NARLabs 國家實驗研究院
國家太空中心
National Space Organization

台灣的氣象衛星

葉文豪

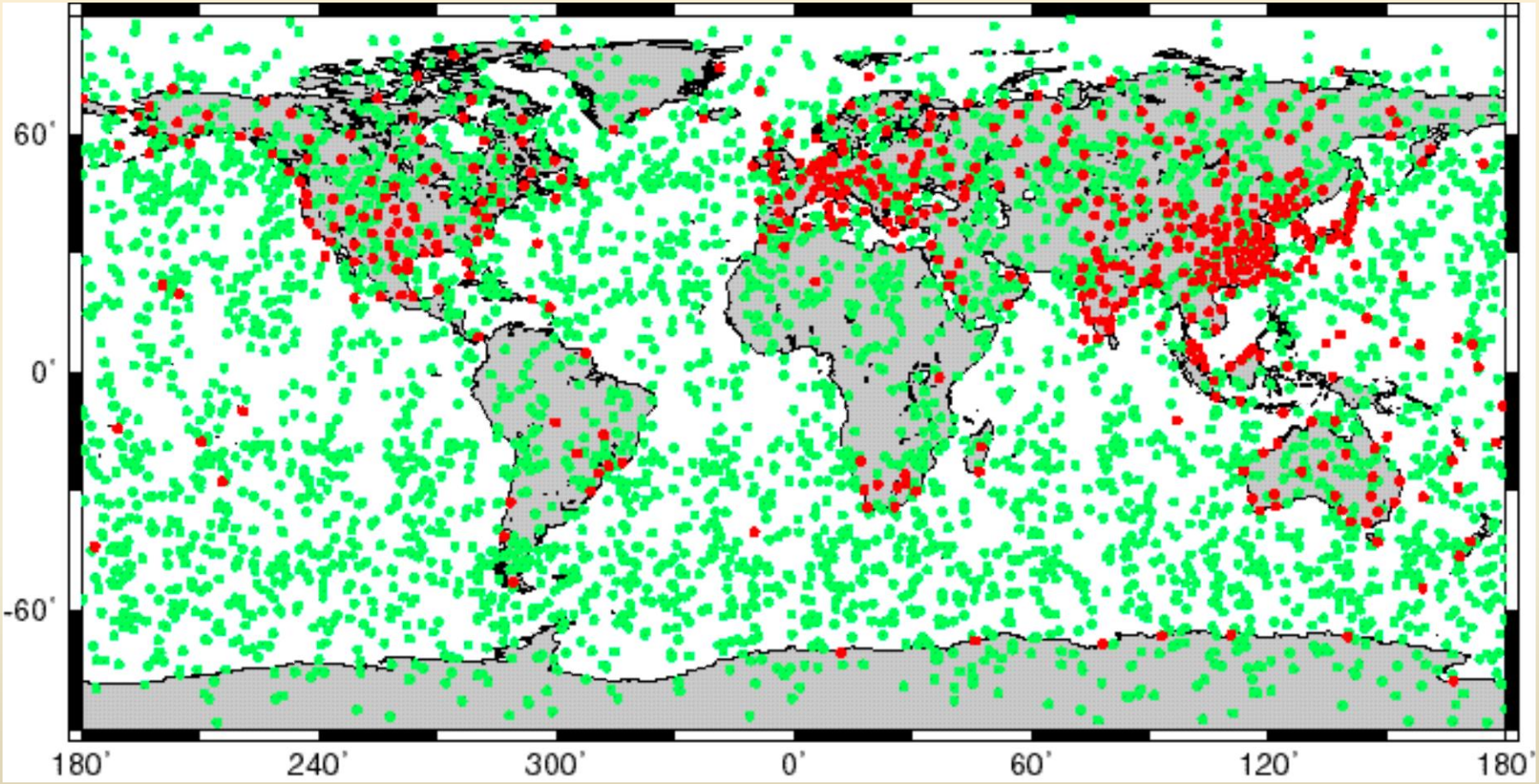
2021年08月20日


獵風者衛星
氣象/科學任務
(預計2022年發射)
福爾摩沙衛星七號
氣象/科學任務
(2019年-現在)
福爾摩沙衛星五號
遙測/科學任務
(2017年-現在)
福爾摩沙衛星三號
氣象/科學任務
(2006年-2020年)
福爾摩沙衛星一號
科學任務
(1999年-2004年)
福爾摩沙衛星二號
遙測/科學任務
(2004年-2016年)
NSPO
NARLabs 國家實驗研究院
國家太空中心
National Space Organization

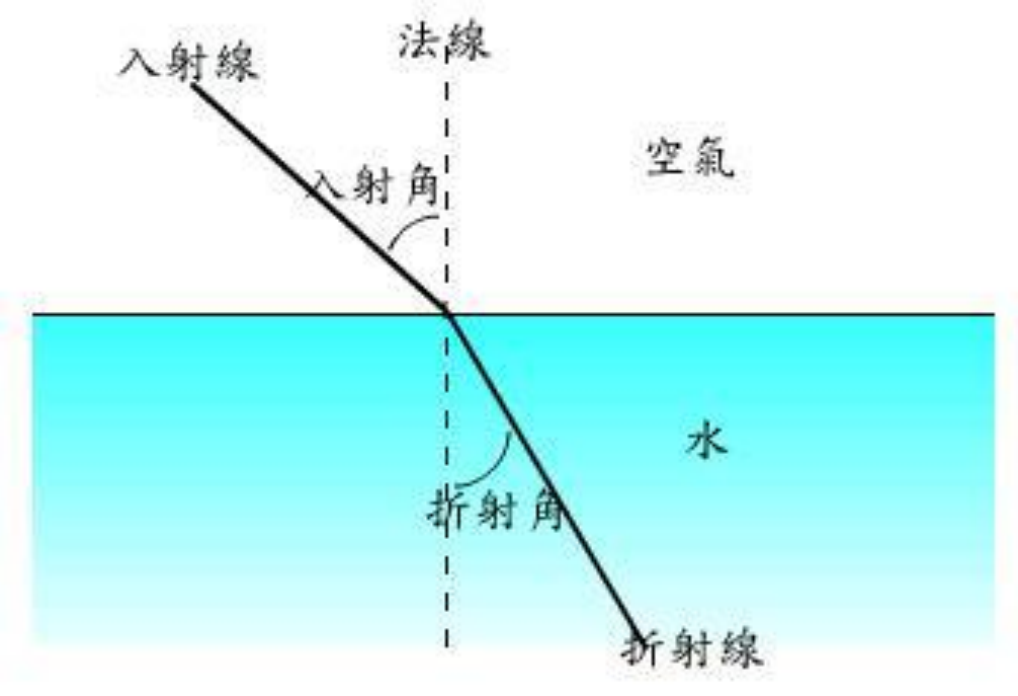
2006

https://www.cgtrader.com/3d-models/space/spaceship/cosmic-satellite-formosat3

福衛三號　一天資料點分布

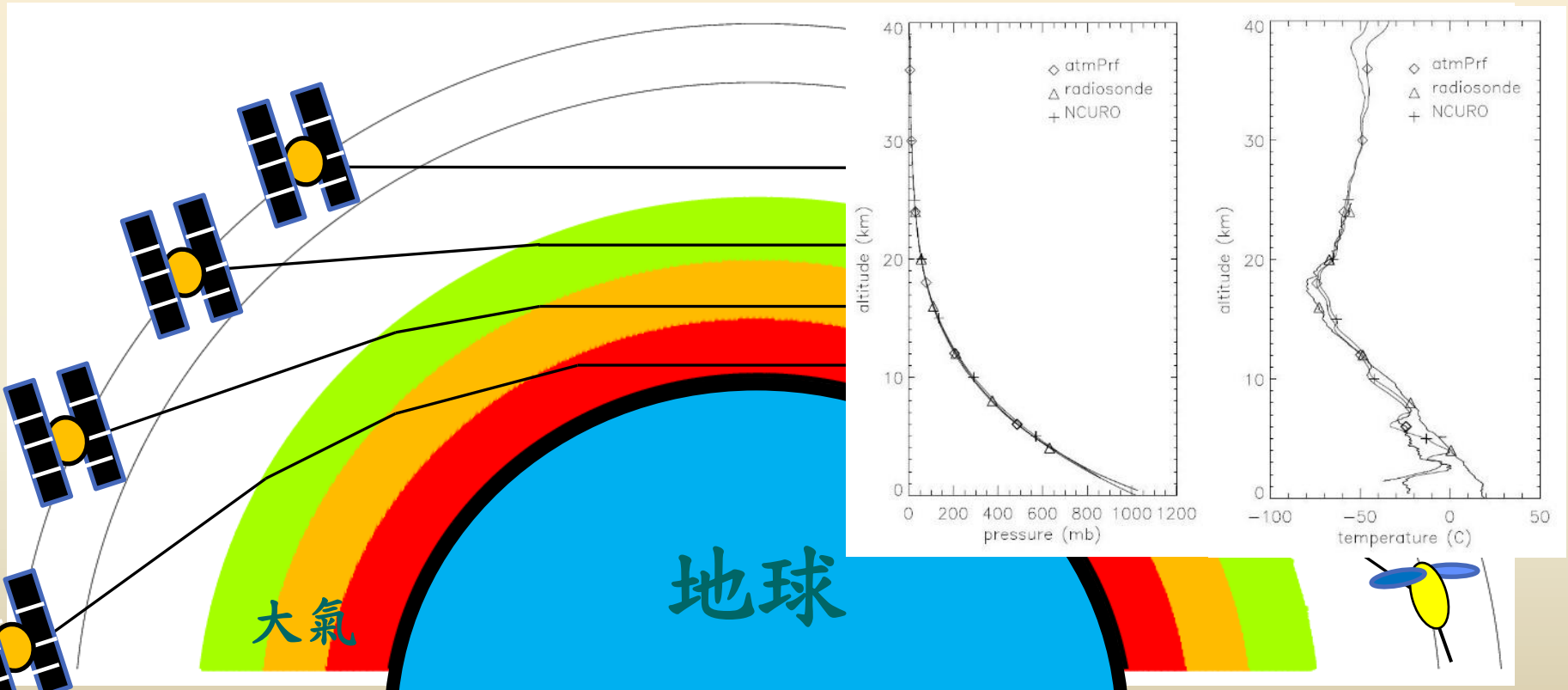


光線折射原理



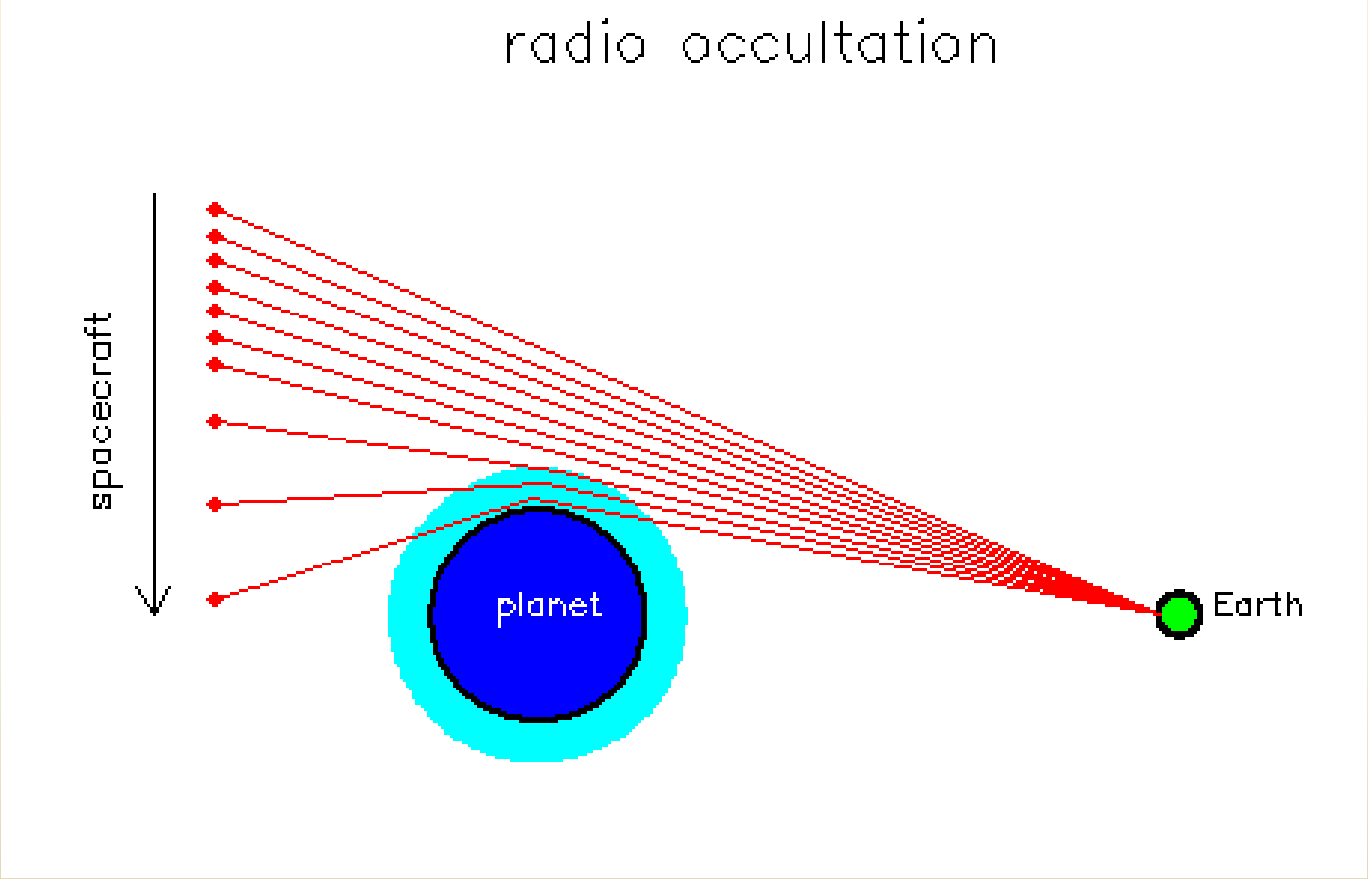
電波掩星觀測原理

GPS衛星　福衛三號衛星



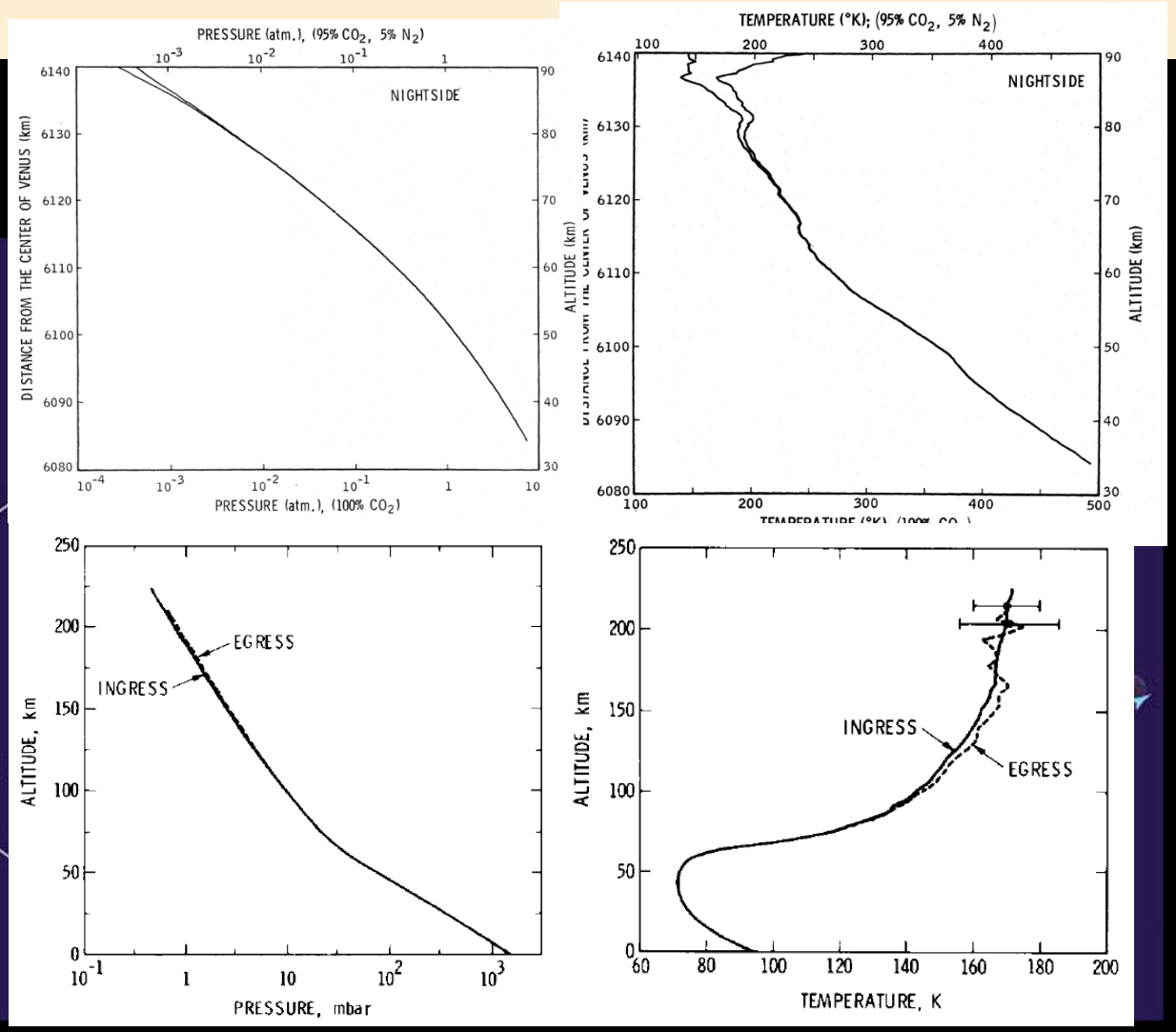
Chiu et al. 2008

行星大氣觀測(“傳統”電波掩星)



http://www.lpl.arizona.edu/undergrad/classes/spring2011/Hubbard_206/Lectures4/Apr05.htm

“航海家”&“水手”衛星計畫

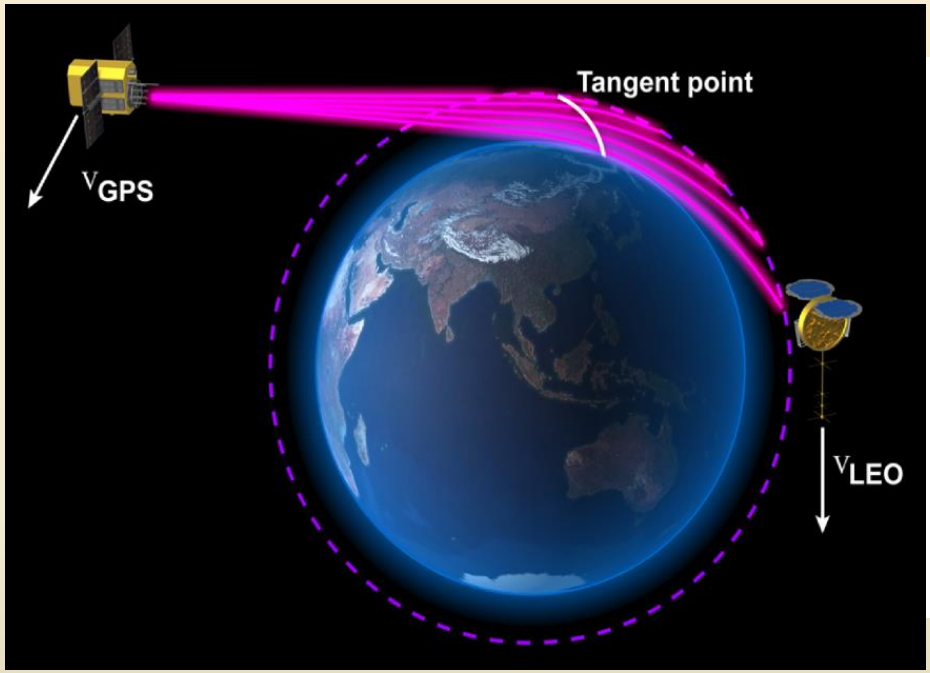


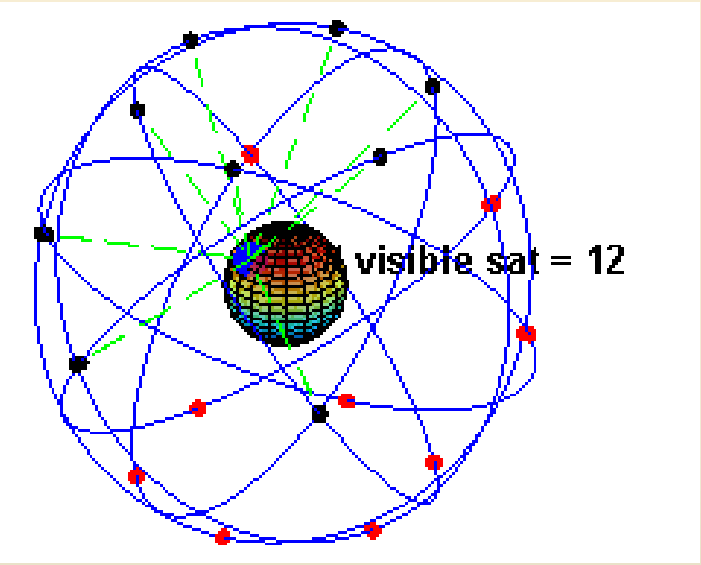
Fjeldbo et al.
ApJ 1971

Lindal et al.
JGR 1983

http://www.khadley.com/courses/astro_121/solar_system.htm

GPS & Radio Occultation





http://en.wikipedia.org/wiki/Image:ConstellationGPS.gif

http://www.image.ucar.edu/DAReS/DART/Research/GPS_Liu/

RO retrieval method (Atm.)

$$L = \int_{GPS}^{LEO} n\, ds$$

$$n(a_p) = \exp\left[\frac{1}{\pi}\int_{a_p}^{a_{top}} \frac{\alpha(a)}{\sqrt{a^2 - a_p^2}}\, da\right]$$

Abel transform

$$dL = a\,d\theta + \frac{\sqrt{r_G^2 - a^2}}{r_G} dr_G + \frac{\sqrt{r_L^2 - a^2}}{r_L} dr_L$$

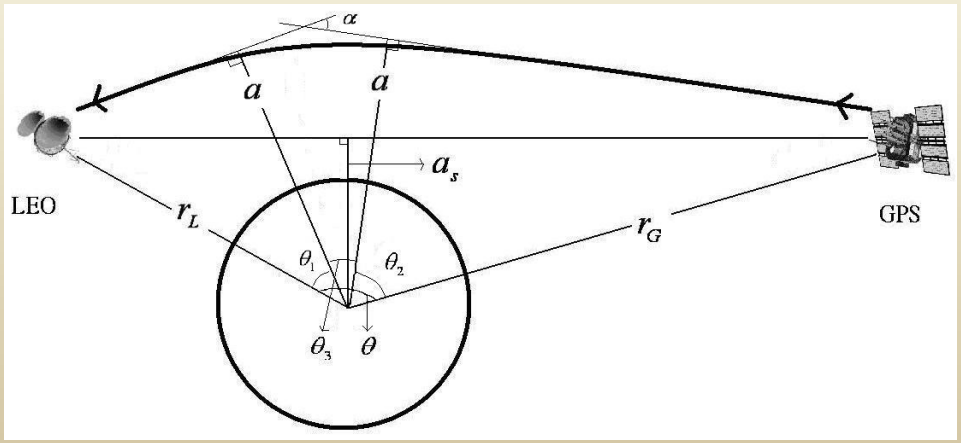
$$n = 1 + N \times 10^{-6}$$

$$N = 77.604\frac{P}{T} + 64.79\frac{e}{T} + 3.776 \times 10^5 \frac{e}{T^2}$$

$$\alpha = \theta - \left[\cos^{-1}\left(\frac{a}{r_L}\right) + \cos^{-1}\left(\frac{a}{r_G}\right)\right]$$

$$P = \rho R T / M$$

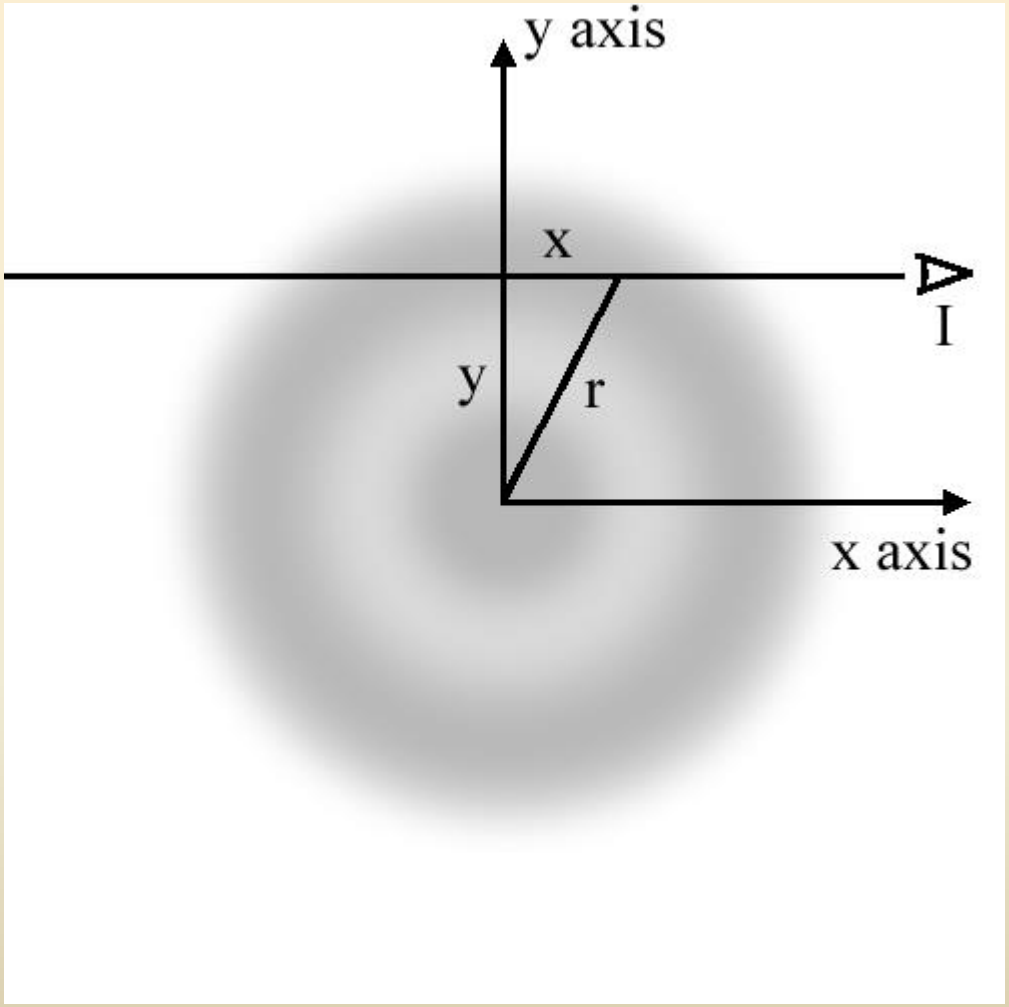
$$N = 77.6\frac{P}{T} = 77.6\frac{\rho R}{M}$$



$$dP = -g\rho dz$$

$$P(z_i) = \frac{M}{77.6R}\int_{z_i}^{Top} -g(z')N(z')dz' + P(Top)$$

Abel transform



$$F(y) = \int_{-\infty}^{\infty} f\left(\sqrt{x^2 + y^2}\right) dx$$

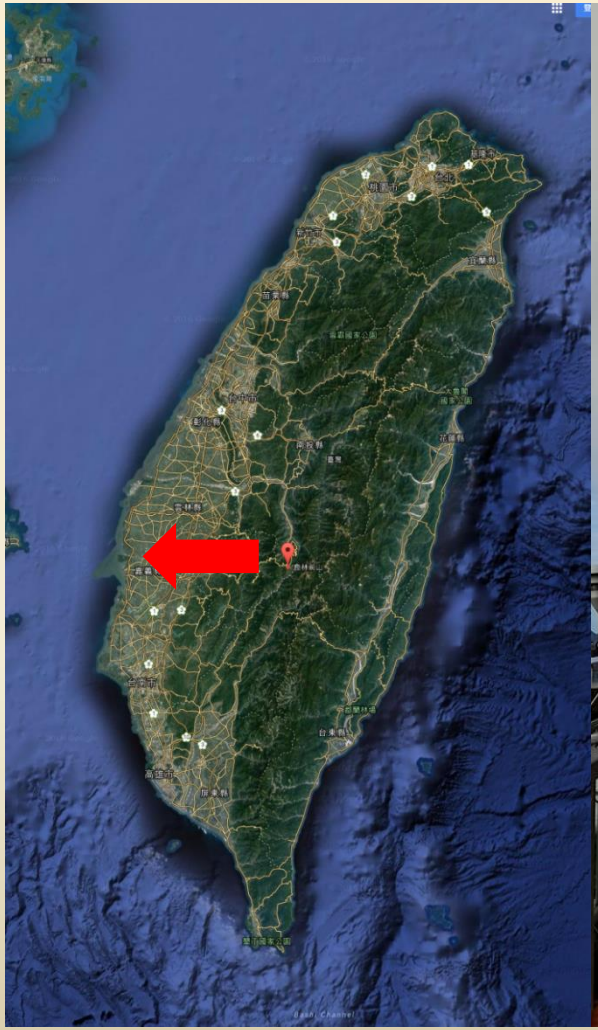
atmosphere

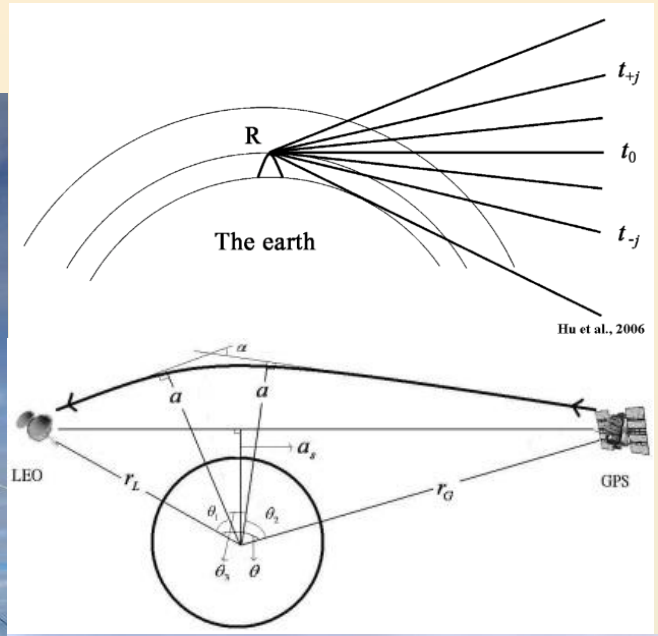
$$n(a_p) = \exp\left[\frac{1}{\pi}\int_{a_p}^{a_{top}} \frac{\alpha(a)}{\sqrt{a^2 - a_p^2}} da\right]$$

ionosphere

$$N(r) = -\frac{1}{\pi}\int_{r}^{LEO} \frac{d\tilde{T}/dr_0}{\sqrt{r_0^2 - r^2}} dr_0$$

Mountain Based Radio Occultation





掩星觀測原理

GPS衛星

福衛三號衛星

Total Electron Content (TEC)

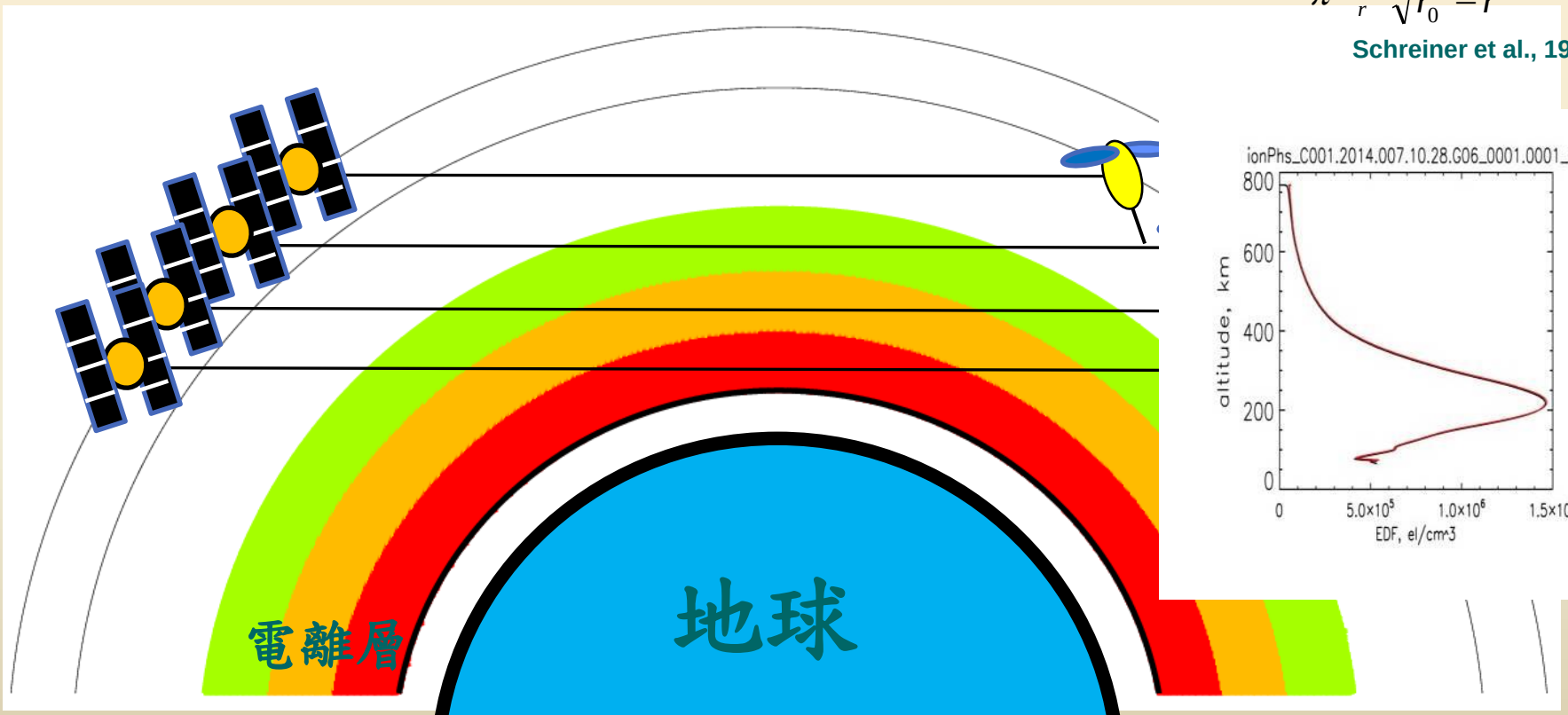
$$TEC = \int Ndl = -\frac{f^2}{40.3\times10^6}\int (n-1)dl = -\frac{f^2 S}{40.3}$$

$$TEC = -\frac{S_1 f_1^2}{40.3} = -\frac{S_2 f_2^2}{40.3} = \frac{(S_1 - S_2) f_1^2 f_2^2}{40.3(f_1^2 - f_2^2)}$$

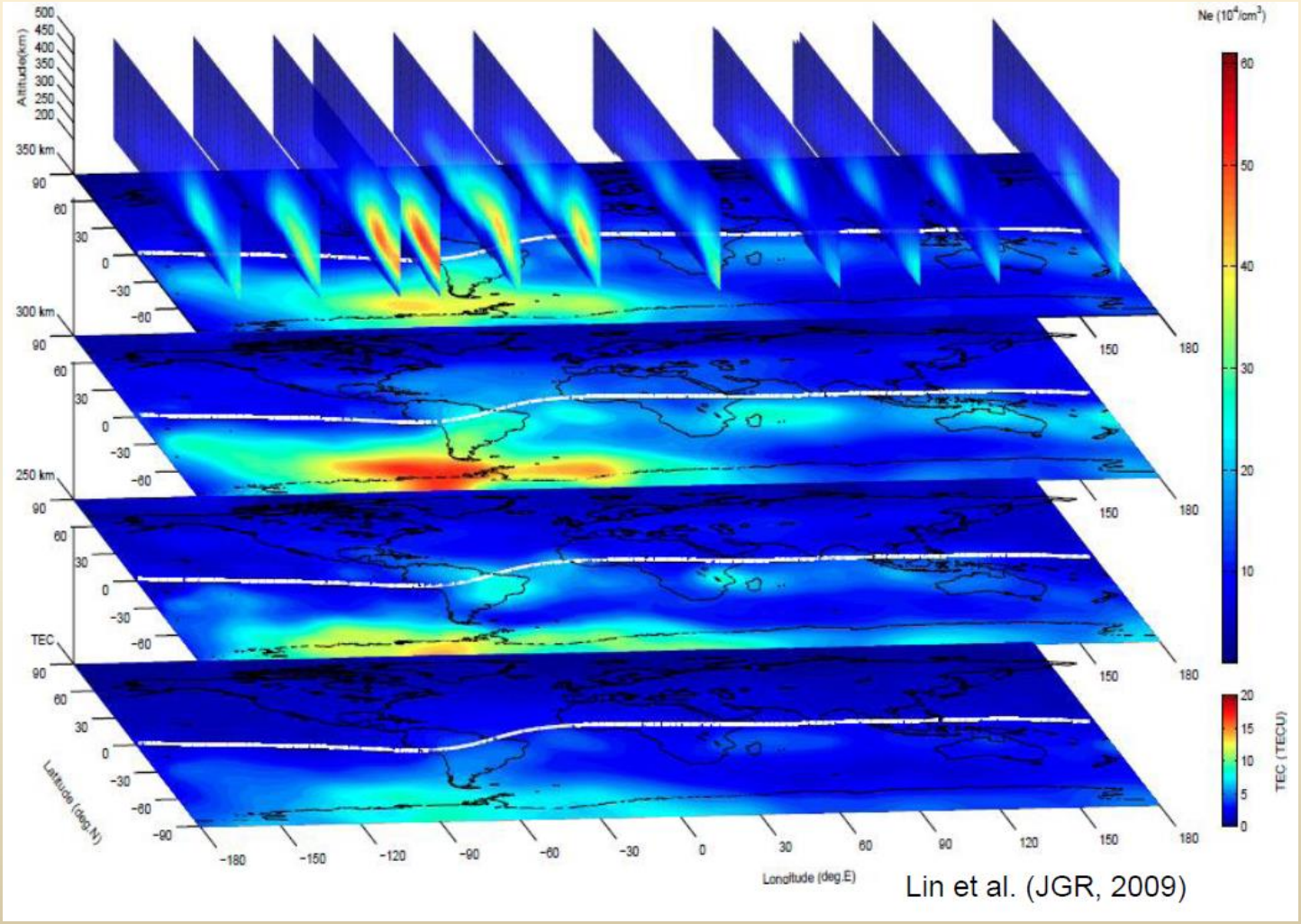
Abel transform

$$N(r) = -\frac{1}{\pi}\int_r^{LEO} \frac{d\tilde{T}/dr_0}{\sqrt{r_0^2 - r^2}} dr_0$$

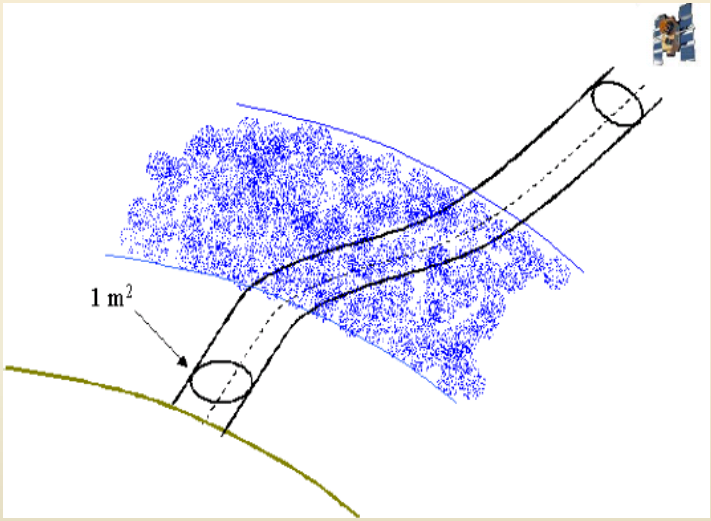
Schreiner et al., 1999

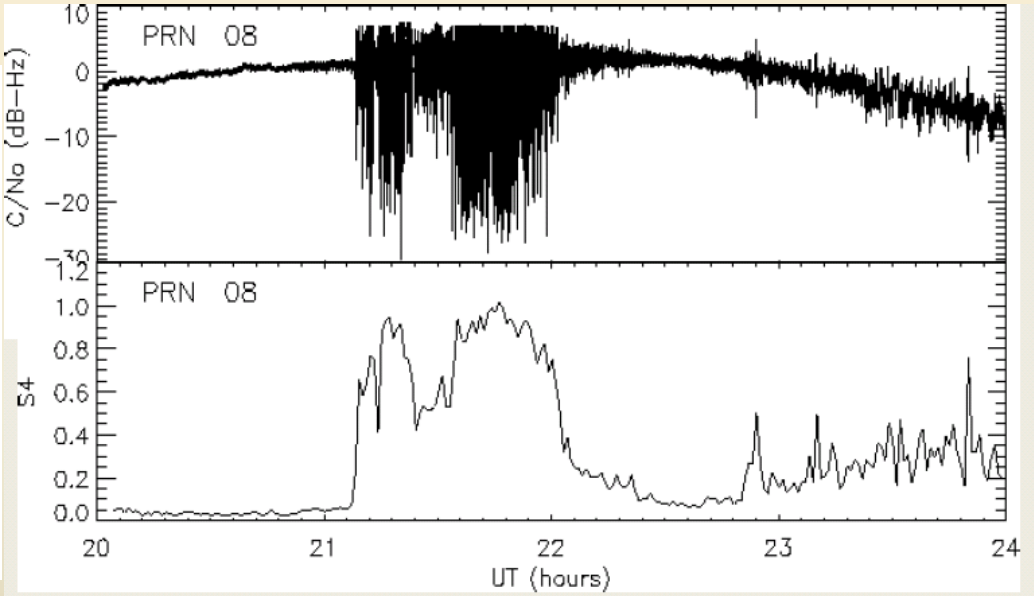


福衛三號觀測全球電子濃度分布



電離層不規則體 造成 訊號品質下降

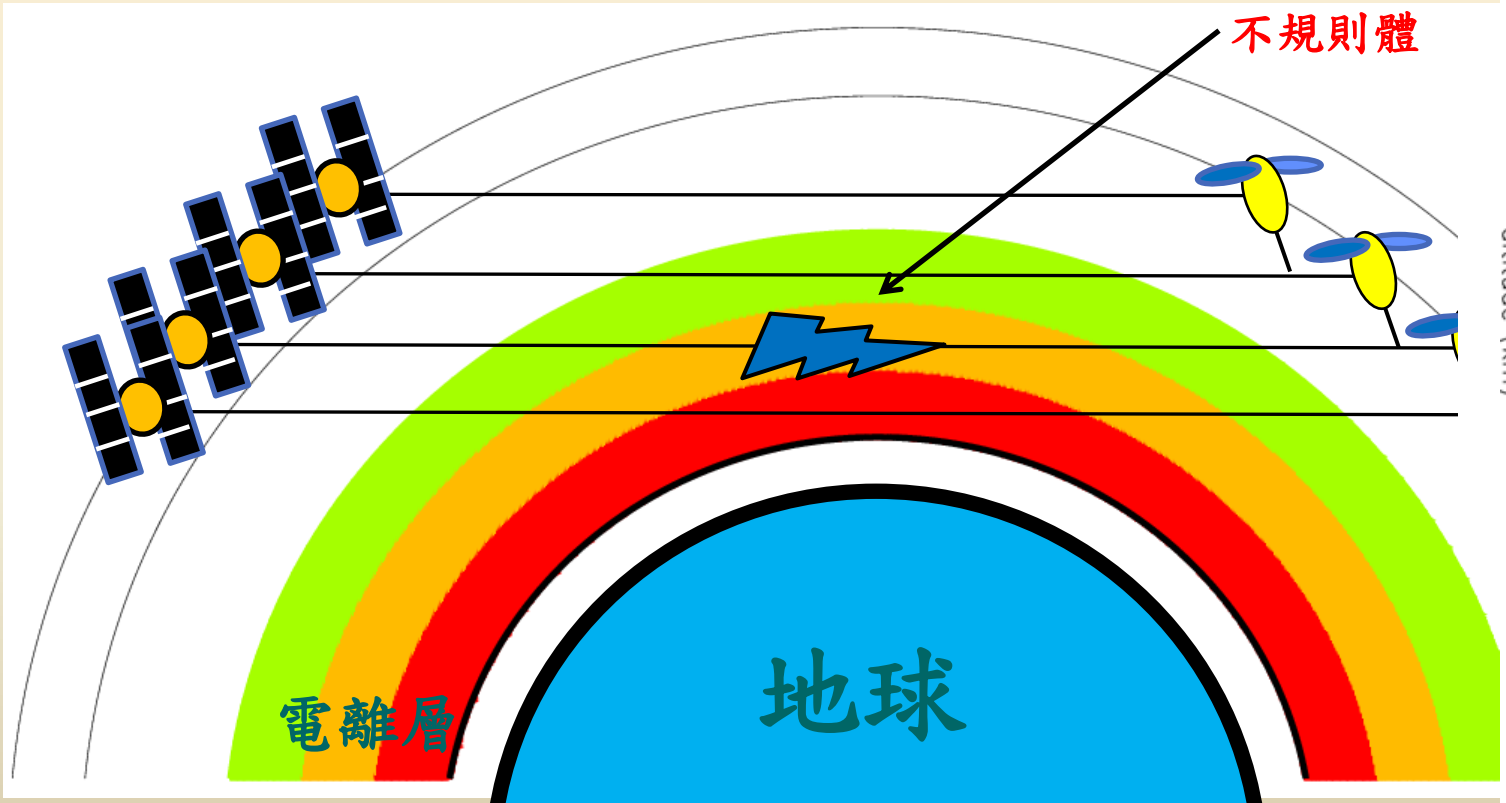


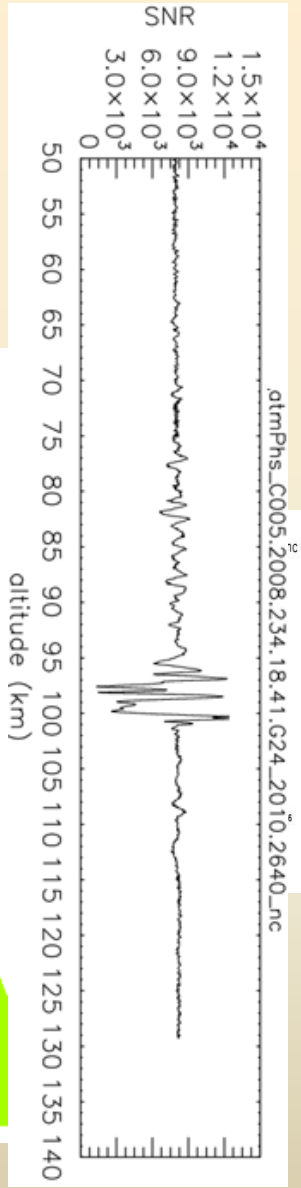


SCINDA MANUAL (Carrano, 2007) p 14

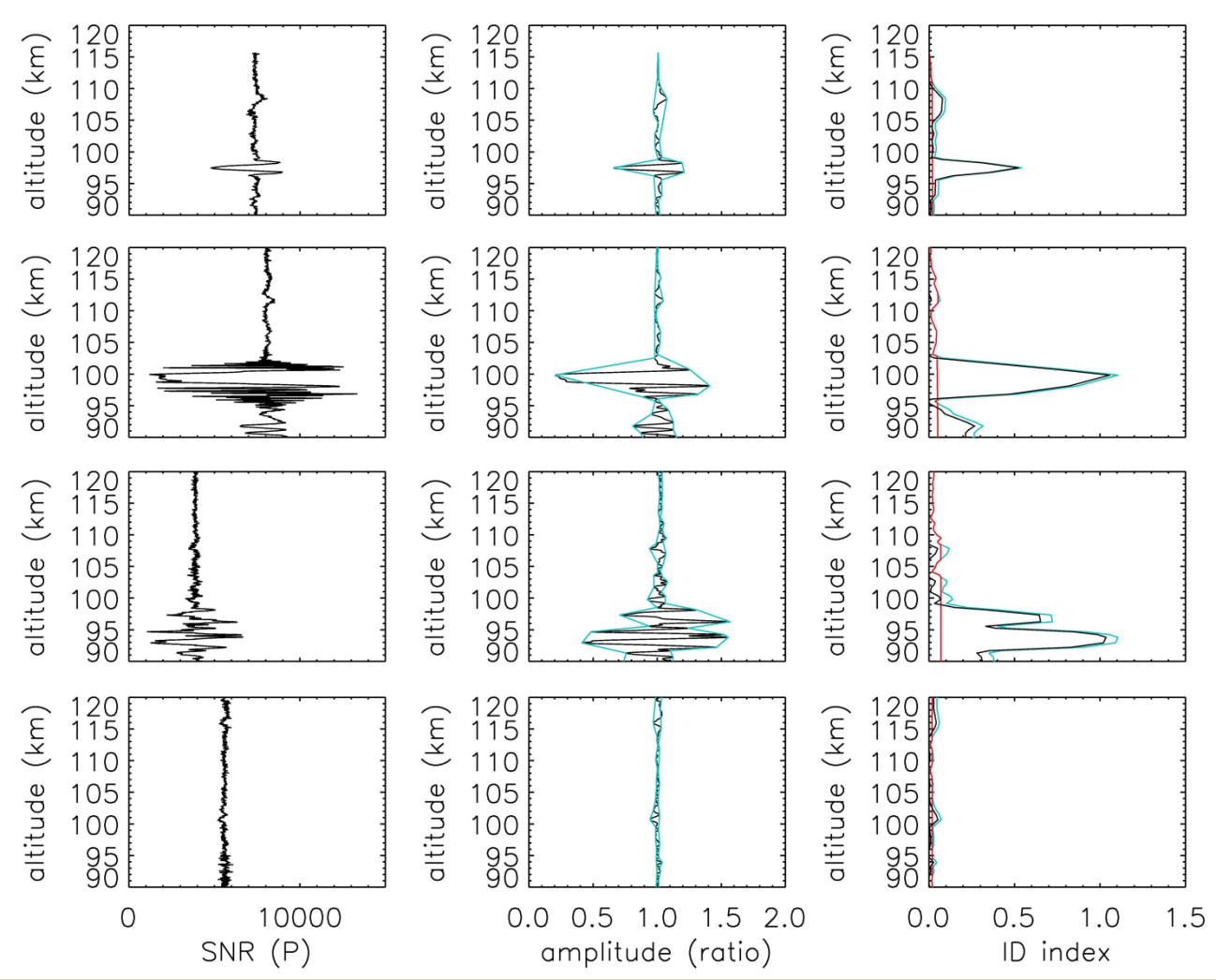
掩星觀測原理

GPS衛星　福衛三號衛星



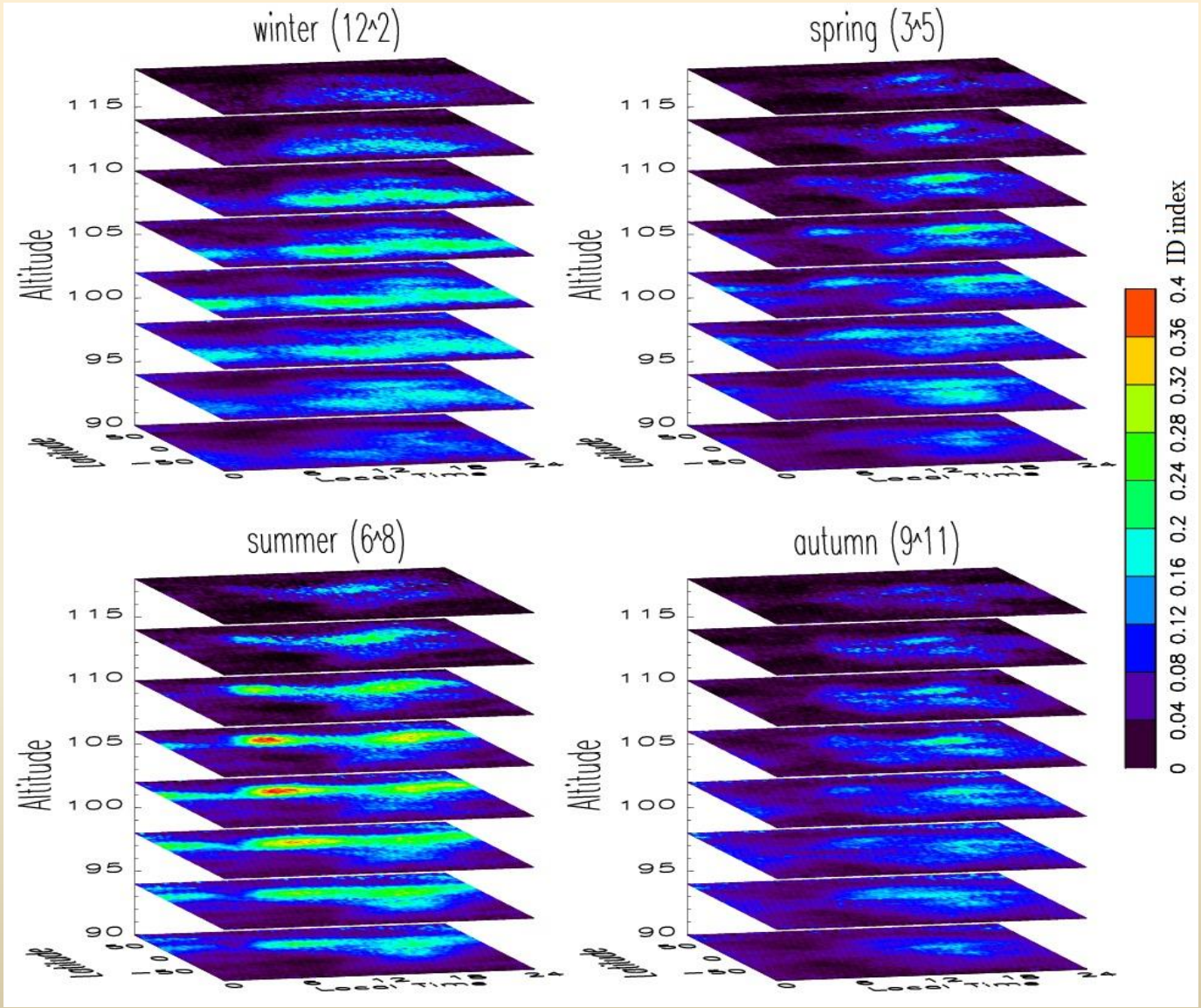


Analysis of RO amplitude



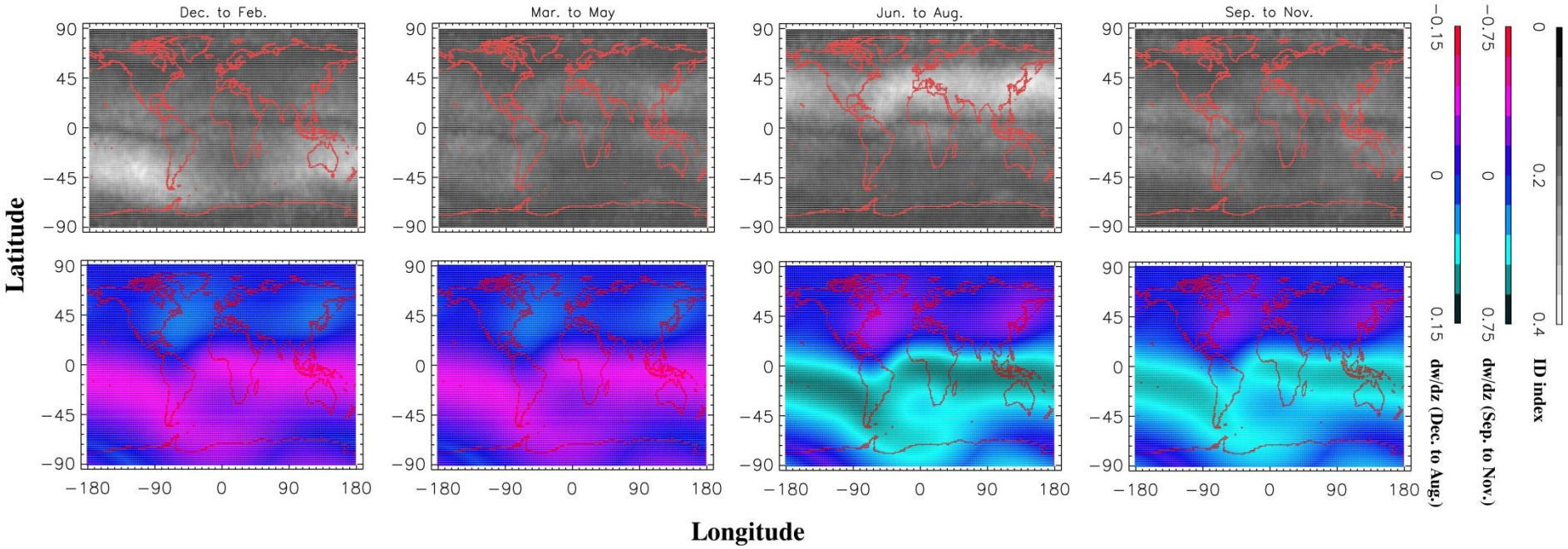
Yeh et al. 2013

Seasonal Es layer activity



Yeh et al. 2013

Comaprison between Es layer activity & wind shear

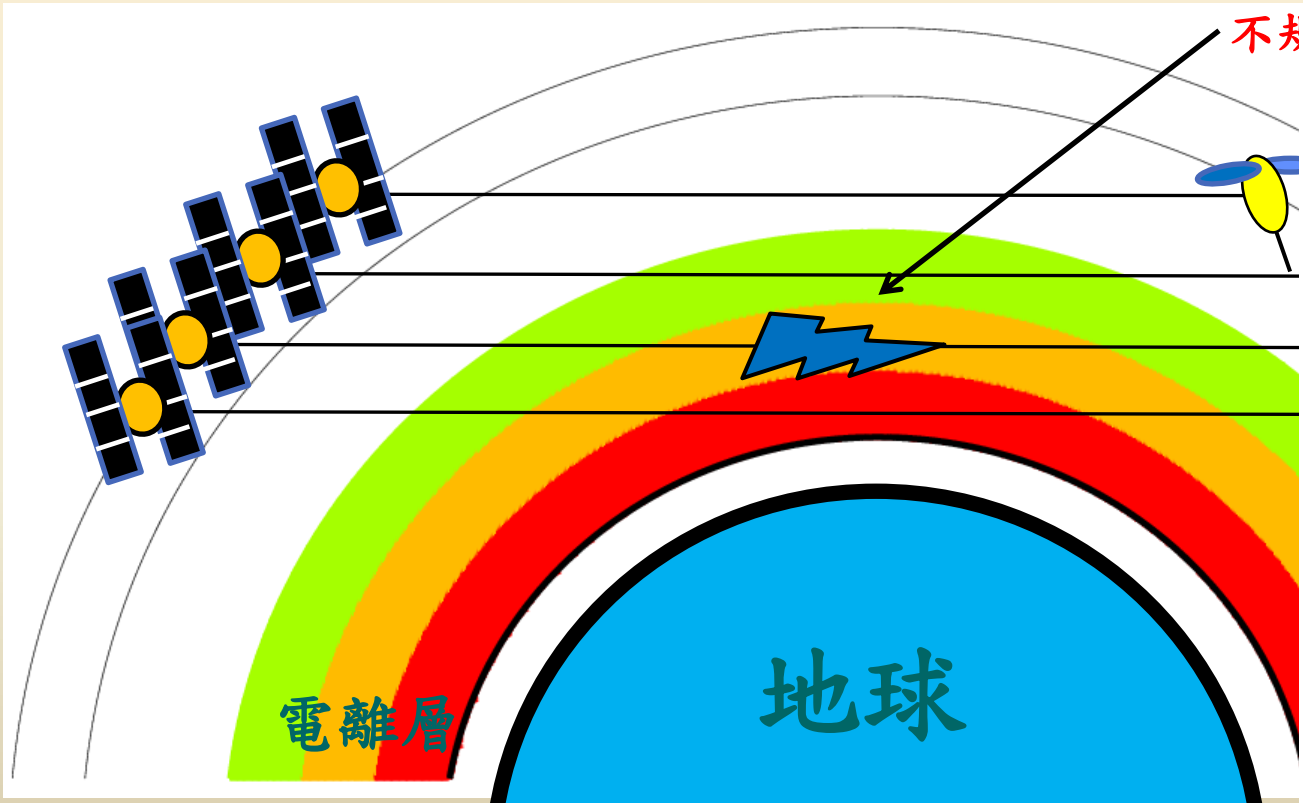


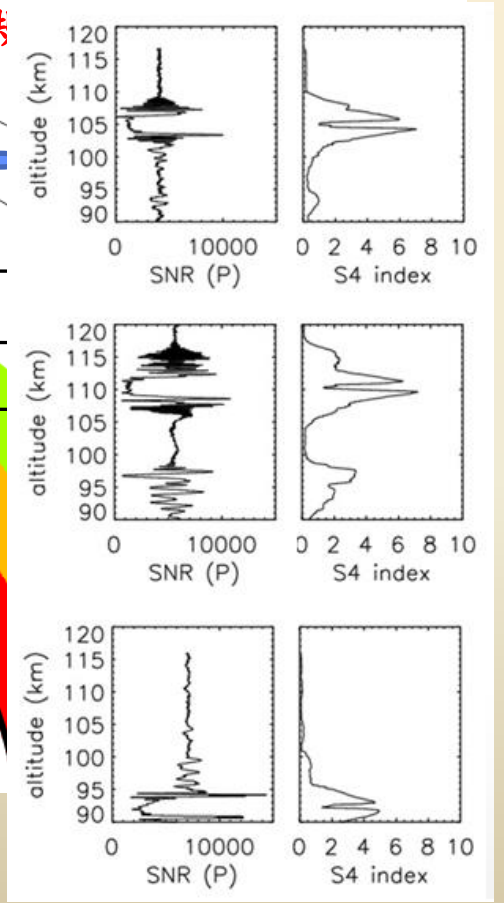
Yeh et al. 2014

Irregularity & S4 index

GPS衛星　福衛三號衛星

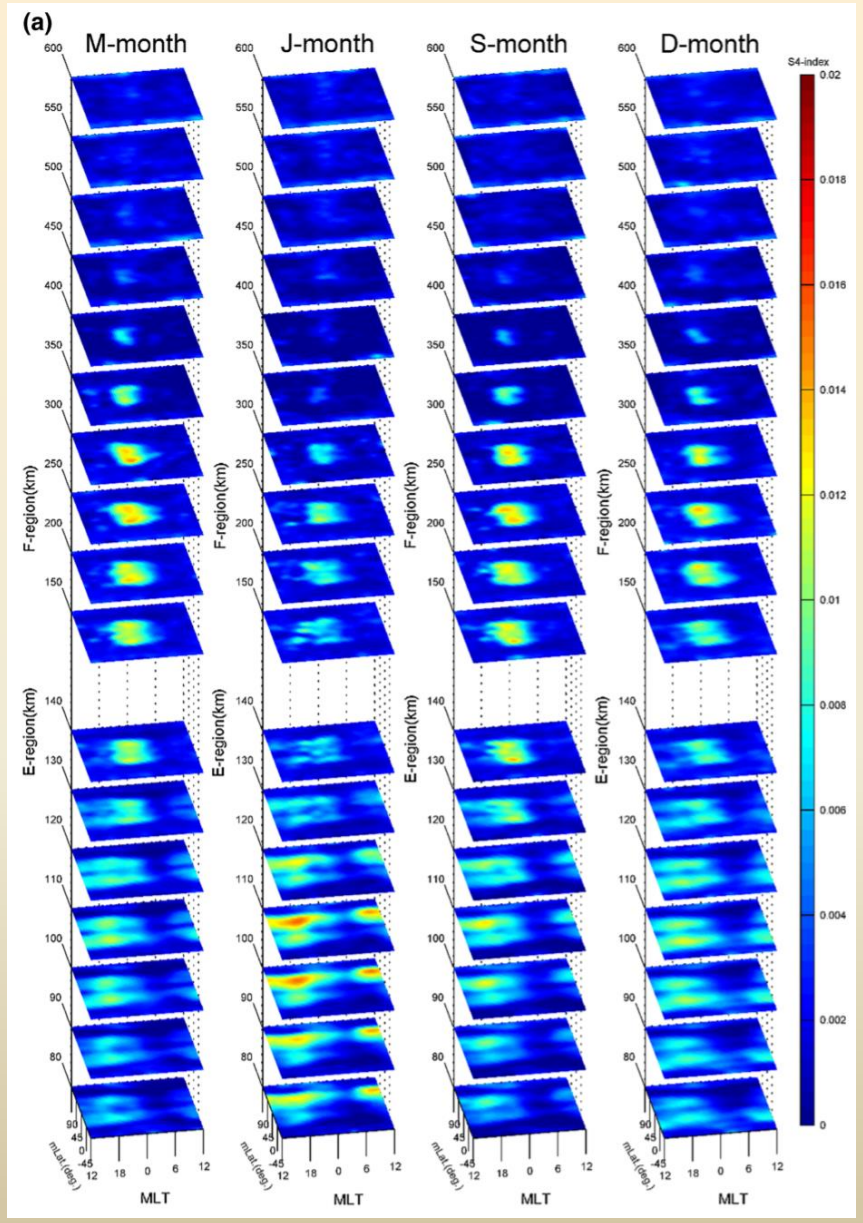
$$S_4 = \frac{\sqrt{\left\langle \left(I - \langle I \rangle\right)^2 \right\rangle}}{\langle I \rangle}$$



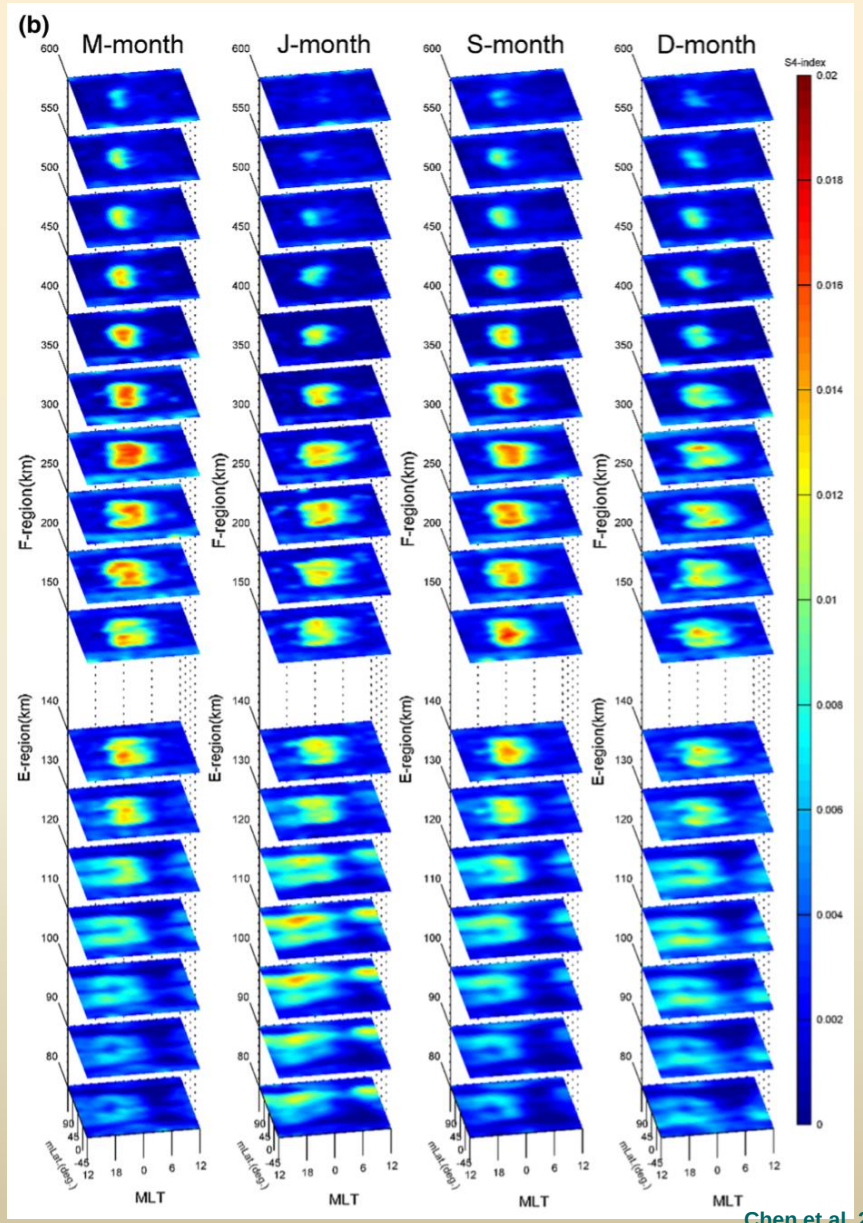


電離層不規則體

太陽活動極小期



太陽活動極大期



Chen et al. 2016

Ionospheric scintillation prediction

電離層閃爍指數

台灣地區預測 | 指數預報 | 發生率預報

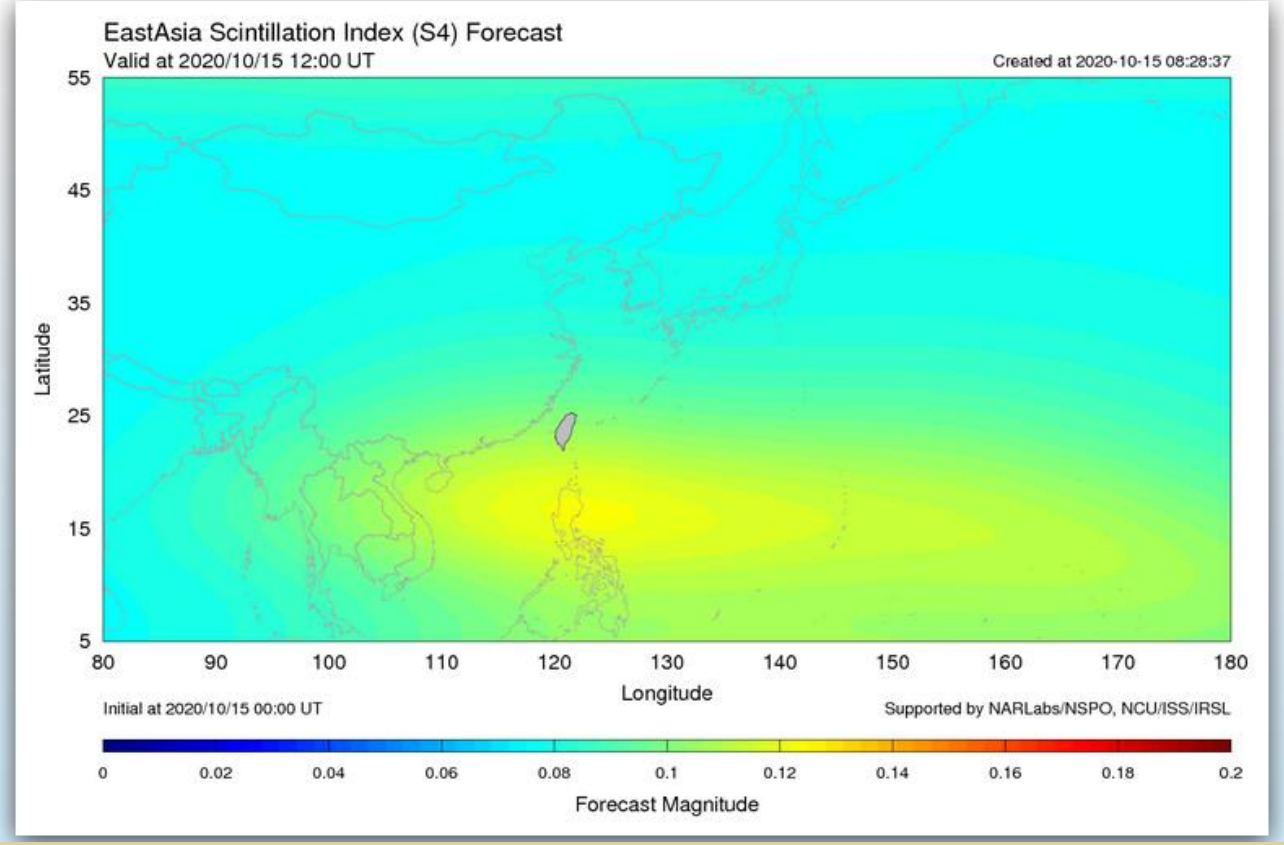
- 全球範圍
- 東亞地區

※單張顯示(靜態)

2020/10/15 12:00 UT

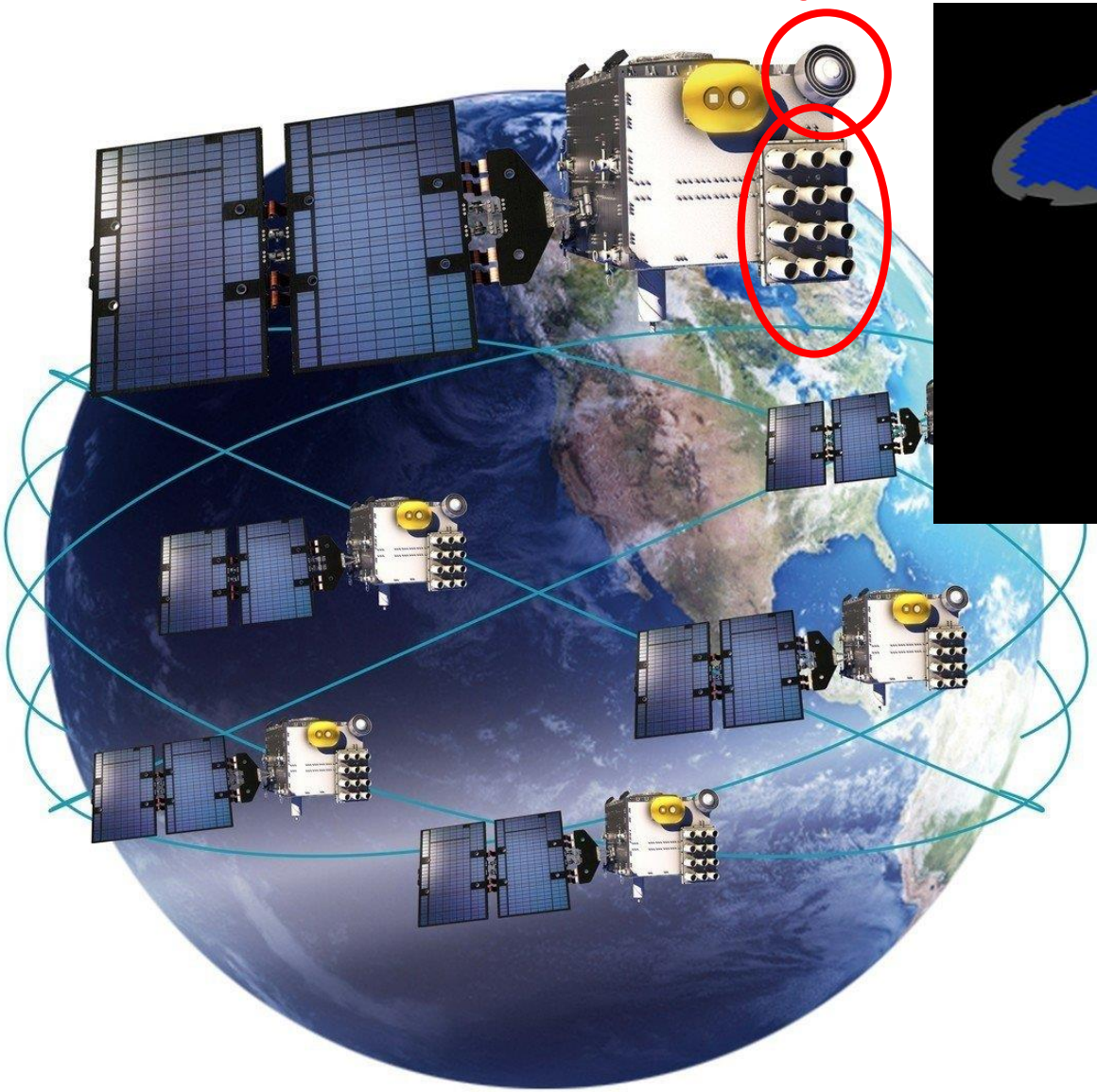
※動態顯示：

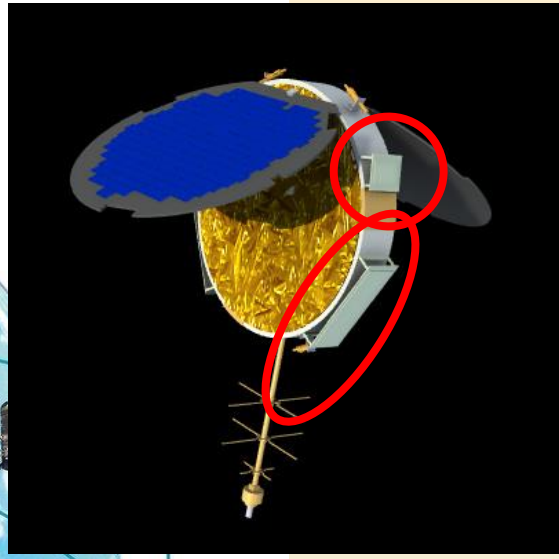
- 12小時
- 24小時
- 36小時
- 48小時
- 60小時
- 72小時



https://swoo.cwb.gov.tw/V2/page/Forecast/Scintillation.html

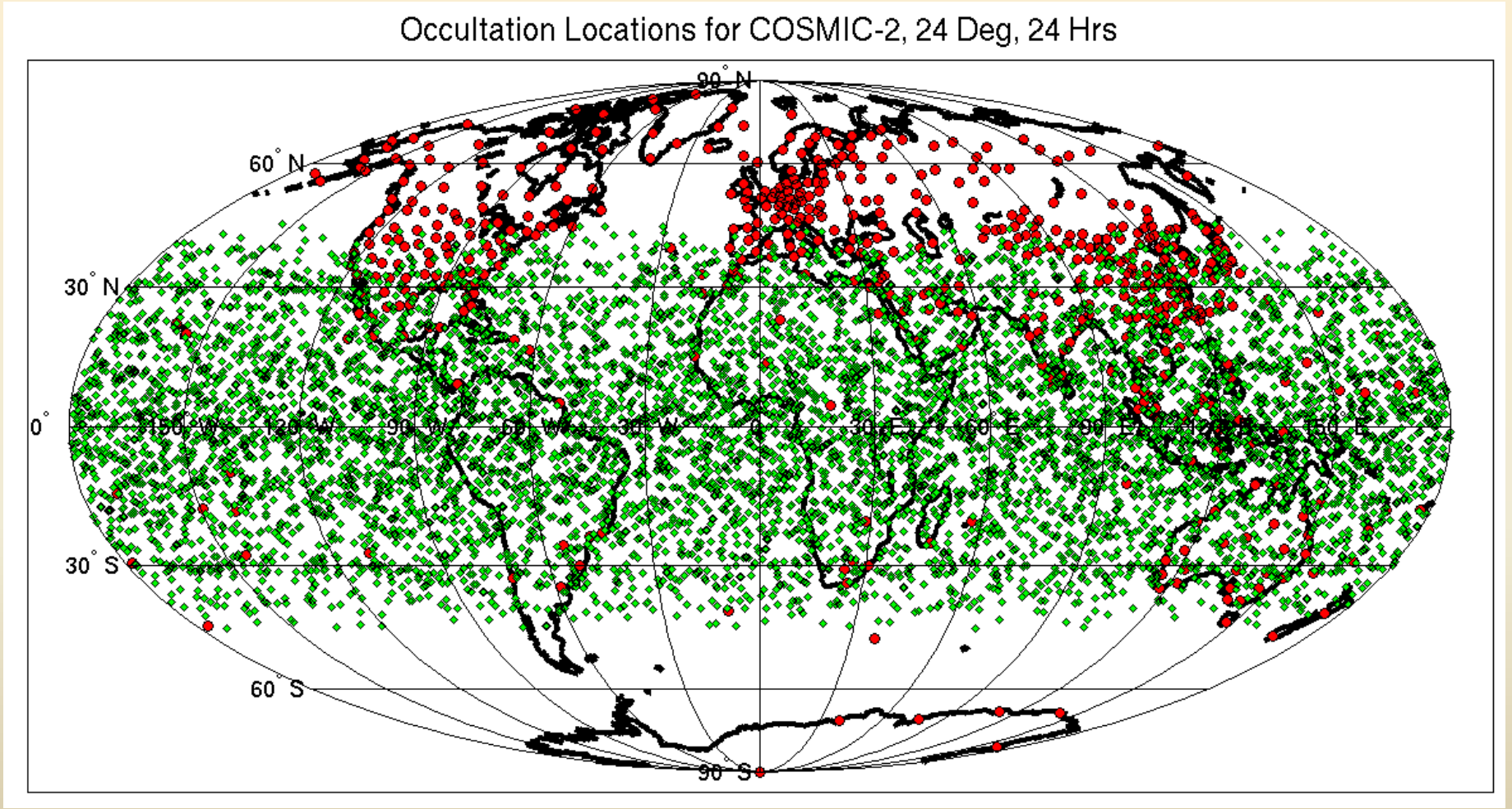
TriG Radio occultation System (TGRS)



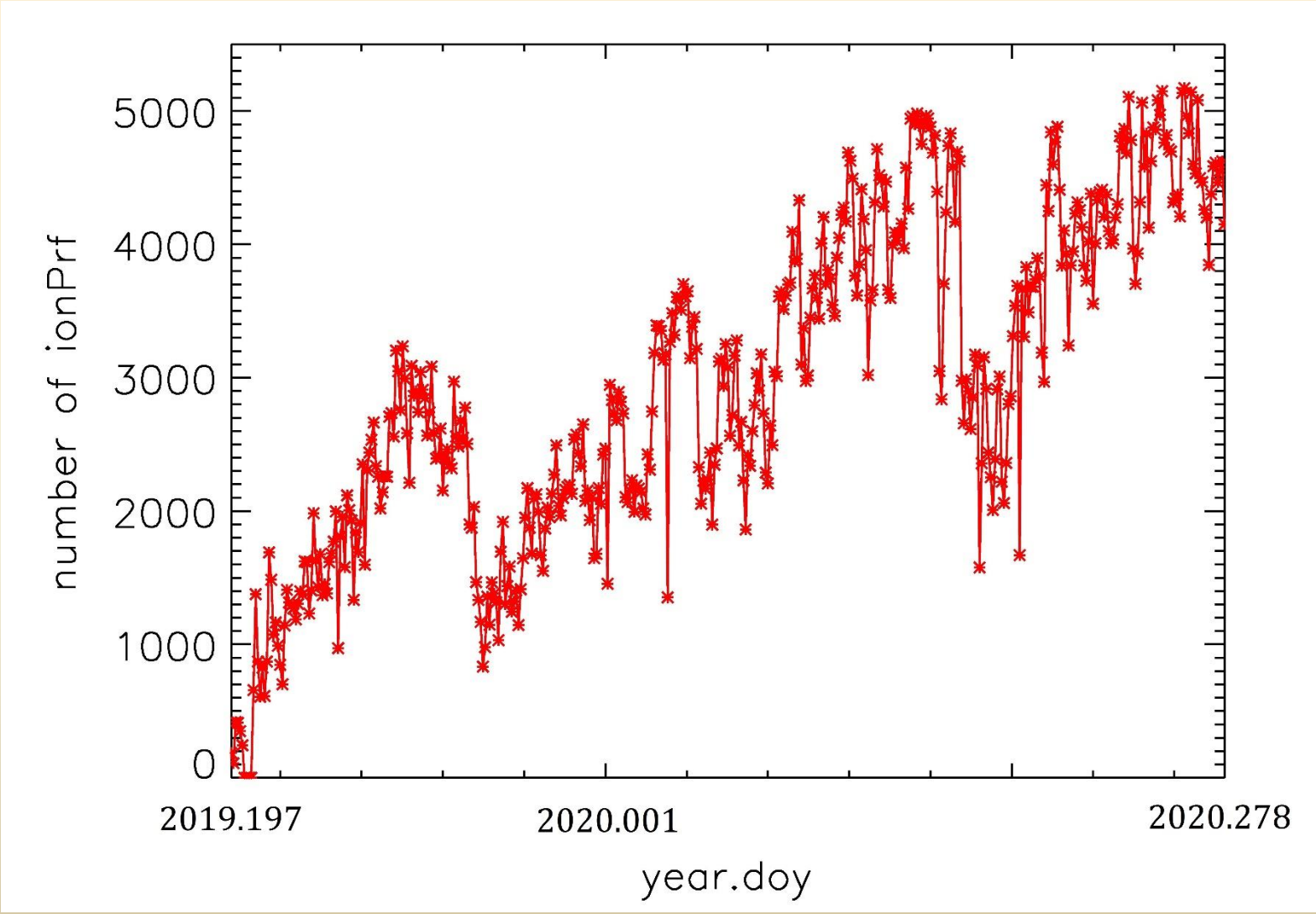


福衛七號氣象衛星星系

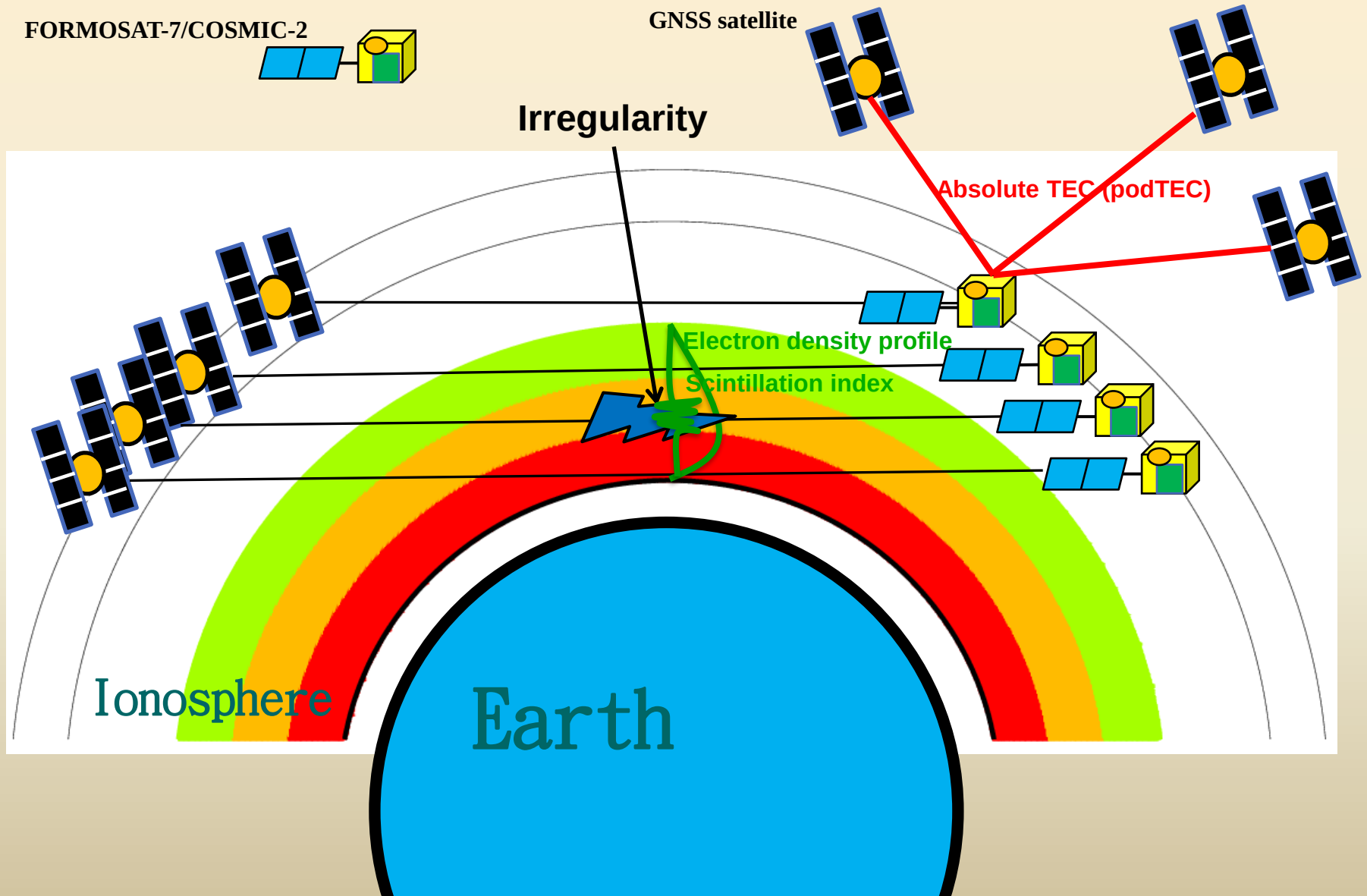
福衛七號　一天資料點分布



Data number of electron density profiles



Ratio Occultation Technique



Plasmasphere electron content

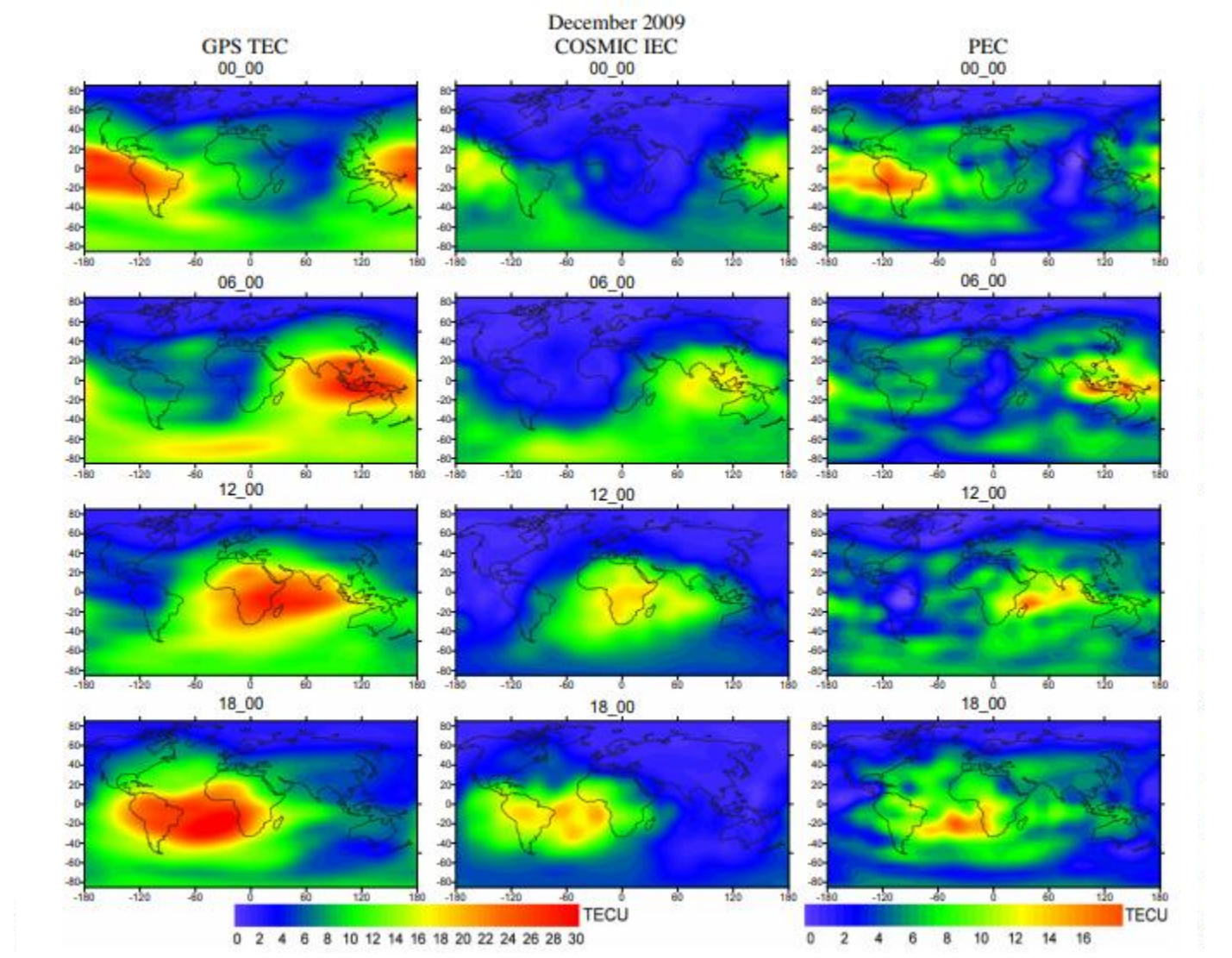
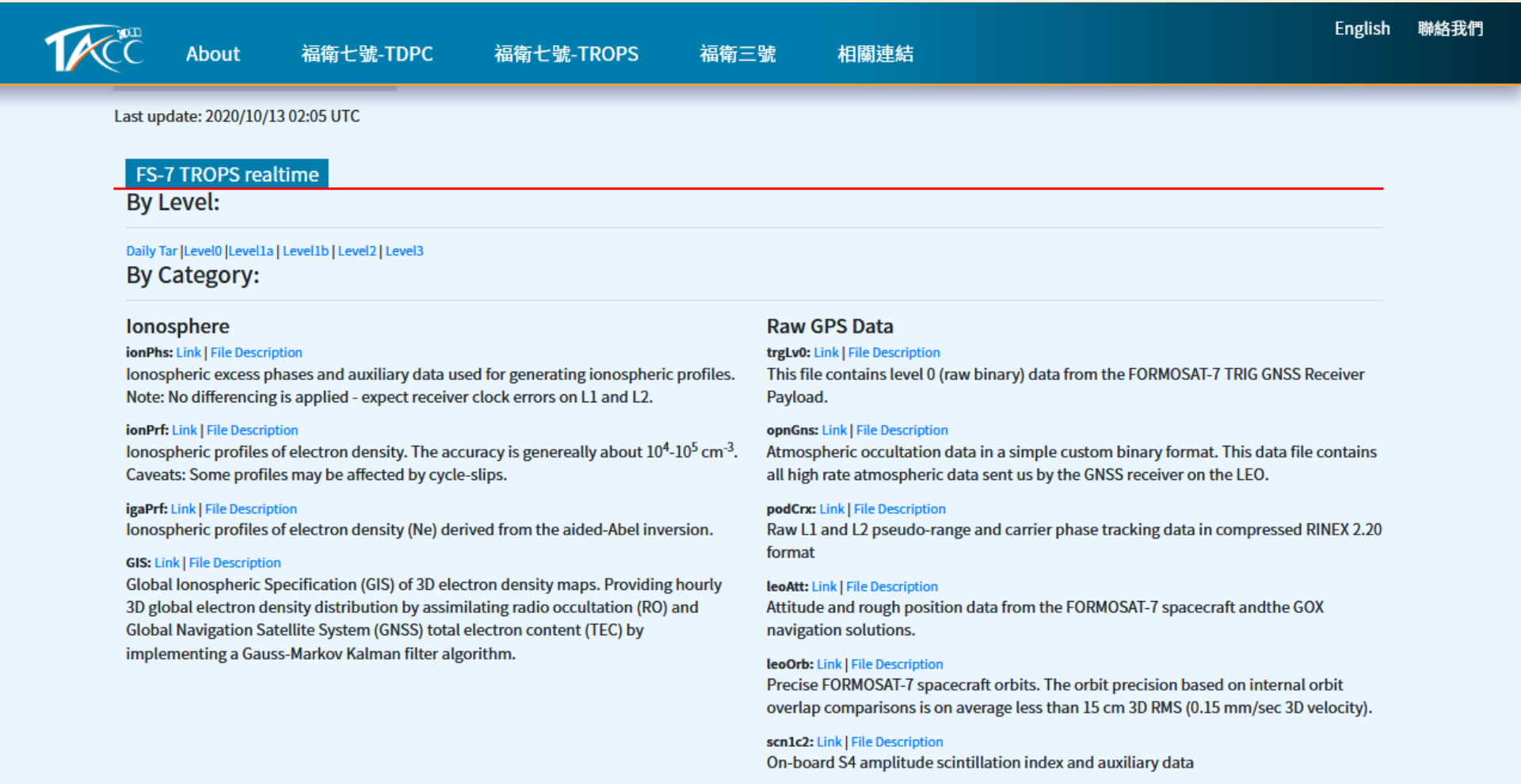


Fig. 5. Same as Fig. 2 but for December 2009.

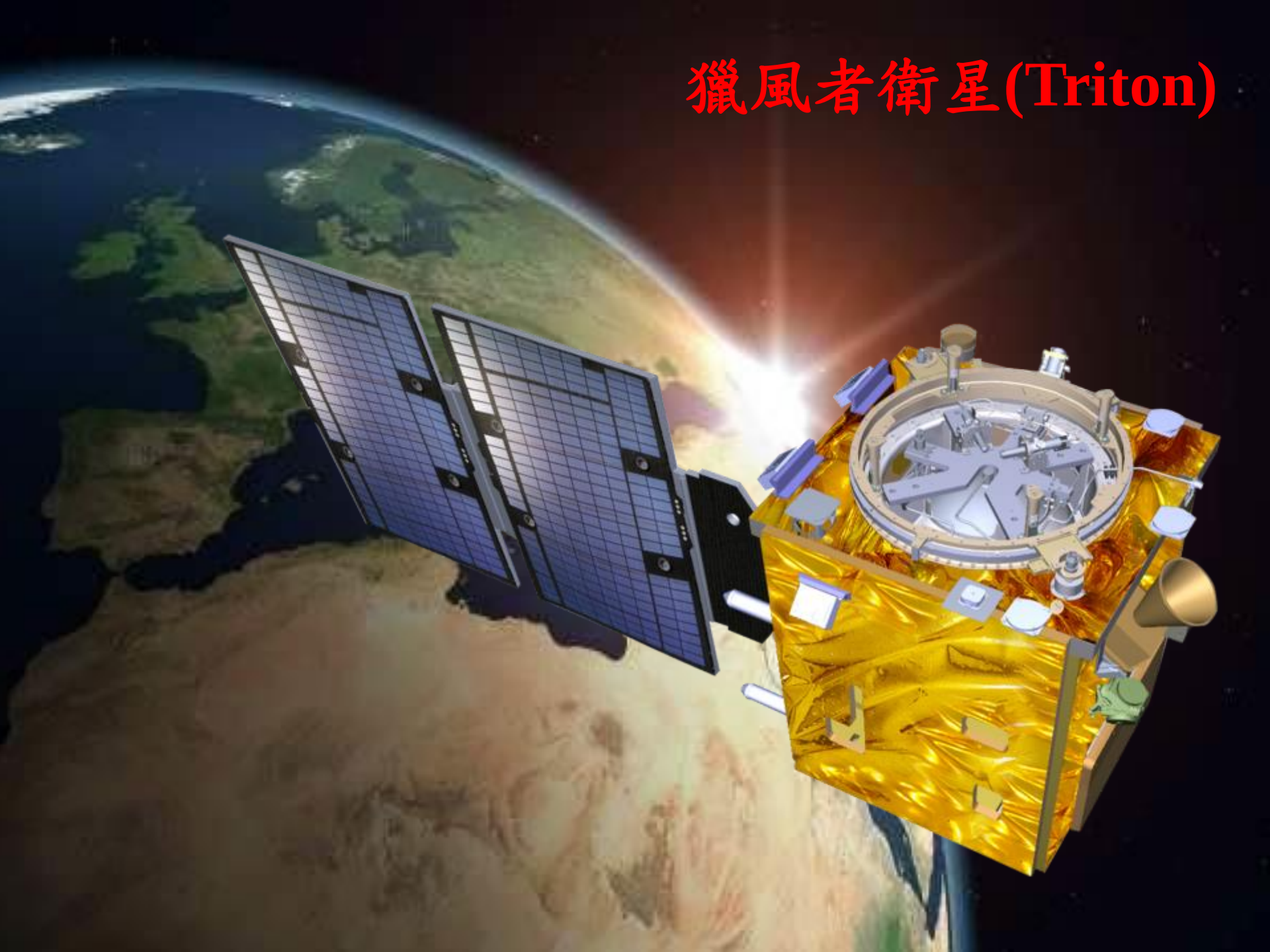
Cherniak et al. 2012

TROPS data download web.



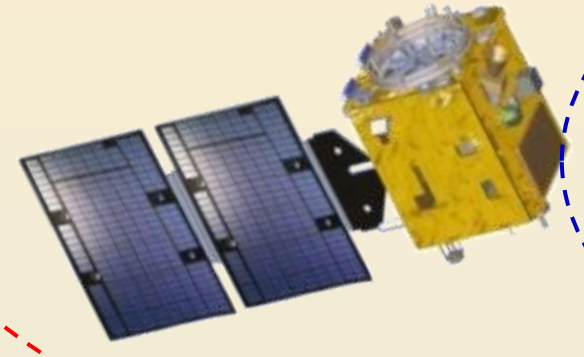
http://tacc.cwb.gov.tw

獵風者衛星(Triton)



Triton vs. FS-7 Mission Satellite

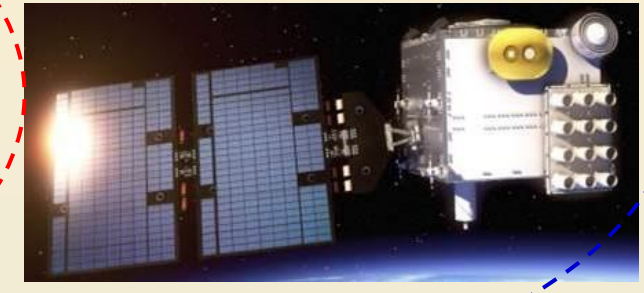
Triton

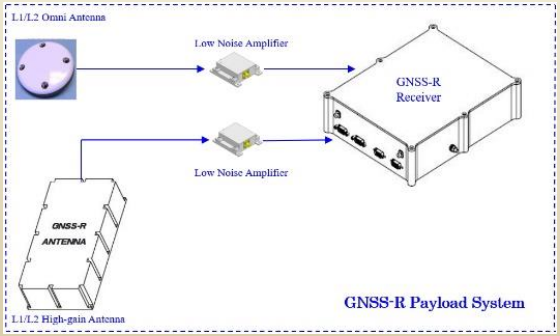


Common components:

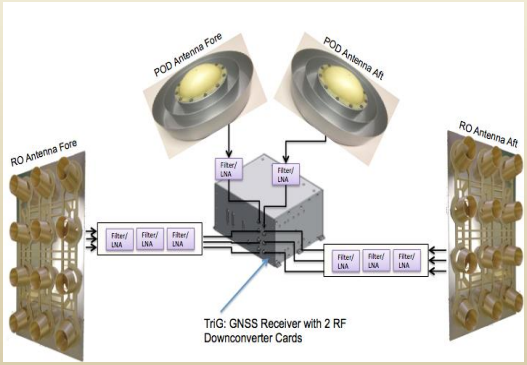
- Propulsion system
- S-band transceiver
- Reaction wheel
- Magnetometer
- Coarse sun sensor
- Magnetic Torquer
- Battery

FS-7 Mission



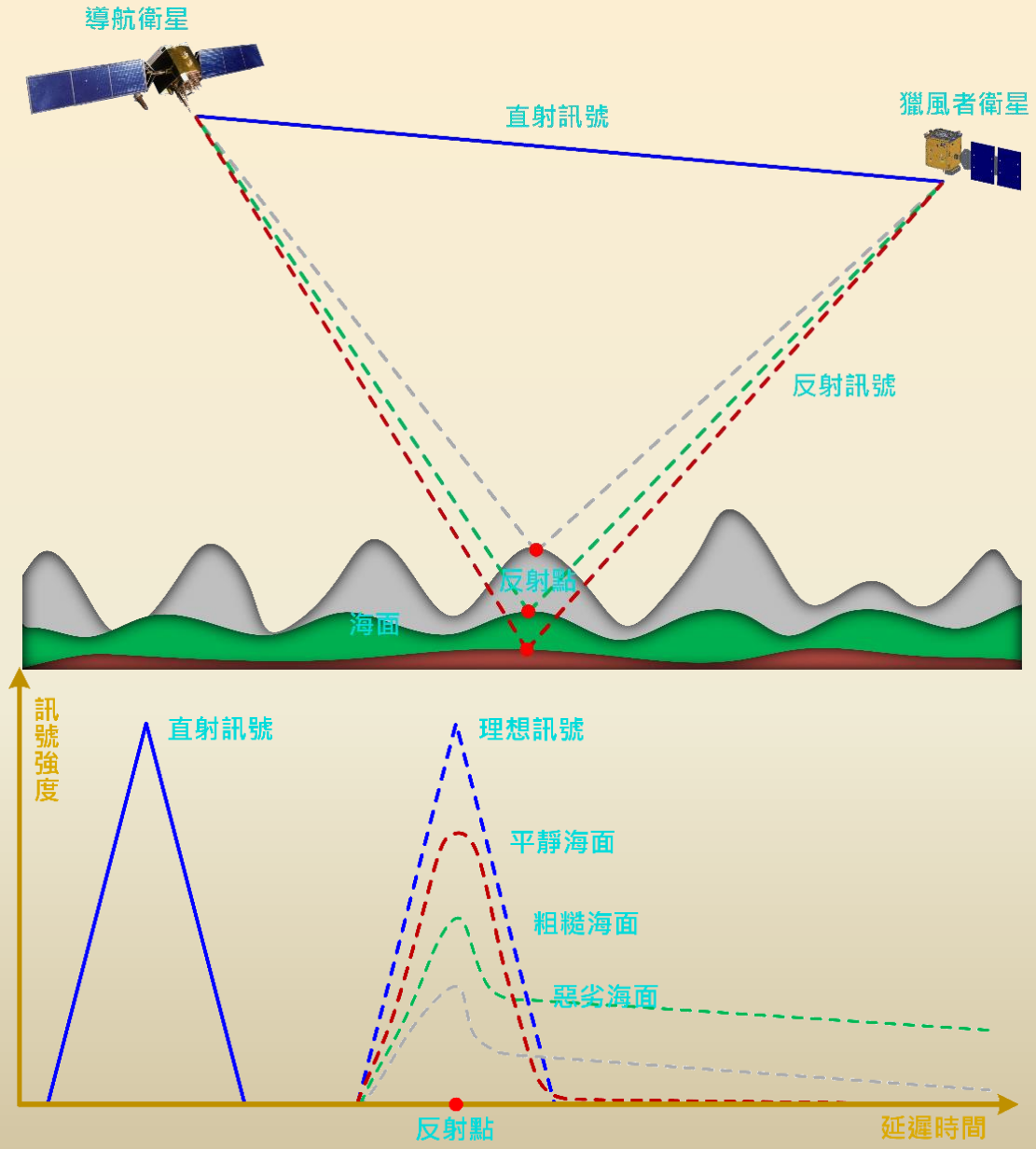


GNSS-R Mission Payload



TGRS Mission Payload

GNSS-Reflectometry principle (1)



Ground GNSS-R Applications

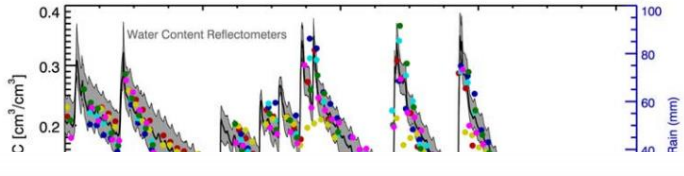
Figure 4-2 Surroundings of Kaohsiung station (Cerdit: Google Earth)

Figure 4-3 Configuration of GNSS station in Kaohsiung harbor

(Credit: National Land Surveying and Mapping Center, NLSC)

李啟民, 2017

Soil moisture



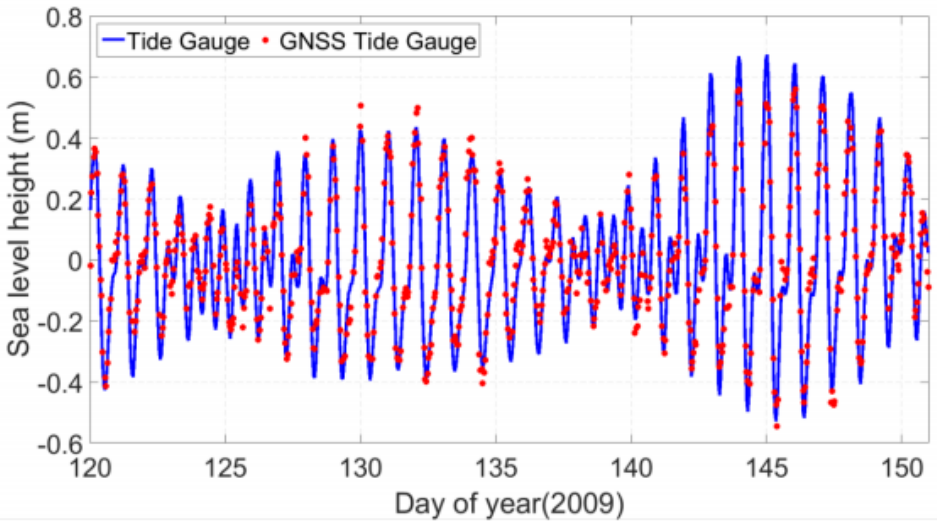


Figure 4-9 Sea level changes from tide gauge and GNSS-based tide gauge

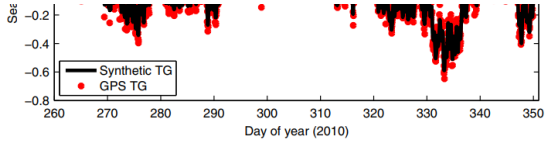
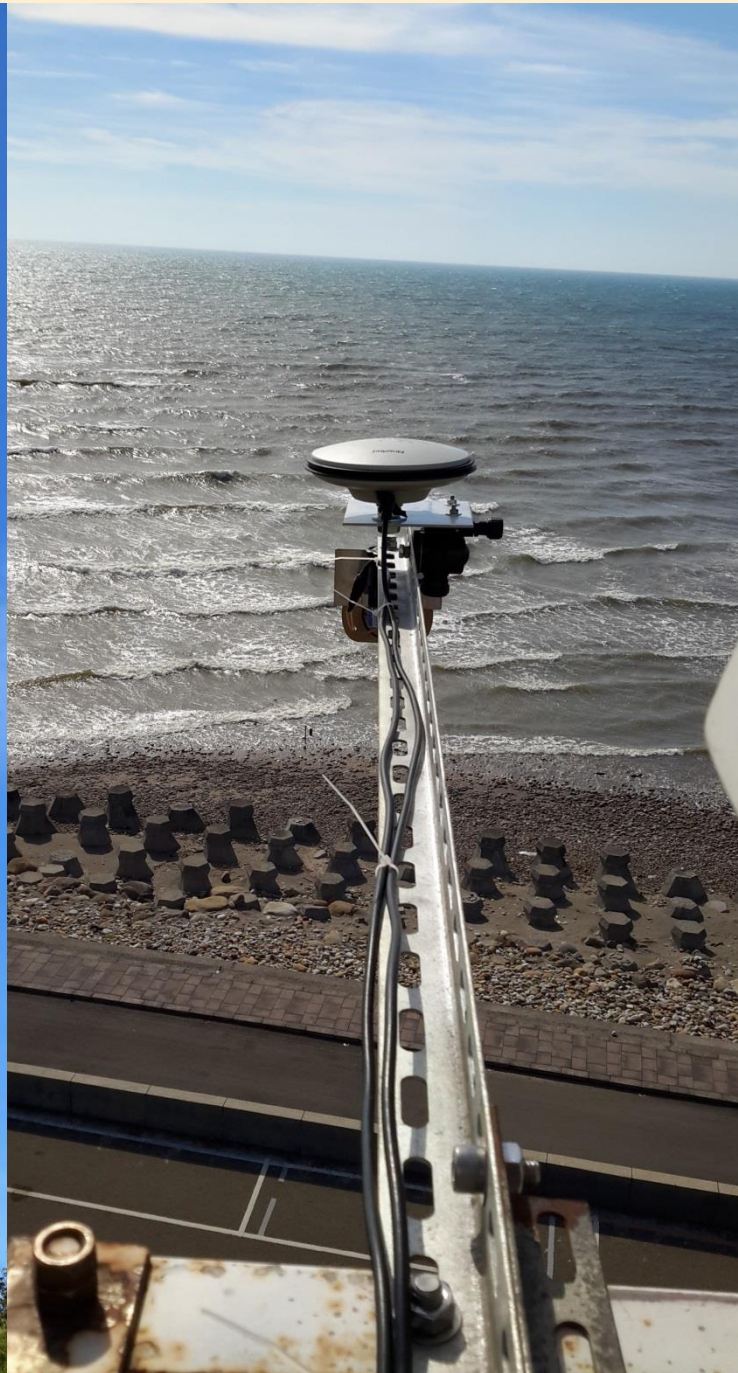
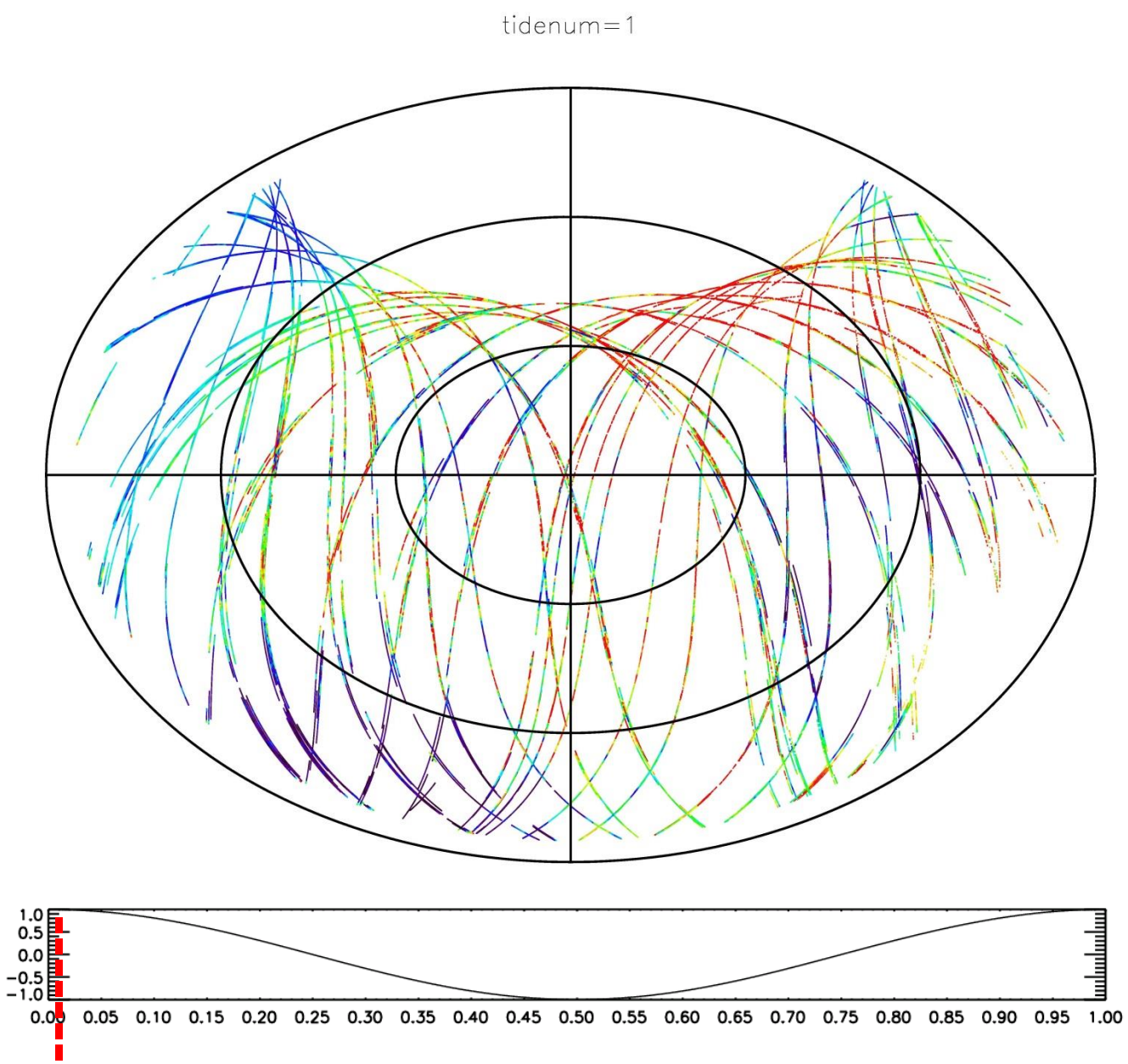


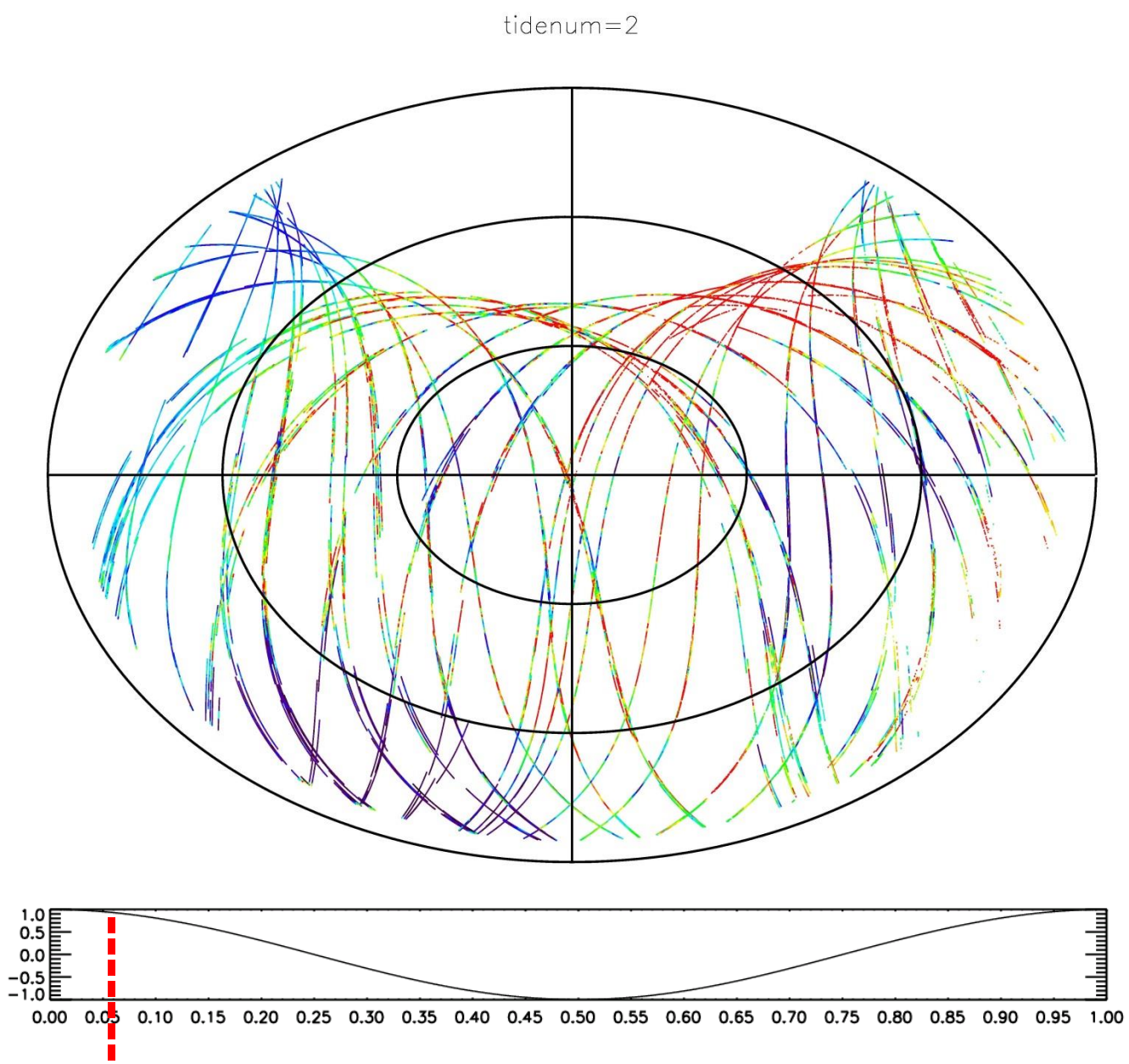
Fig. 6. Sea level from a synthetic tide gauge at Onsala (black line), calculated from a weighted mean of tide gauge observations at Ringhals and Gothenburg, and estimated sea level measurements from the Onsala GPS tide gauge (red dots). (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

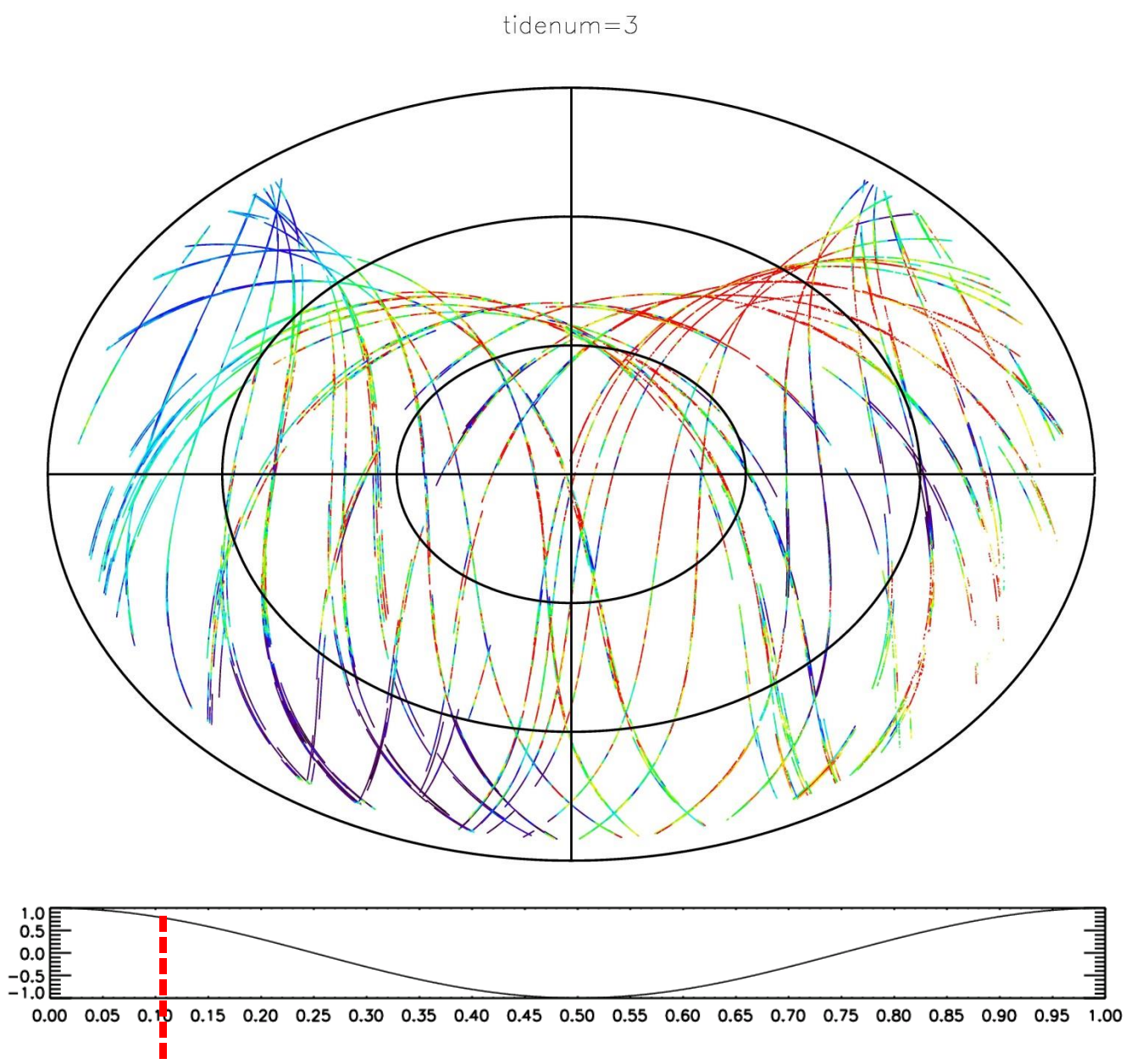
Larson et al., 2012

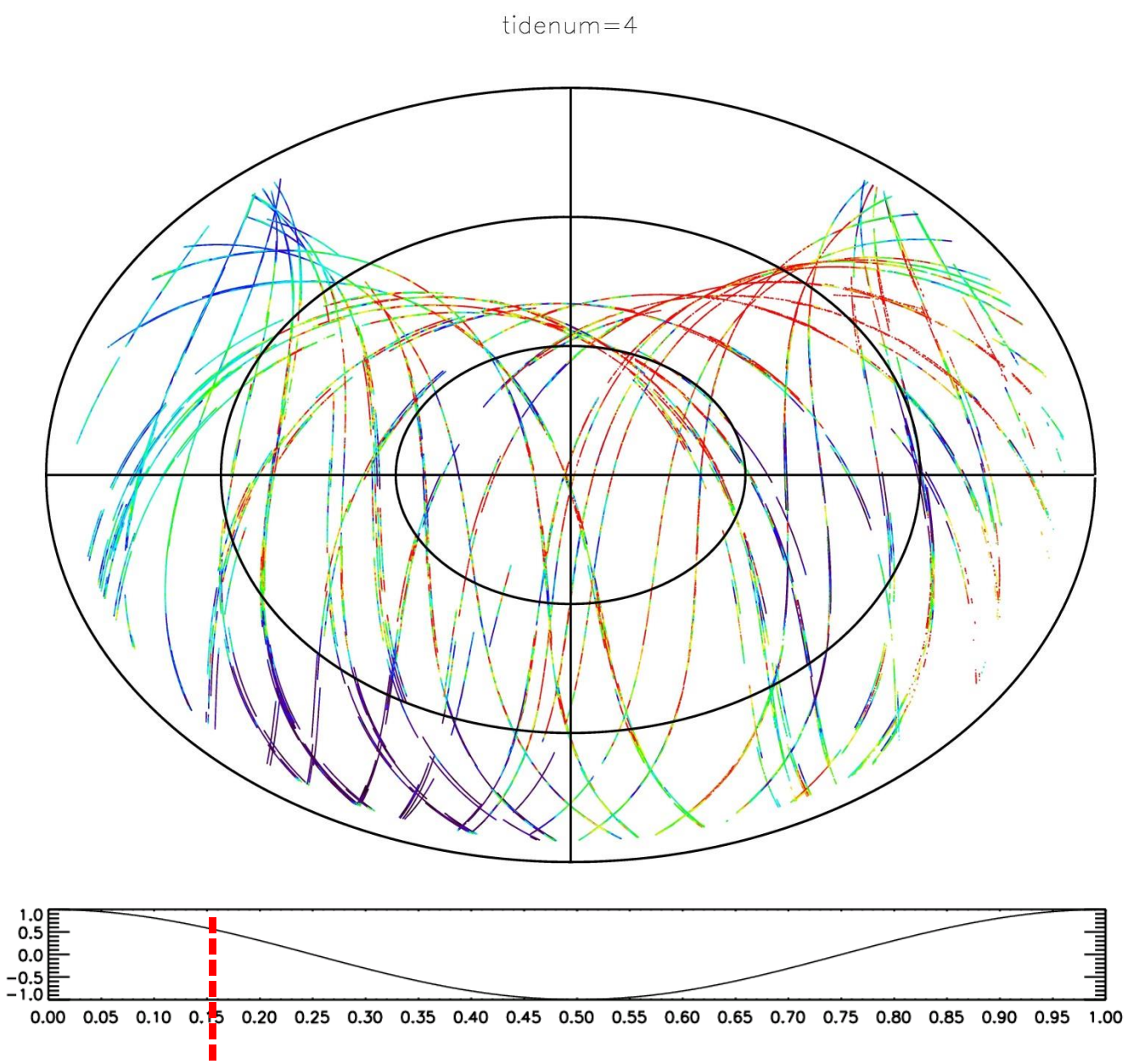
李啟民, 2017

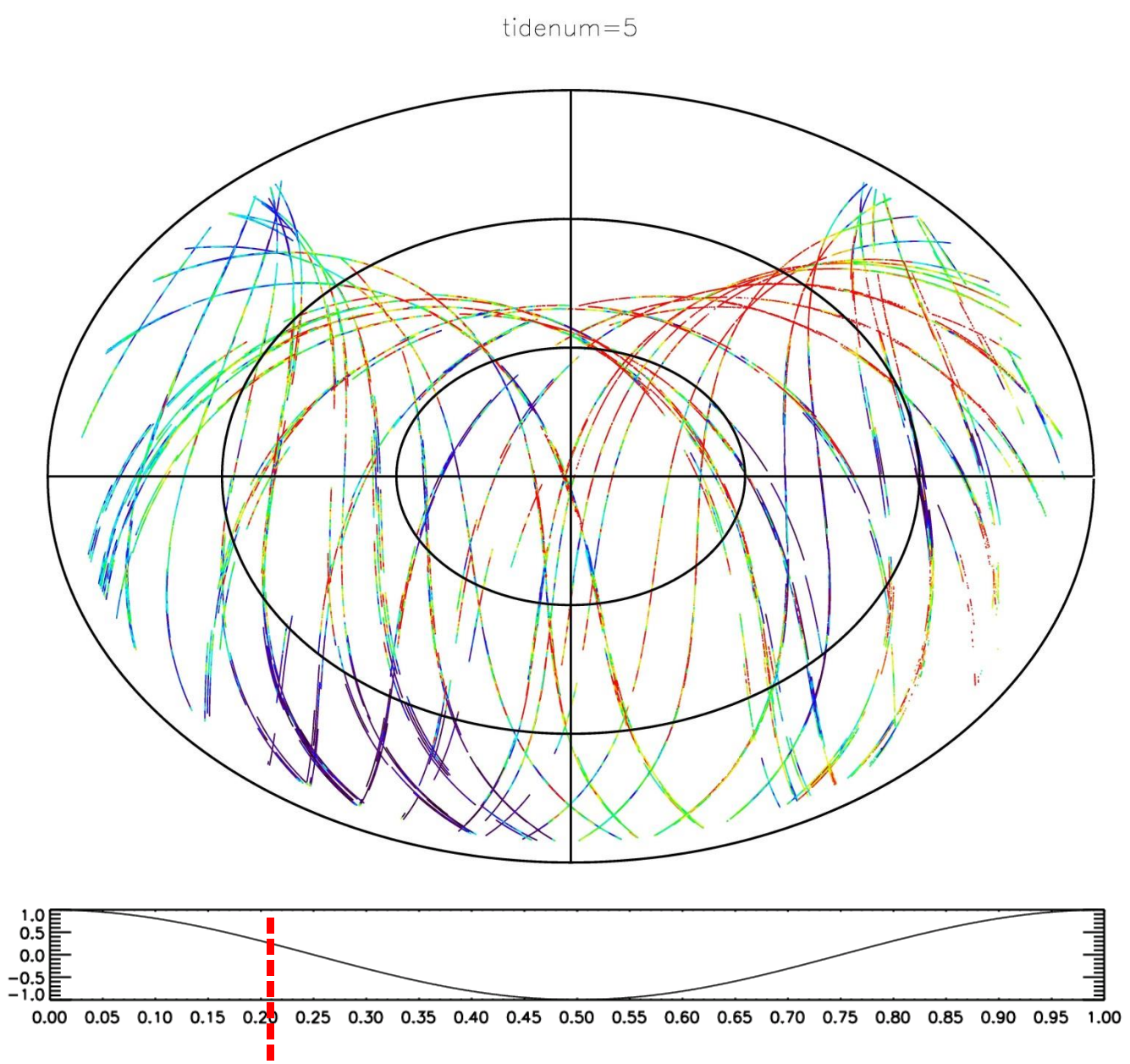


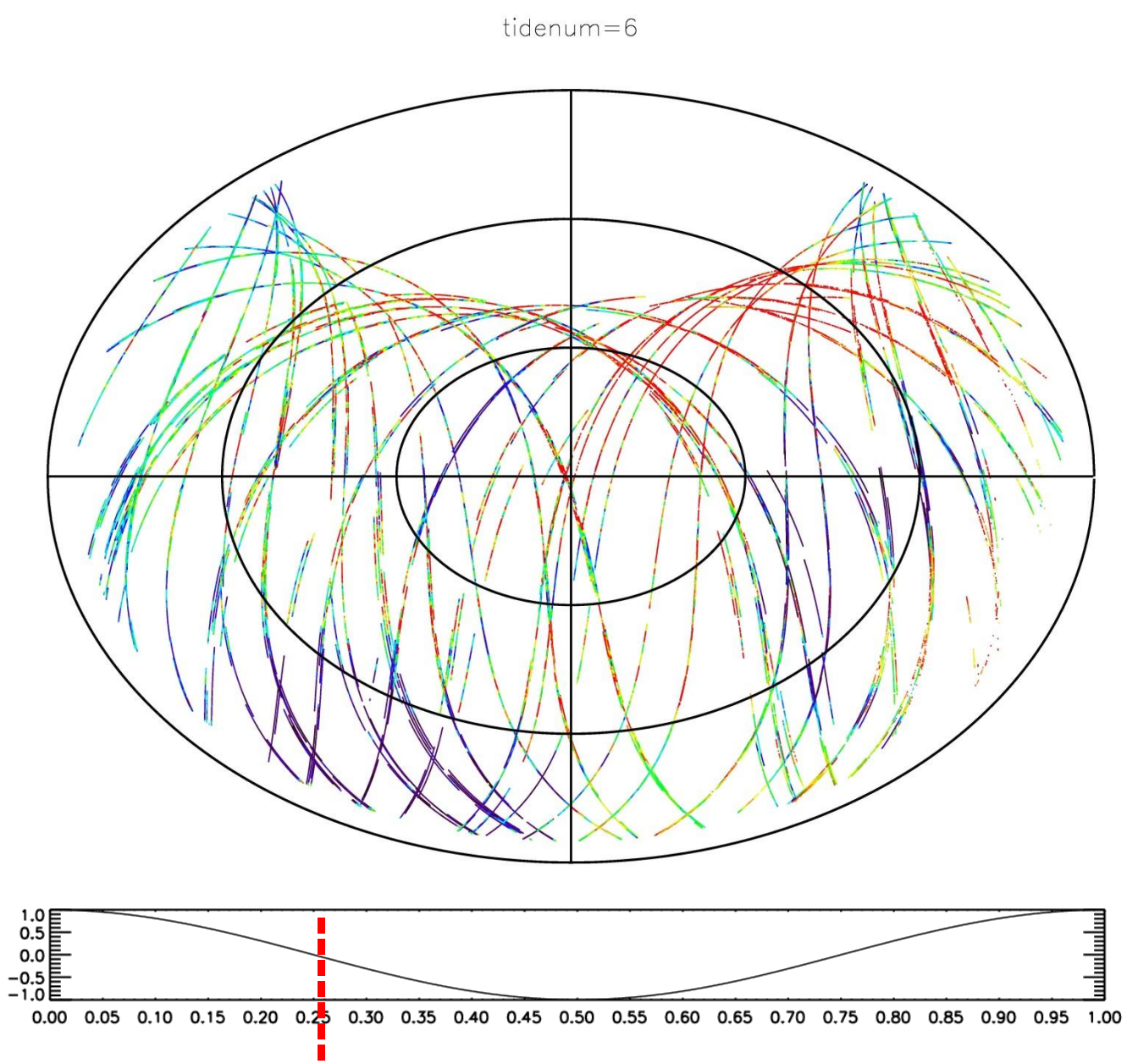

tidenum=1
1.0
0.5
0.0
−0.5
−1.0
0.00
0.05
0.10
0.15
0.20
0.25
0.30
0.35
0.40
0.45
0.50
0.55
0.60
0.65
0.70
0.75
0.80
0.85
0.90
0.95
1.00

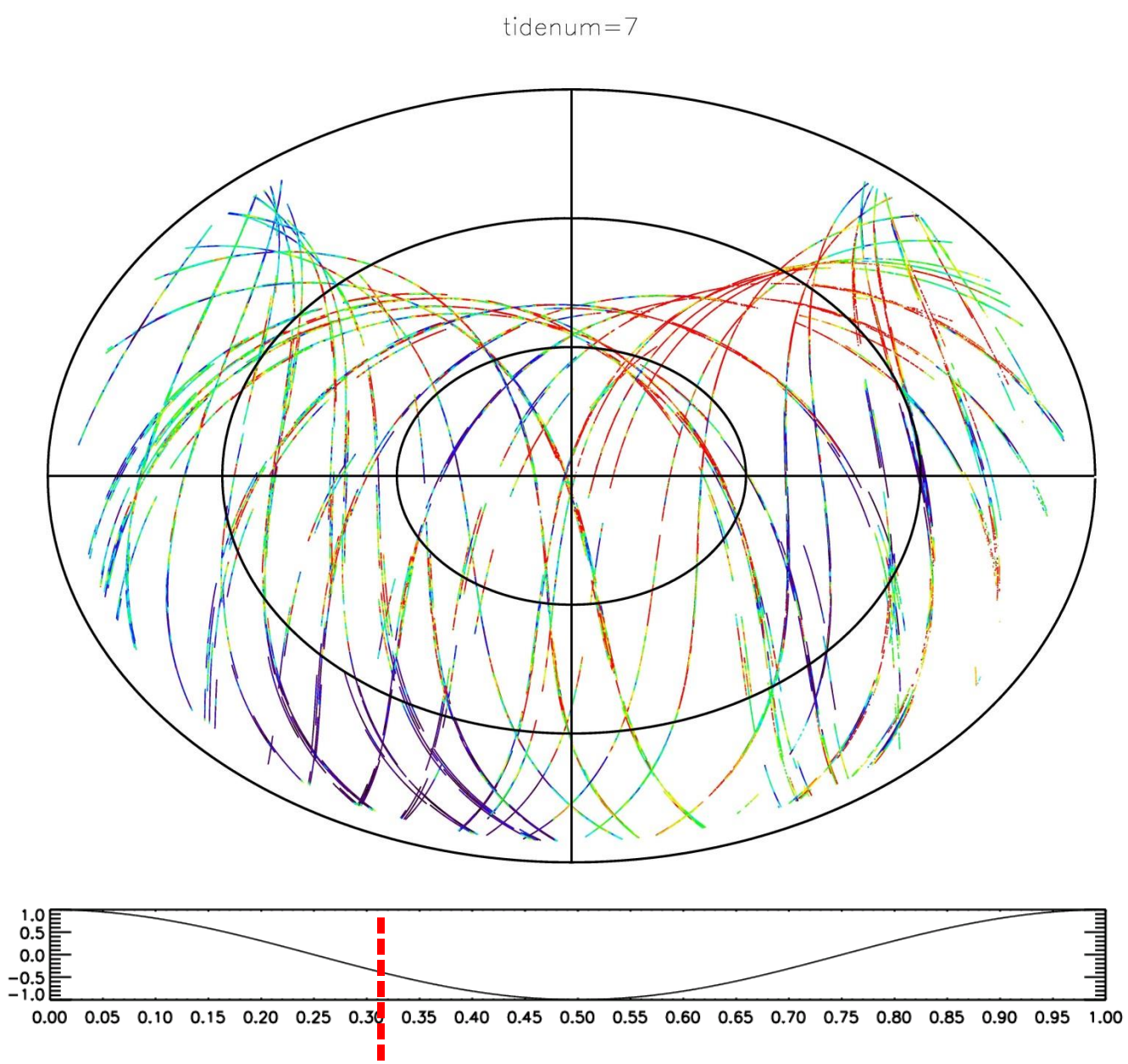

tidenum=2
1.0
0.5
0.0
−0.5
−1.0
0.00
0.05
0.10
0.15
0.20
0.25
0.30
0.35
0.40
0.45
0.50
0.55
0.60
0.65
0.70
0.75
0.80
0.85
0.90
0.95
1.00

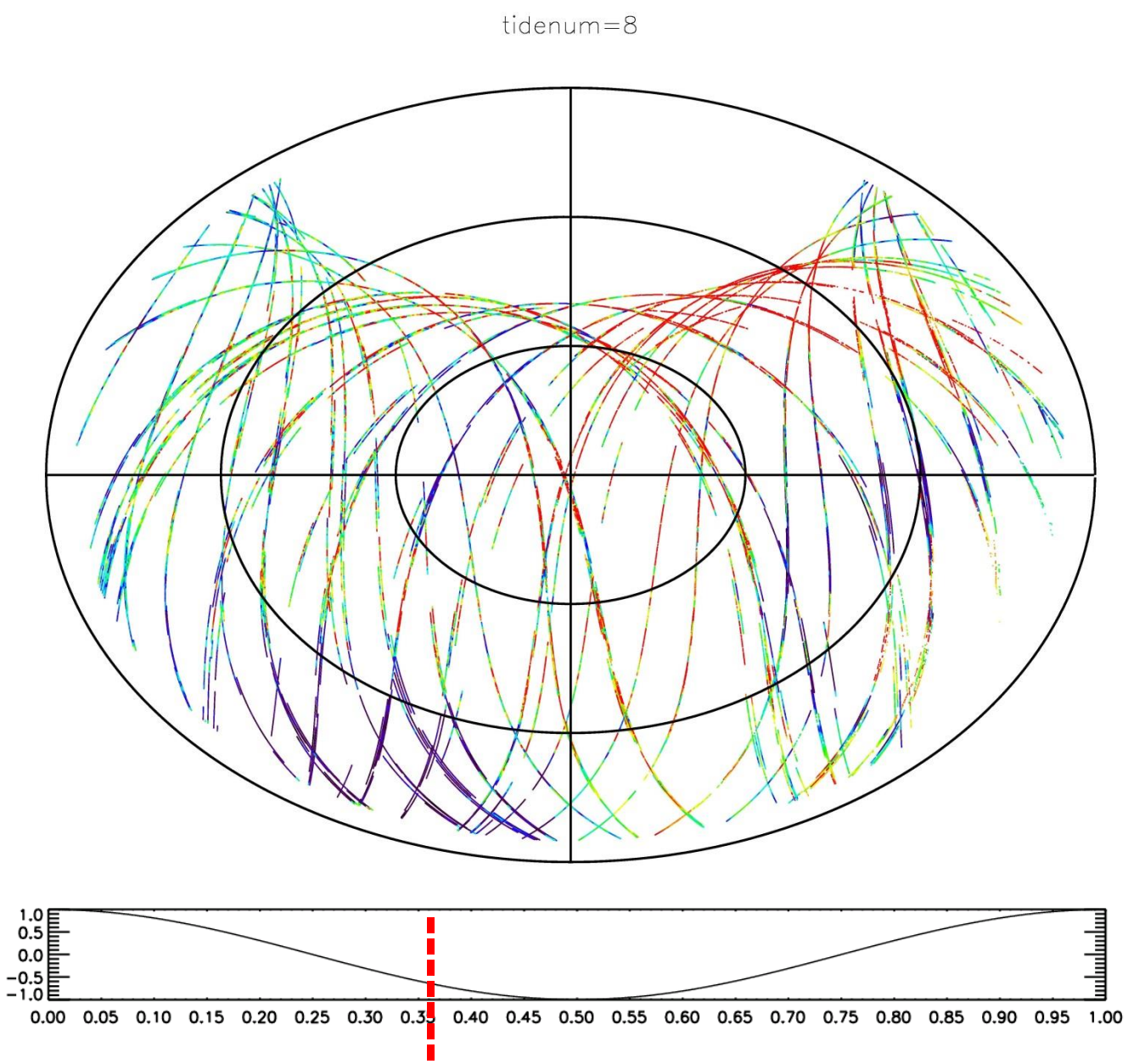

tidenum=3
1.0
0.5
0.0
−0.5
−1.0
0.00 0.05 0.10 0.15 0.20 0.25 0.30 0.35 0.40 0.45 0.50 0.55 0.60 0.65 0.70 0.75 0.80 0.85 0.90 0.95 1.00

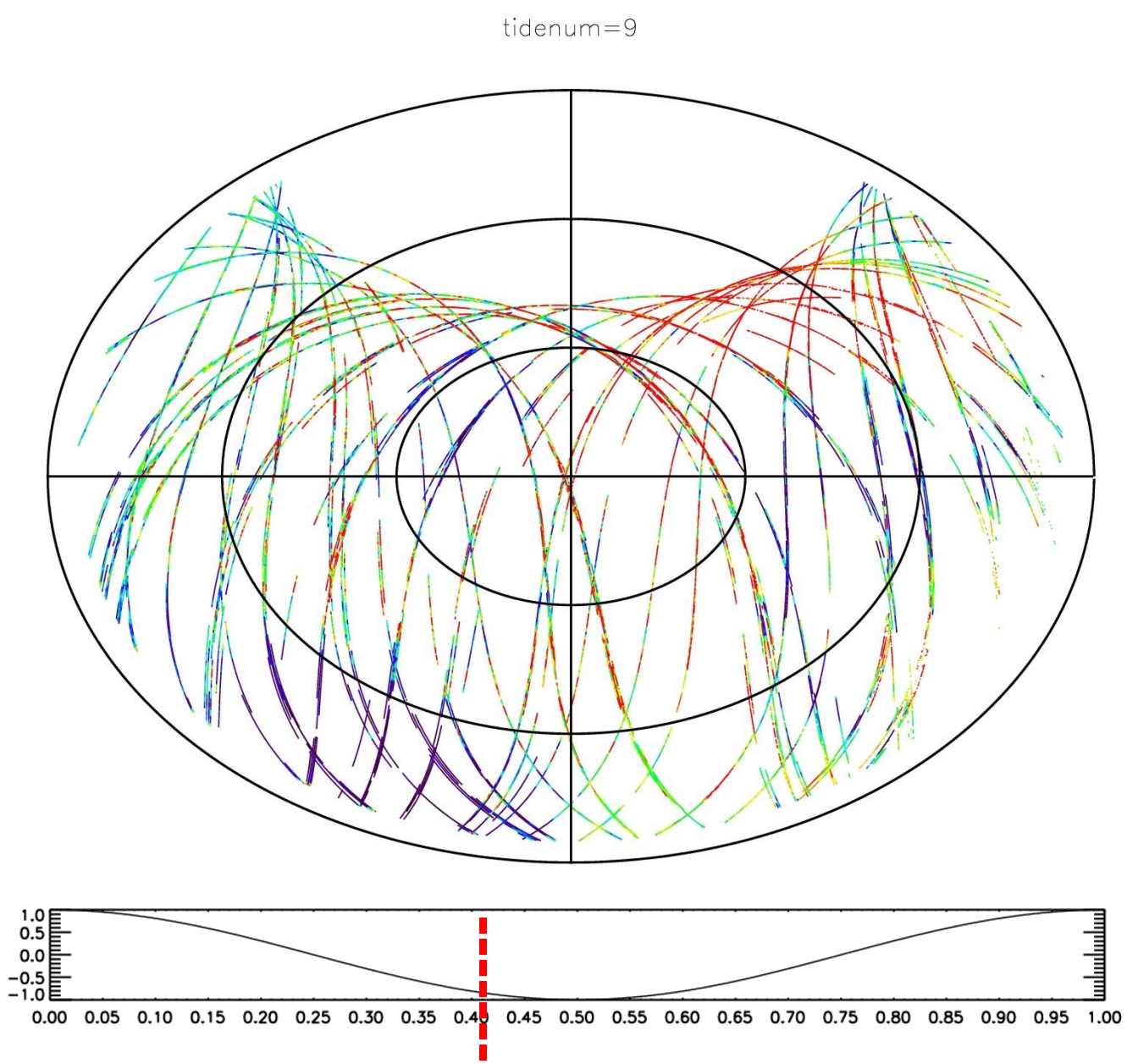

tidenum=4
1.0
0.5
0.0
−0.5
−1.0
0.00 0.05 0.10 0.15 0.20 0.25 0.30 0.35 0.40 0.45 0.50 0.55 0.60 0.65 0.70 0.75 0.80 0.85 0.90 0.95 1.00

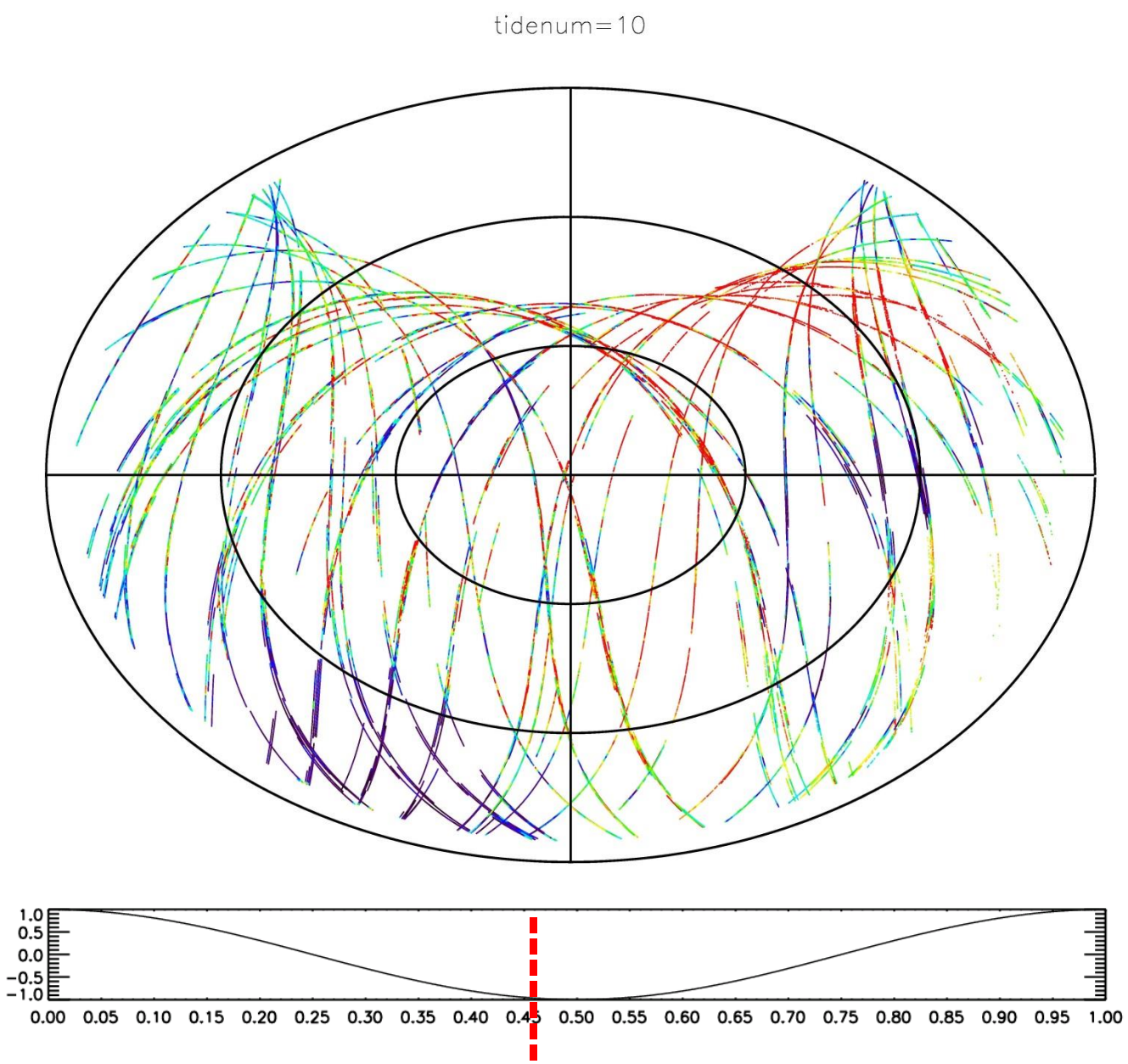

tidenum=5
1.0
0.5
0.0
−0.5
−1.0
0.00 0.05 0.10 0.15 0.20 0.25 0.30 0.35 0.40 0.45 0.50 0.55 0.60 0.65 0.70 0.75 0.80 0.85 0.90 0.95 1.00

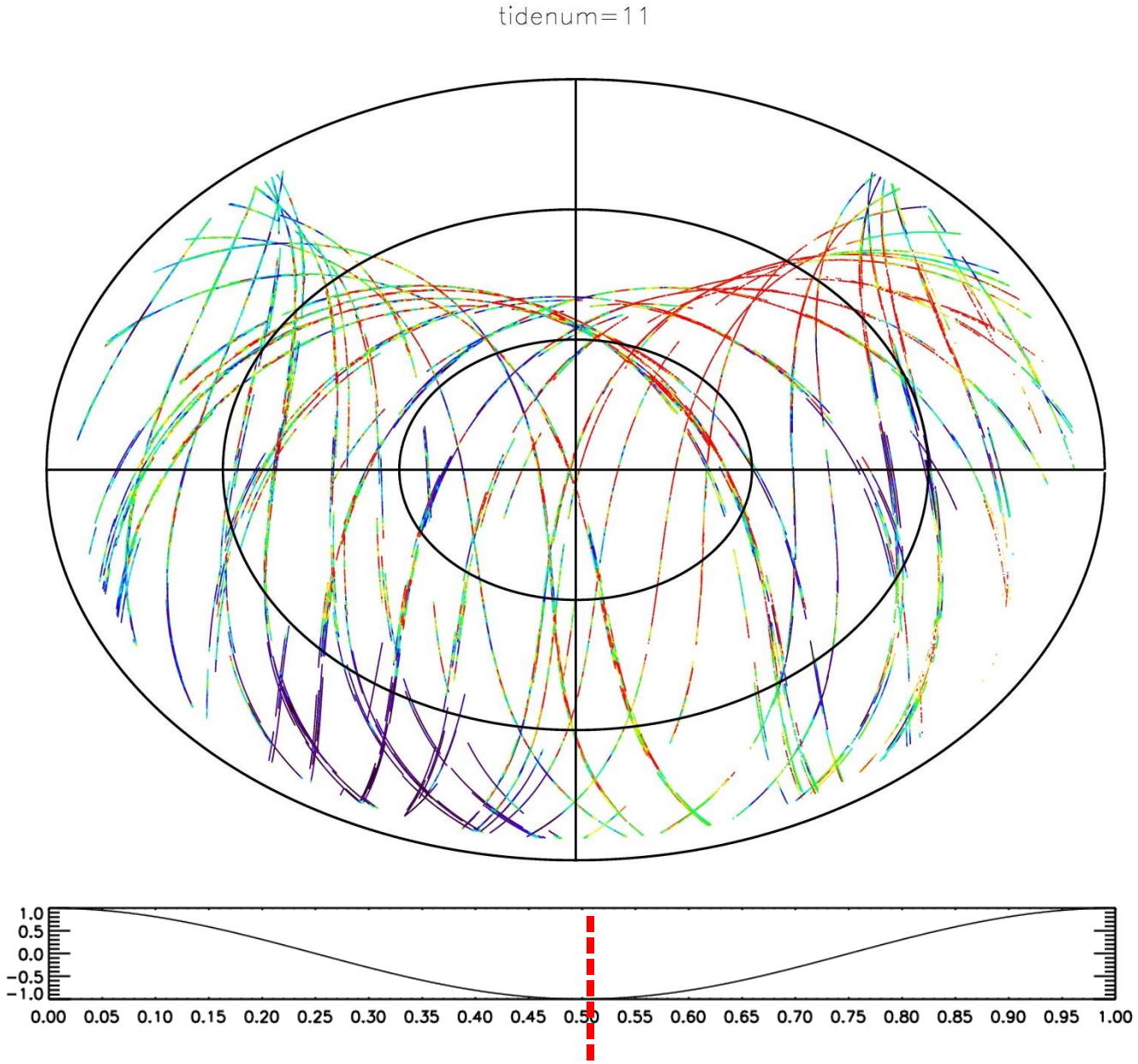

tidenum=6
1.0
0.5
0.0
−0.5
−1.0
0.00 0.05 0.10 0.15 0.20 0.25 0.30 0.35 0.40 0.45 0.50 0.55 0.60 0.65 0.70 0.75 0.80 0.85 0.90 0.95 1.00

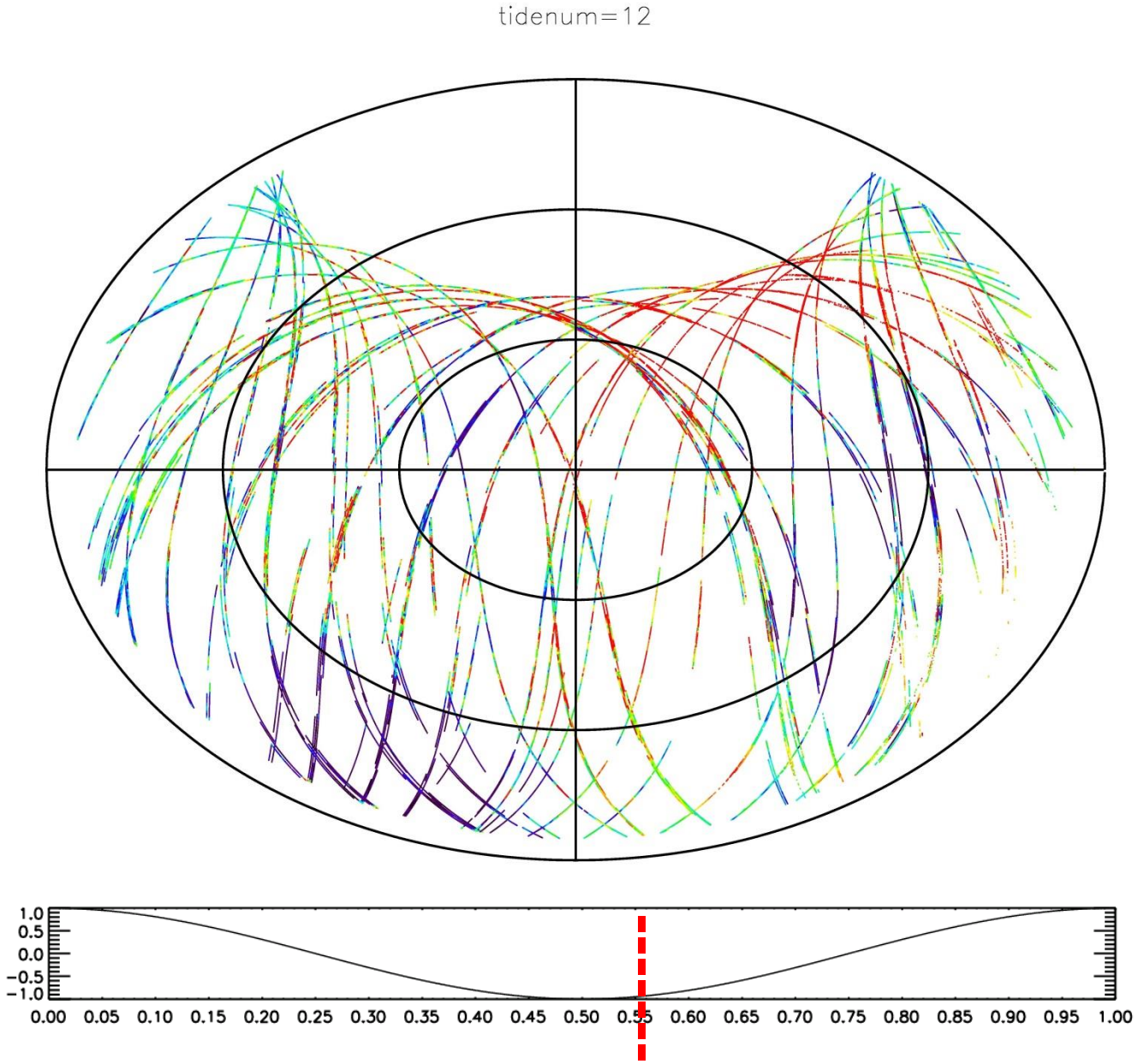

tidenum=7
1.0
0.5
0.0
−0.5
−1.0
0.00 0.05 0.10 0.15 0.20 0.25 0.30 0.35 0.40 0.45 0.50 0.55 0.60 0.65 0.70 0.75 0.80 0.85 0.90 0.95 1.00

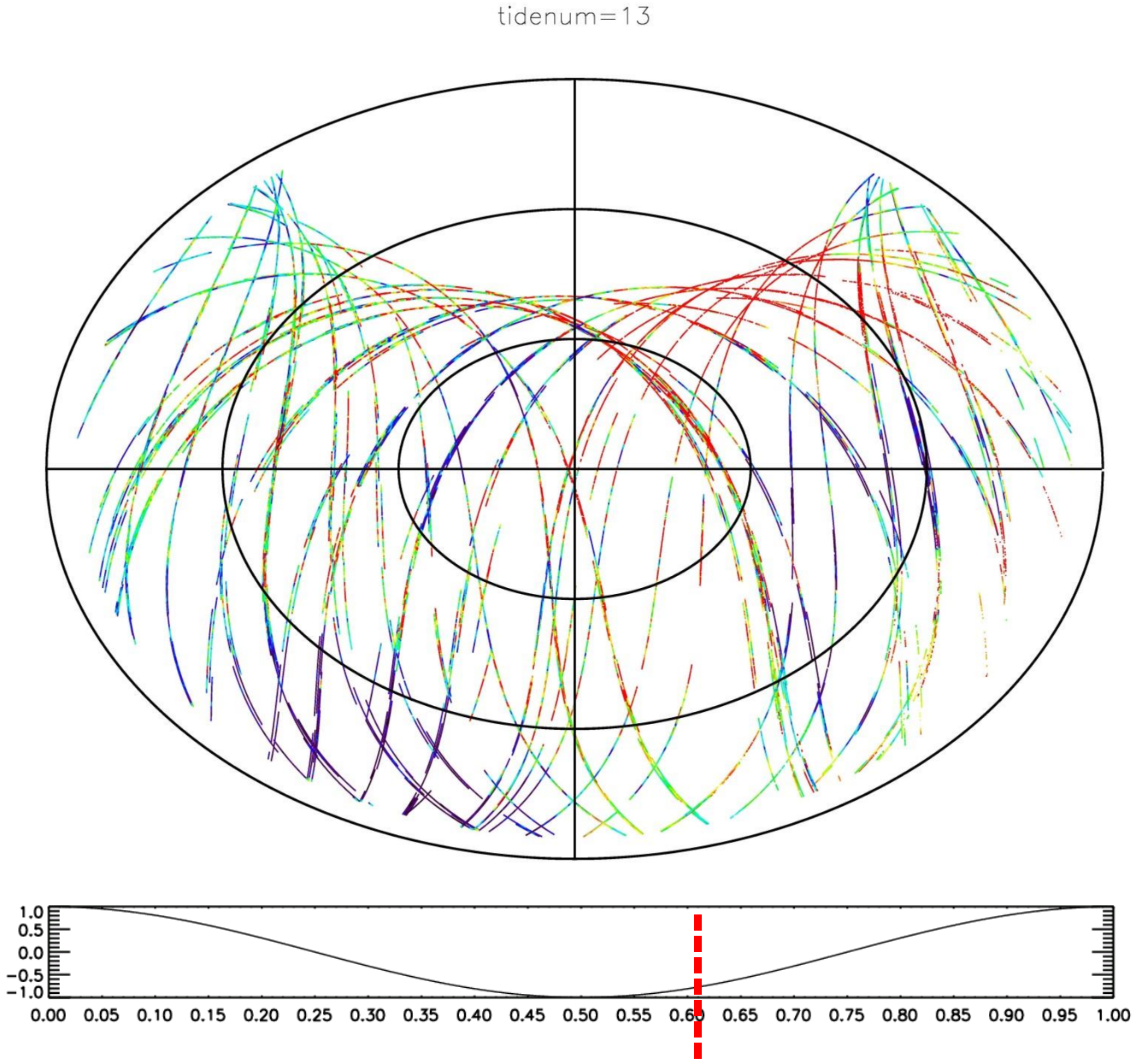

tidenum=8
1.0
0.5
0.0
−0.5
−1.0
0.00 0.05 0.10 0.15 0.20 0.25 0.30 0.35 0.40 0.45 0.50 0.55 0.60 0.65 0.70 0.75 0.80 0.85 0.90 0.95 1.00

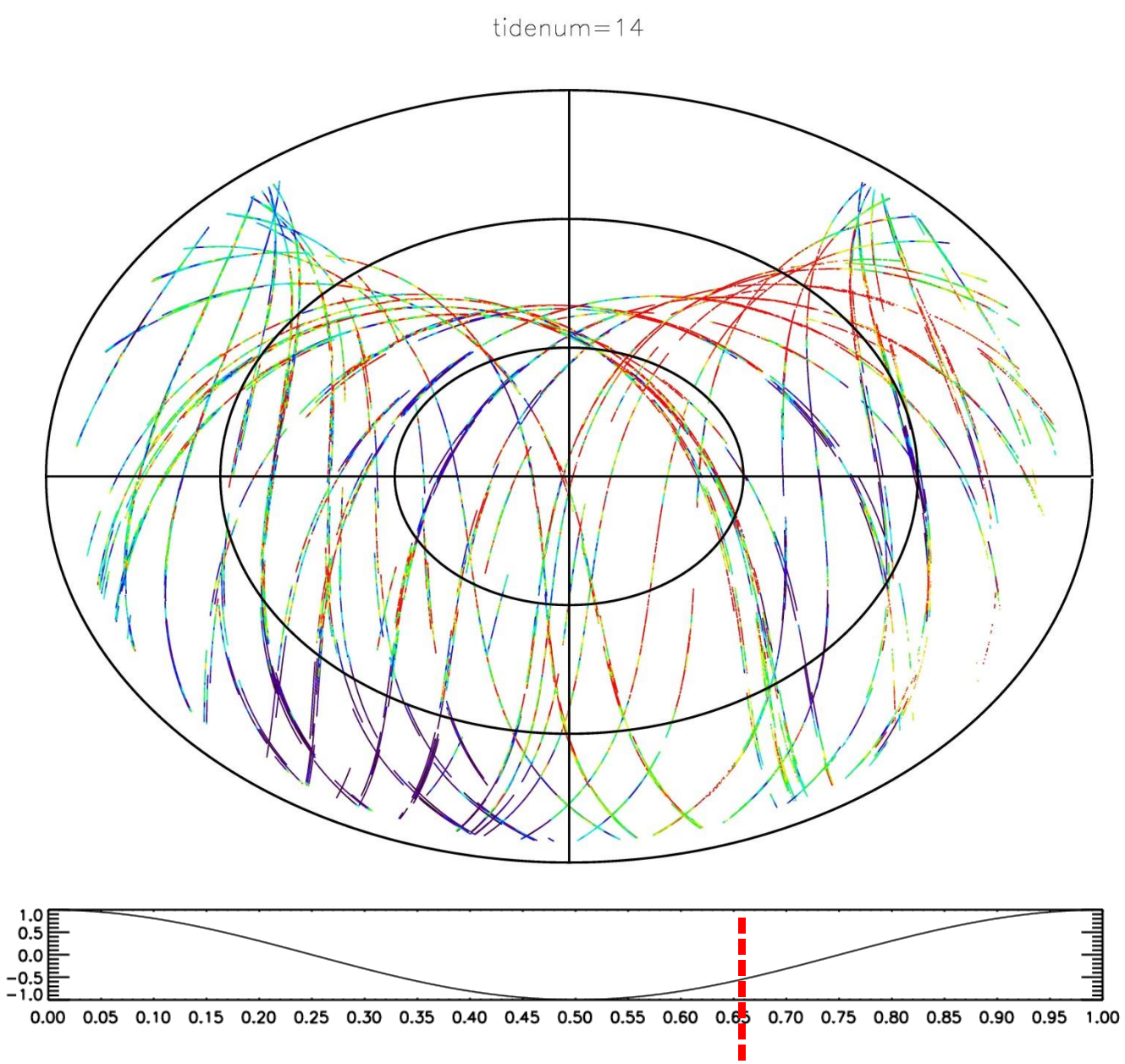

tidenum=9
1.0
0.5
0.0
−0.5
−1.0
0.00 0.05 0.10 0.15 0.20 0.25 0.30 0.35 0.40 0.45 0.50 0.55 0.60 0.65 0.70 0.75 0.80 0.85 0.90 0.95 1.00

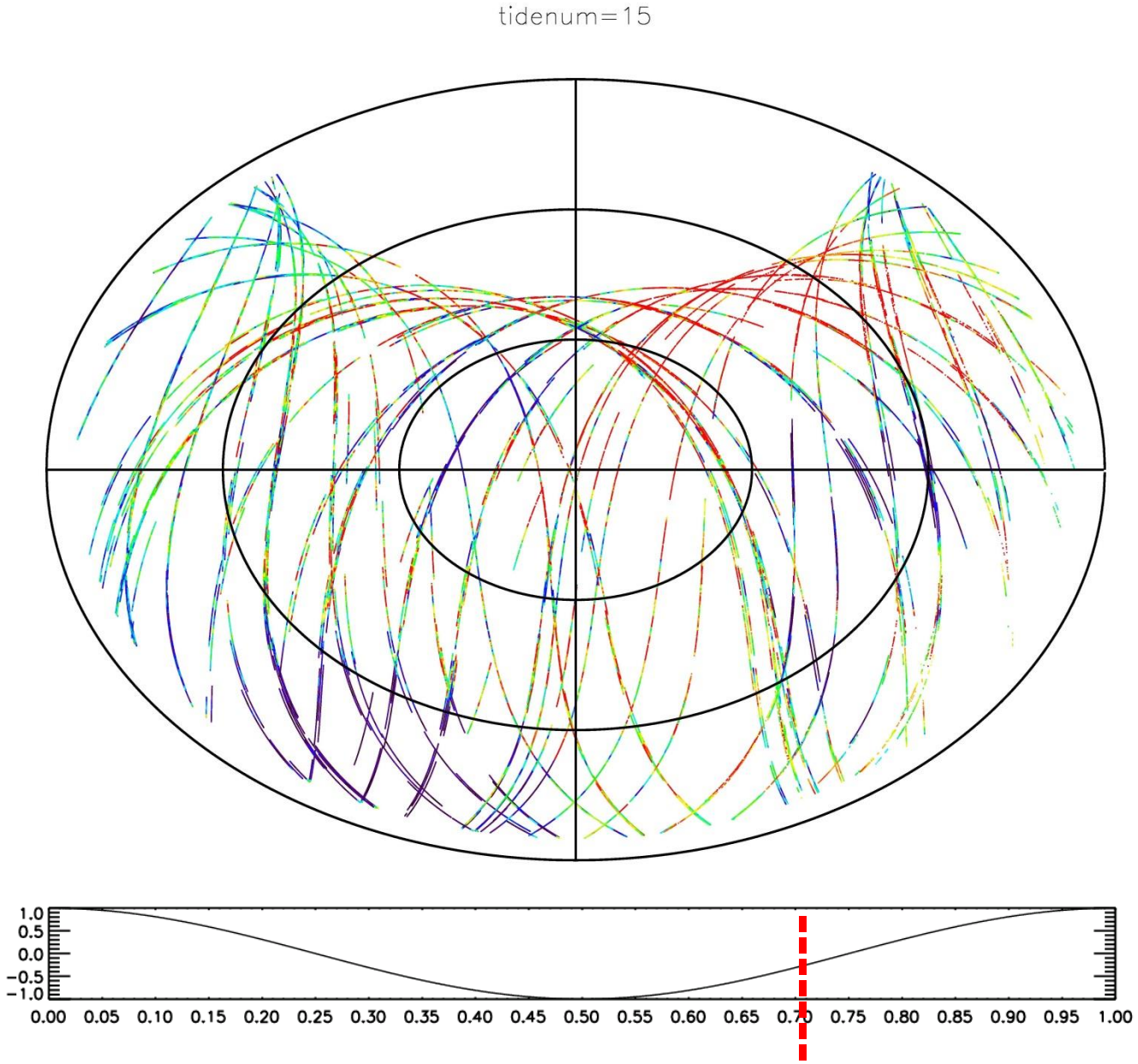

tidenum=10
1.0
0.5
0.0
−0.5
−1.0
0.00 0.05 0.10 0.15 0.20 0.25 0.30 0.35 0.40 0.45 0.50 0.55 0.60 0.65 0.70 0.75 0.80 0.85 0.90 0.95 1.00

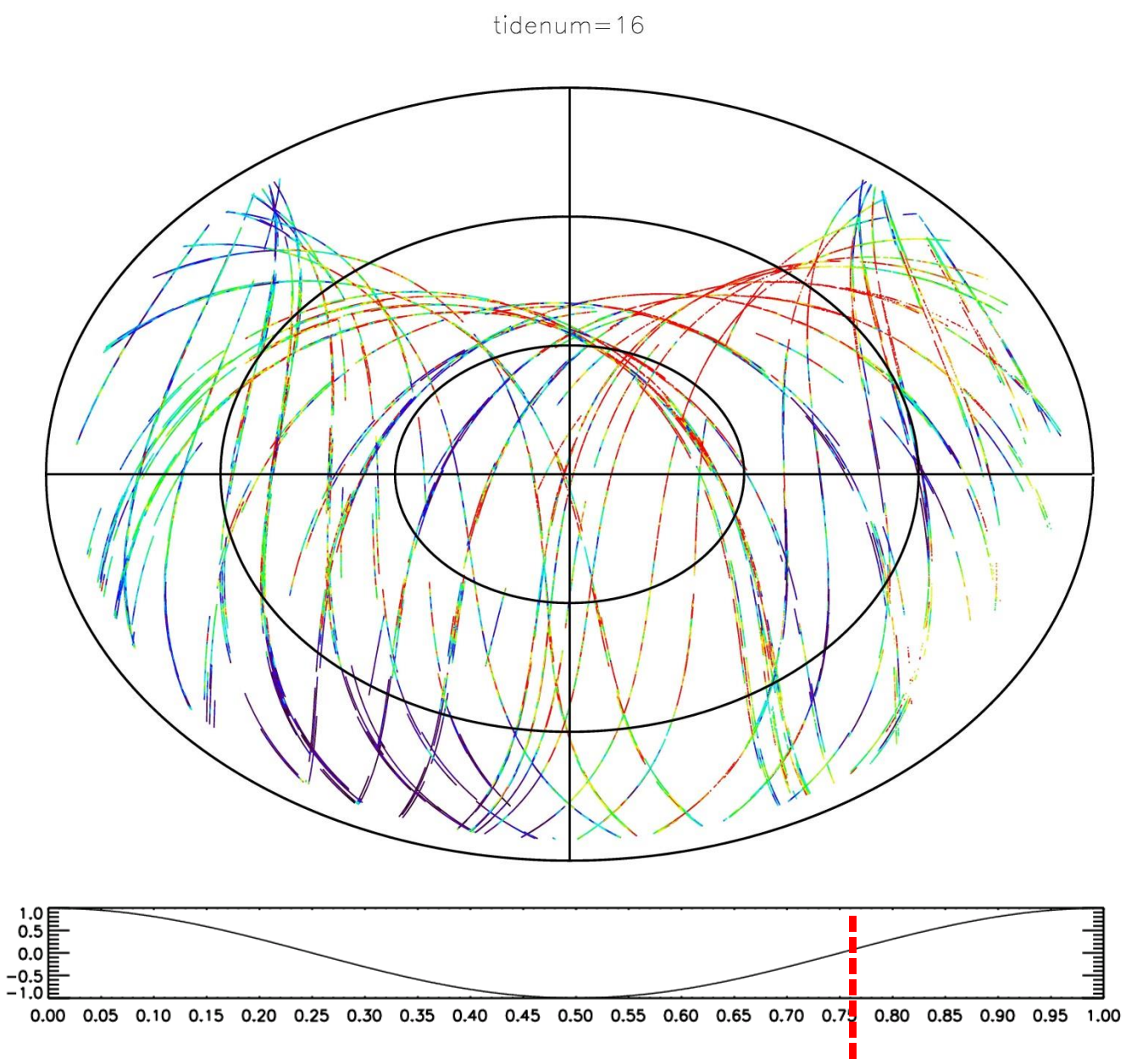

tidenum=11
1.0
0.5
0.0
−0.5
−1.0
0.00 0.05 0.10 0.15 0.20 0.25 0.30 0.35 0.40 0.45 0.50 0.55 0.60 0.65 0.70 0.75 0.80 0.85 0.90 0.95 1.00

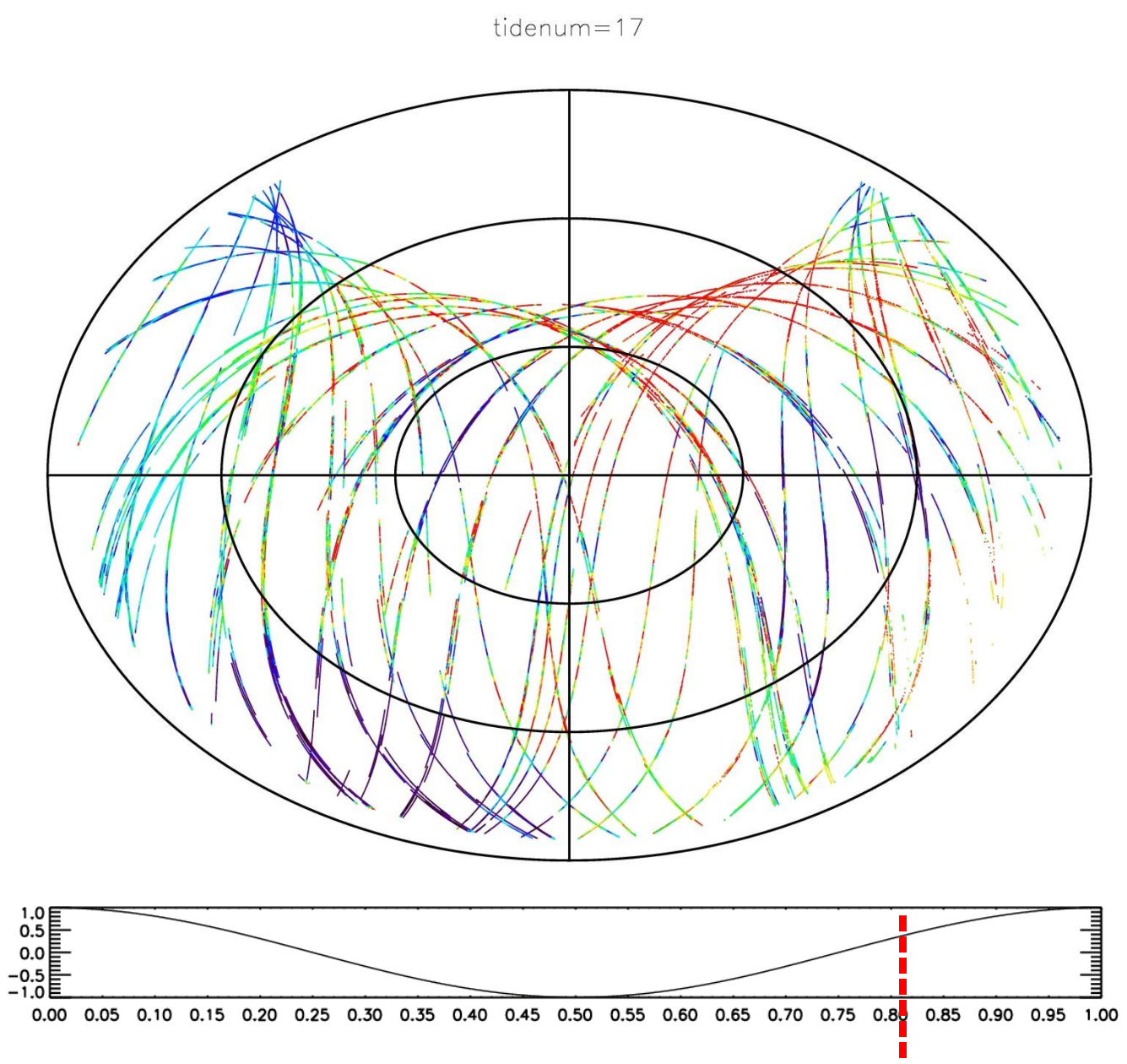

tidenum=12
1.0
0.5
0.0
−0.5
−1.0
0.00 0.05 0.10 0.15 0.20 0.25 0.30 0.35 0.40 0.45 0.50 0.55 0.60 0.65 0.70 0.75 0.80 0.85 0.90 0.95 1.00

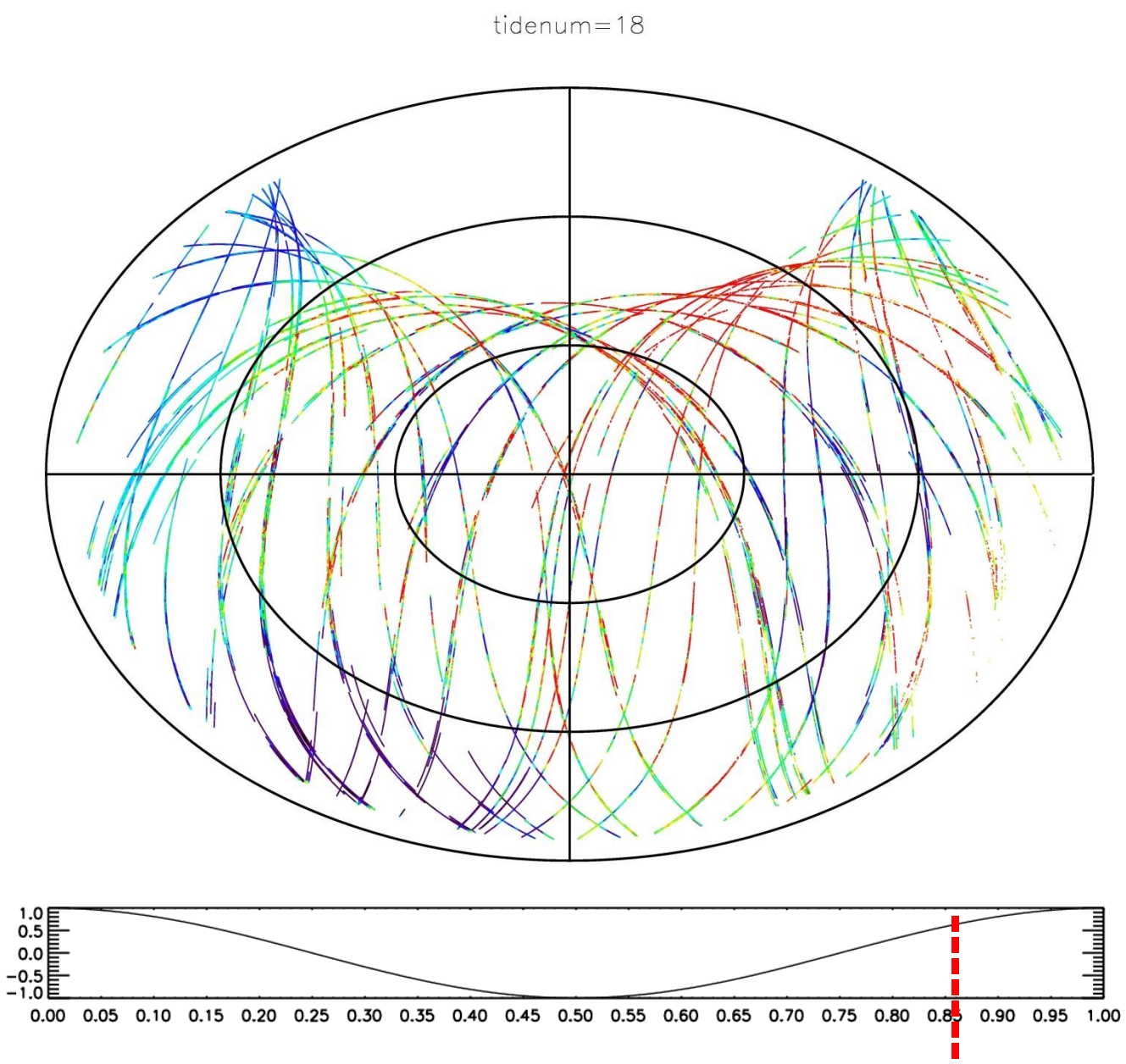

tidenum=13
1.0
0.5
0.0
−0.5
−1.0
0.00 0.05 0.10 0.15 0.20 0.25 0.30 0.35 0.40 0.45 0.50 0.55 0.60 0.65 0.70 0.75 0.80 0.85 0.90 0.95 1.00

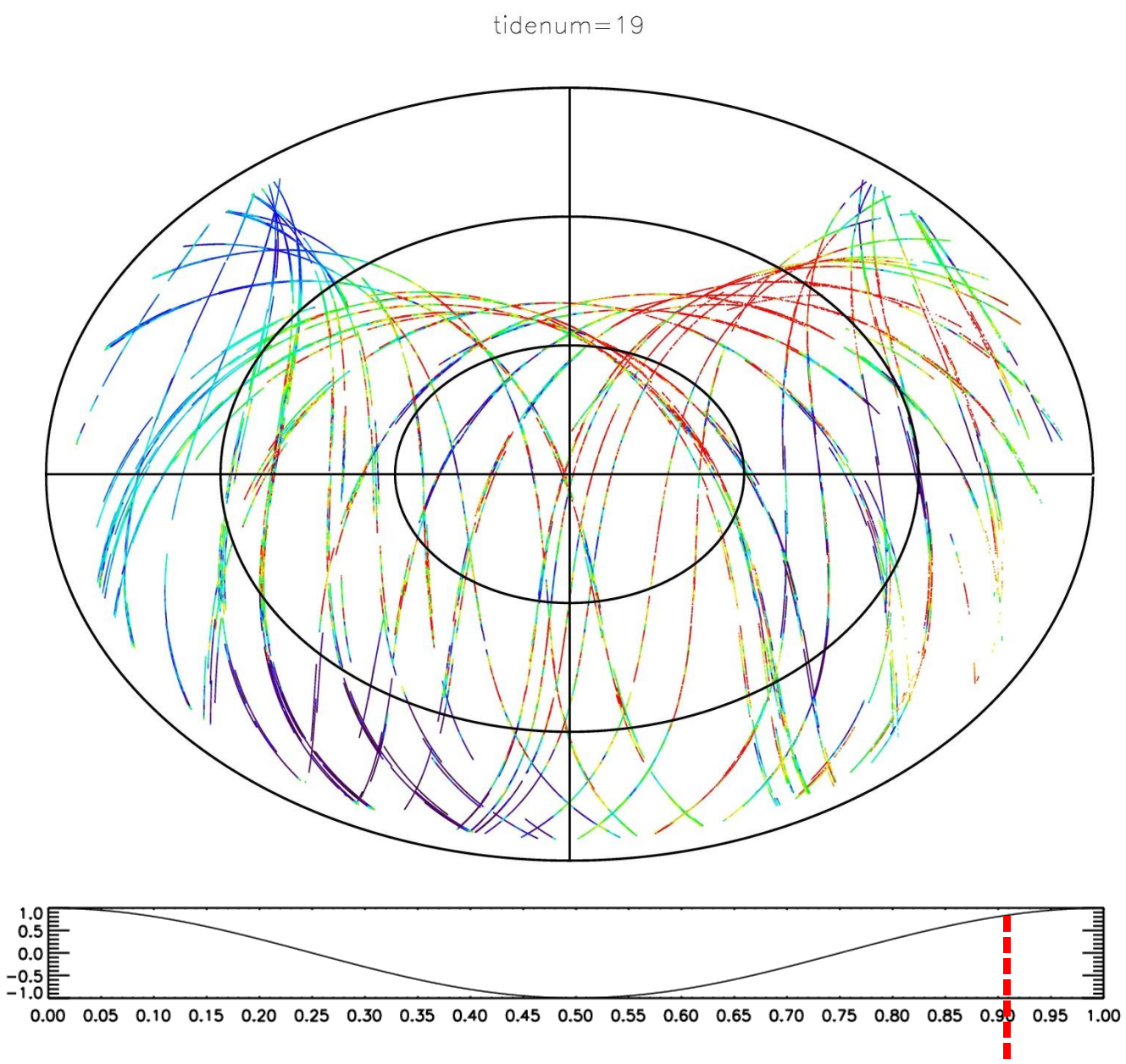

tidenum=14
1.0
0.5
0.0
−0.5
−1.0
0.00 0.05 0.10 0.15 0.20 0.25 0.30 0.35 0.40 0.45 0.50 0.55 0.60 0.65 0.70 0.75 0.80 0.85 0.90 0.95 1.00

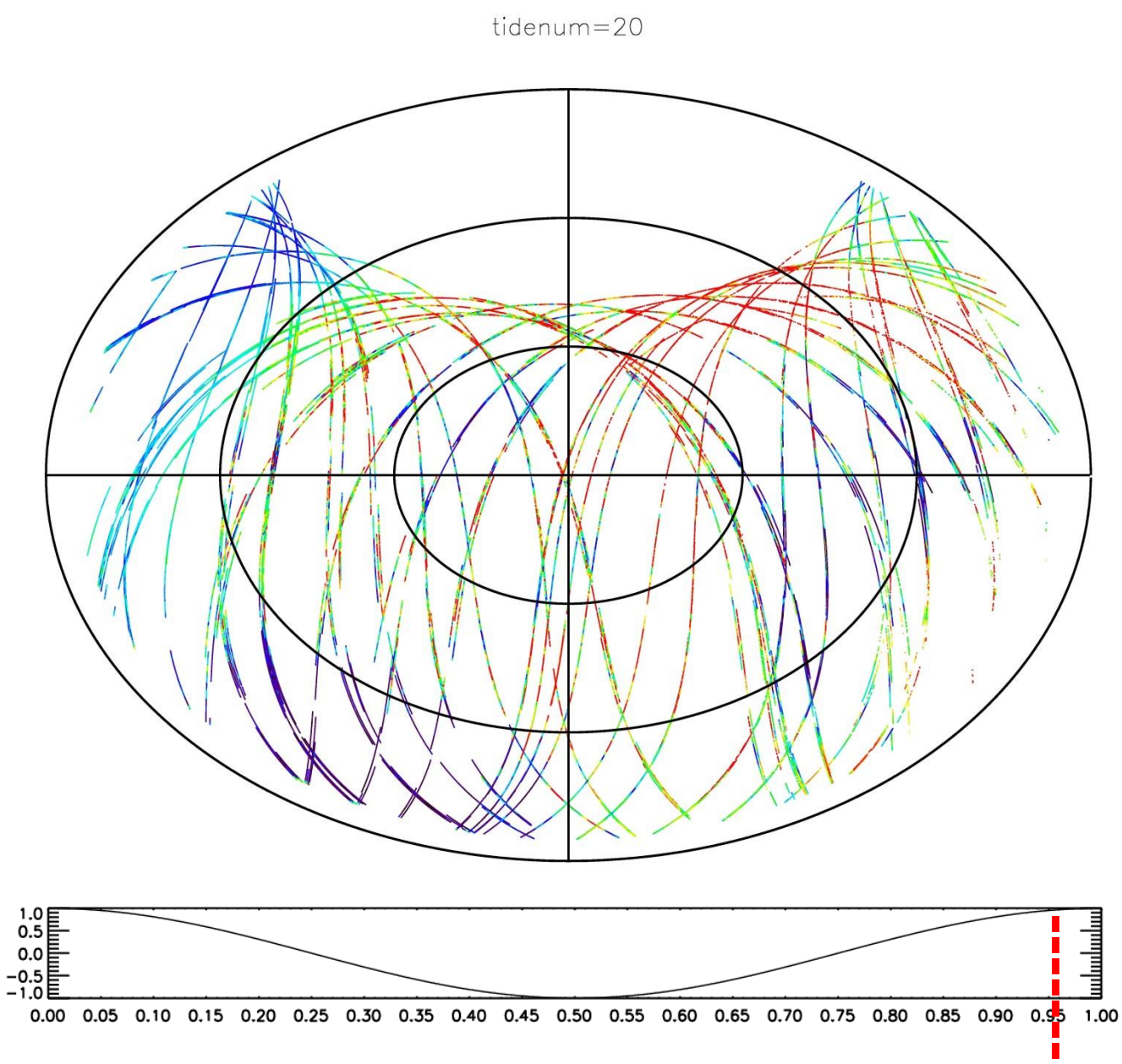

tidenum=15
1.0
0.5
0.0
−0.5
−1.0
0.00 0.05 0.10 0.15 0.20 0.25 0.30 0.35 0.40 0.45 0.50 0.55 0.60 0.65 0.70 0.75 0.80 0.85 0.90 0.95 1.00


tidenum=16
1.0
0.5
0.0
−0.5
−1.0
0.00 0.05 0.10 0.15 0.20 0.25 0.30 0.35 0.40 0.45 0.50 0.55 0.60 0.65 0.70 0.75 0.80 0.85 0.90 0.95 1.00

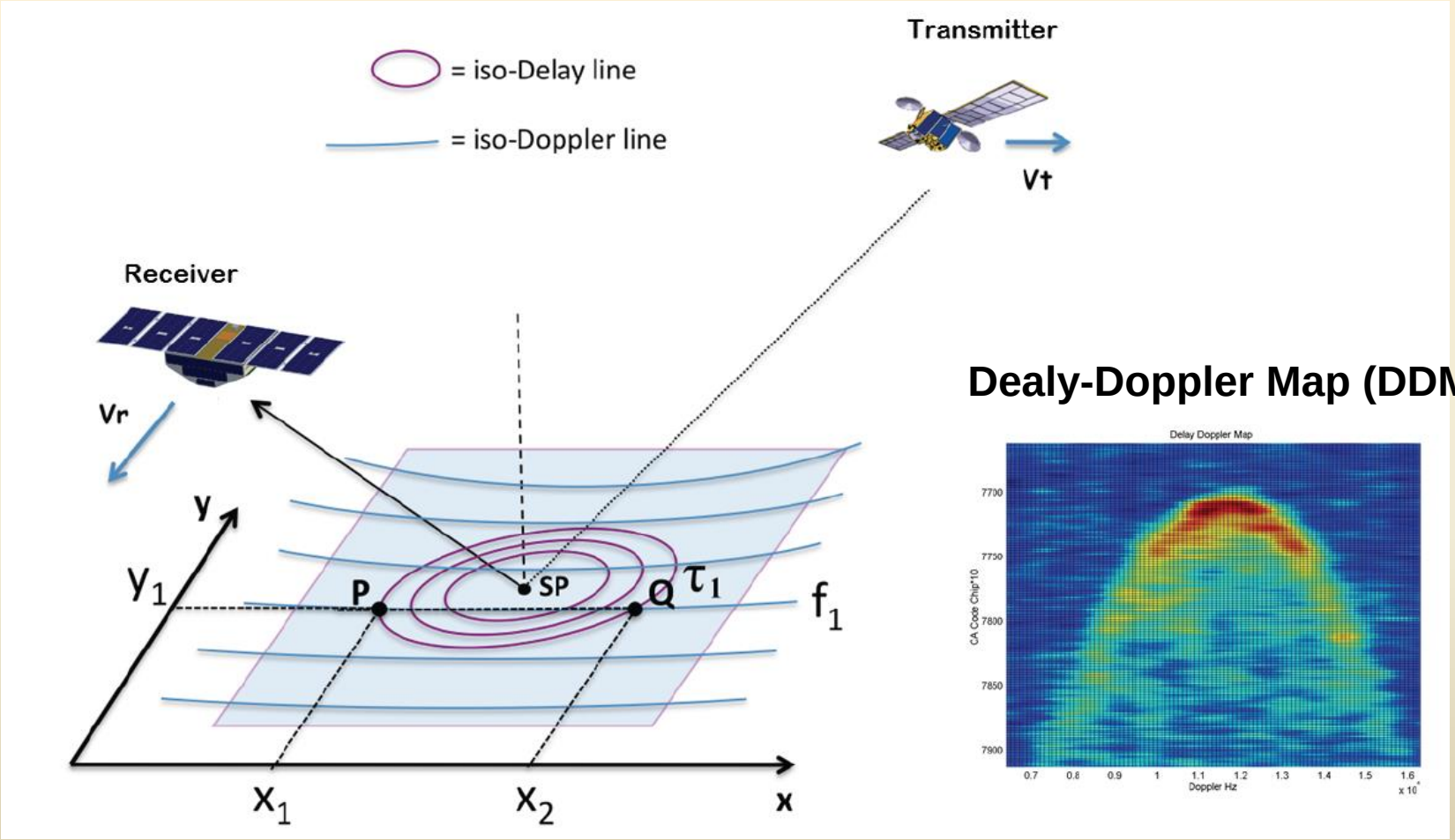

tidenum=17
1.0
0.5
0.0
−0.5
−1.0
0.00 0.05 0.10 0.15 0.20 0.25 0.30 0.35 0.40 0.45 0.50 0.55 0.60 0.65 0.70 0.75 0.80 0.85 0.90 0.95 1.00


tidenum=18
1.0
0.5
0.0
−0.5
−1.0
0.00 0.05 0.10 0.15 0.20 0.25 0.30 0.35 0.40 0.45 0.50 0.55 0.60 0.65 0.70 0.75 0.80 0.85 0.90 0.95 1.00


tidenum=19
1.0
0.5
0.0
−0.5
−1.0
0.00 0.05 0.10 0.15 0.20 0.25 0.30 0.35 0.40 0.45 0.50 0.55 0.60 0.65 0.70 0.75 0.80 0.85 0.90 0.95 1.00


tidenum=20
1.0
0.5
0.0
−0.5
−1.0
0.00 0.05 0.10 0.15 0.20 0.25 0.30 0.35 0.40 0.45 0.50 0.55 0.60 0.65 0.70 0.75 0.80 0.85 0.90 0.95 1.00

GNSS-Reflectometry principle (2)



Dealy-Doppler Map (DDM)

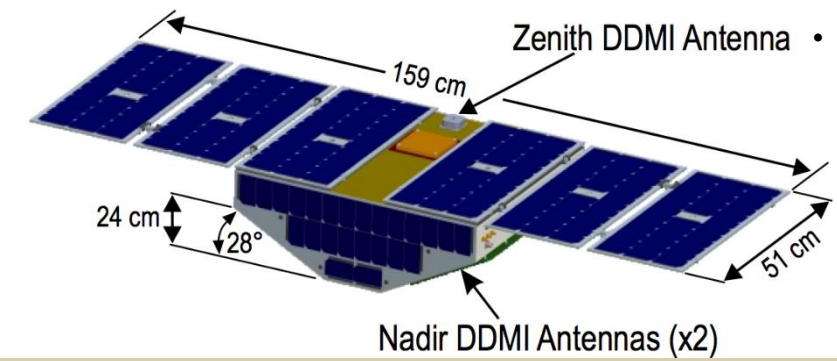
Clarizia, 2012

Current GNSS-R Missions

- **The TDS-1 launched on 8 July 2014, carries SGR-ReSI, small (300x160x30mm), low-mass (1.5kg), low-power (10W)**
- **The ReSI can be accessed and operated for 2 days in every 8 day duty cycle of TDS-1**
- **The ReSI can track, record and process reflected signals simultaneously from 4 GPS transmitters**
- **All ReSI data acquired up to 5 Feb 2015 were processed to plot the delay-Doppler maps (DDMs)**
- **The DDMs were generated onboard at 1Hz with a coherent integration time 1ms.**

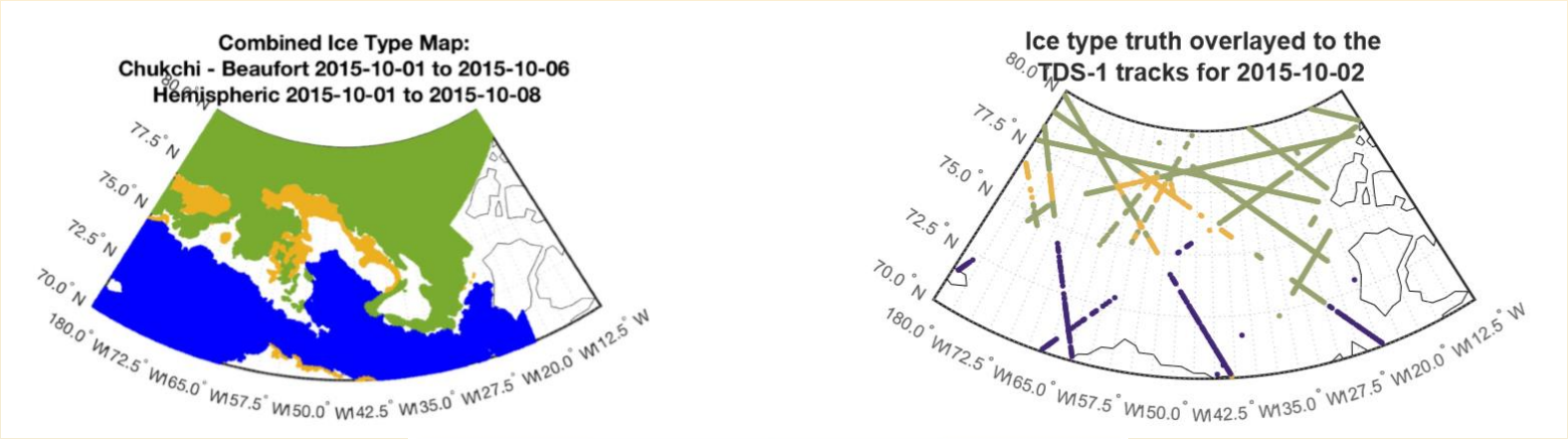
TechDemoSat-1

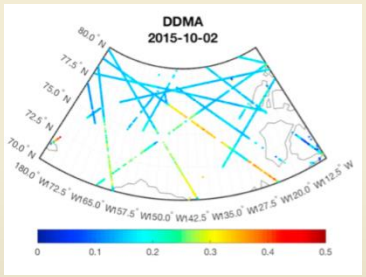
CYGNSS

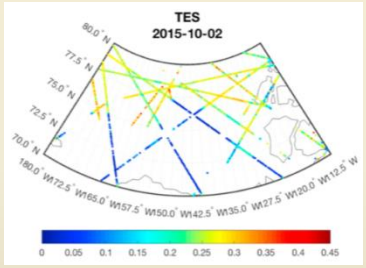


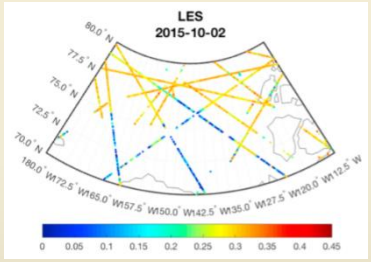
- **Provide estimates of ocean surface wind speed over a dynamic range of 3 to 70 m/s**
- **Provide estimates of ocean surface wind speed during precipitation rates up through 100 millimeters per hour as determined by a spatially averaged rain field with resolution of 5x5 km**
- **Measure ocean surface wind speed with a retrieval uncertainty of 2 m/s or 10%, whichever is greater, with a spatial resolution of 25x25 km**
- **Collect measurements of ocean surface wind speed with temporal sampling better than 12 hour mean revisit time AND spatial sampling that samples greater than 70% of historical storm tracks within 24 hours**

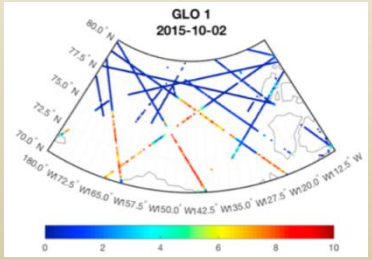
Arctic sea ice detection (TDS-1)

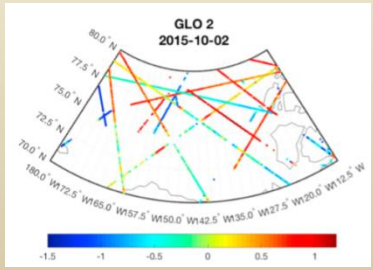


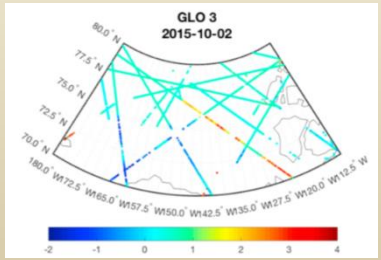












Rodriguez-Alvarez et al., 2019

Flood inundation (CYGNSS)

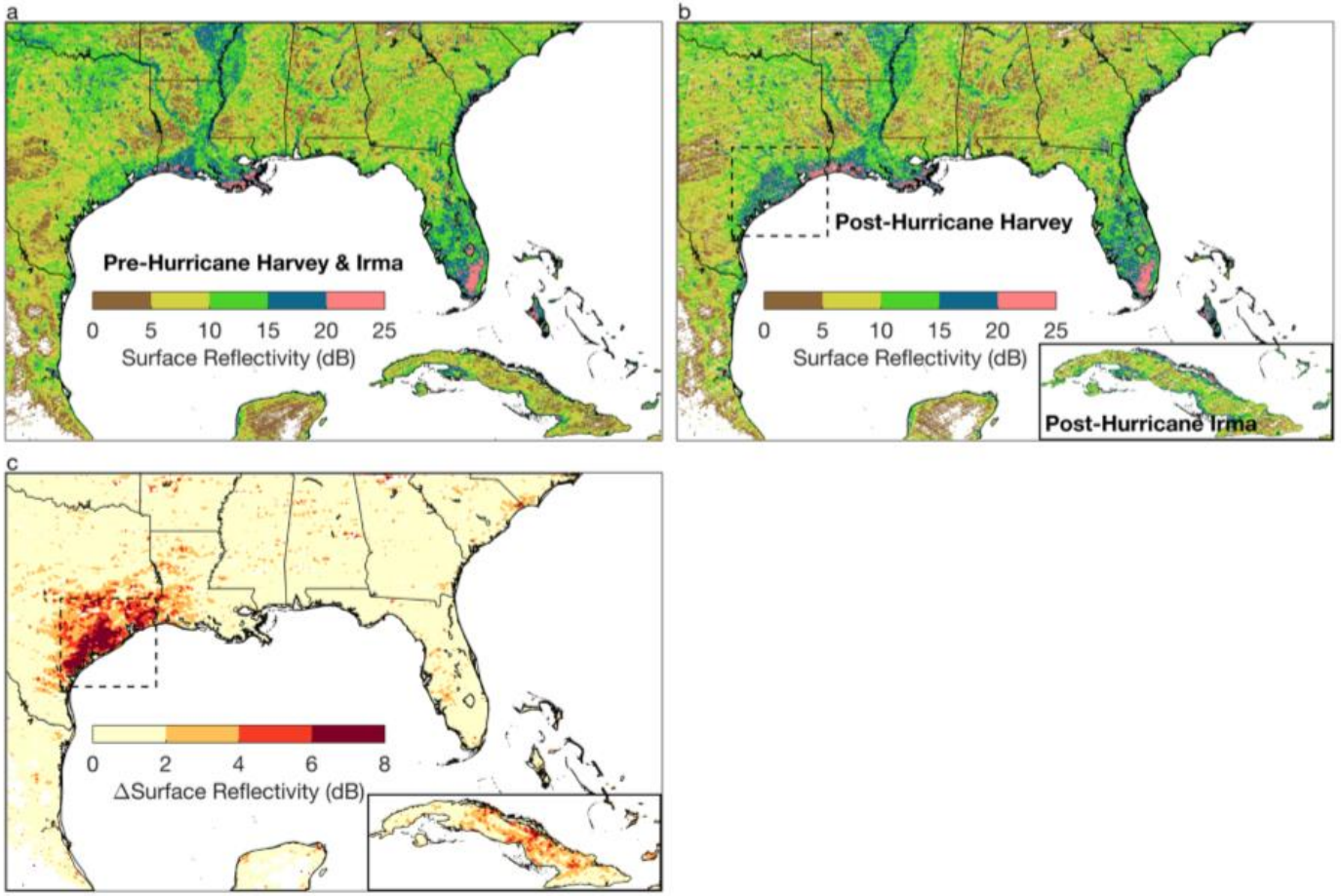


Figure 1. Observations of surface reflectivity from CYGNSS over the southeastern United States and Caribbean. (**a**) Surface reflectivity observations for the time period Jul 1–Aug 20, 2017, before the hurricane season began. (**b**) Surface reflectivity observations after Hurricane Harvey (Aug 25–Sep 15, 2017) for the southeastern United States. Observations in the inset of Cuba were recorded in the time period after Hurricane Irma (Sep 8–Sep 30, 2017). (**c**) Observed change in surface reflectivity after Hurricanes Harvey (southeastern United States) and Irma (Cuba inset). All figures made with MATLAB R2016b.

Chew et al., 2019

Inland waterways

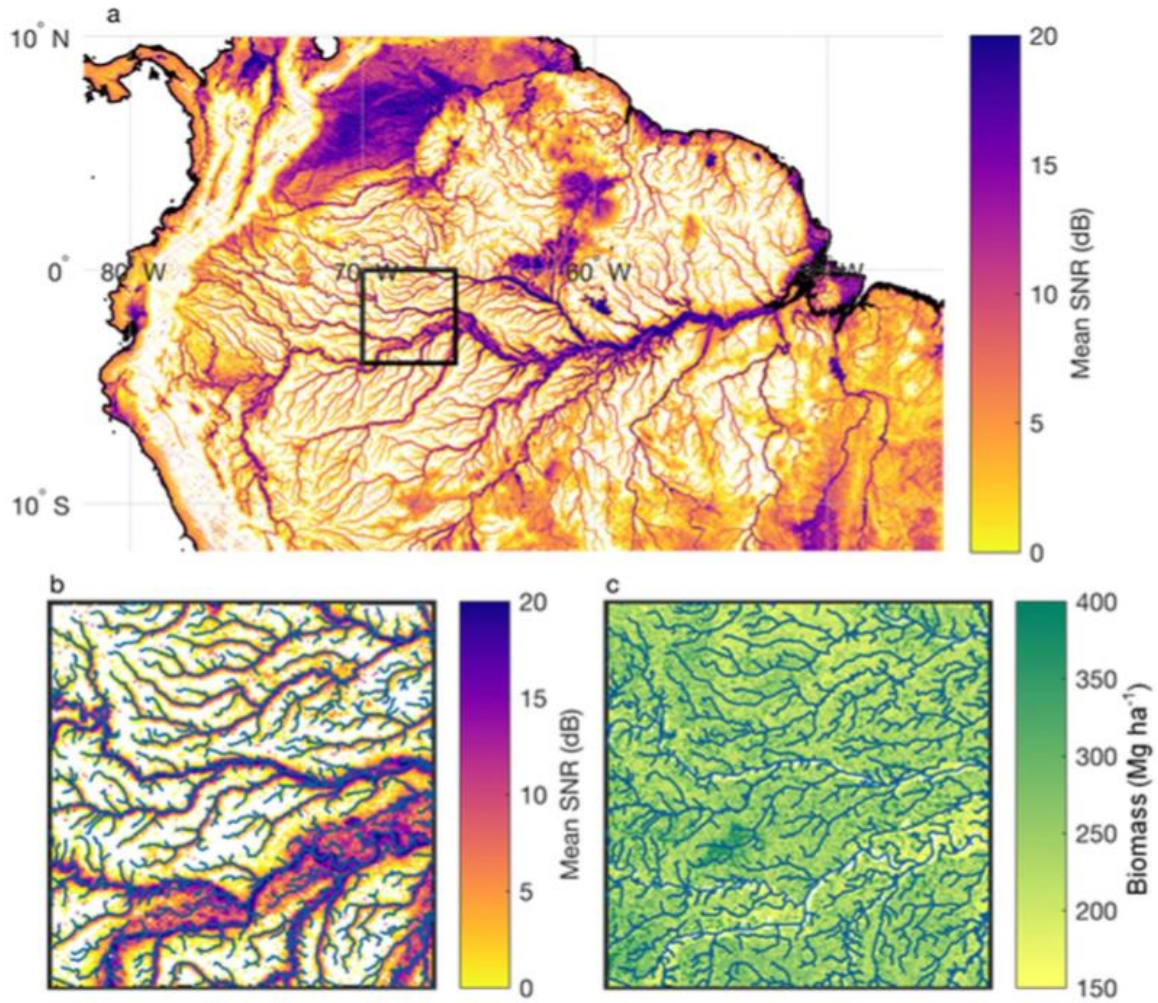


Figure 7. CYGNSS mapping of inland waterways in the Amazon. (a) Mean SNR, gridded to 3 km, over the Amazon for the time period 18 Mar–29 Dec 2017. Areas with surface elevation >600 m above sea level have been masked out due to a limitation in the CYGNSS on-board data compression algorithm. Corrective flight software was uplinked to the constellation in Dec 2017. (b) Inset of the black outlined box in (a), with river outlines from HydroSHEDS[38] overlaid in green. (c) Biomass map[39] for the black outlined box in (a), with river outlines from HydroSHEDS[21] overlaid.

Ruf et al., 2019

GNSS-R wind speed (CYGNSS)

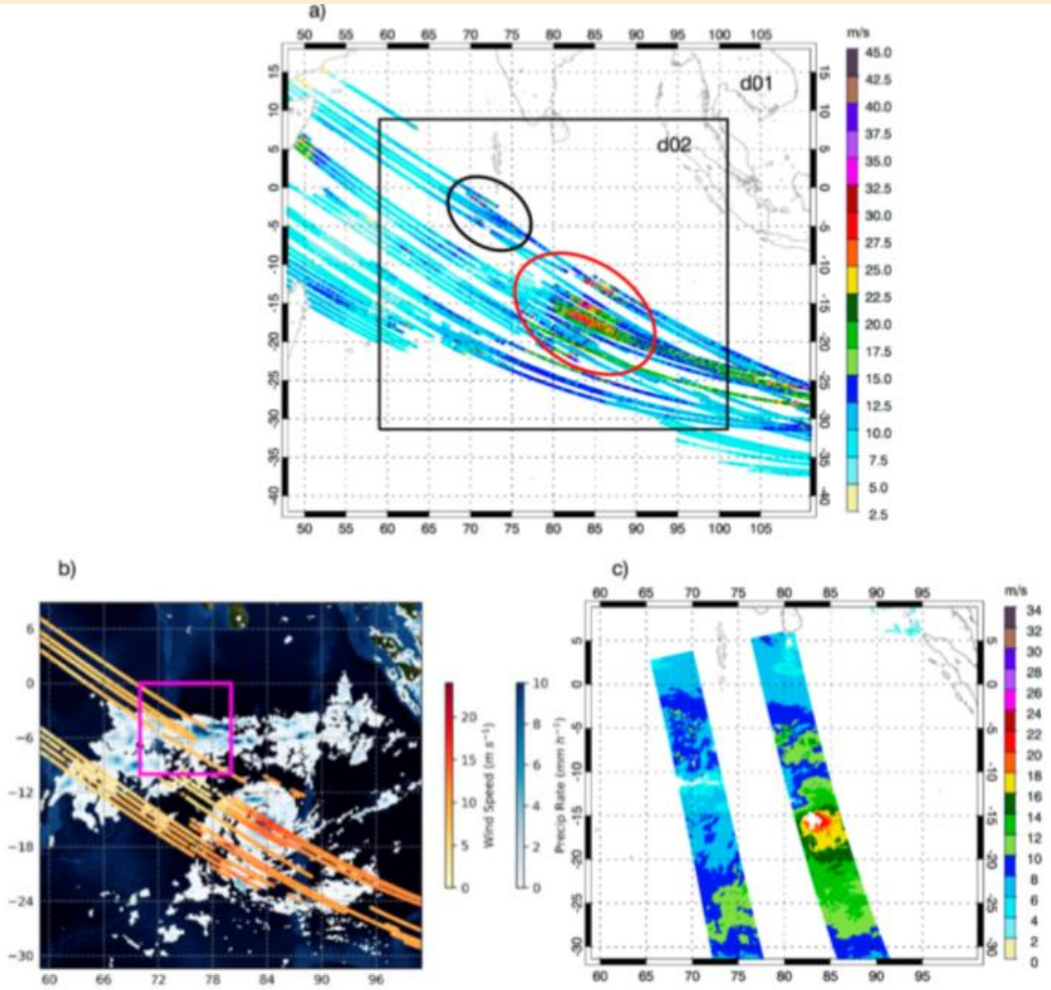
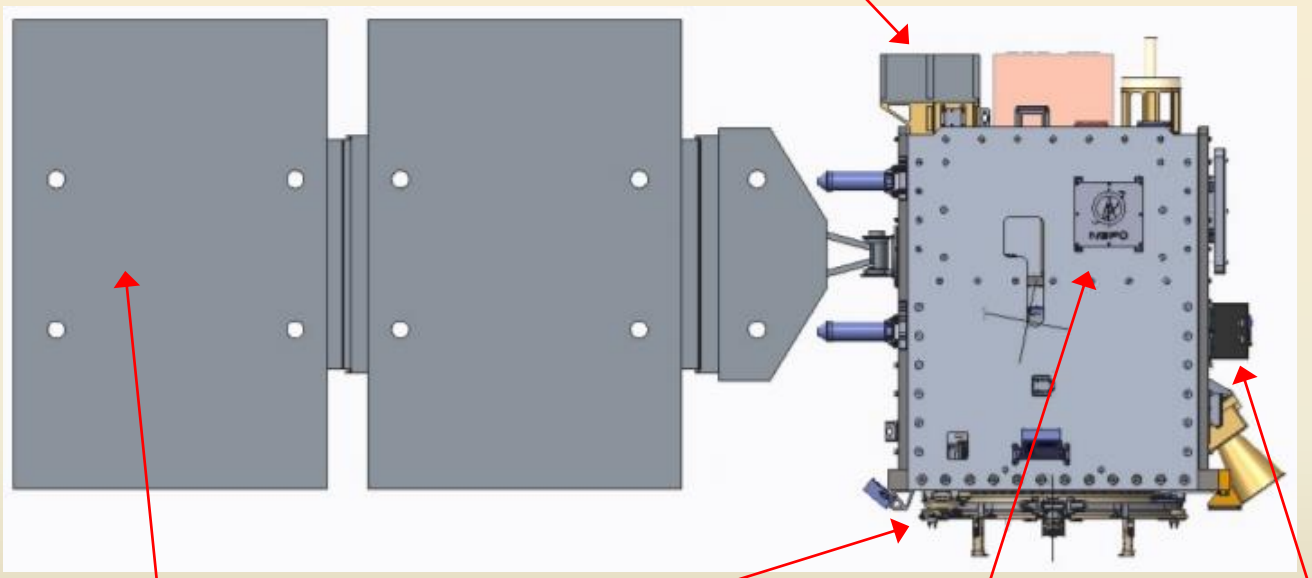


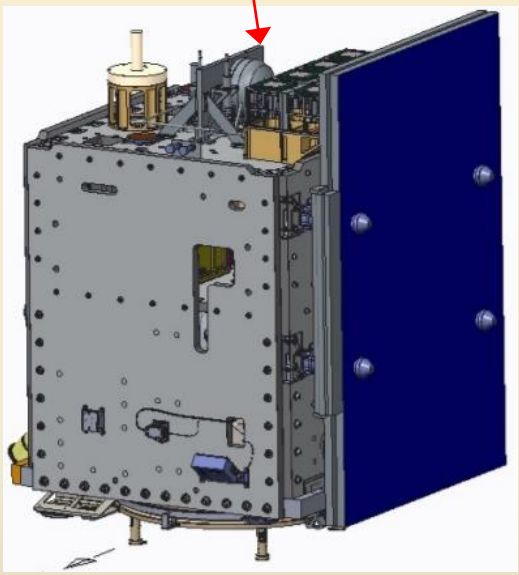
Figure 2. (a) WRF model 9-km and 3-km domains (d01 and d02) and CYGNSS v2.1 YSLF data within 1.5 h from 1500 UTC on 7 January 2018. The black circle shows the high winds in CYGNSS related to the WWB and the red circle shows high winds related to TC Irving. (b) CYGNSS v2.1 FDS data in 1400–1500 UTC over-plotted on IMERG 1-h rainfall at 1400 UTC on 7 January 2018. The magenta box shows the approximate location of the WWB event. (c) ASCAT wind speed at around 1448 UTC on 7 January 2018.

Li et al., 2020

TRITON (獵風者) Mission



Deployed Configuration

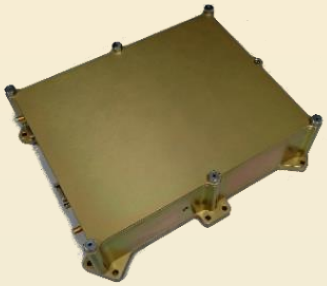


Stowed Configuration

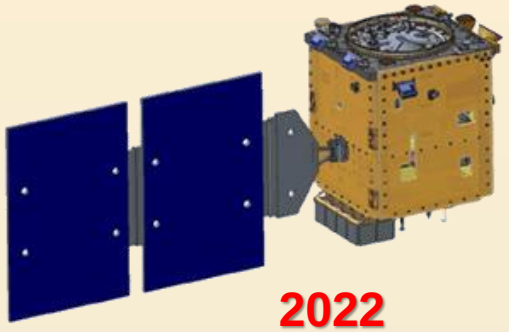
GNSS-R 酬載發展現況

雛形體

工程驗證體



飛行體



2022
進行在軌操作

2016

- 完成雛型體研製
- 完成地面功能測試
- 完成首次的飛機飛試

2017

- 完成環境驗證測試
  (電磁相容、熱真空、振動等測試)
- 進行無人機飛試以驗證操作程序與訊號雜訊特性
- 進行 GPS/Galileo 反射訊號處理系統發展

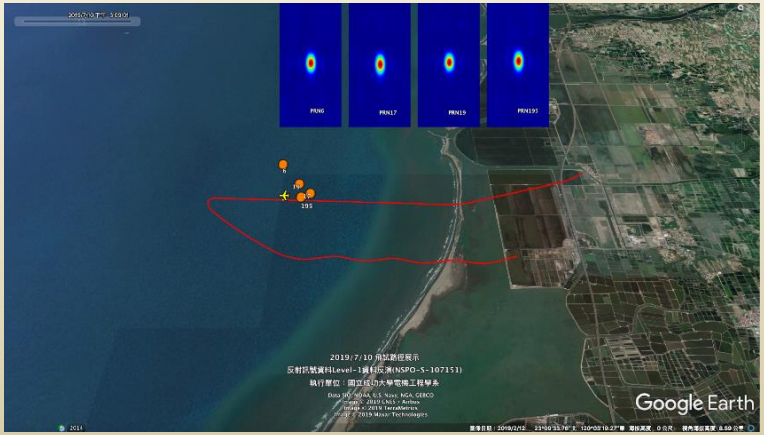
2018

2019

2020

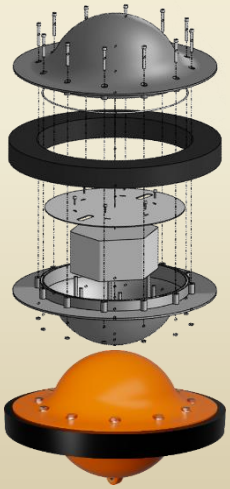
- 飛行體備便
- 與衛星組裝與進行測試
- 持續進行飛機飛試與資料分析
- 持續進行酬載參數調教
- 持續進行 Level-1 資料反掩

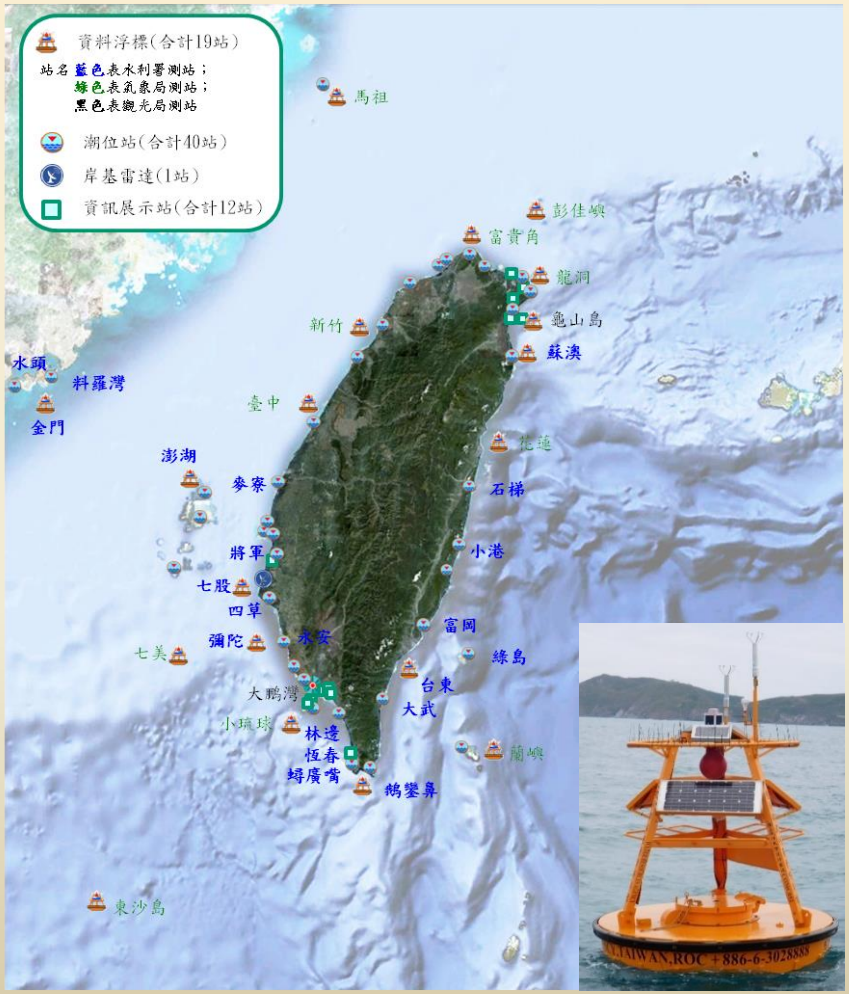
GNSS-R 無人機飛試 (2018/2019)



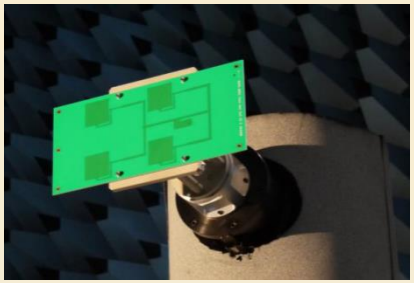
海空聯合觀測與驗證 (2020/2021)

1. 歐洲中尺度再分析場 (ECMEF)
2. Buoy
   - 水利署
   - 觀光局
   - 氣象局
3. Drifter
   - 中大水文所錢老師團隊

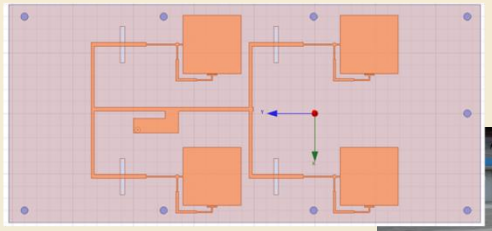




AIDC Flight Test 2020/07/27

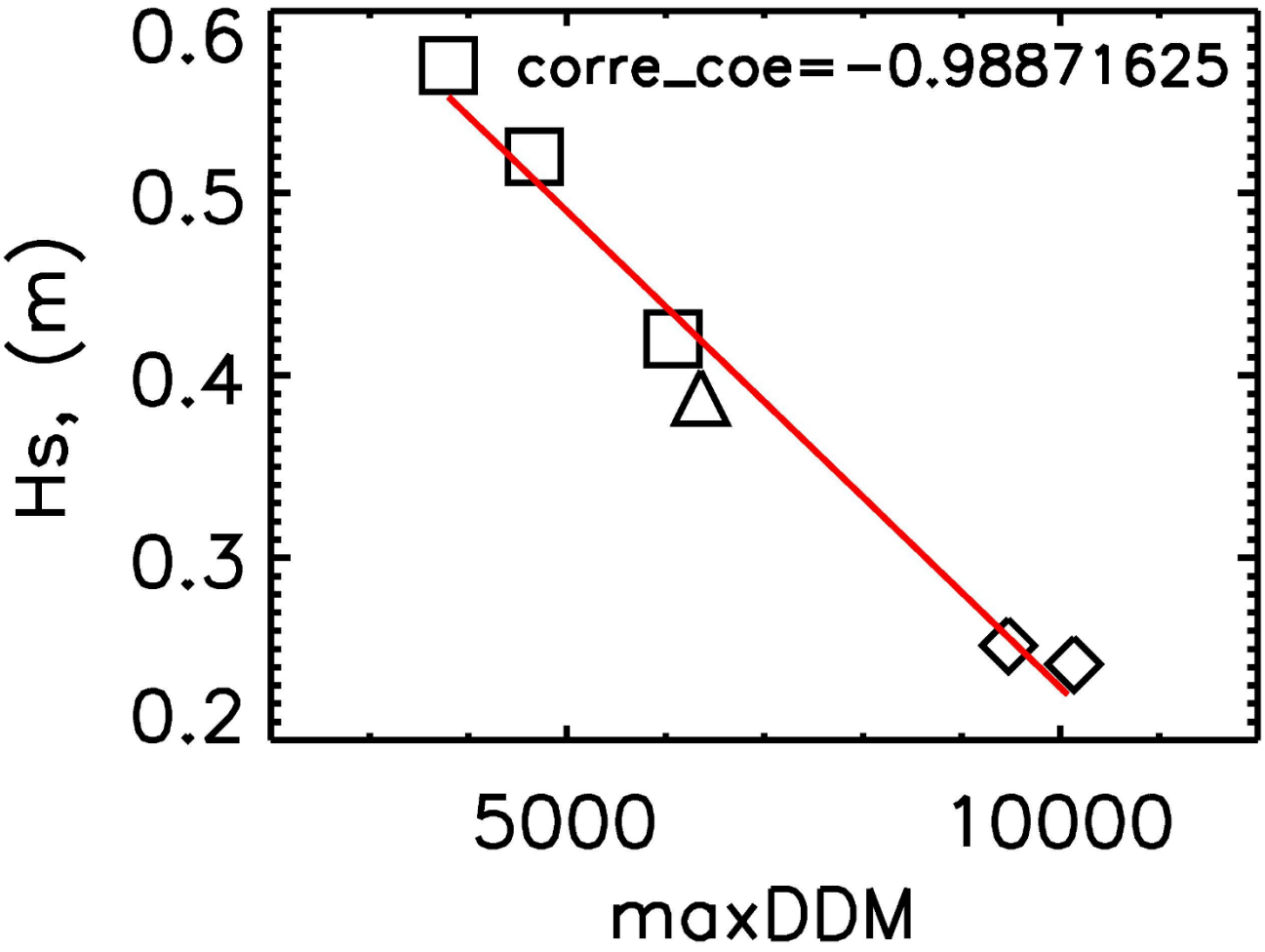


飛機前進方向



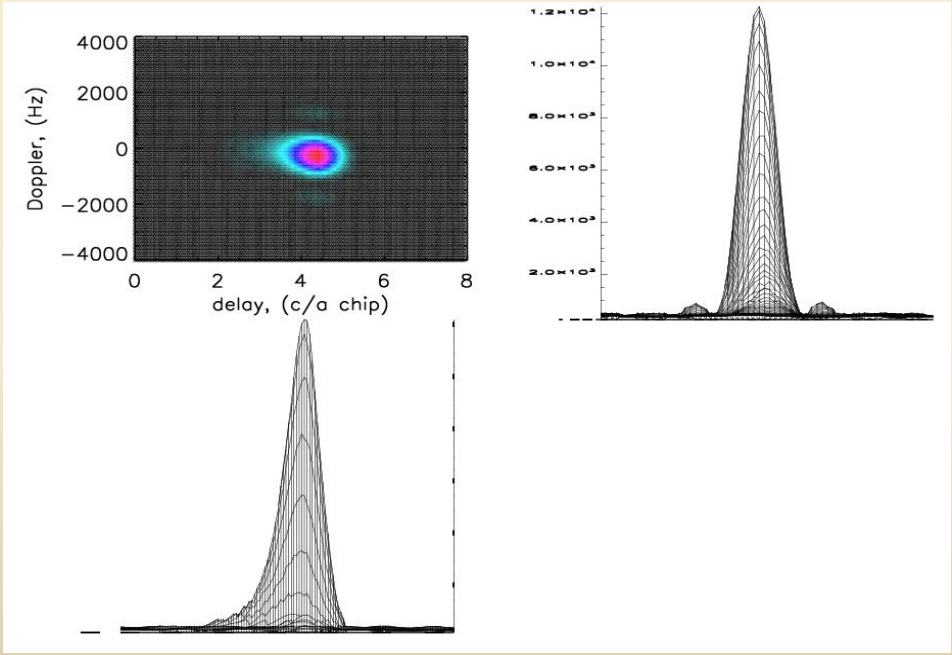
Drifter observation 20200727

Significant wave height vs. signal strength

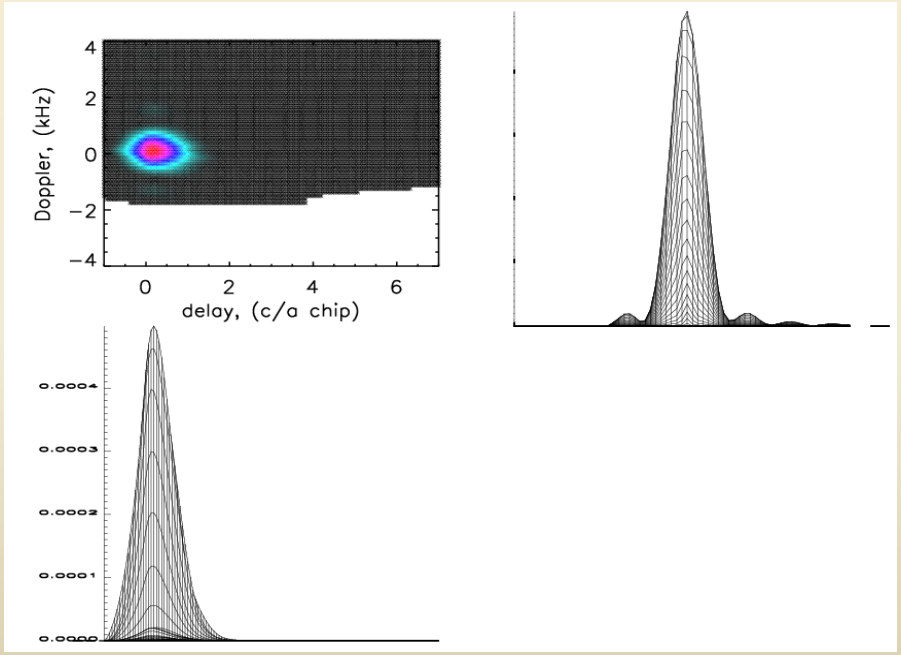


Flight Test DDM Comparison

Obs.



Simulate

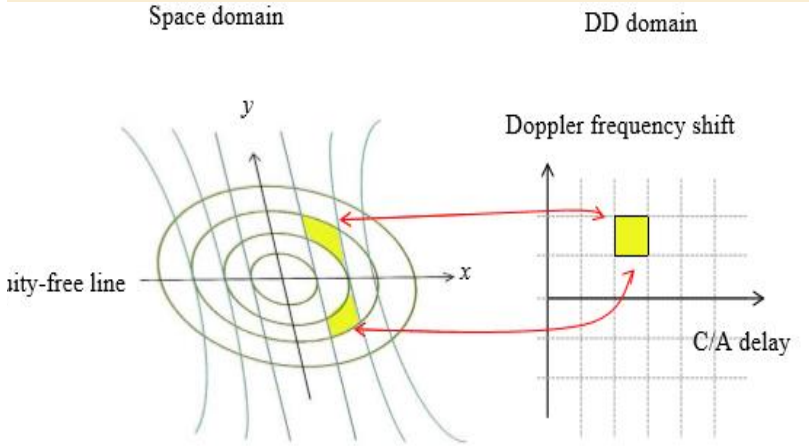


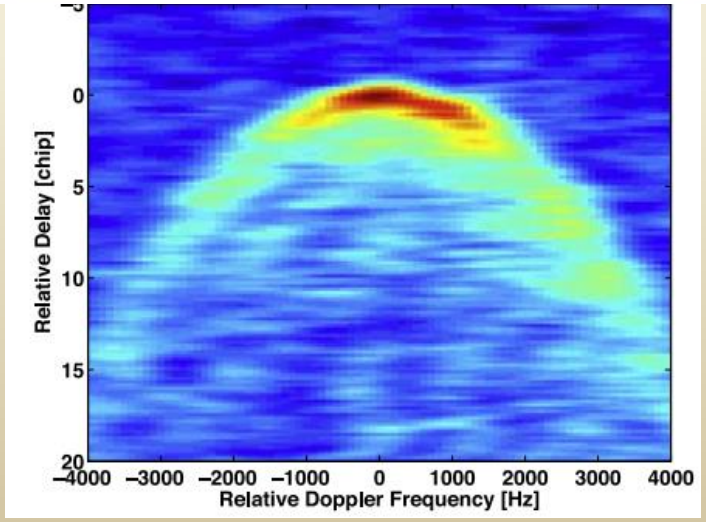
Zavorotny-Voronovich Model

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

- Delay-Doppler Map
- 1. Path Losses
- 2. Antenna Gain
- 3. Bistatic Normalized Radar Cross Section (NRCS)
- 4. Woodward Ambiguity Function (WAF)

DD Domain — Spatial Domain





$$\sigma_o(\boldsymbol{r}) = \frac{\pi|\Re|^2 q^4}{q_z^4} f_q\left(\frac{-\boldsymbol{q}_\perp}{q_z}\right)$$

$$f_q\left(\frac{-\boldsymbol{q}_\perp}{q_z}\right) = 1/2\,\pi \det(\boldsymbol{M}) exp\left[-\left(\frac{1}{2}\boldsymbol{q}_\perp^t \boldsymbol{M}^{-1}\boldsymbol{q}_\perp\right)\right]$$

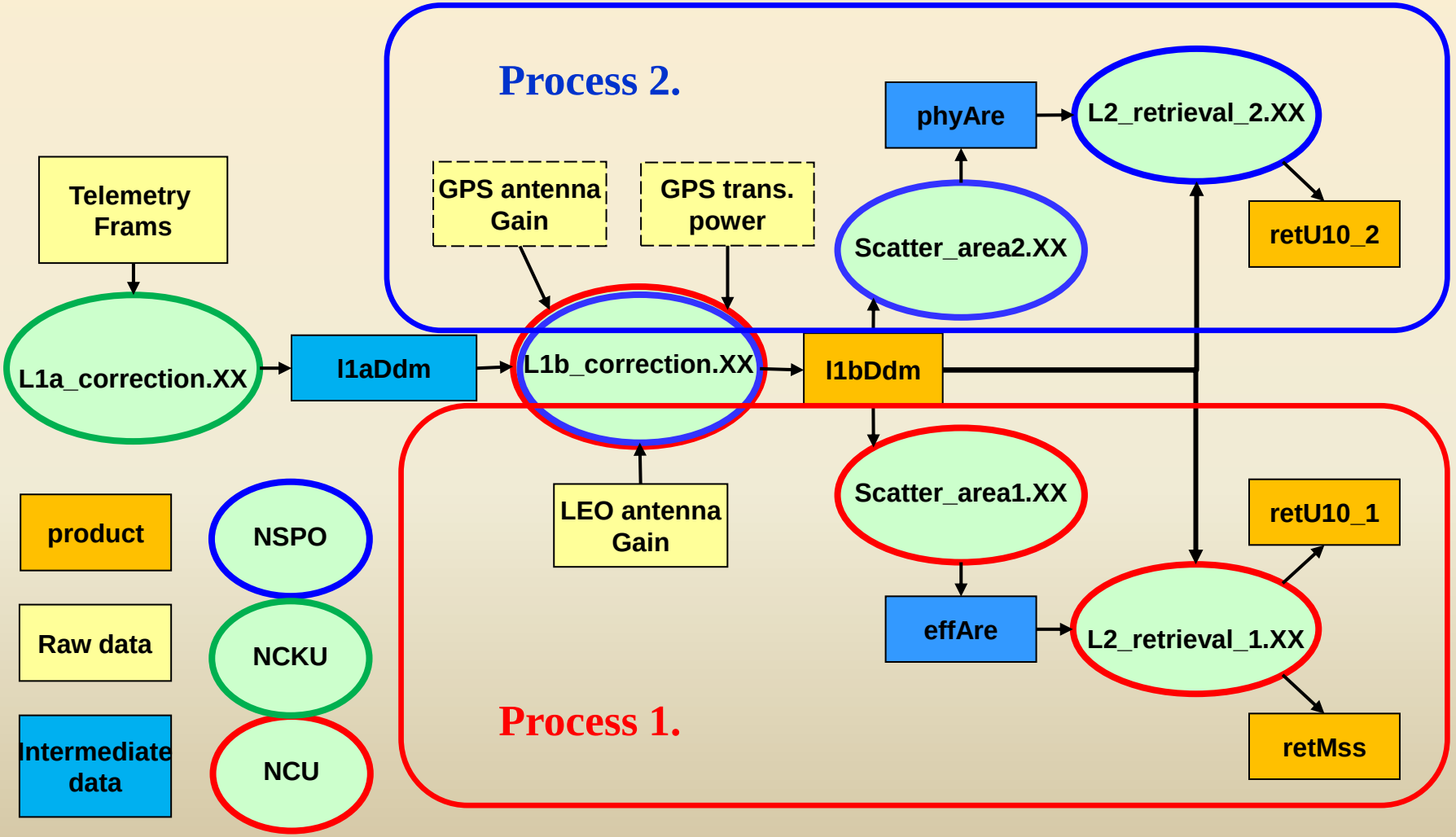
$$\boldsymbol{q}_\perp(q_x, q_y) = \left(\frac{R_{0x}}{R_0} + \frac{R_{vx}}{R_v}, \frac{R_{0y}}{R_0} + \frac{R_{vy}}{R_v}\right)$$

$$\boldsymbol{M} = \begin{bmatrix} \cos(\phi) & -sin(\phi) \\ sin(\phi) & cos(\phi) \end{bmatrix} \begin{bmatrix} \sigma_{up}^2 & 0 \\ 0 & \sigma_{cross}^2 \end{bmatrix} \begin{bmatrix} \cos(\phi) & sin(\phi) \\ -sin(\phi) & cos(\phi) \end{bmatrix}$$

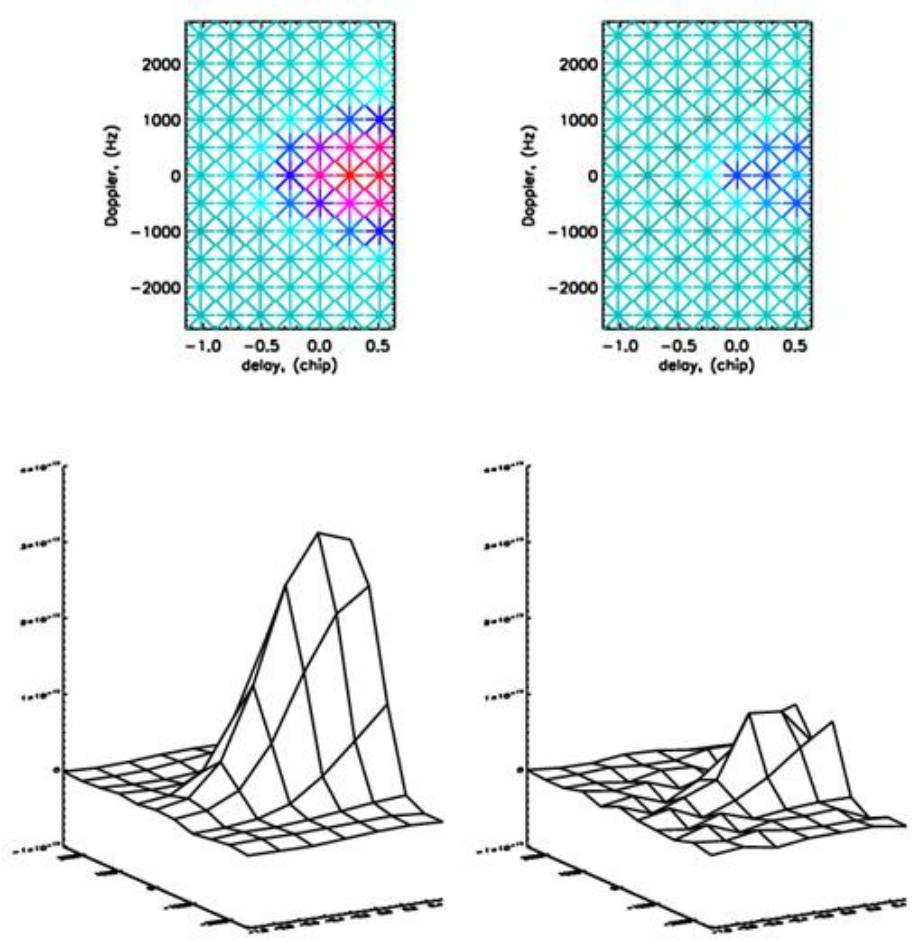
- $\sigma_{up}^2; \sigma_{cross}^2$: Directional Mean Square Slopes (**DMSS**);
- ϕ: Principal Wave Slope Direction (**PWSD**).

Clarizia, 2012

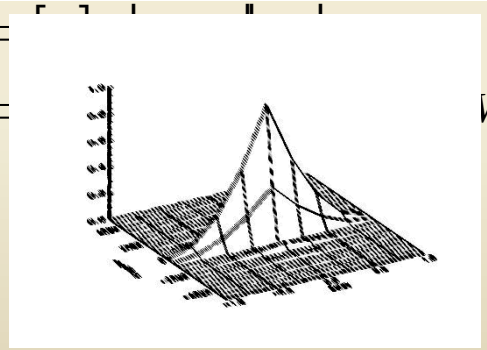
GNSS-R data process system

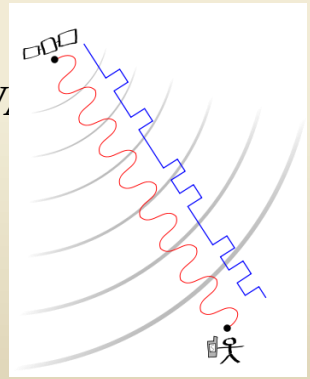


Woodward ambiguity remove



訊號種類	頻率(MHz)
基本頻率	$f_0 = 10.23$
載波 L1	$154f_0 = 1575.42$
載波 L2	$120f_0 = 1227.60$
P 電碼(調制於 L1、L2)	$f_0 = 10.23$
C/A 電碼(調制於 L1)	$f_0/10 = 1.023$



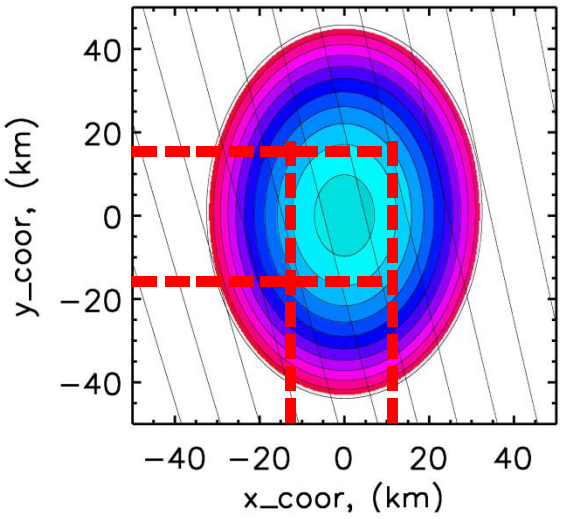


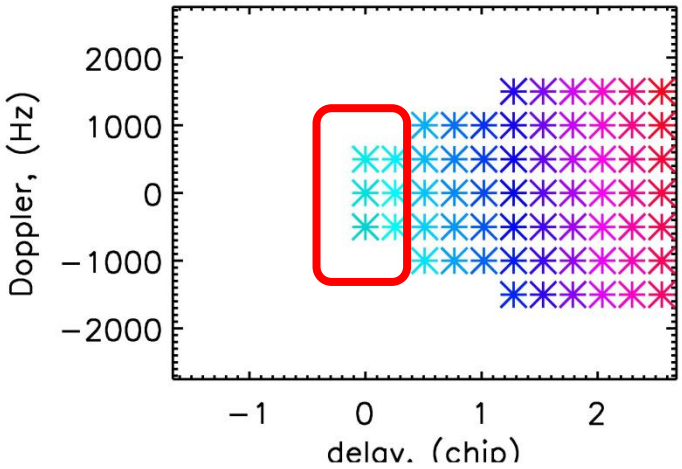
$$\Lambda^2\left(\frac{\delta\tau}{\tau_c}\right) sinc^2\left(\frac{\delta f_D}{T_i}\right)$$

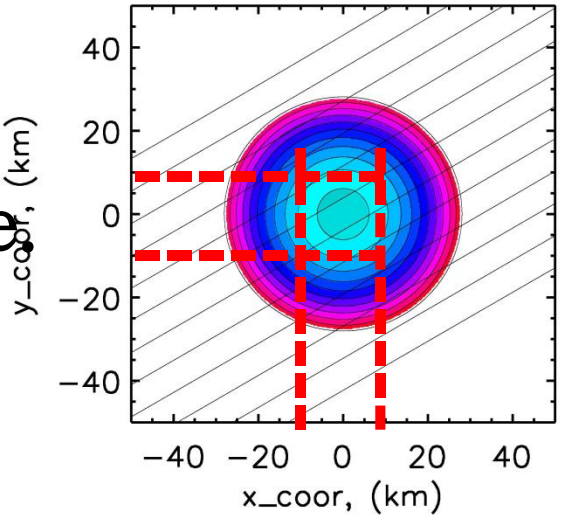
Relation between spacial and DDM domain (CYGNSS)

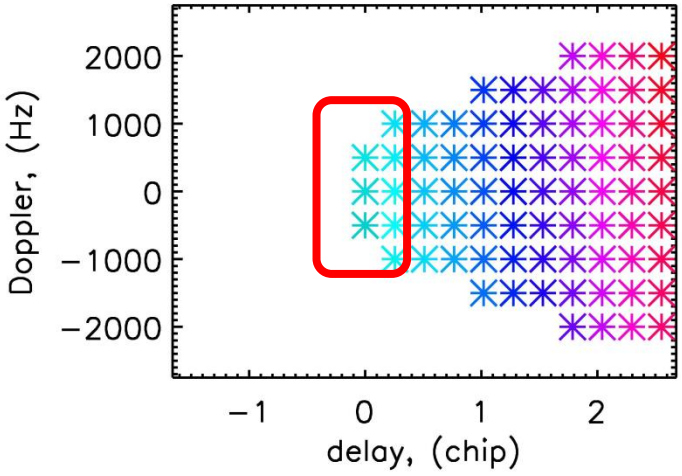
Low ele.

High ele.







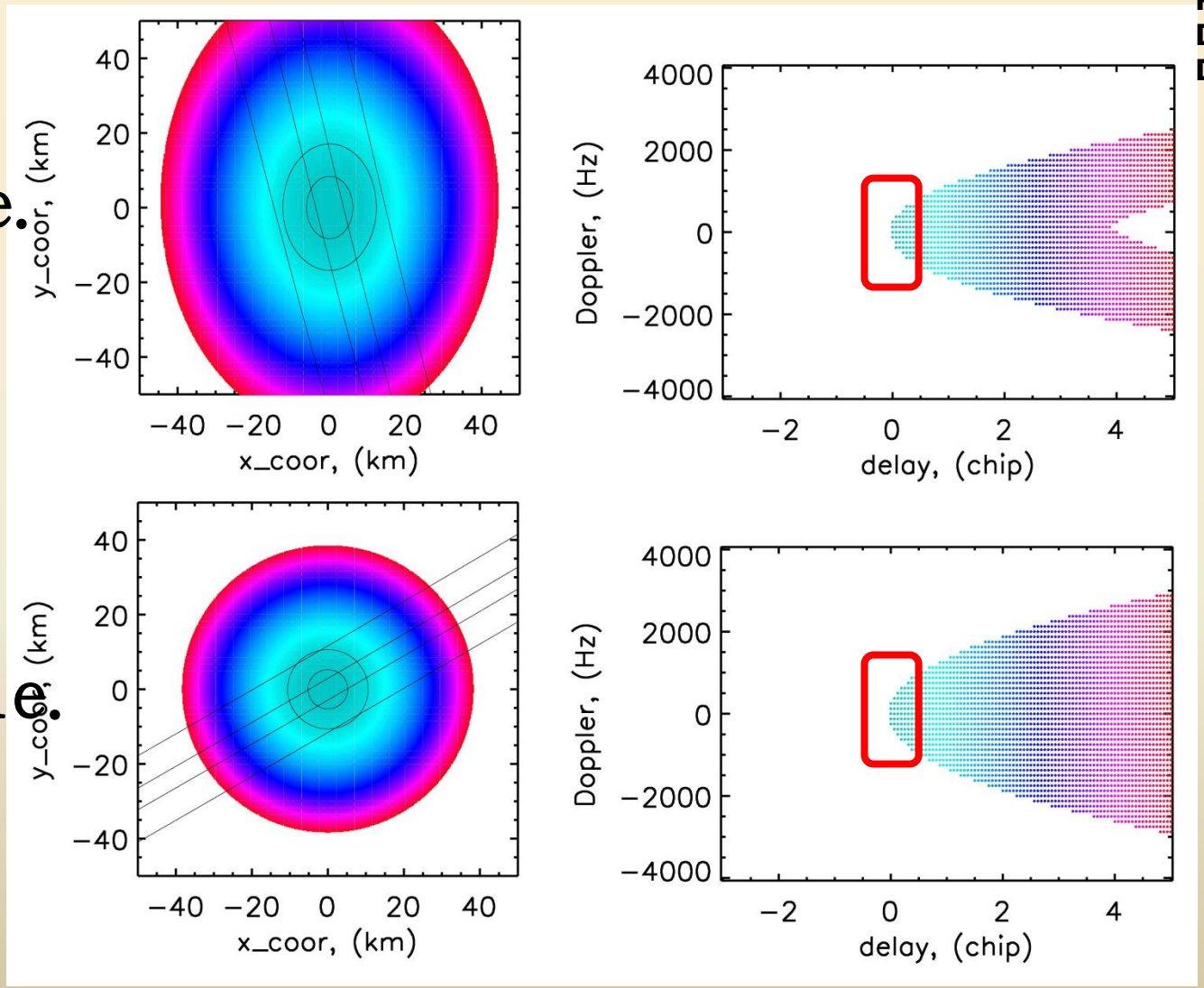


Resolution：
Delay~0.25chip
Doppler~500Hz

Relation between spacial and DDM domain (TRITON)

Low ele.

High ele.

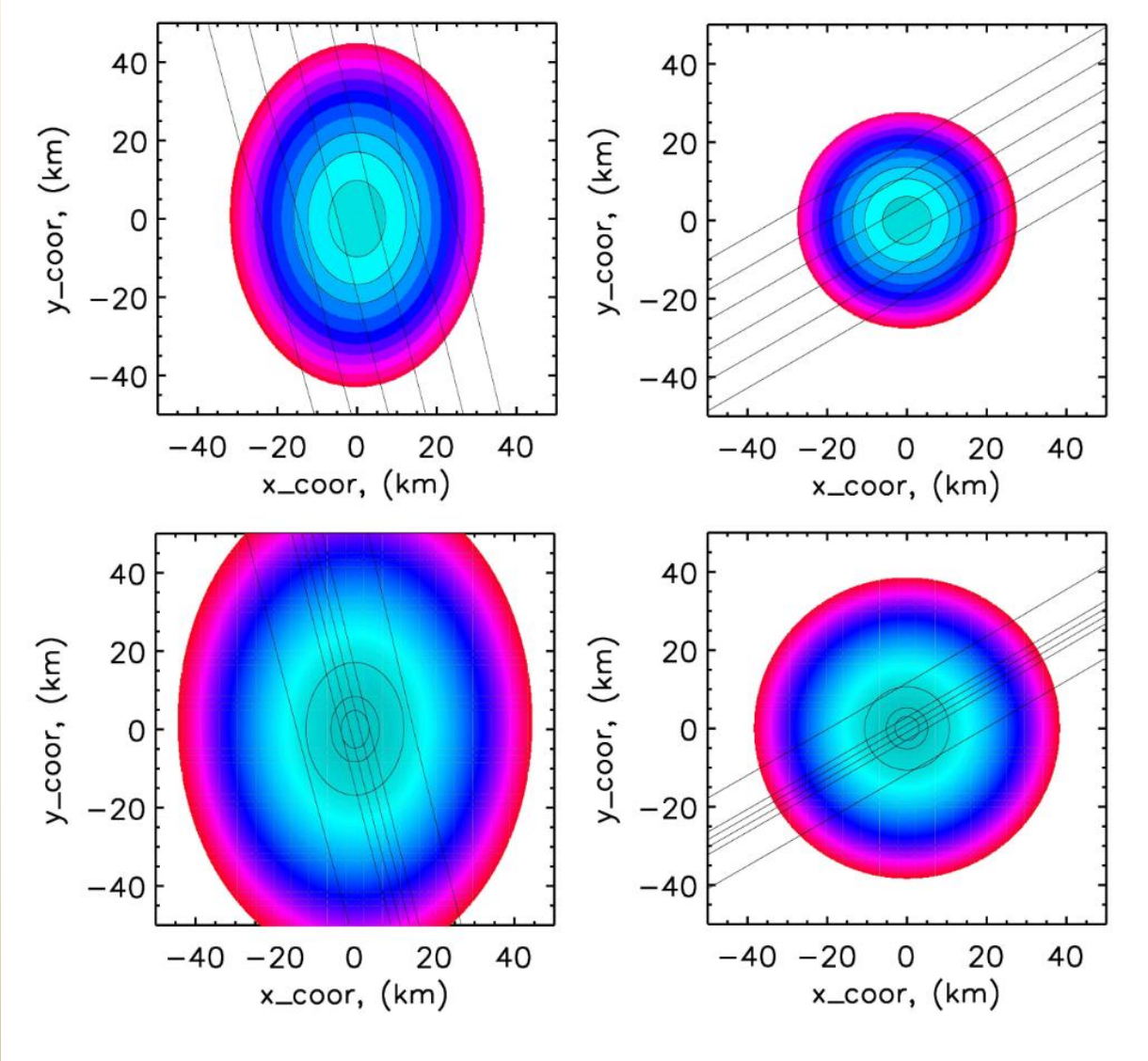


Resolution：
Delay=0.0625chip
Doppler~125Hz

Spatial resolution between TRITON & CYGNSS

CYGNSS

TRITON



Conclusions

多多支持國家衛星計畫


Thank you !!