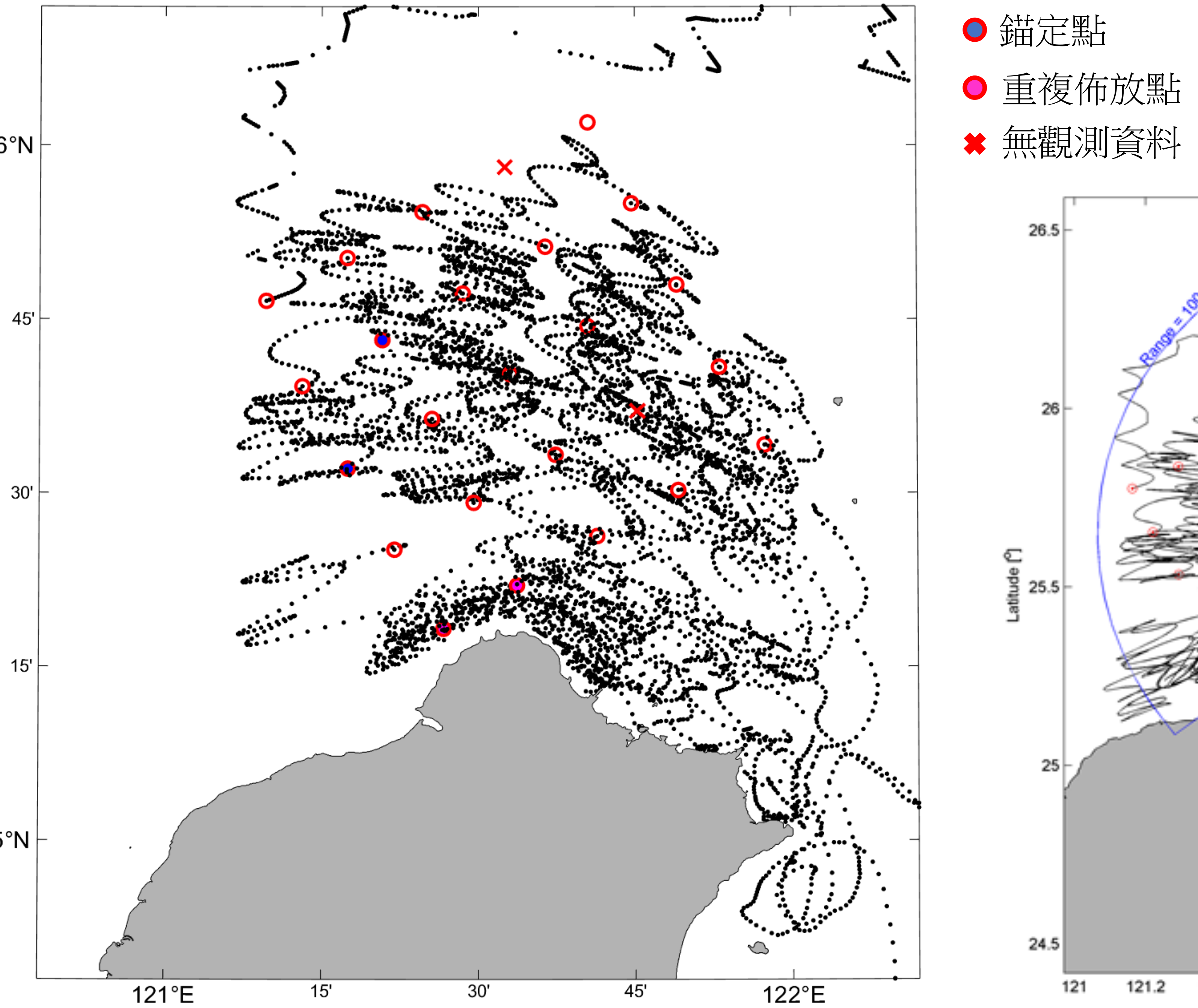


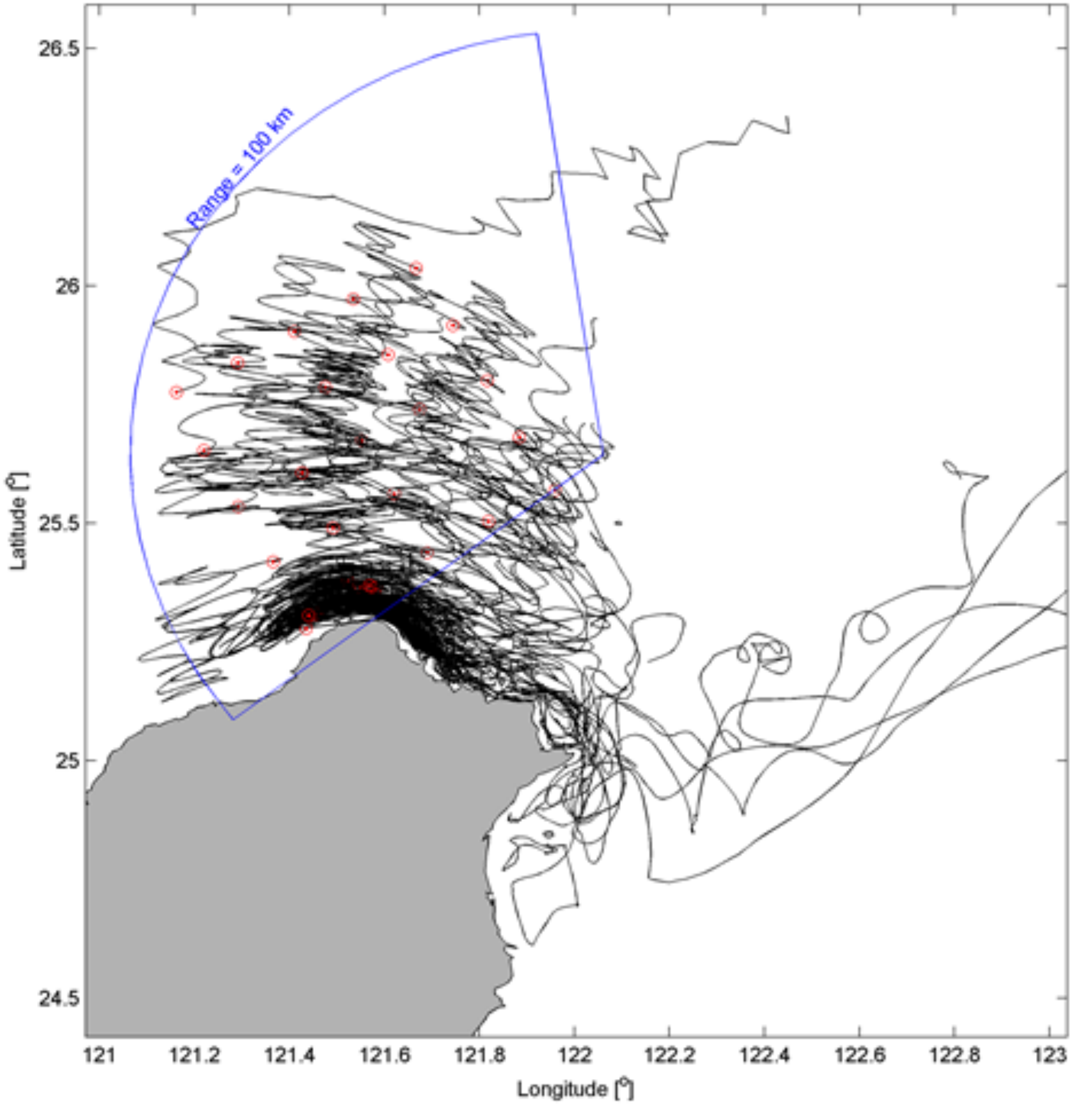
浮標位置與雷達涵蓋關係





河北省
山東省
江蘇省
安徽省
上海市
浙江省
南韓
日本
Cheju-do
Fukue-jima
Kyushu
Shikoku
Tanega-shima
Okinawa-jima
沖繩縣
Miyako-jima
Ishigaki-shima
新北市
桃園縣
© 2020 ZENRIN


錨定點
重複佈放點
無觀測資料
45'
30'
15'
121°E
15'
30'
45'
122°E


Range = 100 km
26.5
26
25.5
25
24.5
Latitude [°]
121
121.2
121.4
121.6
121.8
122
122.2
122.4
122.6
122.8
123
Longitude [°]

表面海流與海洋擴散效率

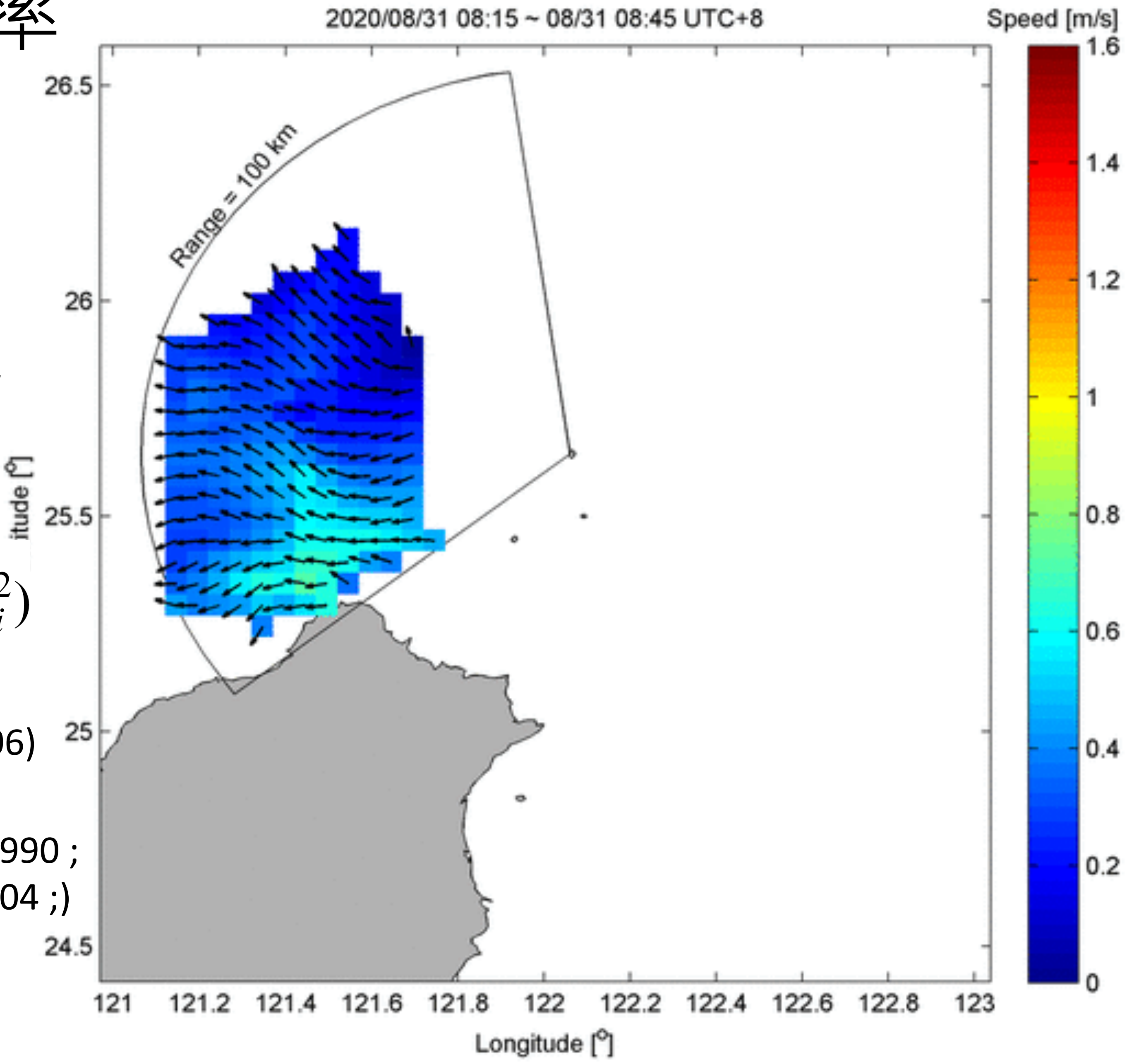
- 利用GPS衛星定位系統回傳微型資料浮標在空間上移動的位置，並進而求得流速與流向。
- Determination of Effective diffusivity, Ke from Cluster’s displacement variance

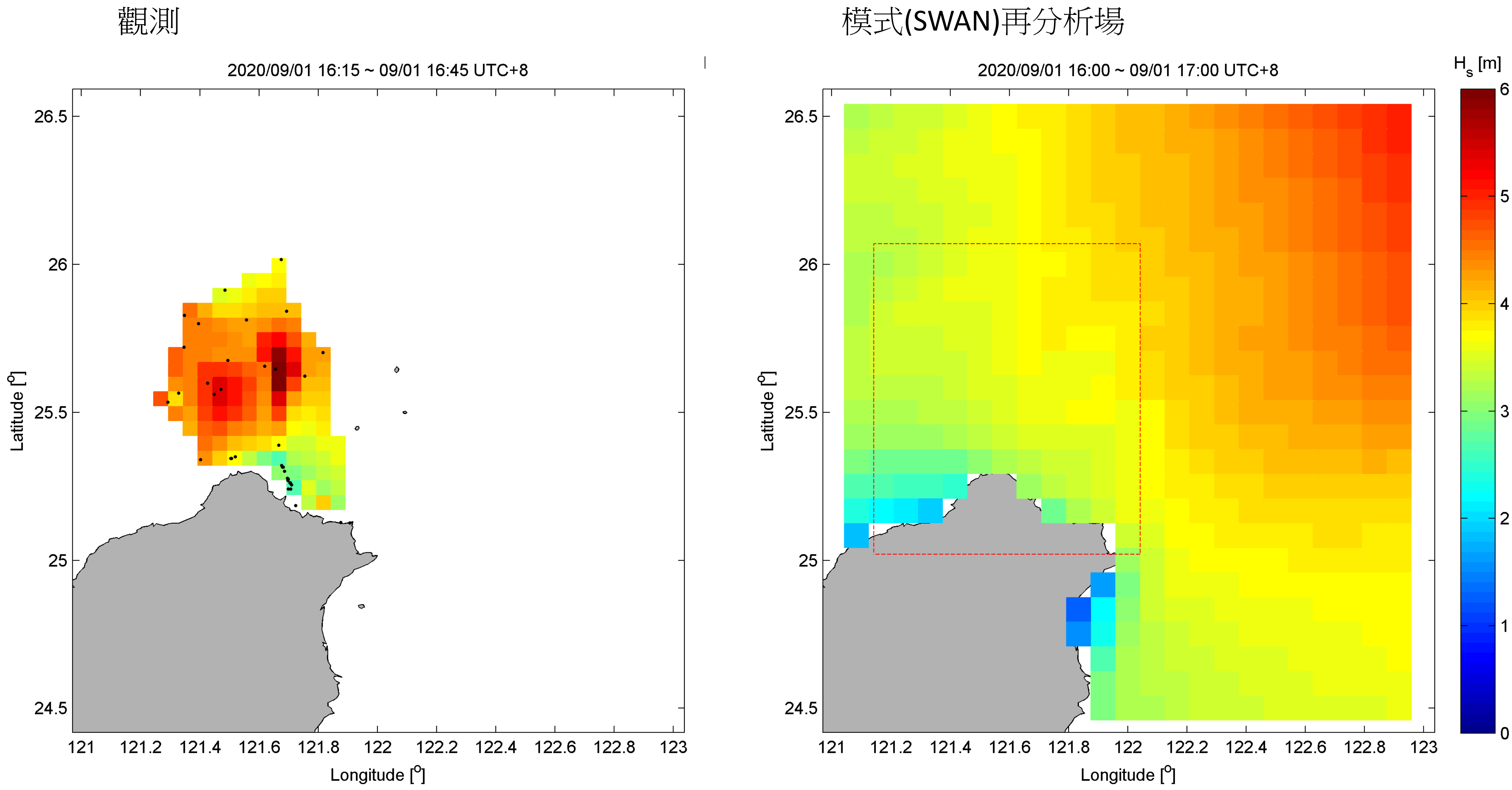
$$K_{\rm e} = 1/4\frac{\partial\sigma^2}{\partial t} \qquad \sigma^2 = \frac{1}{n}\sum_{i=1}^{n}(x_i^2 + y_i^2)$$

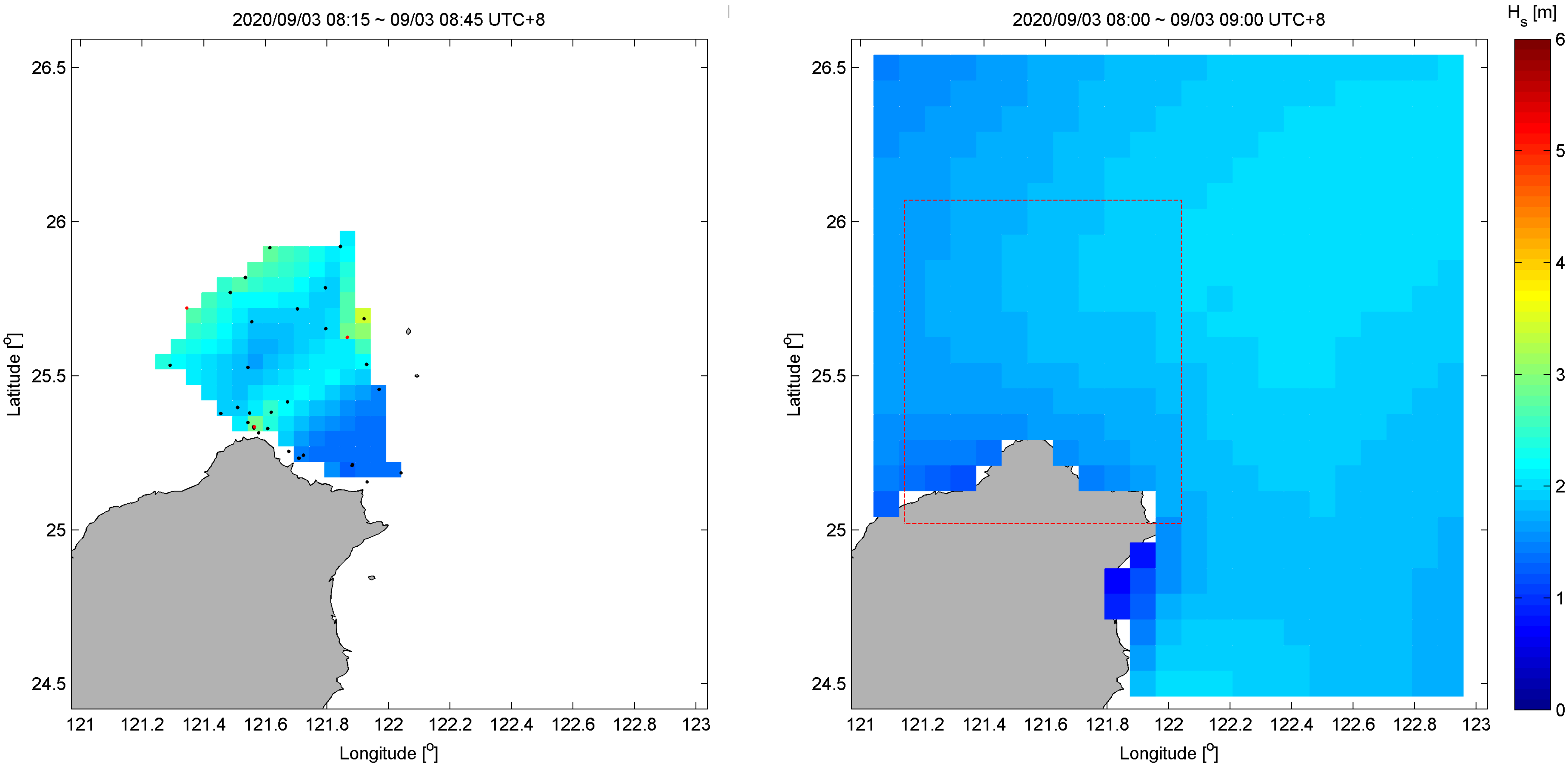
(Manning and Churchill, 2006)

$$K = \frac{1}{2}\frac{\partial\sigma_i^2}{\partial t}$$

(Okubo, 1974 ; List et al., 1990 ; Johnson, 2004 ; Olsson, 2004 ;)



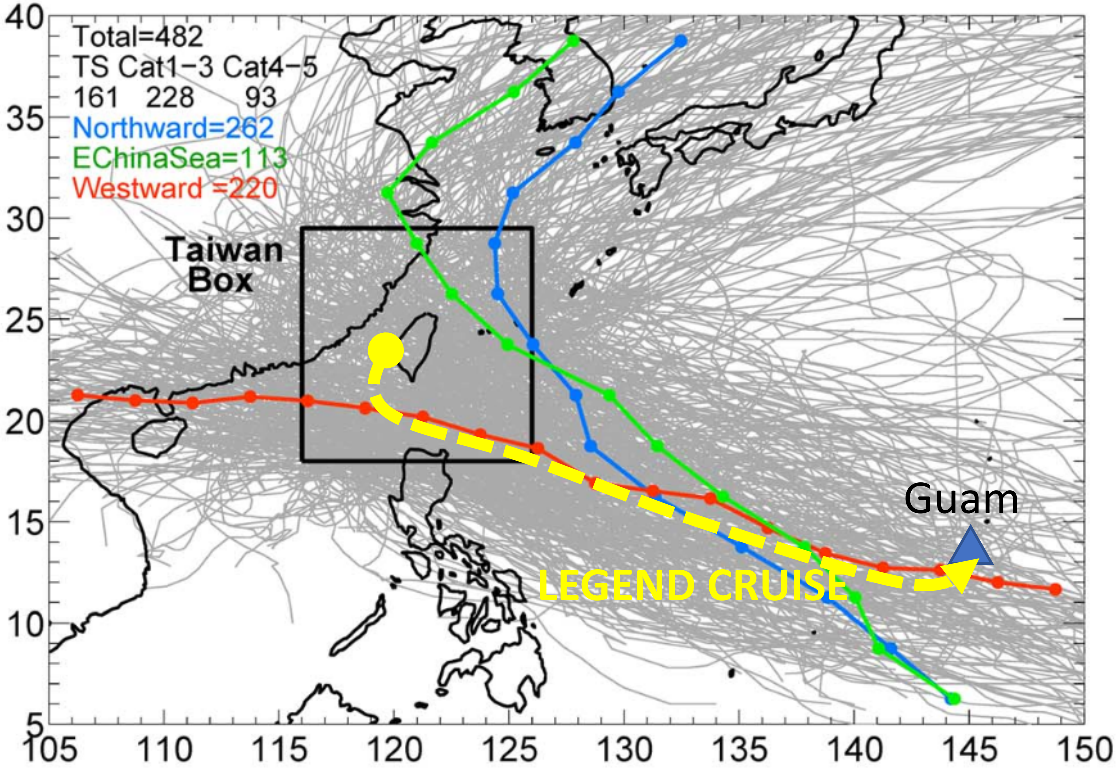

觀測
模式(SWAN)再分析場
2020/09/01 16:15 ~ 09/01 16:45 UTC+8
2020/09/01 16:00 ~ 09/01 17:00 UTC+8
Latitude [°]
Longitude [°]
26.5
26
25.5
25
24.5
121
121.2
121.4
121.6
121.8
122
122.2
122.4
122.6
122.8
123
H$_s$ [m]
6
5
4
3
2
1
0



2020/09/03 08:15 ~ 09/03 08:45 UTC+8
2020/09/03 08:00 ~ 09/03 09:00 UTC+8
Latitude [°]
Longitude [°]
26.5
26
25.5
25
24.5
121
121.2
121.4
121.6
121.8
122
122.2
122.4
122.6
122.8
123
H_s [m]
6
5
4
3
2
1
0

Scheduled R/V-cruise 2021, 2022 (summer)

- 探索地球系統：太平洋遠征(1/3)
  Exploring the Earth System: Pacific Grand Expedition
  Lead by Prof. BY Kuo
- Purpose: In-situ Mean Squared Slope (MSS) monitoring
- Plan: Deploy 40 drifting buoys forming spatial array along the cruise.



(Liang, A. (T.-Y.), L. Oey, S. Huang, andS. Chou, JGR-Atmospheric. 2017)

Ship's Particulars		
Vessel Name	LEGEND	
L.O.A. / L.B.P.	76.23 m / 68.42 m	
Molded Breadth / Depth	16.0 m / 6.5 m	
Accommodation	Crew 19 / Scientists 24	
Built	Mar. 2018	