



**From FORMOSAT-3/COSMIC to
FORMOSAT-7/COSMIC-2 Mission:
A New Era of Operational GNSS Radio
Occultation Constellation Observing System**

Chen-Joe Fong, Vicky Chu, and Chun-Chiang Lin

2019.9.19

Outline

- Introduction
 - FORMOSAT-3/COSMIC Review
 - FORMOSAT-7/COSMIC-2 Launch Review
 - Constellation Deployment
 - Satellite Checkout Results
 - Early Results
 - Conclusion
- 

Introduction

- As the world's **first** GPSRO constellation, **FORMOSAT-3/COSMIC** has clearly demonstrated the value of GPSRO in Weather, Climate and Space Weather.
- Since its launch on April 15th, 2006, FORMOSAT-3 has accumulated over **6.9 million atmospheric** and **4.5 million ionospheric** radio occultation (RO) data profiles globally.
- There are over **4,300 community** users from **91 countries** currently making use of the FORMOSAT-3 data for operational weather forecasting, climate change monitoring, space weather, and other related science and research.
- **FORMOSAT-7/COSMIC-2** launched on June 25th, 2019 and consisting of six satellites is the follow-on program of FORMOSAT-3/COSMIC and will **continue the legacy of FORMOSAT-3**.
- FORMOSAT-3 is also the world's most important source of **ionospheric** RO data. For the collected 5 million ionosphere RO data profiles, **90%** of which are primarily from the FORMOSAT-3 mission.
- The Taiwan space weather community has achieved a number of breakthroughs using FORMOSAT-3 RO profile data, and created an opportunity for **space weather numerical weather prediction (NWP)**.

FORMOSAT-3 / COSMIC - Minotaur Launch Success

Launch Date: April 15, 2006 at UTC 01:40

Launch Site: Vandenberg AFB, CA, U.S.A.

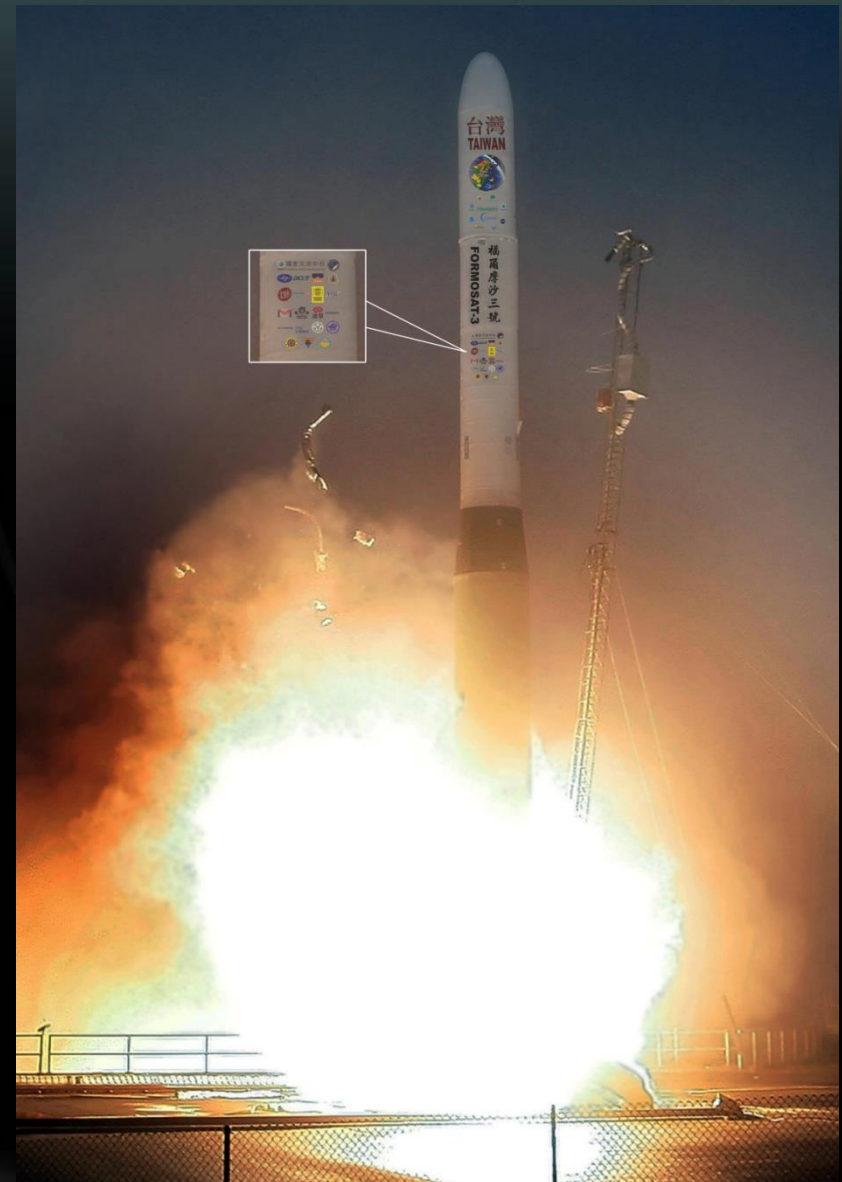
Initial Orbit : Altitude ~515 km; Inclination ~72°

Final Orbit : Altitude ~800 km; Inclination ~72°

FORMOST-3 / COSMIC

Total Cost : ~ U.S. \$ 100 M

- The first Radio Occultation Constellation that demonstrates the value of GPSRO in Weather, Climate and Space Weather.



FORMOSAT-7/COSMIC-2 – Falcon Heavy Launch Success

Launch Date: June 25, 2019 at UTC 06:30

Launch Site: LC-39A, Kennedy Space Center, U.S.A.

Initial Orbit : Altitude ~720 km; Inclination ~24°

Final Orbit : Altitude ~550 km; Inclination ~24°

FORMOST-7 / COSMIC-2

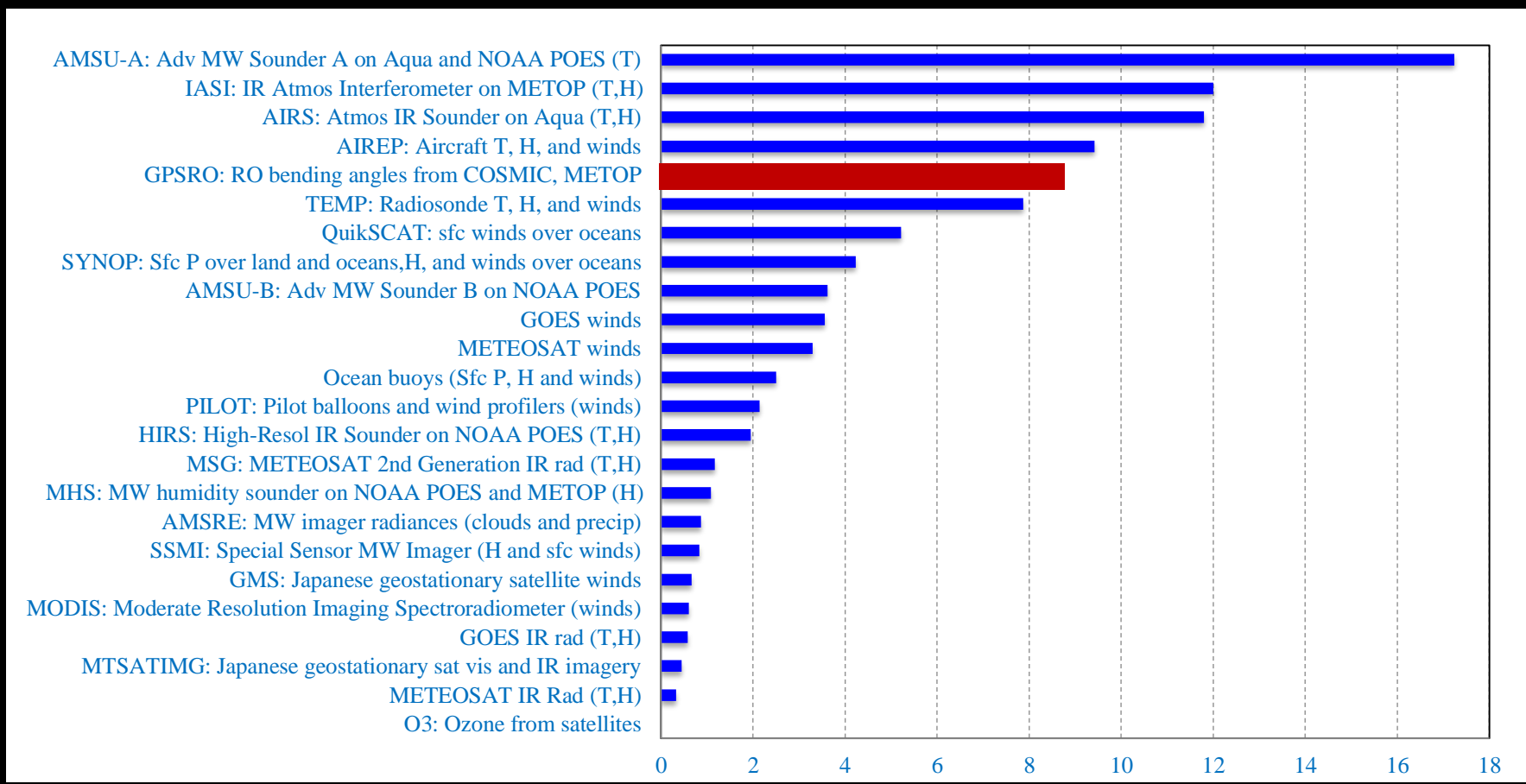
Total Cost : ~ U.S. \$ 200 M





GPSRO has Significant Impact:

NSPO Ranked #5 among all observing systems in reducing forecast errors, despite the small number of soundings.



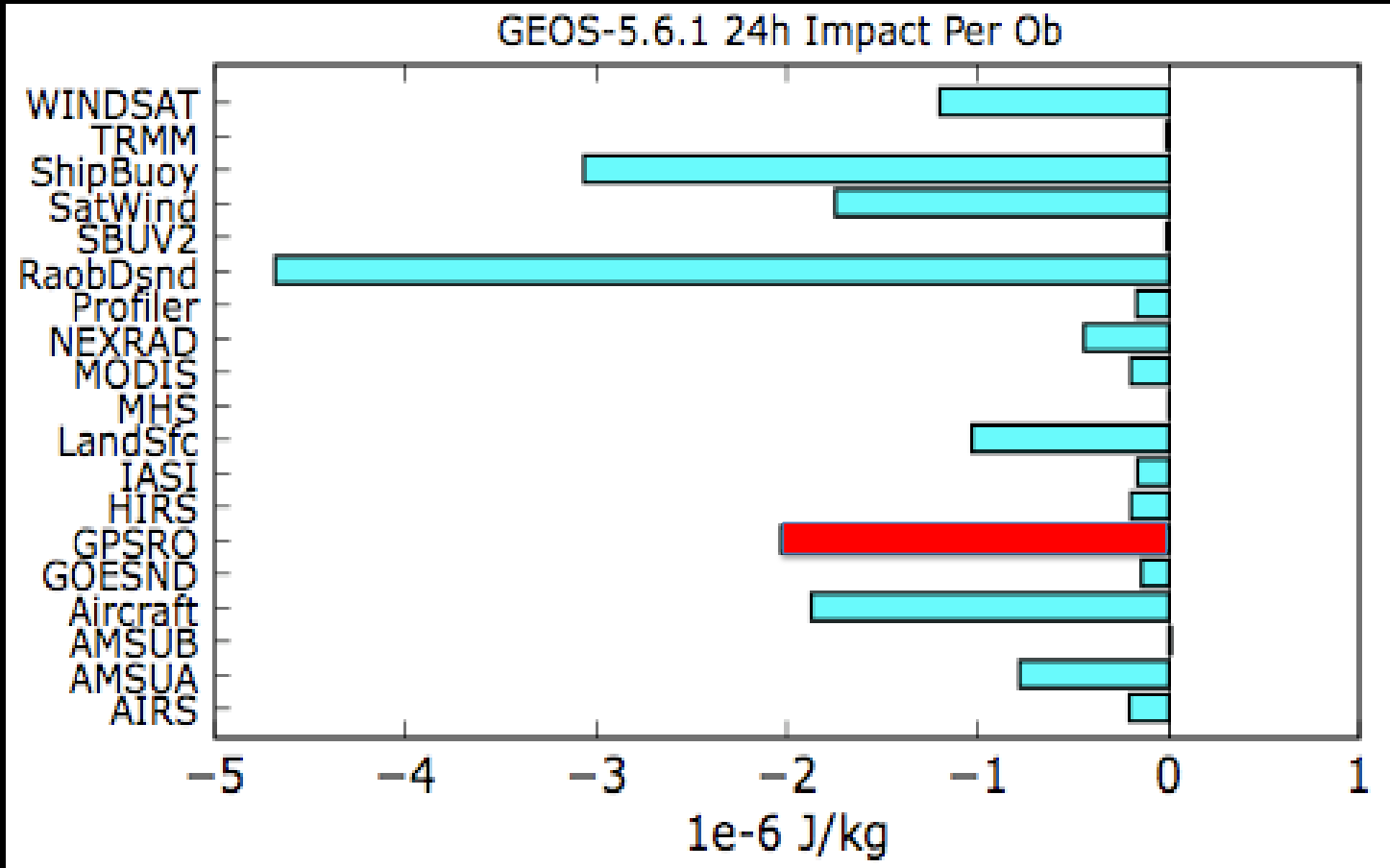
Published in the Quarterly Journal of the Royal Meteorological Society

Forecast error contribution (%)

Courtesy: Carla Cardinali and Sean Healy, ECMWF, 22 October, 2009

全球氣象界最具權威的歐洲中程氣象預報中心宣稱，福衛三號資料對氣象預報準確度的改善，是全球排行第五名。

RO Ranked #3 among other NOAA Instruments in Impact per Observation

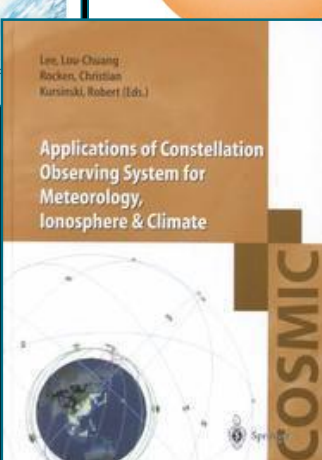
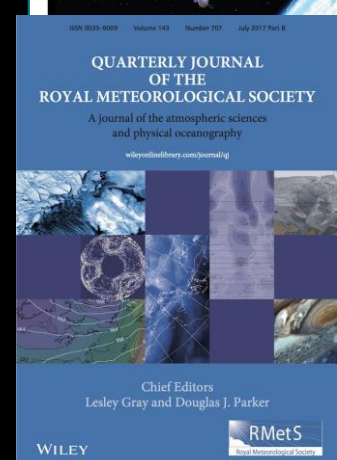
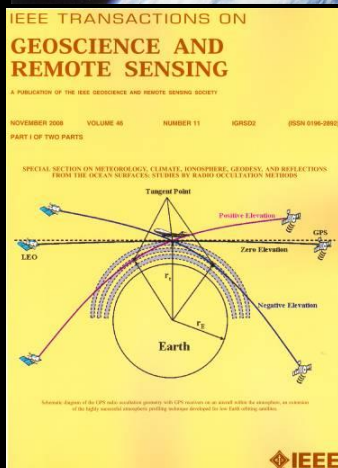
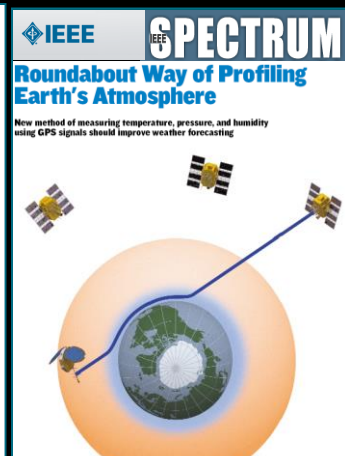
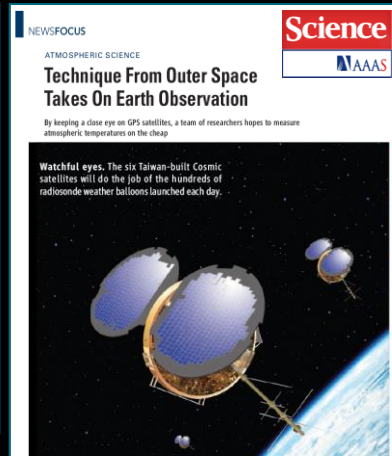
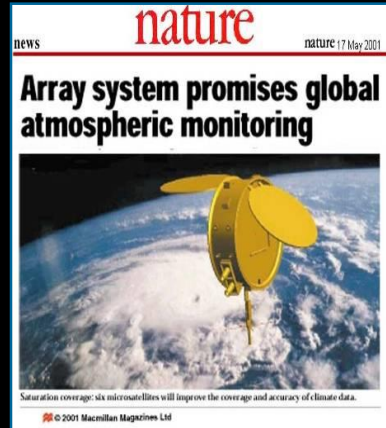
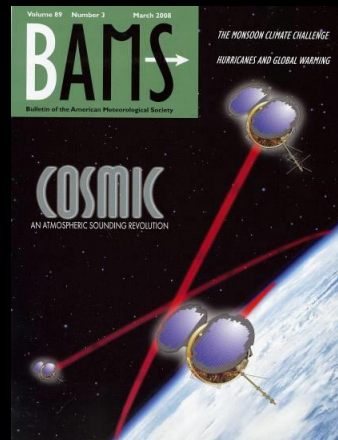


FORMOSAT-3/COSMIC
GPSRO

Adjoint-based estimate of 24-hr global forecast error reduction in wind, temperature and surface pressure combined as energy (J/kg)

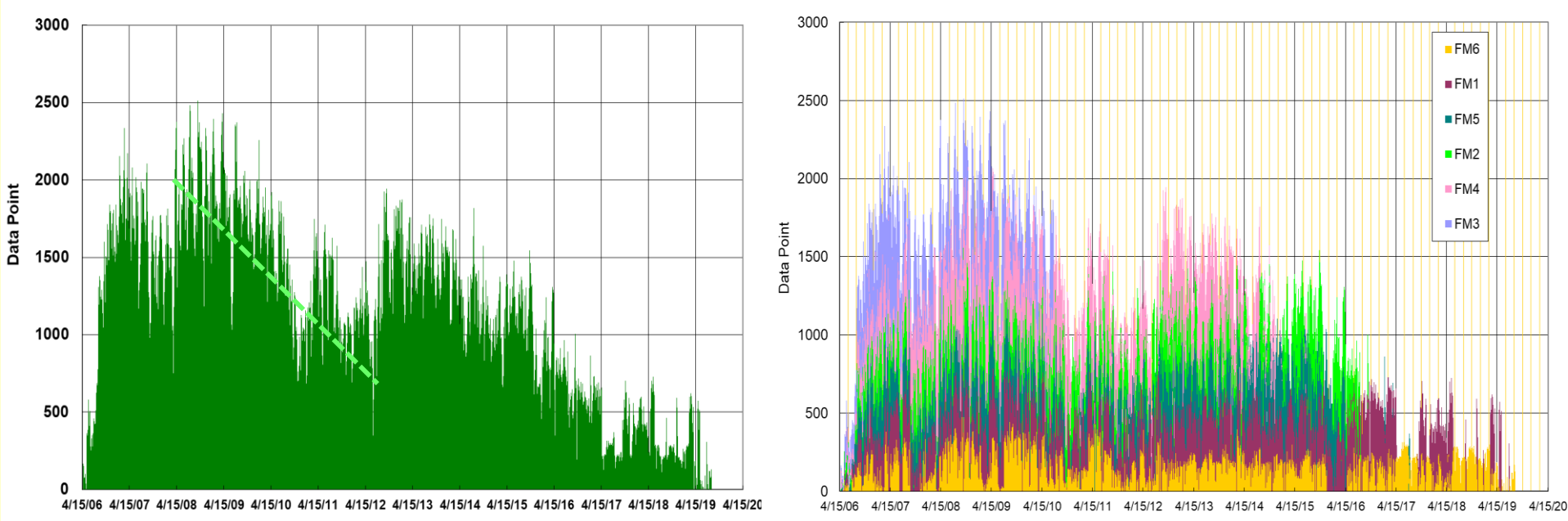
FORMOSAT-3 / COSMIC Appears on Major Global Publications

國際知名期刊雜誌 爭相報導福三衛星星系



FORMOSAT-3/COSMIC RO Accumulated Atmospheric Profiles

FORMOSAT-3/COSMIC RO Accumulated Atmospheric Profiles
 Total atmospheric occultations: 6,953,103
 (as-of-2019-9-9)



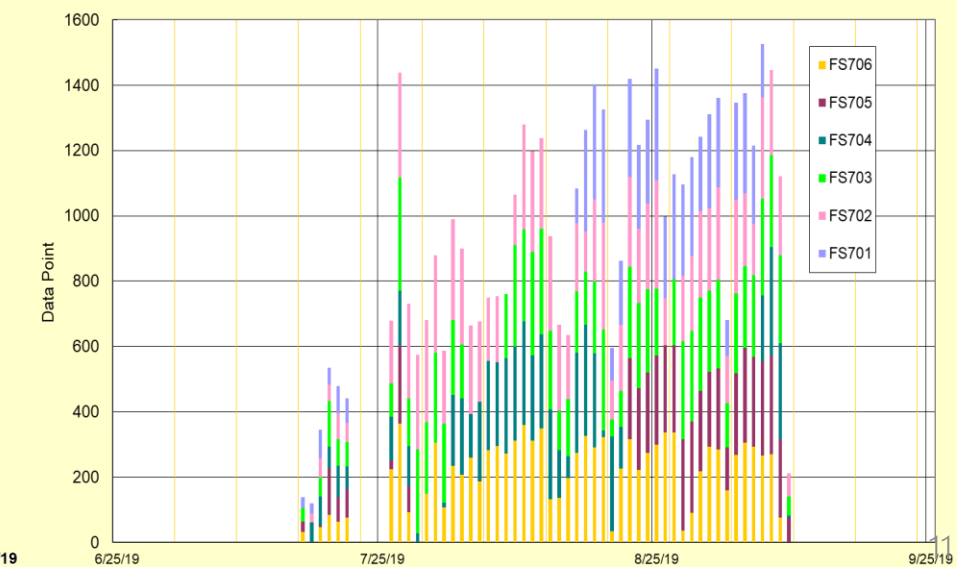
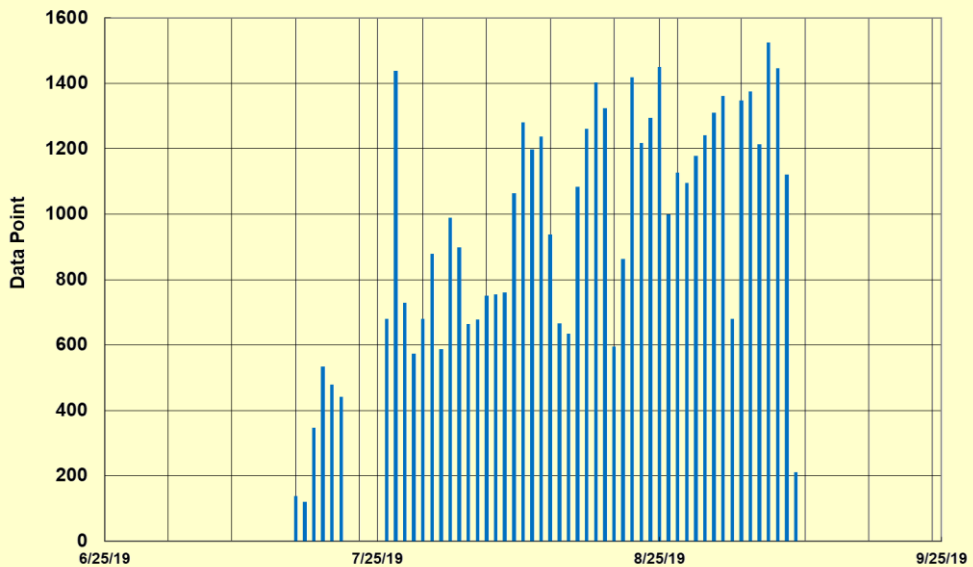
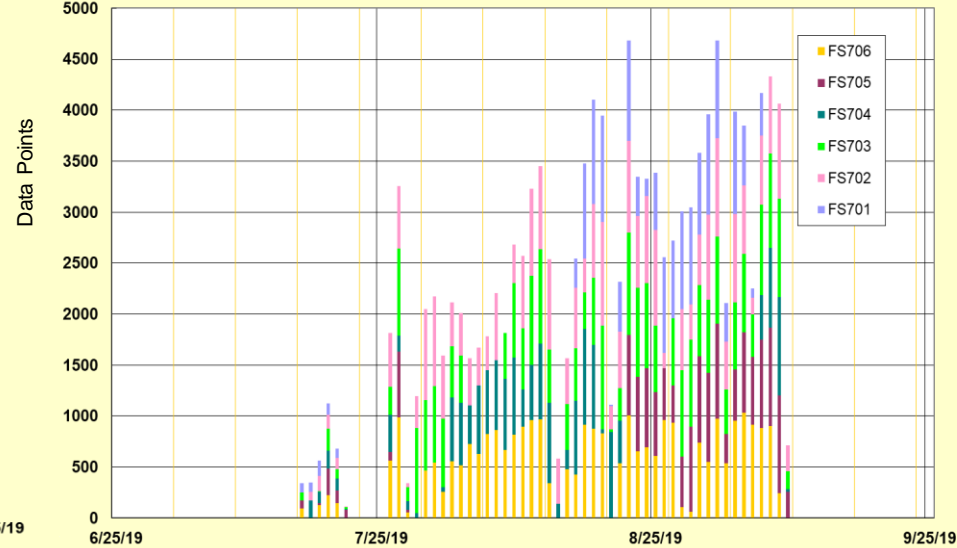
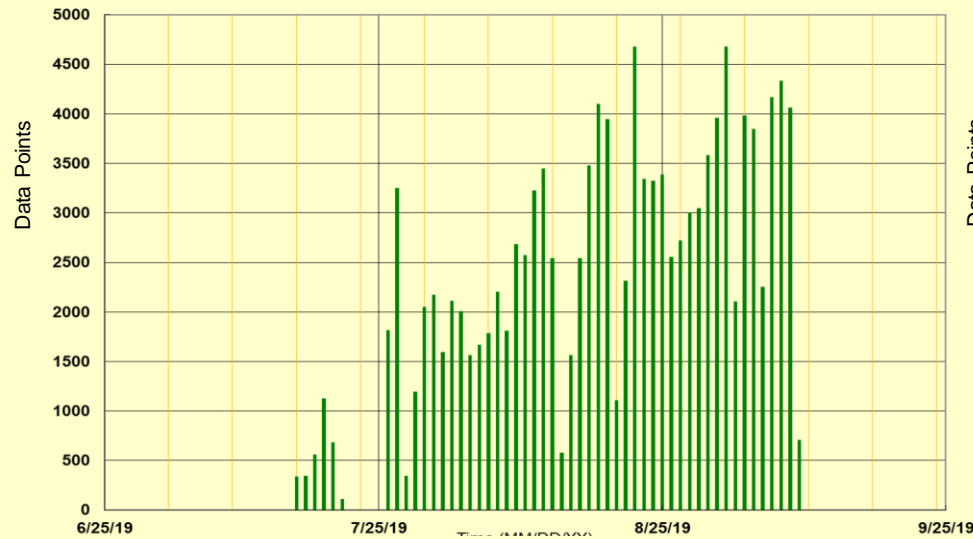
Total RO Data Profiles (as-of-2019-9-9)

MISSION	Total Atm Occs	Total Ion Occs	Working Days
CHAMP	468,029	306,318	
CNOFS	152,610	0	
FORMOSAT-3/COSMIC	6,953,103	4,643,619	4,895
FORMOSAT-7/COSMIC-2	129,035	49,769	76
GPSMET	5,002	0	
GPSMETAS	4,577	0	
GRACE	565,148	260,561	
KOMPASAT5	546,247	0	
METOPA	2,580,112	0	
METOPB	1,406,082	0	
PAZ	86,925	0	
SACC	353,944	0	
TSX	825,536	0	
Total	14,076,350	5,260,267	



FORMOSAT-7/COSMIC-2 RO Accumulated Profiles (as-of-2019-9-9)

Total atmospheric / ionospheric occultations: 129,035 / 49,769



Global Data User's Status: 91 Countries, 4313 Users (as-of-2019-08-31)

U.S.A.	1079	Spain	22	Colombia	5	Mongolia	1
Taiwan	725	Malaysia	19	The Netherlands	5	Lebanon	1
India	562	Poland	19	Norway	5	Qatar	1
China	485	Egypt	17	Cyprus	5	Kyrgyz	1
Japan	102	Thailand	16	United Arab Emirates	4	Oman	1
South Korea	88	Nepal	16	Israel	4	Vanuatu	1
Germany	82	Philippine	15	Bangladesh	4	Ecuador	1
Iran	79	Turkey	13	Peru	4	Trinidad and Tobago	1
Canada	74	Denmark	13	Ghana	4	Panama	1
U.K.	73	Portugal	13	Macau	3	Ireland	1
Russia	73	New Zealand	12	Costa Rica	3	Romania	1
Australia	65	Sweden	12	Venezuela	3	Serbia	1
Brasil	63	Pakistan	11	Tanzania	3	Armenia	1
Indonesia	61	Switzerland	11	Jamaica	3	Greece	1
France	61	Kazakhstan	10	Iraq	2	Belarus	1
Italy	51	Belgium	10	Saudi Arabia	2	Albania	1
Argentina	38	Chile	9	Fiji	2	Luxembourg	1
Ethiopia	34	Uganda	8	Puerto Rico	2	Kenya	1
South Africa	33	Finland	7	Cuba	2	Cameroon	1
Singapore	31	Czech	7	Hungary	2	Rwanda	1
Vietnam	29	Ukraine	7	Iceland	2	Madagascar	1
Austria	27	Mexico	6	Senegal	2	Algeria	1
Nigeria	25	Bulgaria	6	Bhutan	1		

There are over 4,313 community users from 91 countries currently making use of the FORMOSAT-3/COSMIC data.

Campaign Slogan → Legendary Reality

“The Most Accurate and Stable Thermometer in Space”

was first used by **Rick Anthes** in the opening remarks of

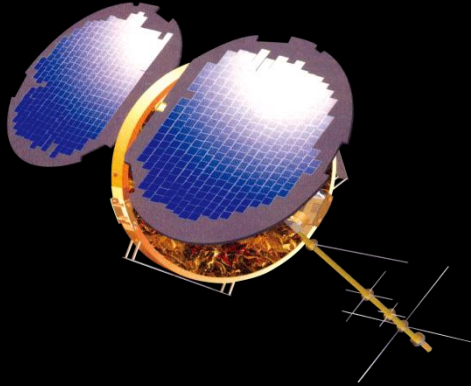
Emeritus UCAR President

FORMOSAT-3/COSMIC Workshop 2006 < Early Results and IOP Campaigns >

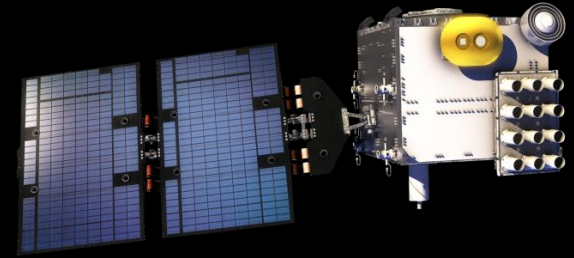
Taipei, November 28 – December 1, 2006



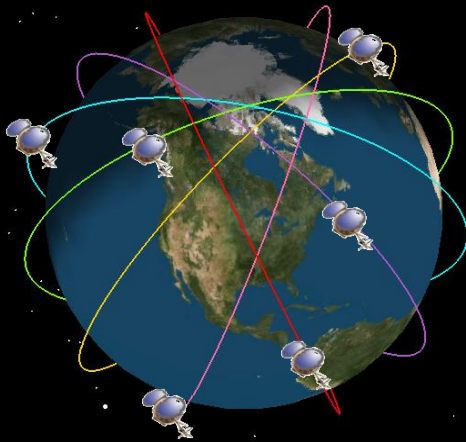
NSPO **FORMOSAT-3 / COSMIC-1** → **FORMOSAT-7 / COSMIC-2**



FORMOSAT-3 / COSMIC

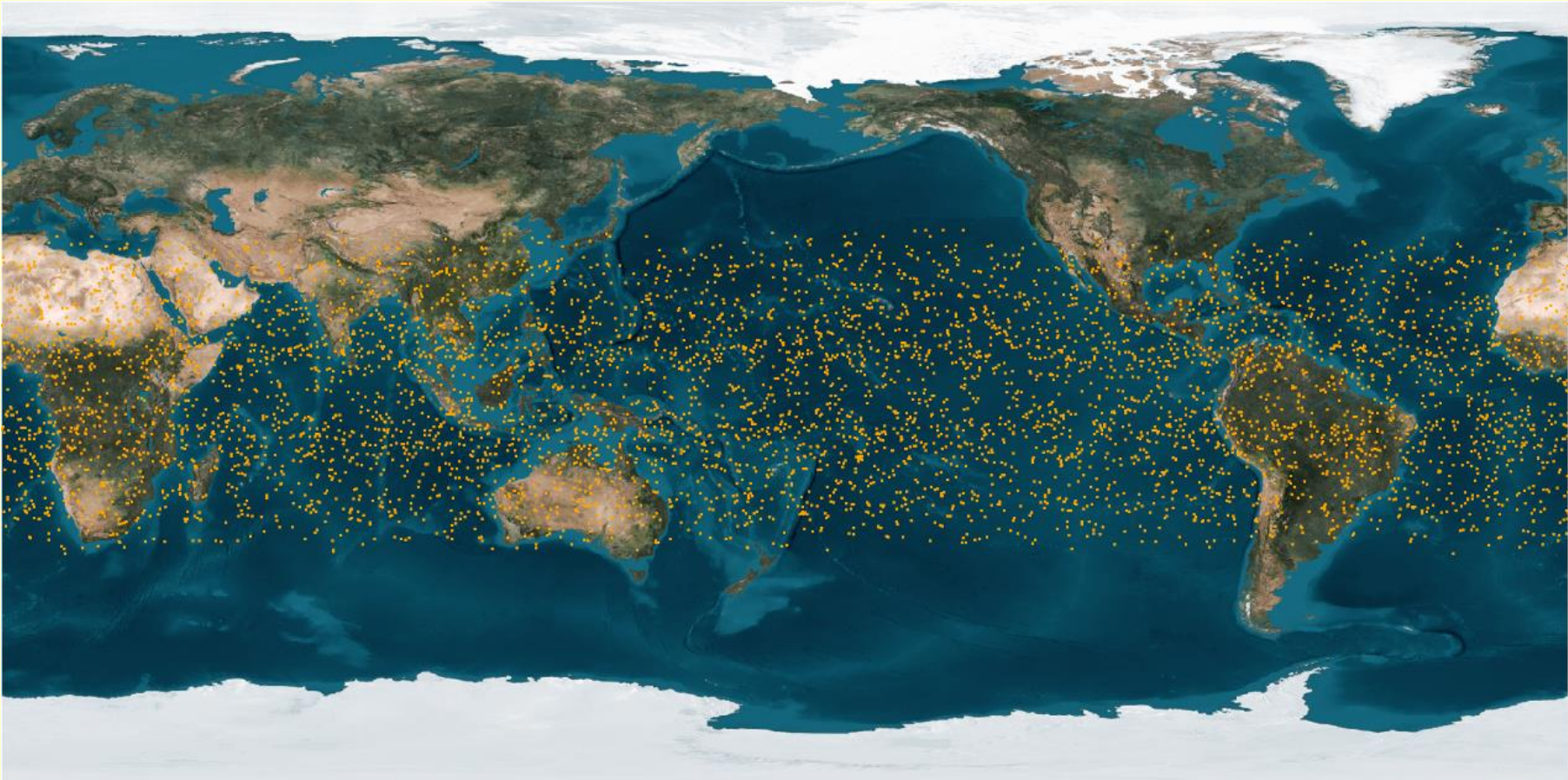


FORMOSAT-7 / COSMIC-2

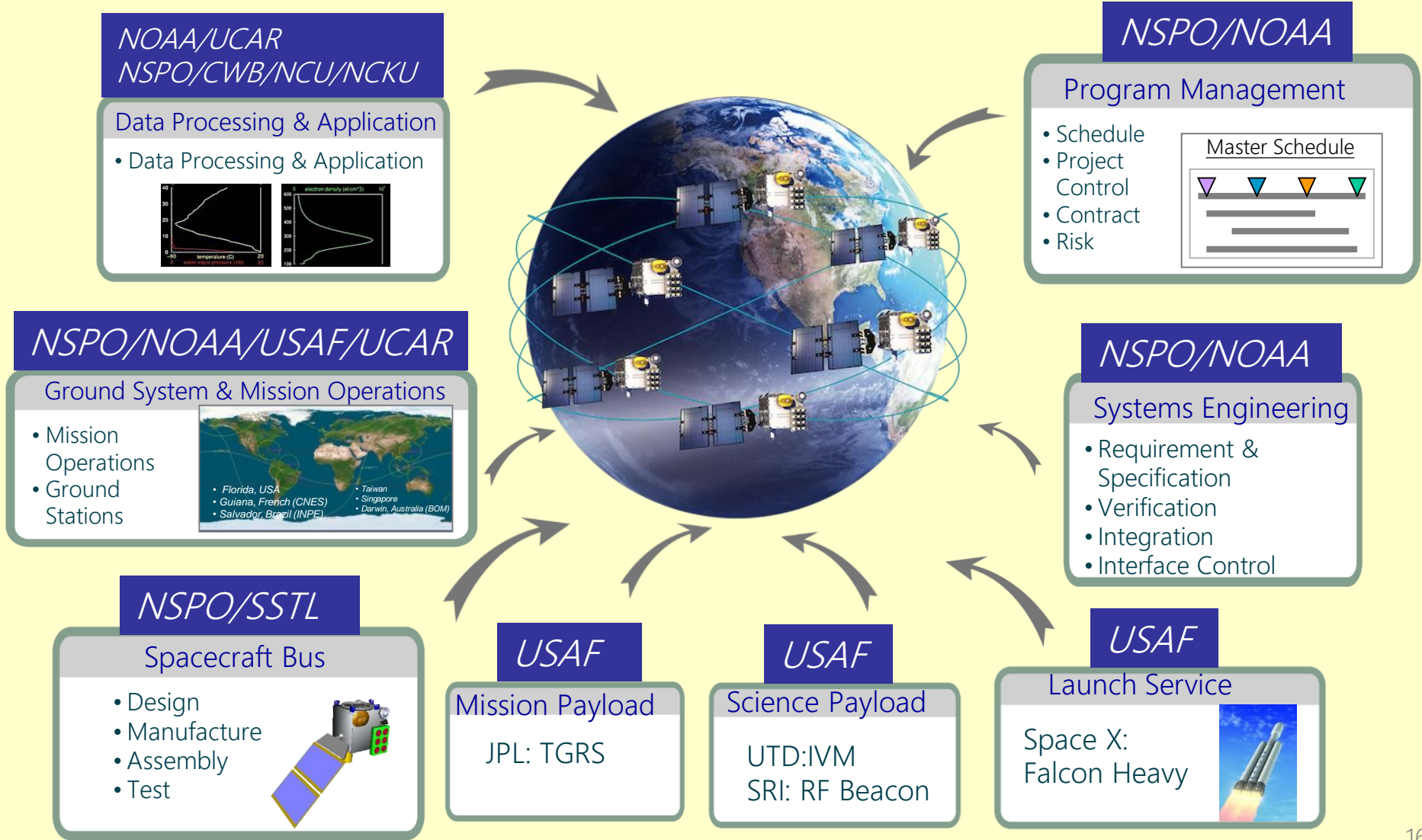


FORMOSAT-7 mission will continue the legacy of FORMOSAT-3

FORMOSAT-7/COSMIC-2 Mission Goals

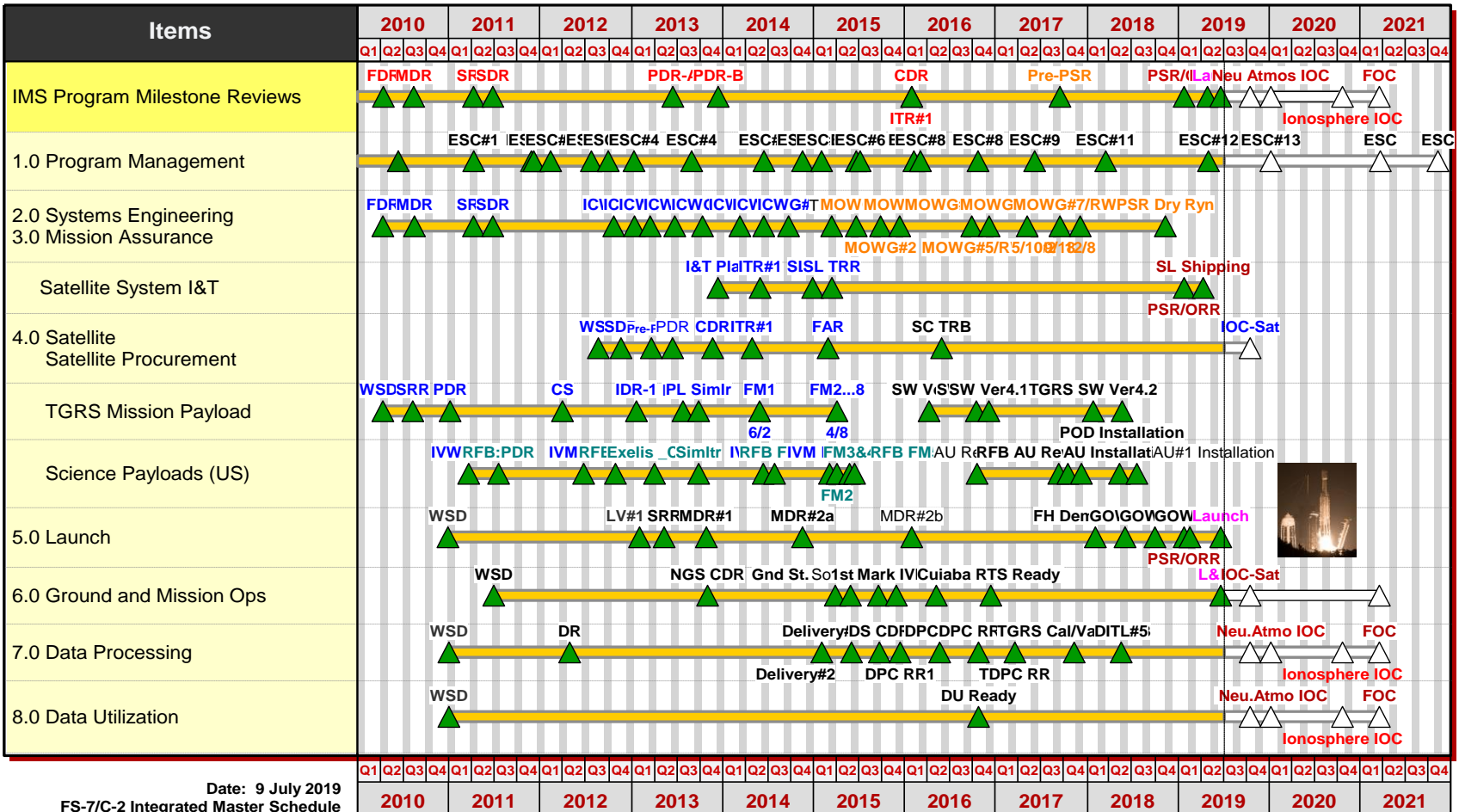


- Provision of 4000 atmospheric profiles per day with data latency of 45 minutes, and 30 minutes for ionospheric profiles.



Joint Integrated Master Schedule (IMS)

FORMOSAT-7 / COSMIC-2 Program Integrated Master Schedule



Pre-Shipment Review (PSR)@NSPO



FORMOSAT-7/COSMIC-2 PSR/ORR 2019/1/30

Post-Mission Readiness Review (MRR) & ESC#12@NOAA



Launch Site Satellite Processing Activities

- SC shipping container and EGSE unloading
- SC unpack and setup
- Battery Charge
- Spacecraft Functional Checkout
- Spacecraft Leak Test
- Spacecraft FSW Final Setup
- Spacecraft Fueling
- Separation System Integration
- SA Retention Cable Replacement
- Spacecraft Mating to Dispenser
- Encapsulation
- Battery Trickle Charge and Monitoring
- Launch



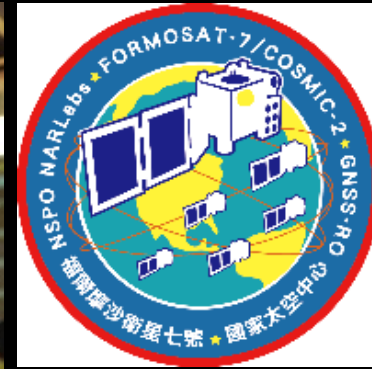
Spacecraft Mating to Dispenser and Encapsulation



Launch Campaign in KSC

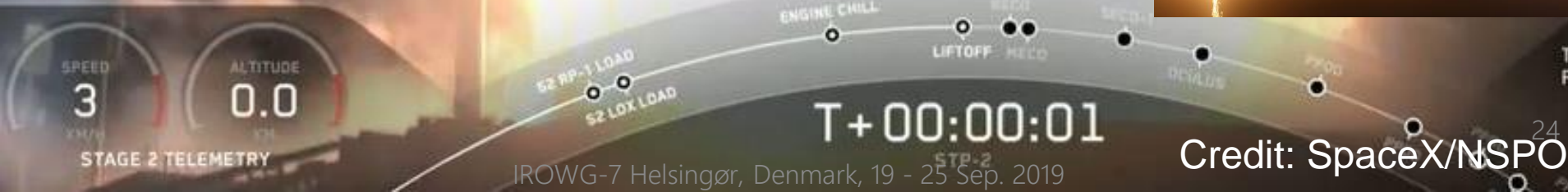


Taiwan SOCC (Launch Day)



Launch

- “Five, four, three, two, one, zero, ignition, Lift-off!” The Falcon Heavy rocket from US SpaceX carrying six FORMOSAT-7/COSMIC-2 satellites was successfully launched at the Kennedy Space Center (KSC) in the United States at 14:30 p.m. of June 25th, Taiwan time.



Taiwan SOCC (Launch Day)

- President of Taiwan, Tsai Ing-Wen visited the satellite operations and control center (SOCC) of National Space Organization (NSPO), National Applied Research Laboratories (NARLabs) in Hsinchu, Taiwan.
- After the rocket was launched, NSPO of NARLabs in Taiwan and the KSC in the United States simultaneously cheered!



FS705, FS706, FS702, FS704, FS701, and FS703 are separated from the Rocket. It takes ~16 min. for this event.

LIVE 福衛七號發射直播3：衛星與台灣地面站接觸&記者會

FS705

FS703

FS704

我們有三個絕佳視角

16:09:52
福衛七號與火箭分離

SPEED 25286 KM/H

ALTITUDE 721 KM

SEC-2 PROX1 NPSAT1 OTB GPIM COSMIC 2 COSMIC 2 COSMIC 2 COSMIC 2 COSMIC 2

T+01:31:23

CREDIT: TTV & SpaceX

- Six FORMOSAT-7/COSMIC-2 satellites were successfully separated from the rocket at 91-107 minutes after the launch, and entered into the parking orbit with the 720-kilometer altitude and inclination angle of 24 degrees.

Satellites Contact Timeline

- After the launch, the Satellite Operations and Control Center (SOCC) of NSPO in Hsinchu began to do the orbit calculation after it successfully received the state vector or Orbit Parameter Message (OPM) of the satellite and the rocket at the separation moment, which was returned by the Falcon Heavy launch vehicle.

4. First Taiwan Ground Contact (T+378 min.)

1. Launch Time (T+0)

6/25 14:30 (Taiwan Time)

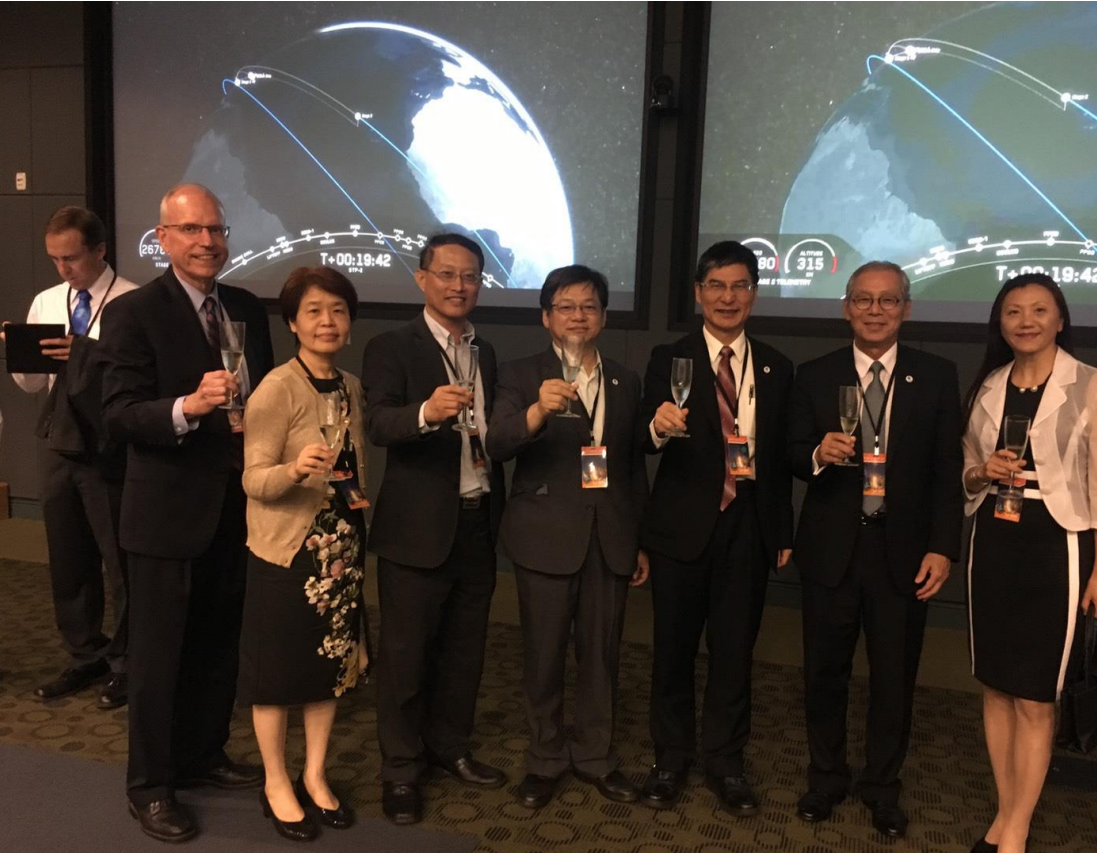
3 6/25 20:48~20:59 TS2

2 6/25 19:03~19:10 Darwin

1 6/25 17:15~17:26 Darwin

2. Spacecraft Separation (T+91~107 min.)

3. First Darwin Station Contact (T+165 min.)

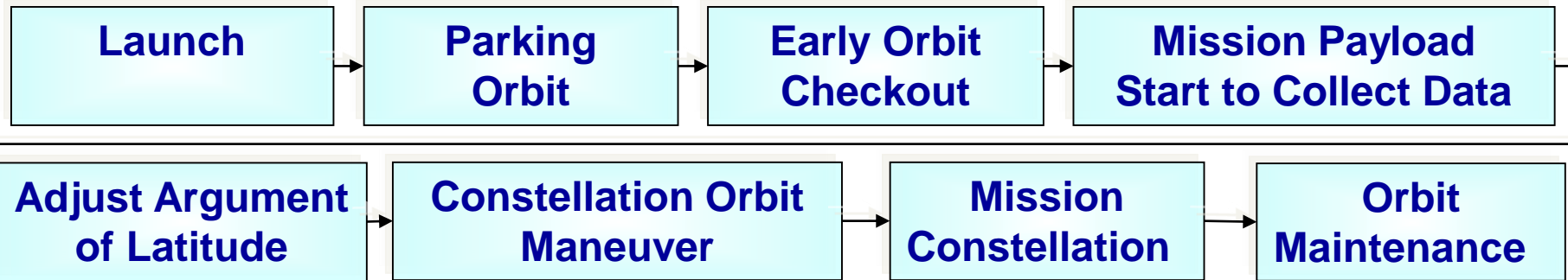




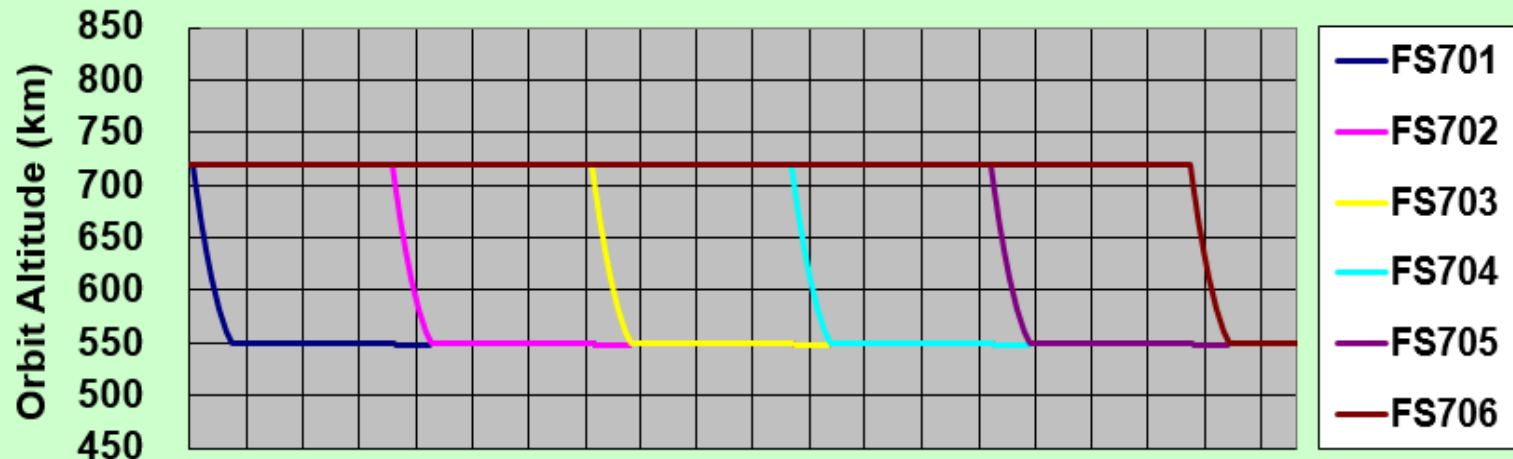
- Taiwan is making great contribution to the international community because of the FORMOSAT-7 mission. It shows the greatest value of science and technology. My dear people and friends, such an important achievement comes from the efforts of many of our colleagues at NSPO, CWB, and the scientific research teams in Taiwan, with support from the government, who devote themselves quietly to achieve it. They are truly our space heroes. - **President Tsai Ing-Wen**
- For the success we achieved today, how many difficulties have been overcome? How many challenges have been confronted? It is such a great achievement accomplished. On behalf of the government, I would like to express my heartfelt gratitude and salute. Thank you! – **Premier Su Tseng-chang**

Operations Sequence

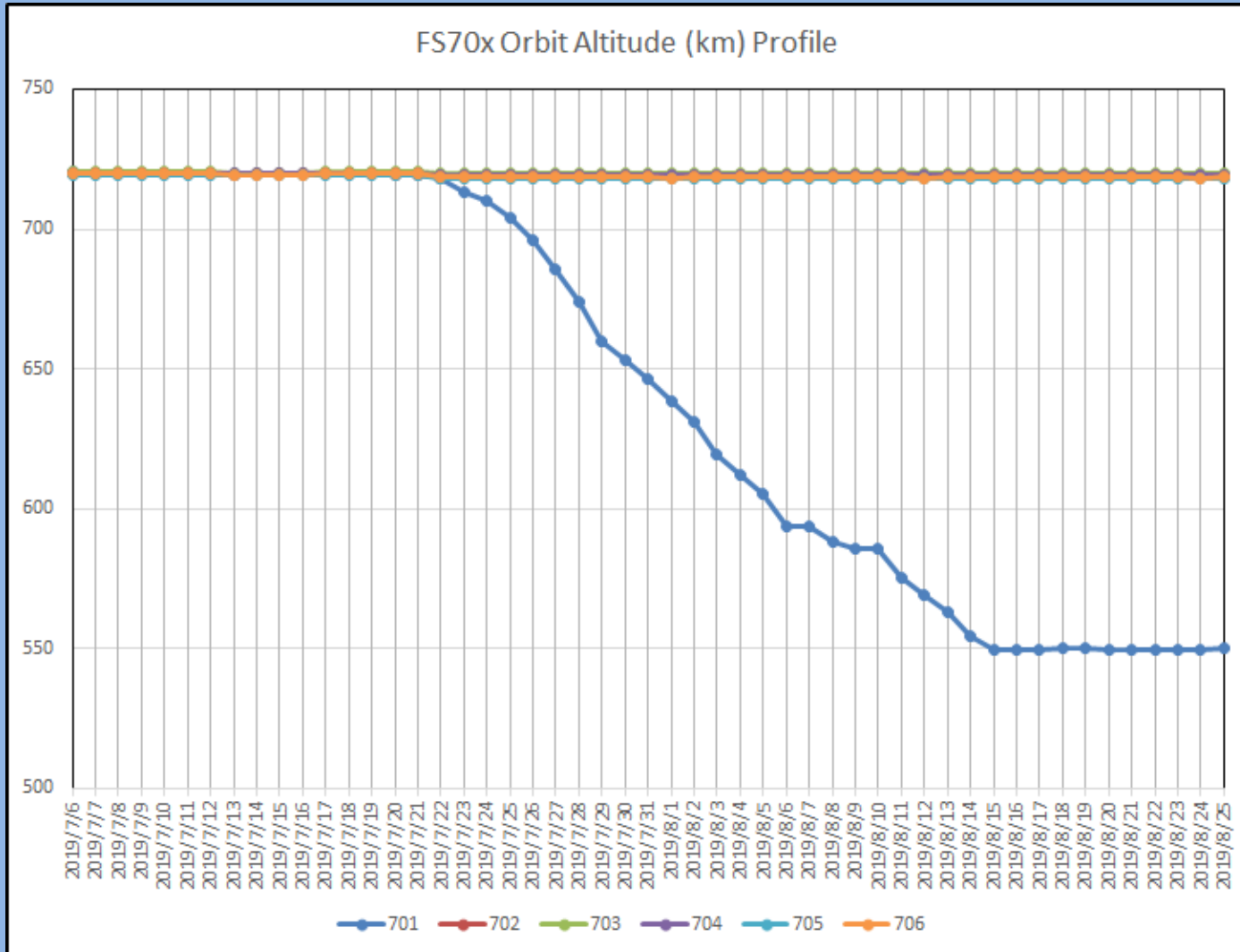
- The flight operations team (FOT) completes health checks on spacecraft bus and payload instruments within one month.



FORMOSAT-7 Constellation Altitude Deployment Profile

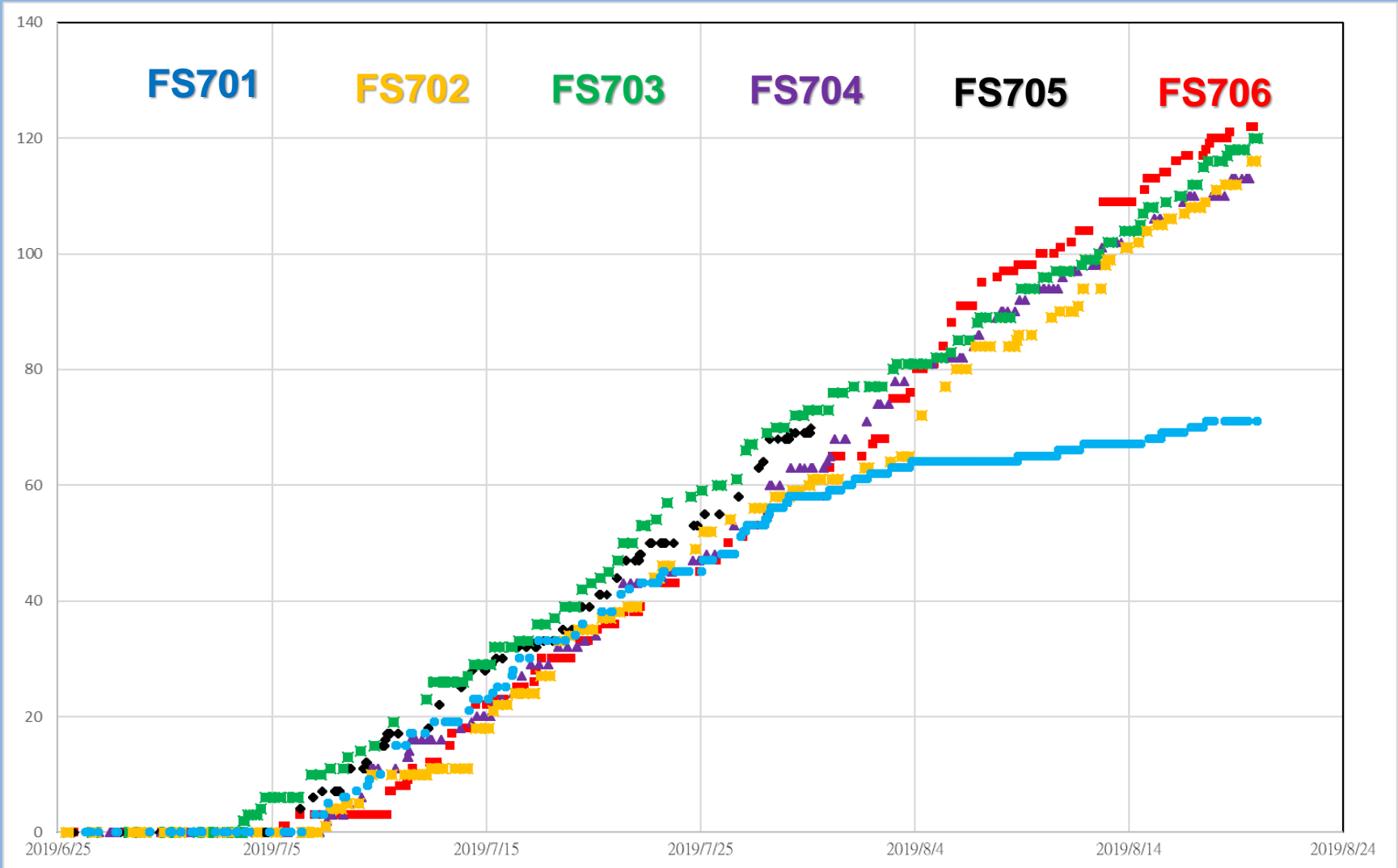


Six Satellites (FS70X) Altitude Profiles



Credit: FORMOSAT-7 FOT & FDF

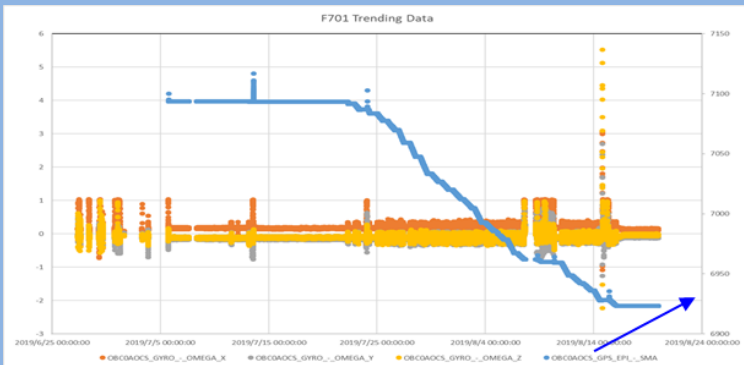
FS701 - FS706 GPS Total Reboot Counts



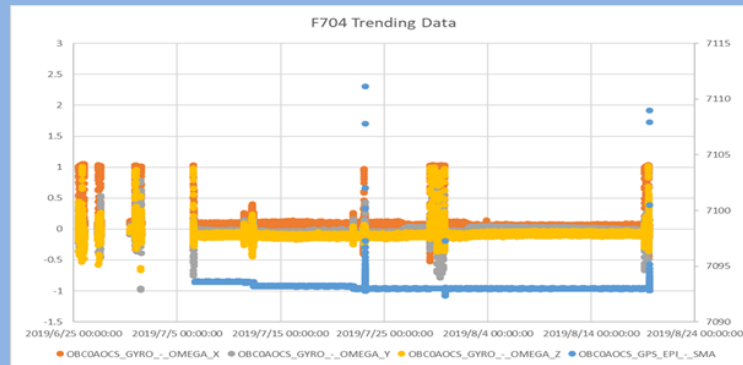
GPS SMA (Altitude) and Gyro Rate Profile

(Day 176~232)

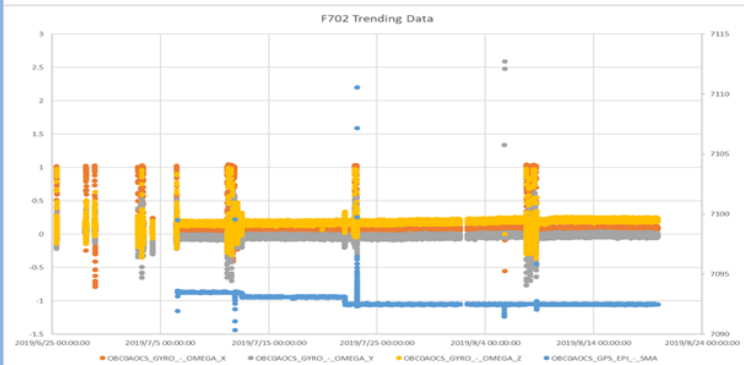
FS701



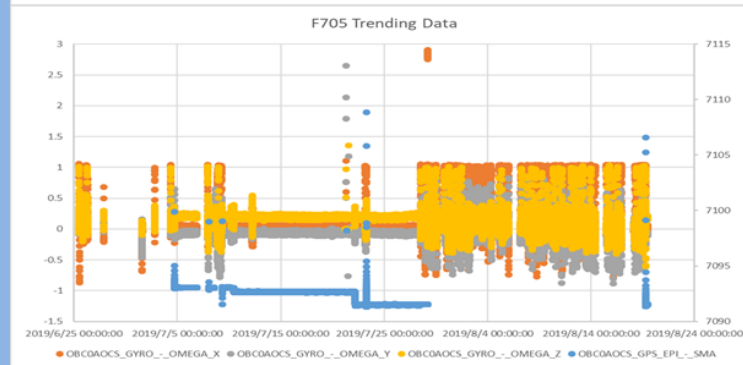
FS704



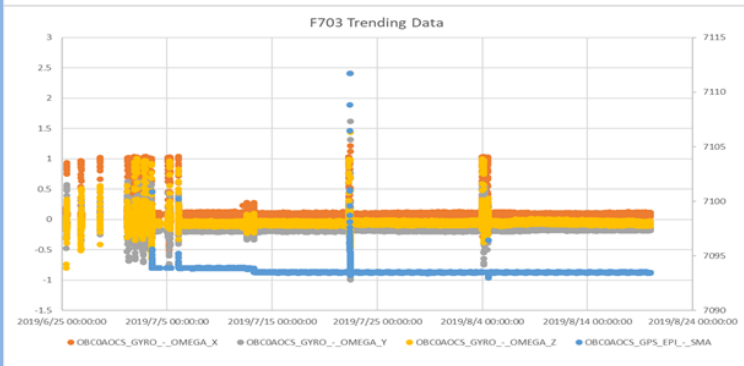
FS702



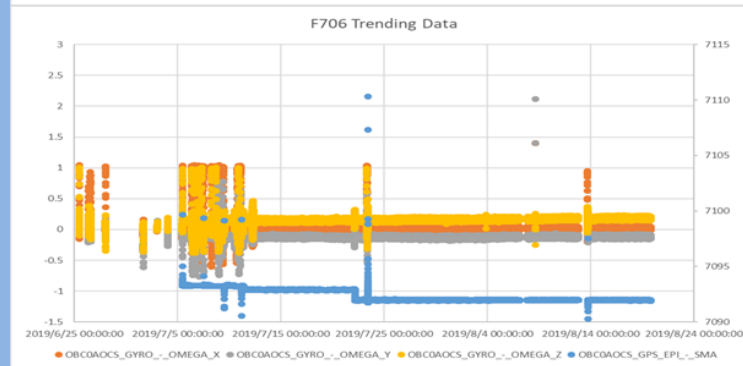
FS705



FS703



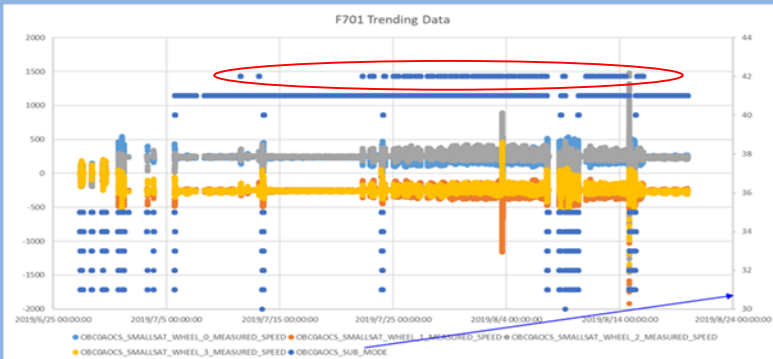
FS706



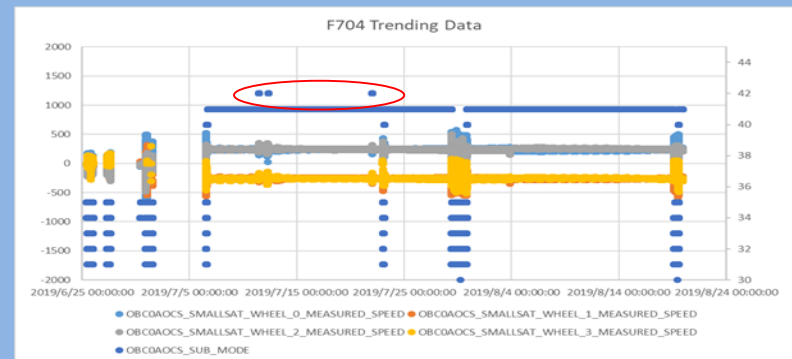
Wheel Speed and AOCS Sub Mode Profile

(Day 176~232)

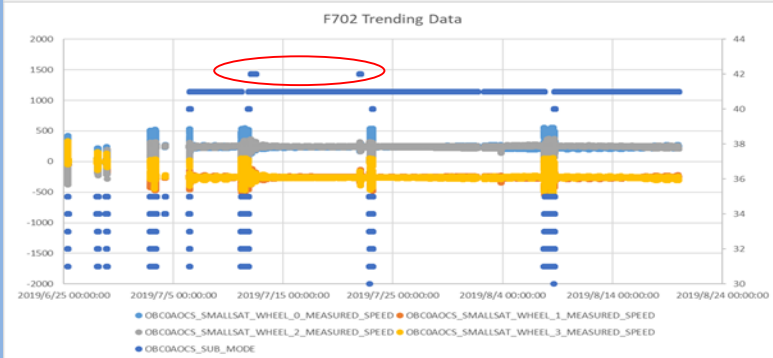
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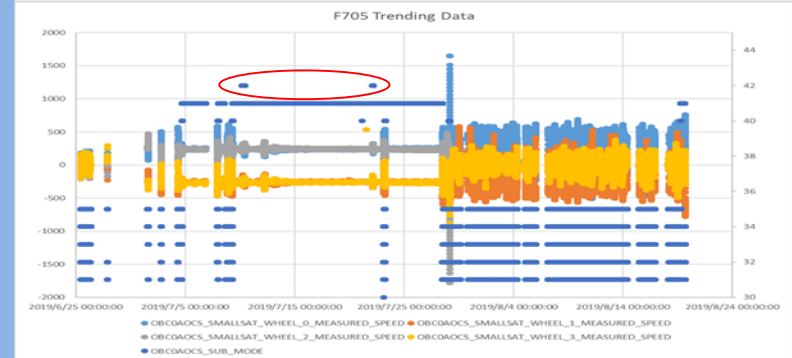
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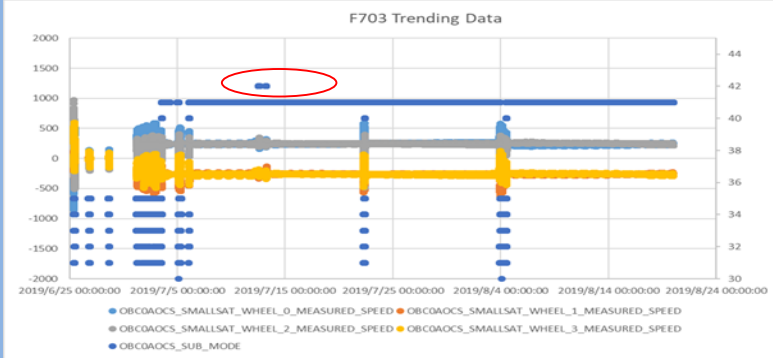
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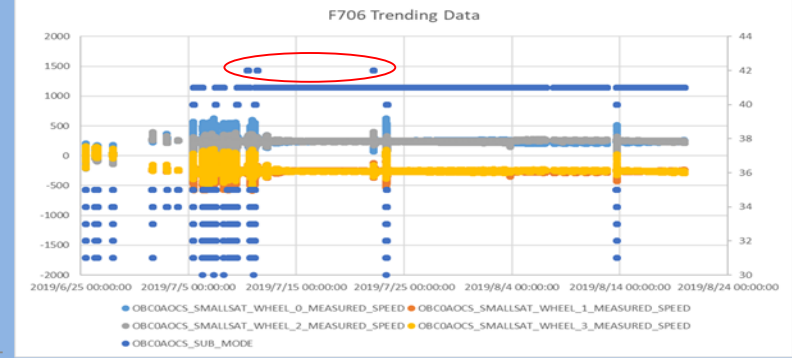
FS705



FS703



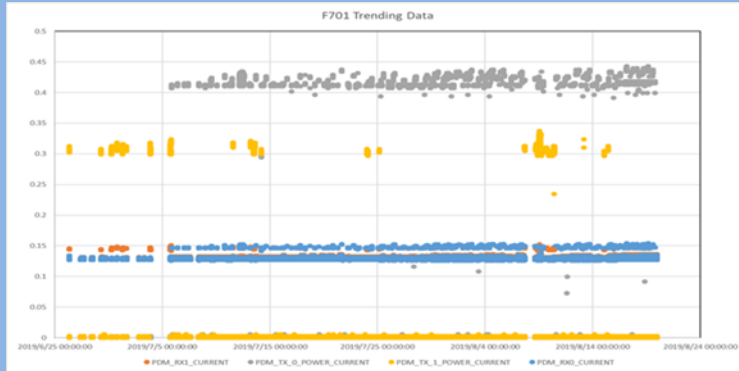
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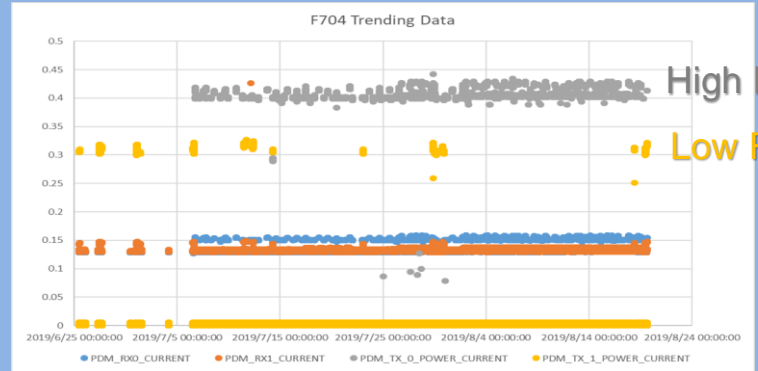
TX and RX Current Profile

(Day 176~232)

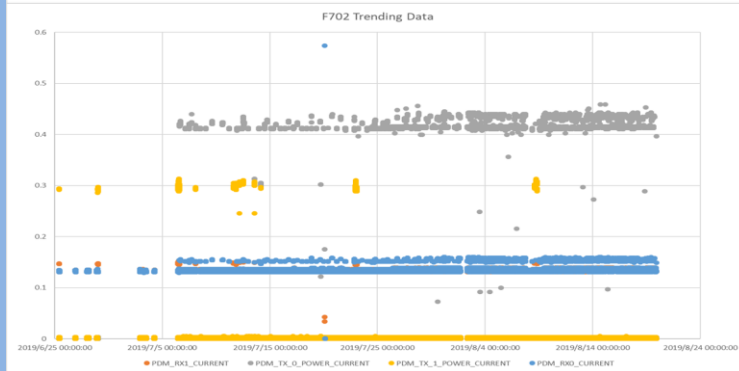
FS701



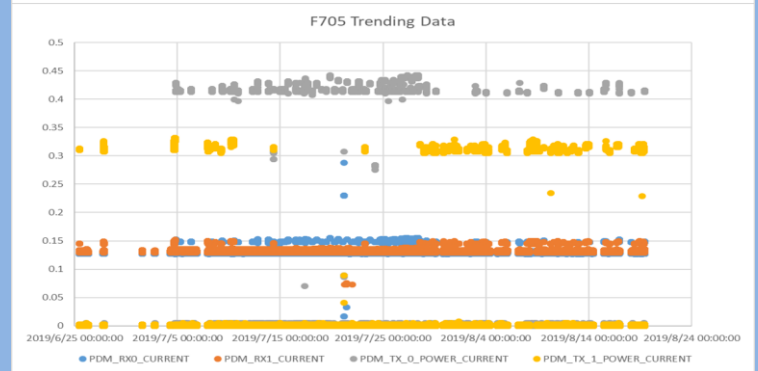
FS704



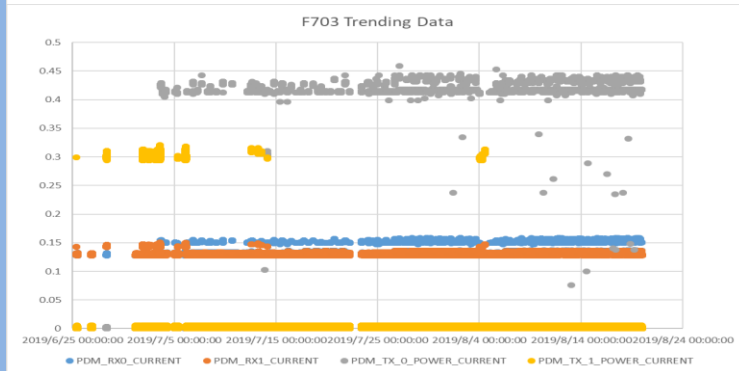
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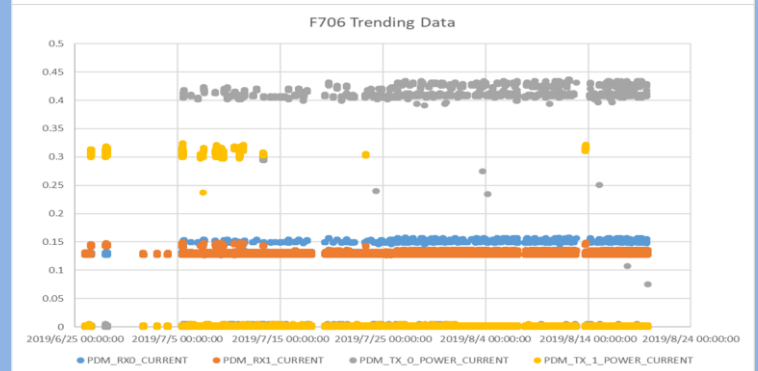
FS705



FS703



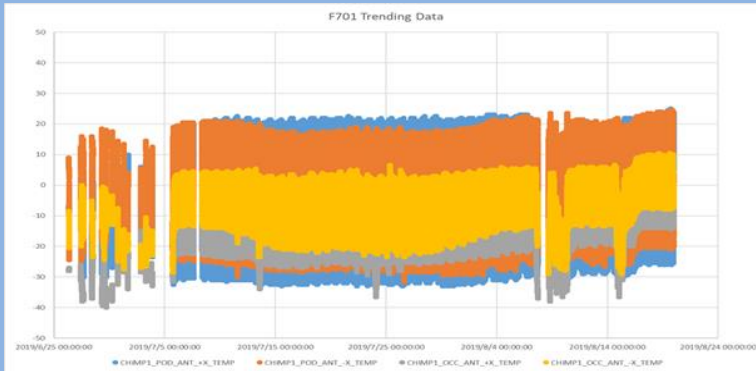
FS706



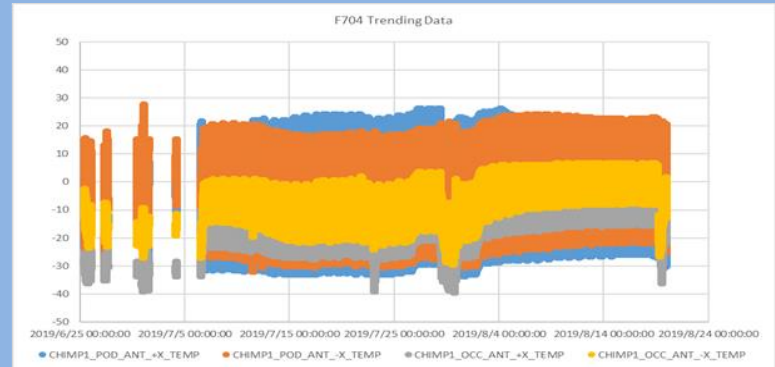
POD and OCC Antenna Temperature Profile

Day 176~232

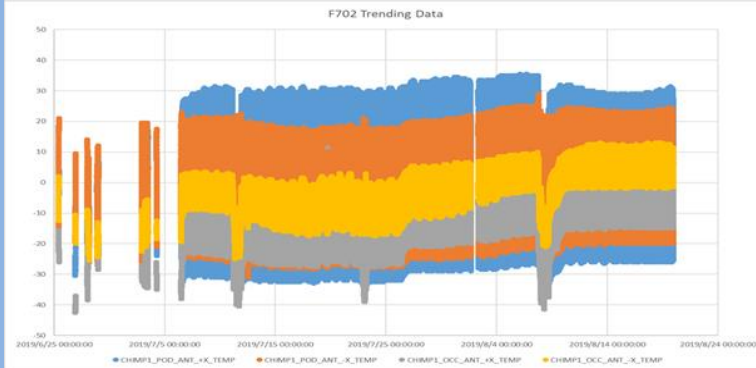
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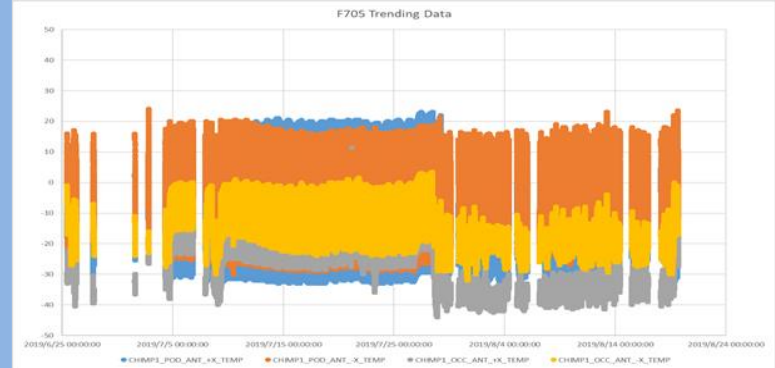
FS704



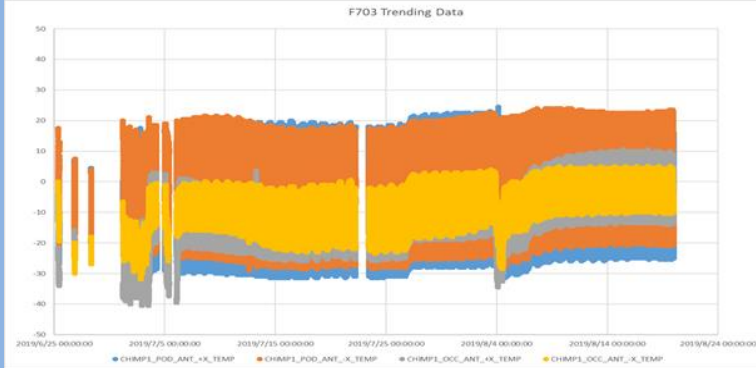
FS702



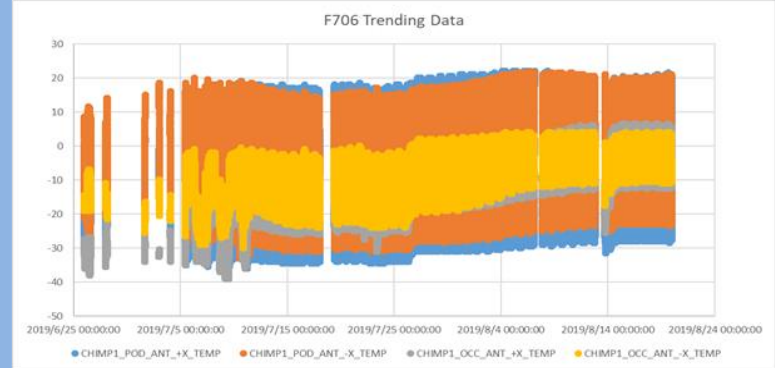
FS705



FS703



FS706



The First Retrieved Profiles from FORMOSAT-7 on T+29 Days



About

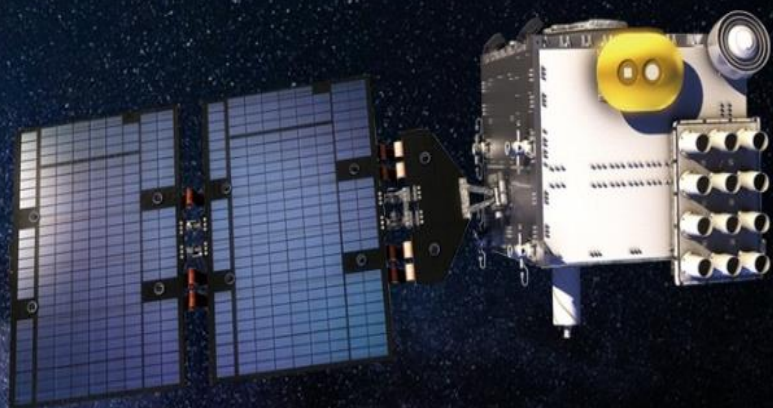
FS7-TDPC

FS7-TROPS

FS3

Links

中文 Contacts signup



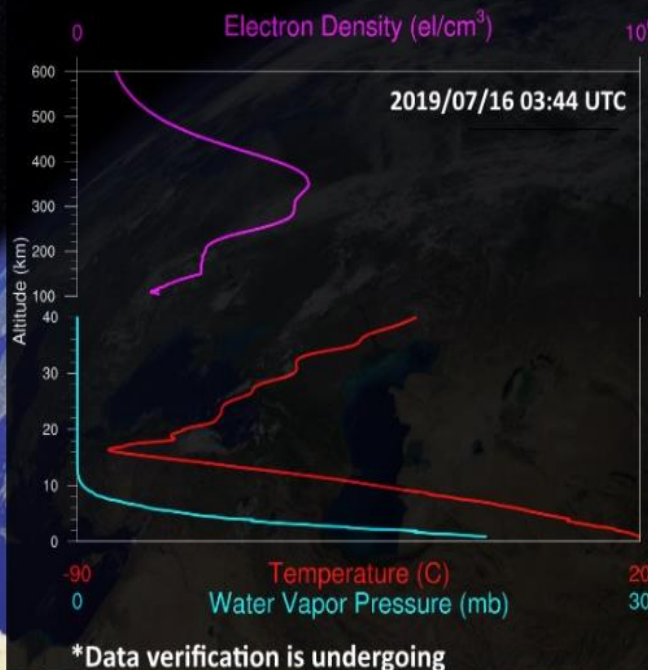
Welcome to TACC

Satellite status & position

FORMOSAT-7(FS7-1~6)

- Working days: 29
- Atmospheric profiles: 3,408
- Ionospheric profiles: 2,489

The First Profile From FORMOSAT-7/COSMIC-2



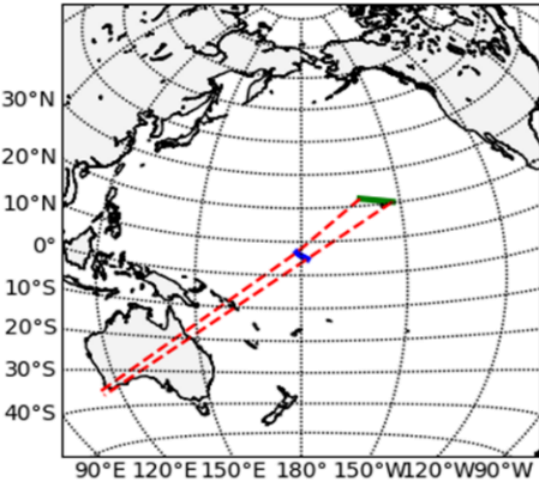
http://tacc.cwb.gov.tw/v2/index_e.html

The First Retrieved Profiles from FORMOSAT-7

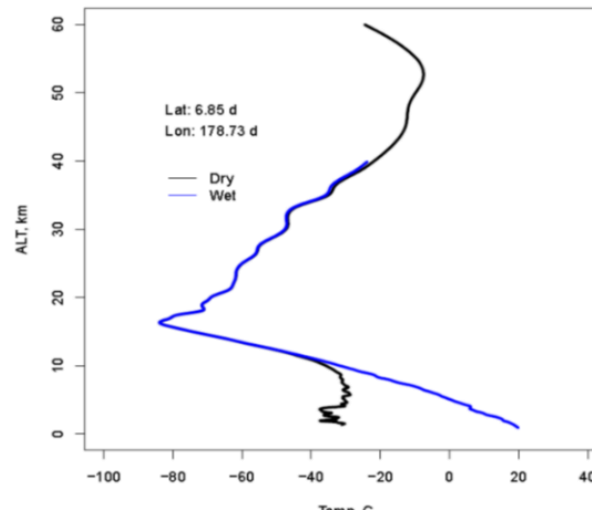
(July 16th, 2019)

- The first RO data was successfully observed on Formosat-7 Satellite on July 16th.

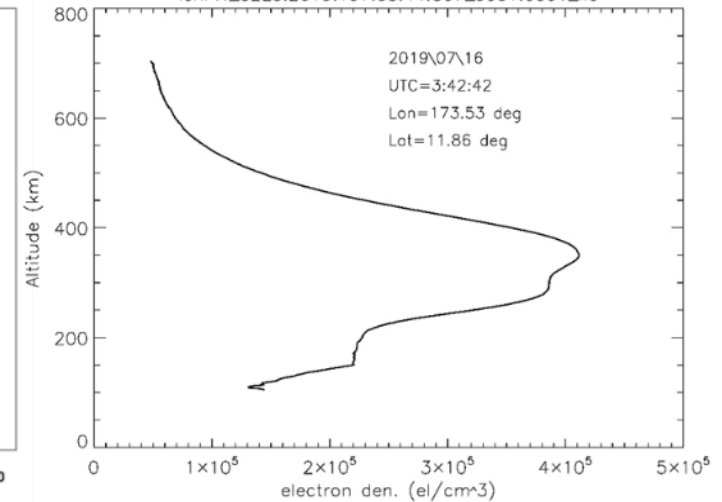
— Occultation path
 — Leo path
 - - - Radio ray



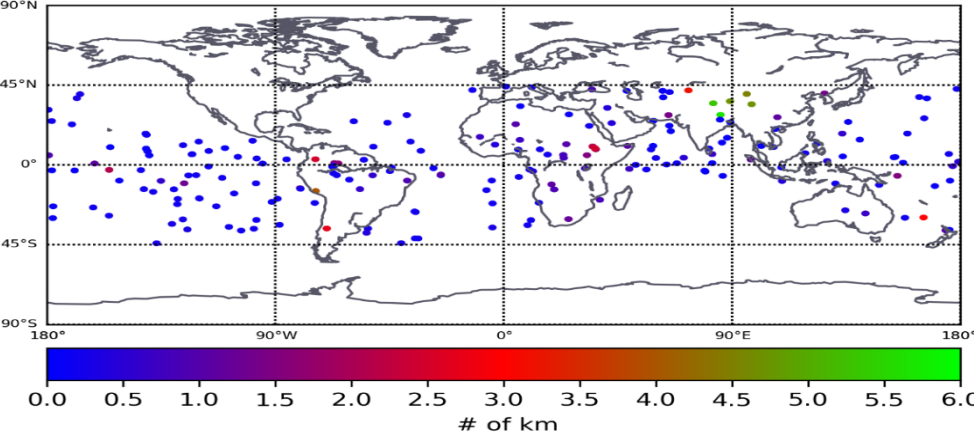
atmPrf_C2E3.2019.197.03.44.G07_0001.0001_nc



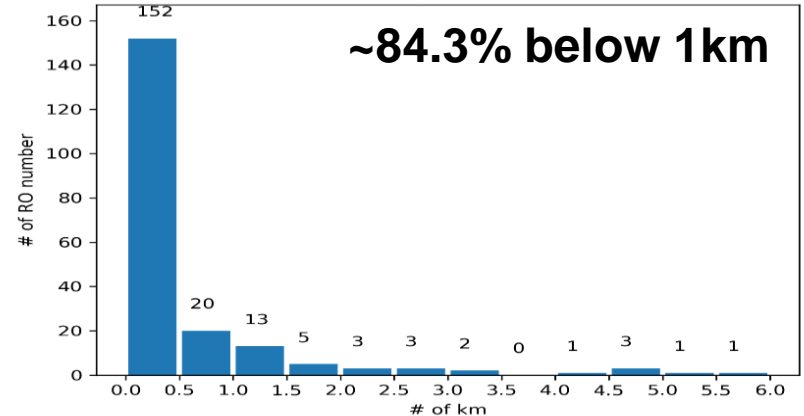
ionPrf_C2E3.2019.197.03.44.G07_0001.0001_nc



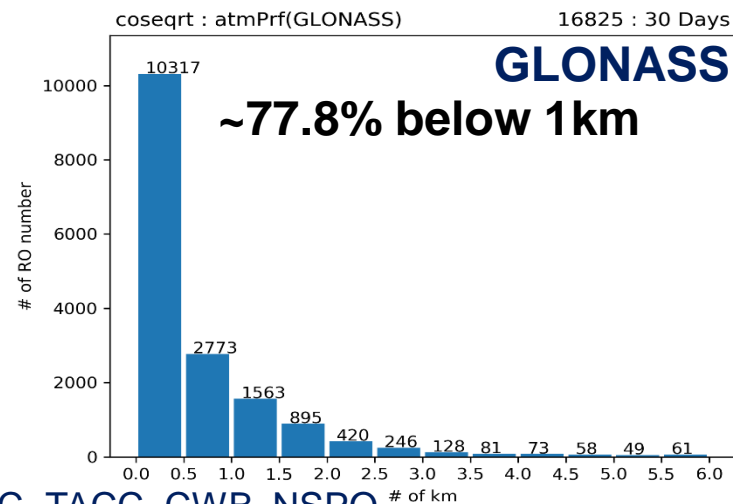
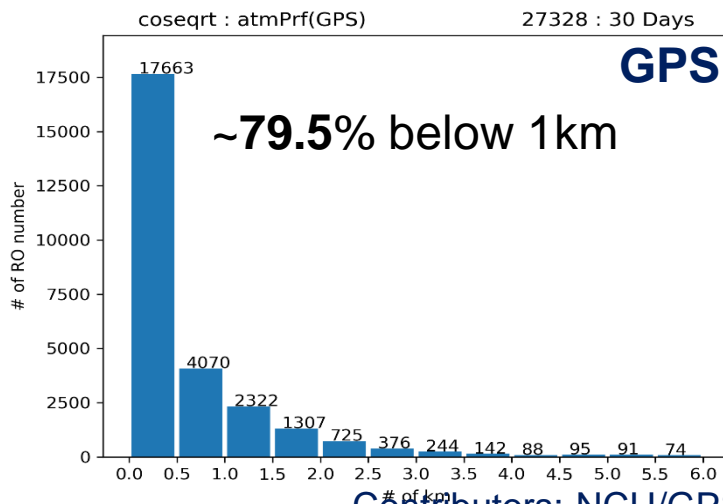
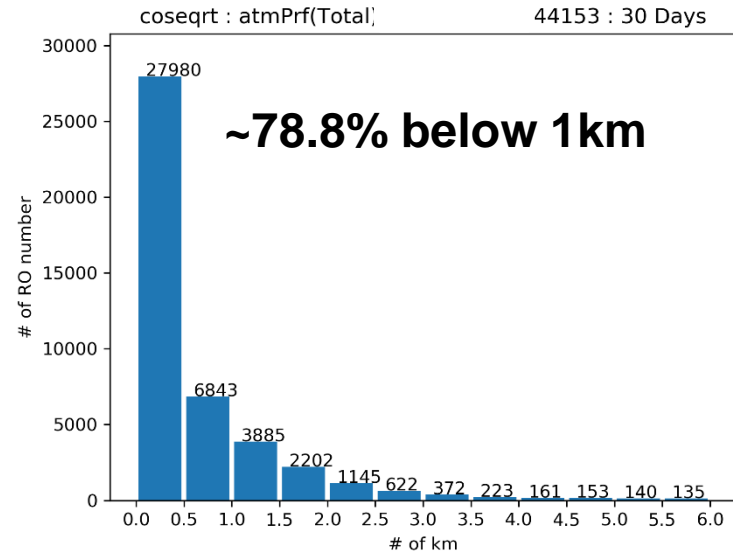
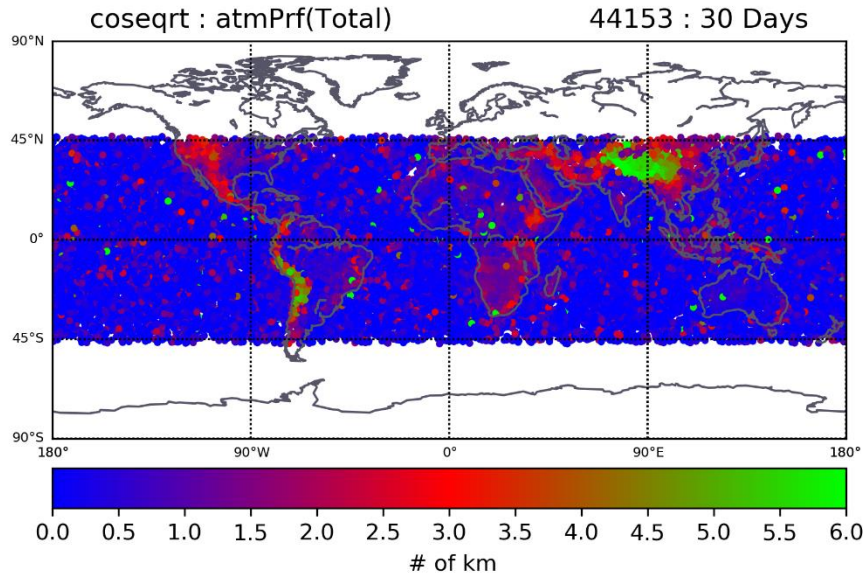
coseqrt : wetPrf @ 2019.197 : 204(Day)



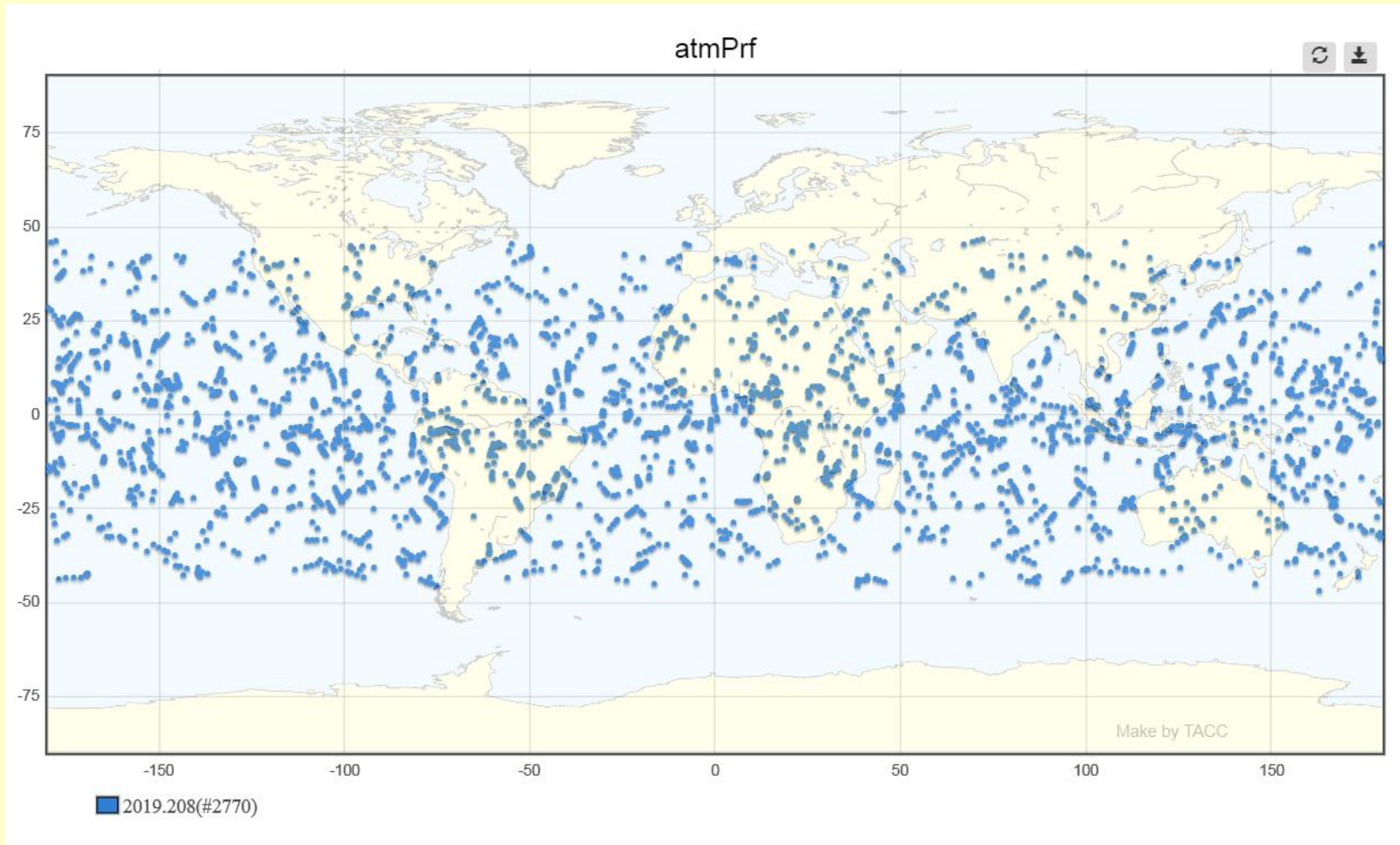
coseqrt : wetPrf @ 2019.197 : 204(Day)



FORMOSAT-7 NRT Data (30 days)



The RO distribution on 27th July 2019



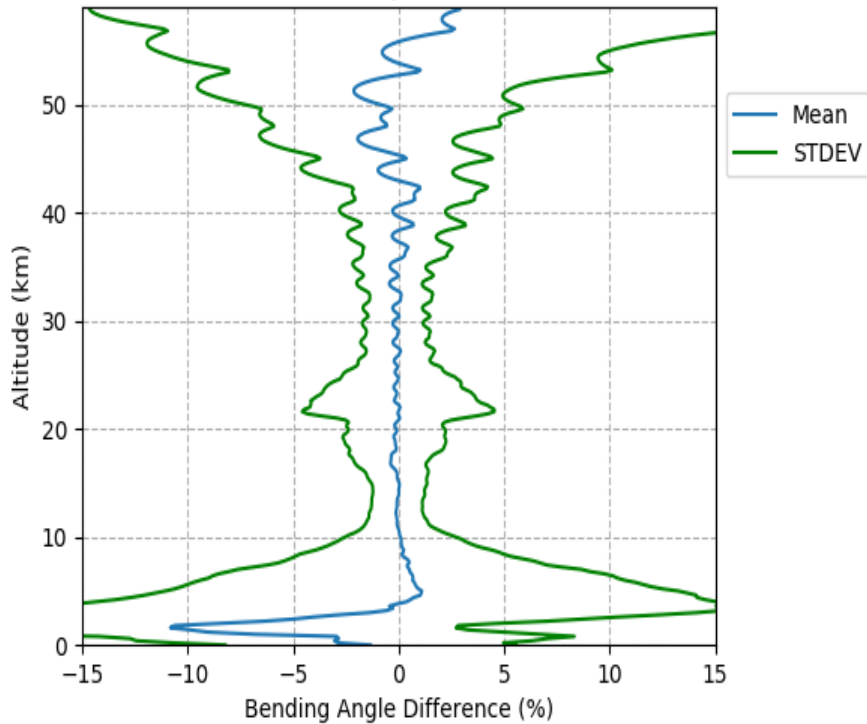
FORMOSAT-7 atmPrf vs ECMWF

2019/08/01 – 2019/08/22

■ FORMOSAT-7 atmPrf V.S. ECMWF (2019/08/01-2019/08/22)

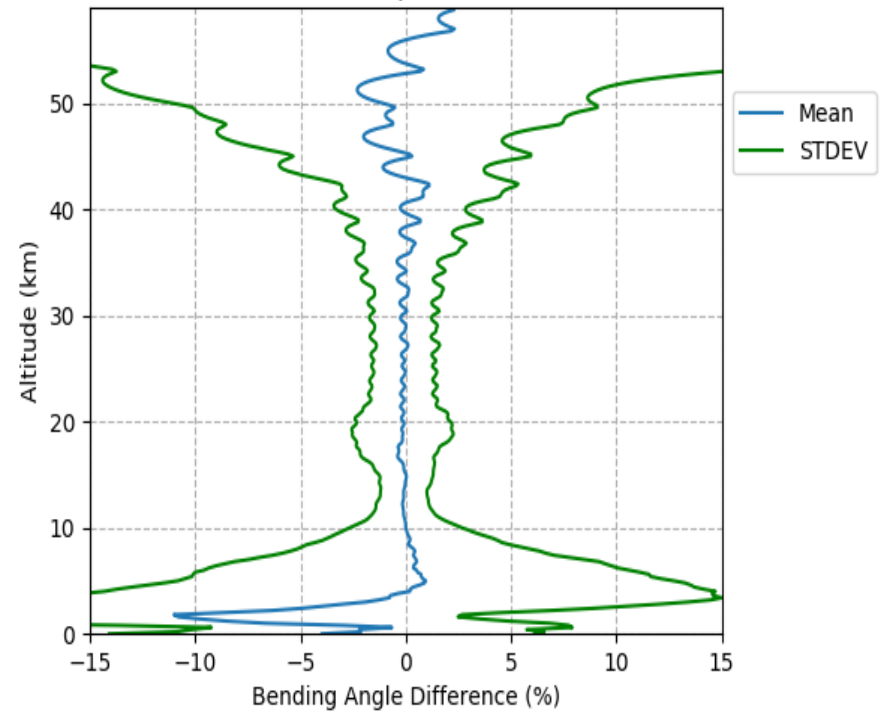
GPS

FS7 GPS - ECMWF From 2019.213 ~ 2019.235
Total atmPrf profiles: 26864



GLONASS

FS7 GLONASS - ECMWF From 2019.213 ~ 2019.235
Total atmPrf profiles: 16552

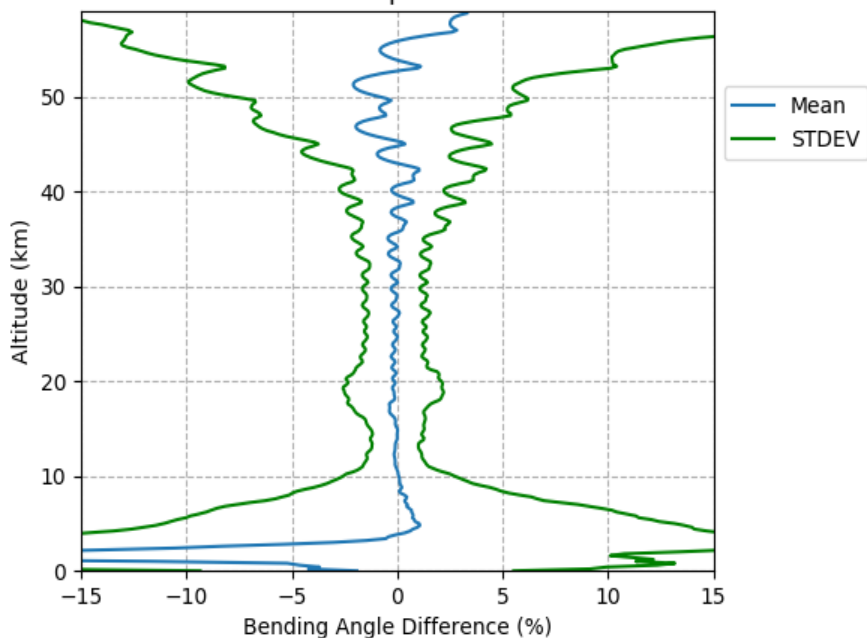


2019/08/01 – 2019/08/22

FORMOSAT-7 GPS atmPrf V.S. ECMWF (2019/08/01-2019/08/22)

GPS

FS7 GPS L2C - ECMWF From 2019.214 ~ 2019.235
Total atmPrf profiles: 20228

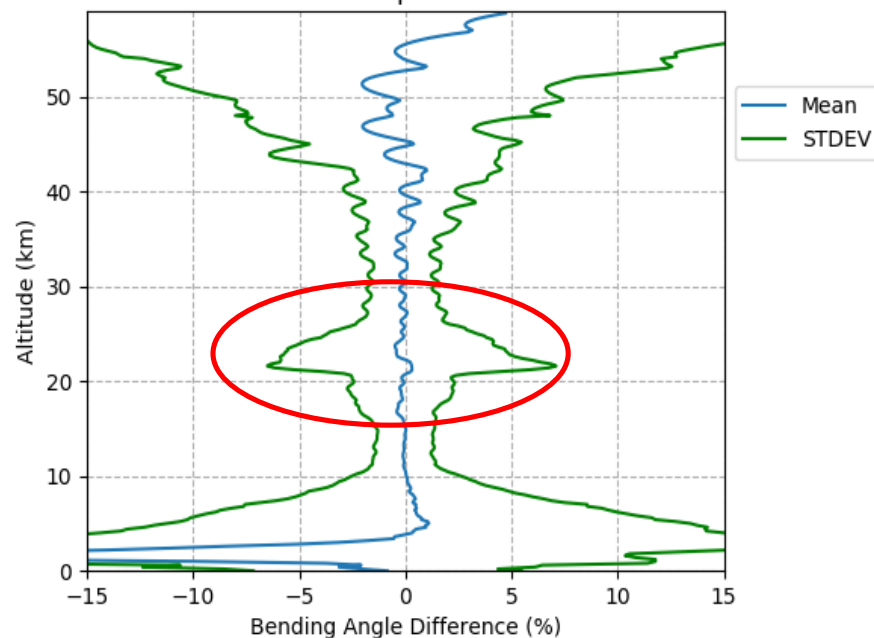


GPS **L2C** SAT.

PRN:1,3,5,6,7,8,9,10,12,15,17,24,25,26,27, 29,30,31,32

GPS

FS7 GPS L2P - ECMWF From 2019.214 ~ 2019.235
Total atmPrf profiles: 10581



GPS **L2P** SAT.

PRN:2,11,13,14,16,18,19,20,21,22,23,28

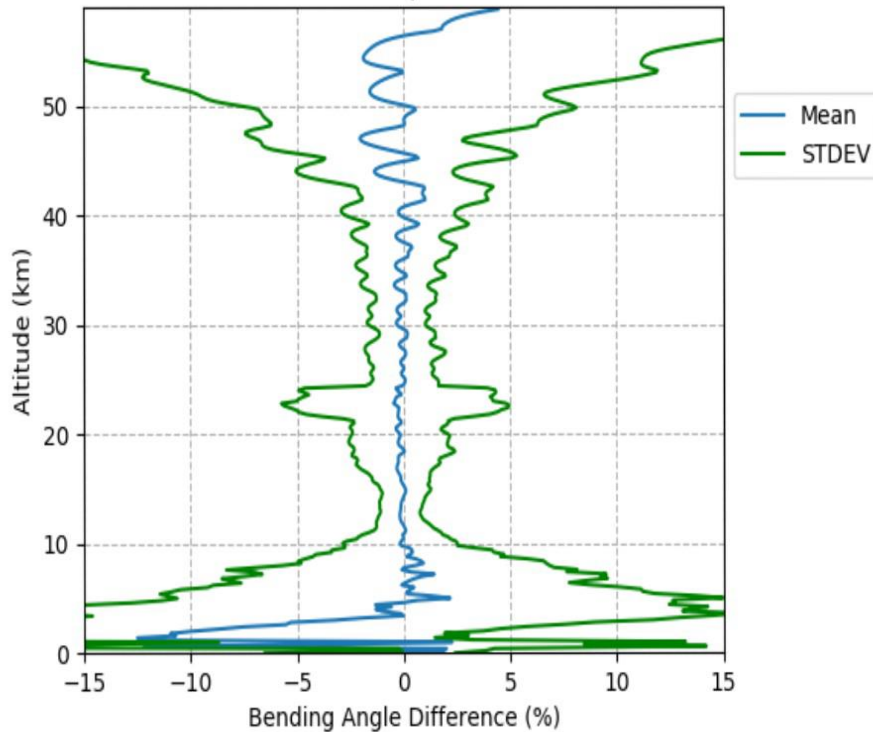
Contributors: NCU/GPSARC, TACC, CWB, NSPO

FS701 720km & 550km atmPrf vs ECMWF

■ FORMOSAT-701 720km & 550km atmPrf V.S. ECMWF

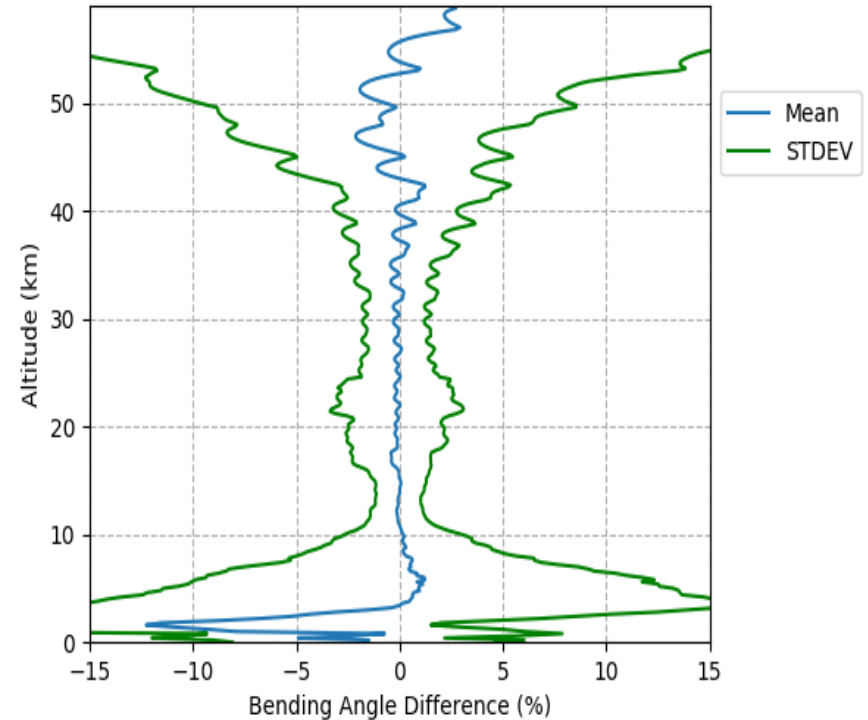
FS701 @720km

FS701 GNSS - ECMWF From 2019.197 ~ 2019.202
Total atmPrf profiles: 398



FS701 @550km

FS701 GNSS - ECMWF From 2019.213 ~ 2019.235
Total atmPrf profiles: 3918

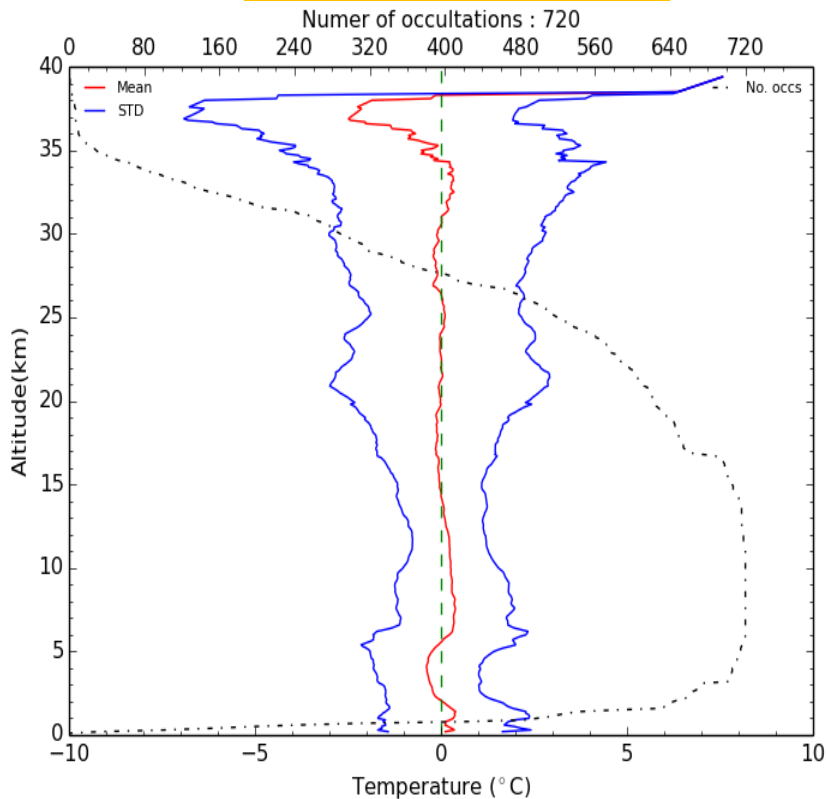


FORMOSAT-7 wetPrf vs RadioSonde

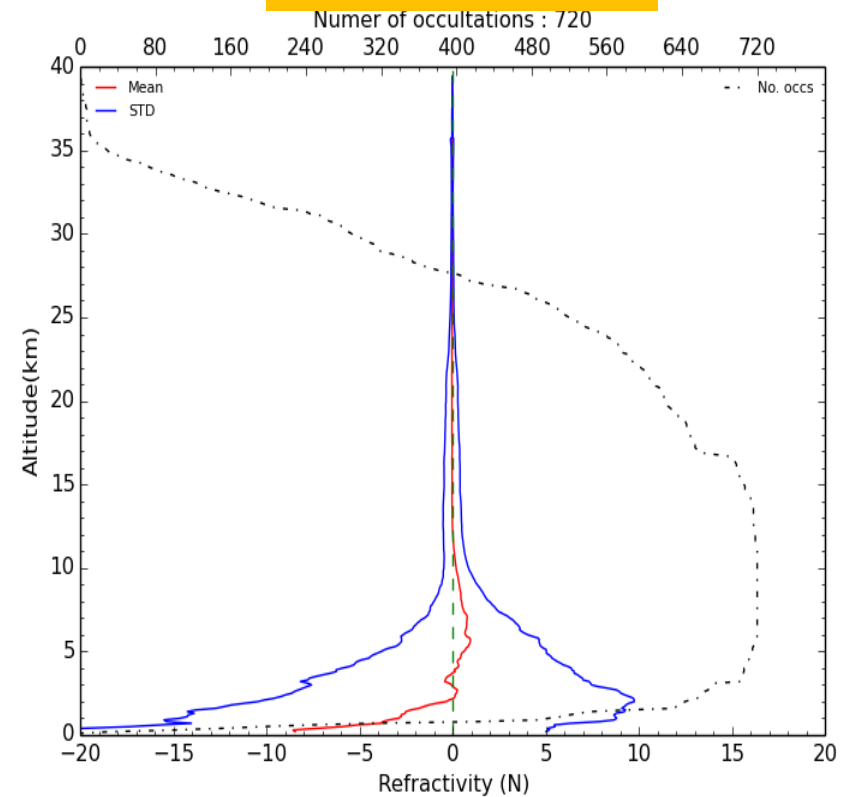
2019/08/01-2019/08/22

■ FORMOSAT-7 wetPrf V.S. RadioSonde (2019/08/01-2019/08/22)

Temperature



Refractivity



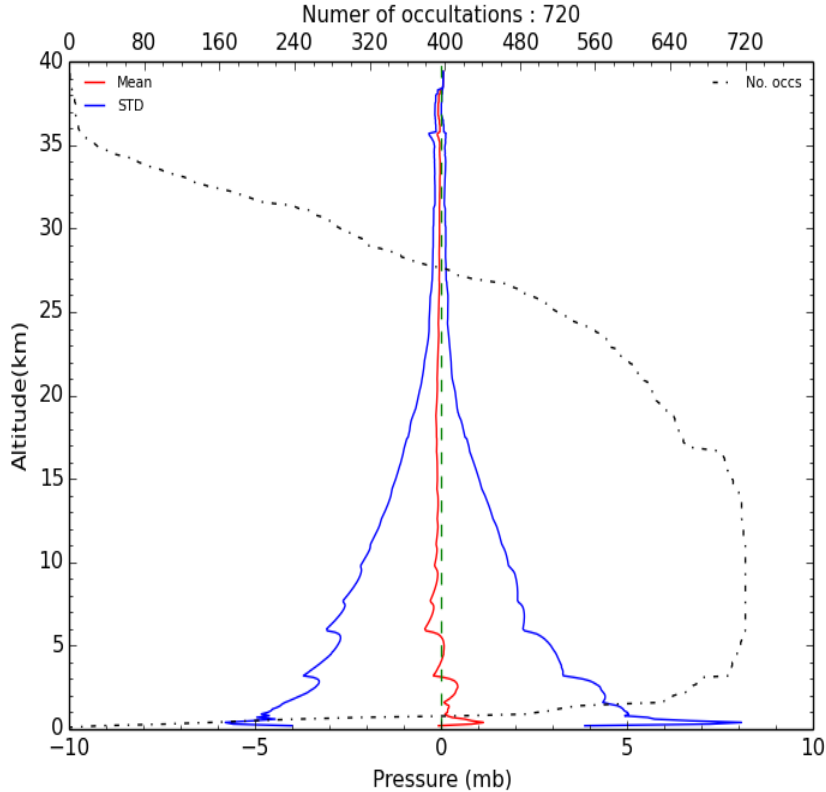
FORMOSAT-7 wetPrf vs RadioSonde

2019/08/01-2019/08/22

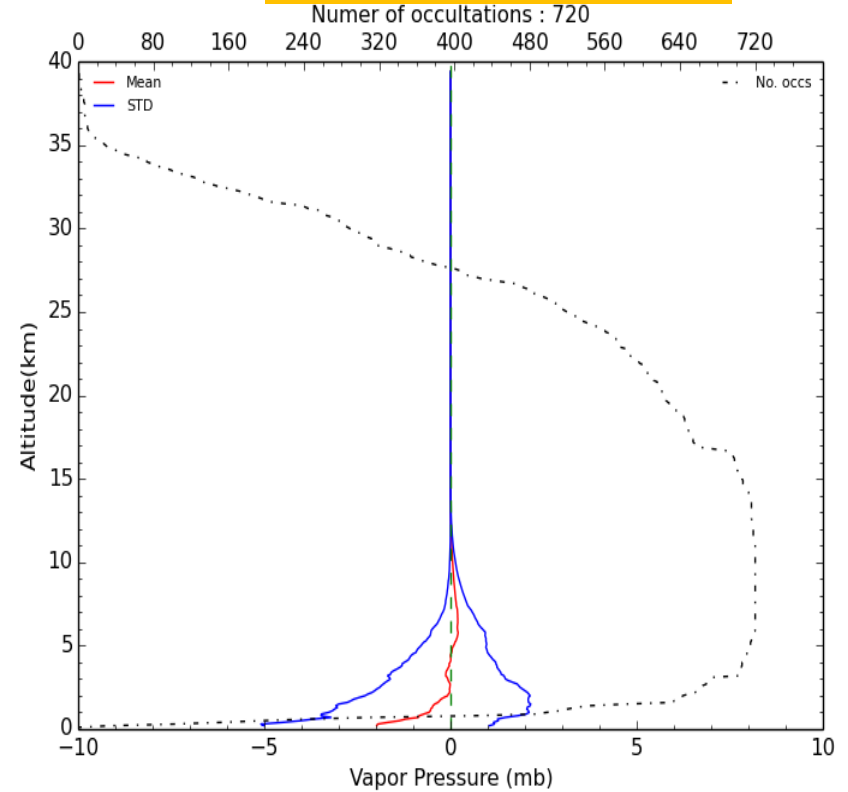
■ FORMOSAT-7 wetPrf V.S. RadioSonde (2019/08/01-2019/08/22)

Pressure

sonde



Vapor Pressure

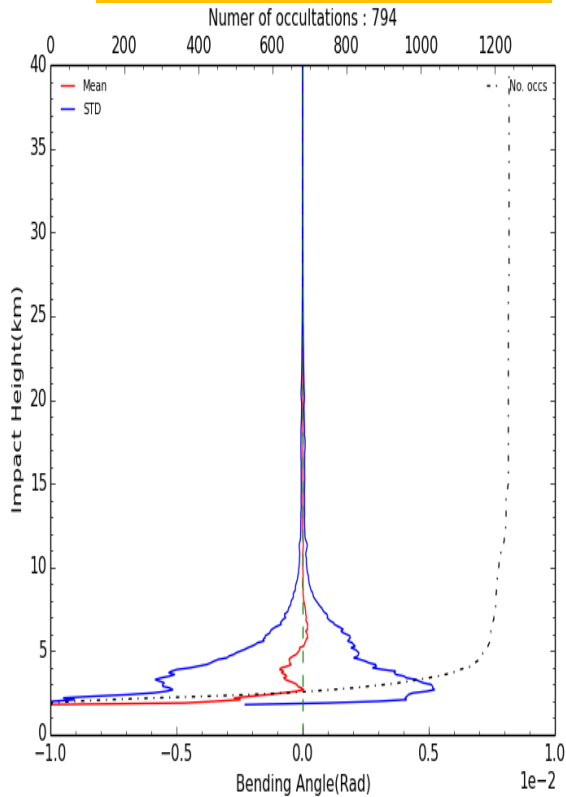


FORMOSAT-7 atmPrf vs MetOP atmPrf

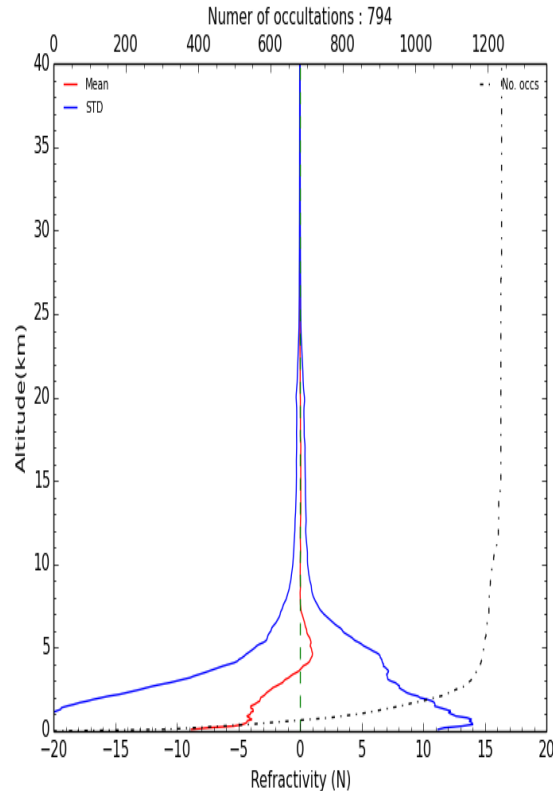
2019/08/01-2019/08/22

FORMOSAT-7 atmPrf V.S. MetOP atmPrf 2019/08/01-2019/08/22

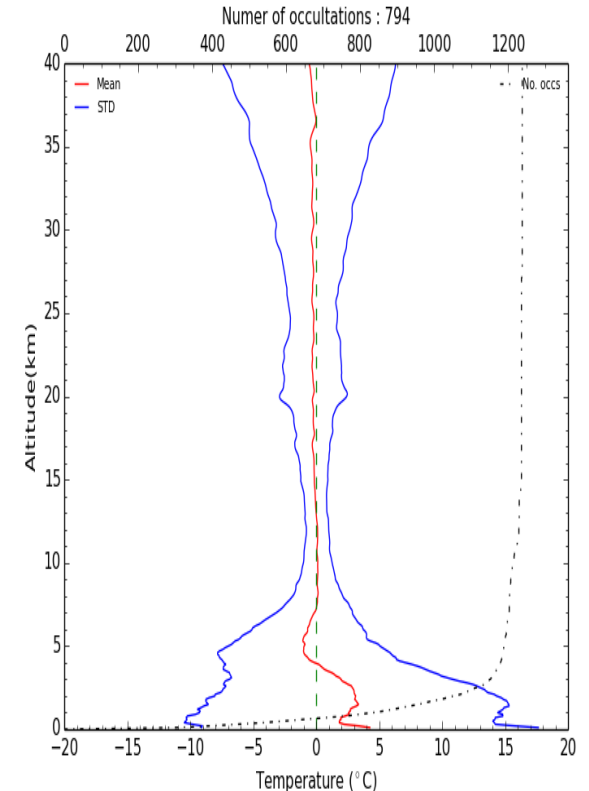
Bending Angle



Refractivity



Dry Temperature

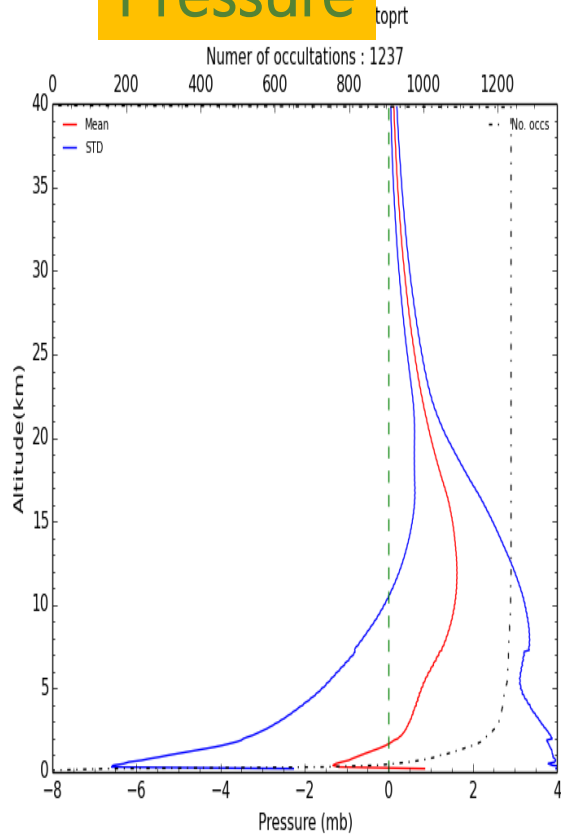


FORMOSAT-7 wetPrf vs MetOP wetPrf

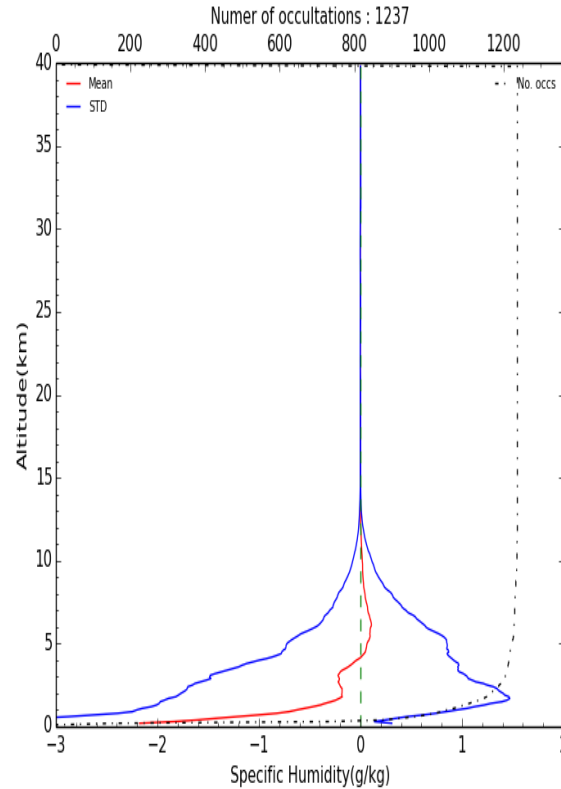
2019/08/01-2019/08/22

FORMOSAT-7 wetPrf V.S. MetOP wetPrf 2019/08/01-2019/08/22

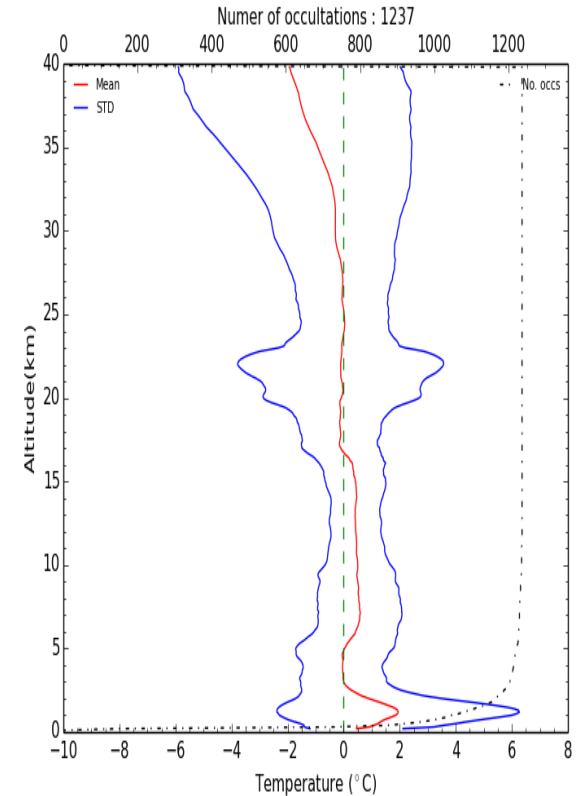
Pressure



Specific Humidity



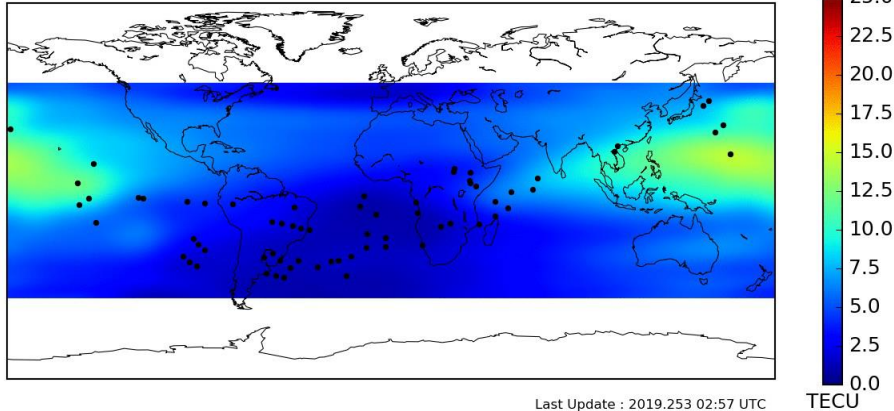
Wet Temperature



Ionospheric products

TEC maps

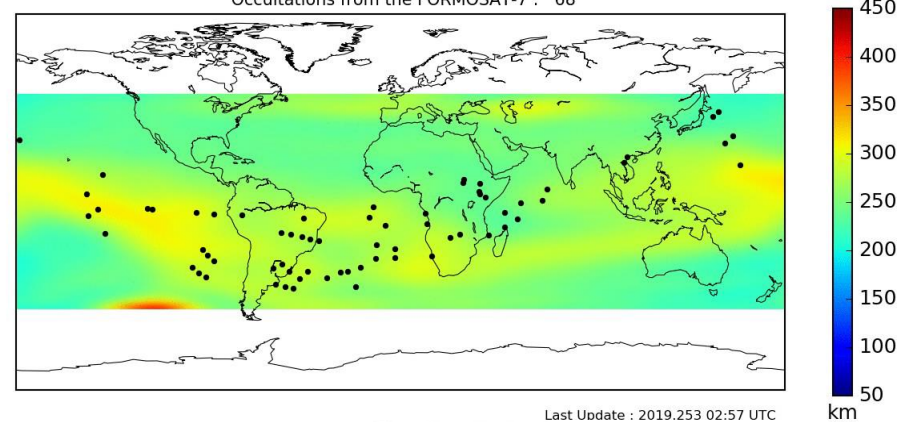
Ionospheric TEC Map : 2019.252 02:00 - 2019.252 05:00
Occultations from the FORMOSAT-7 : 68



Last Update : 2019.253 02:57 UTC

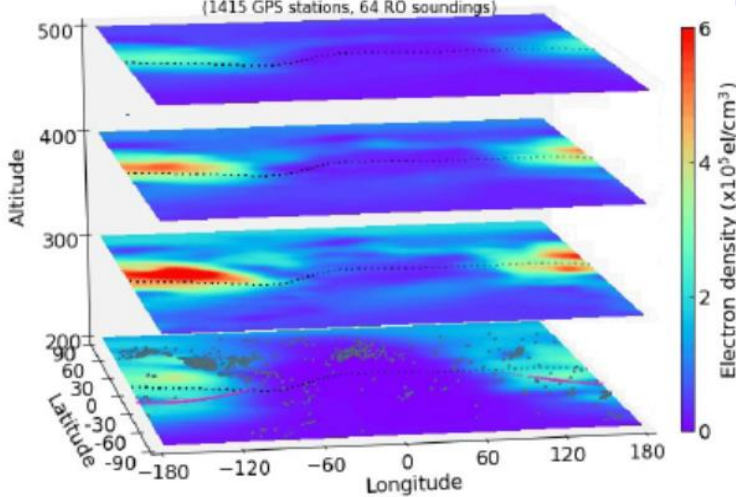
hmF2 maps

Ionospheric hmF2 Map : 2019.252 02:00 - 2019.252 05:00
Occultations from the FORMOSAT-7 : 68



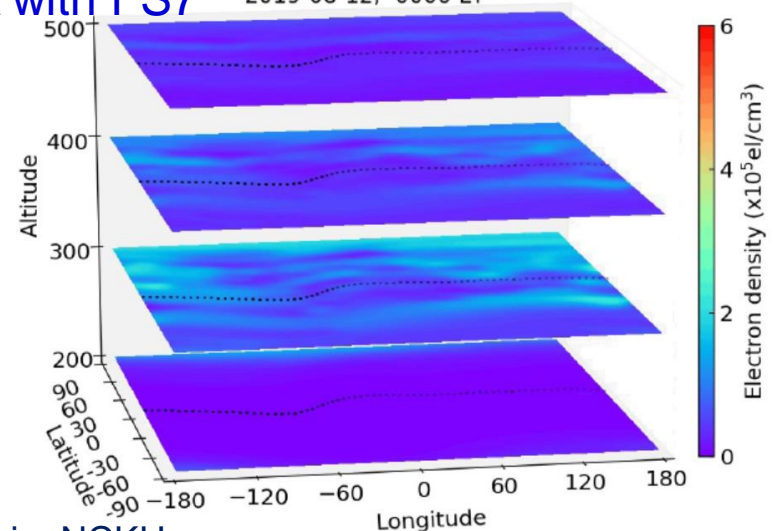
Last Update : 2019.253 02:57 UTC

GIS profiles (F7C2-GPS)
2019-08-12; 0000 UT
(1415 GPS stations, 64 RO soundings)



Ionospheric DA with FS7

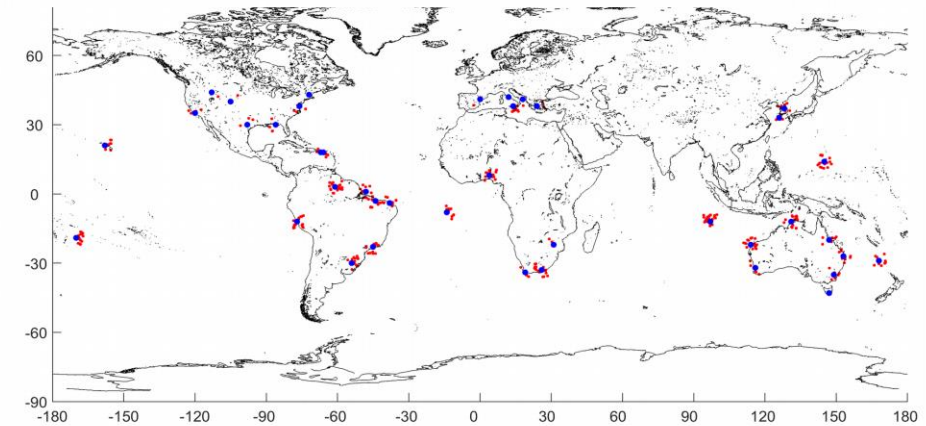
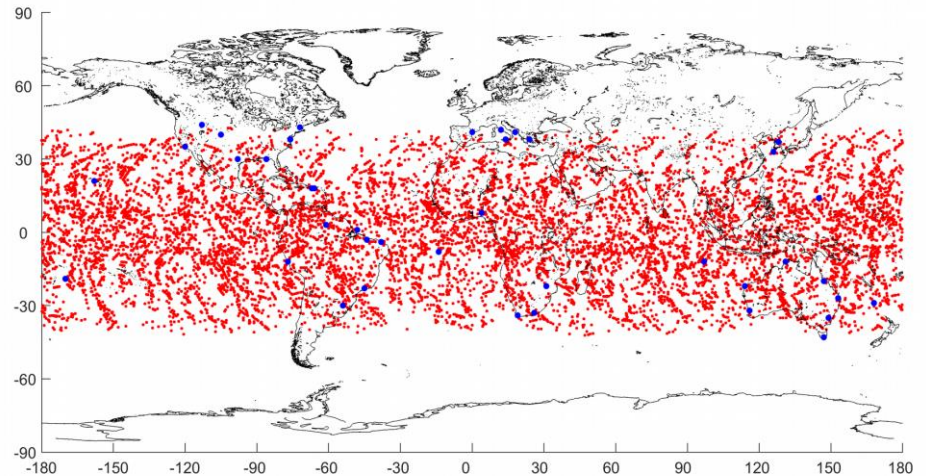
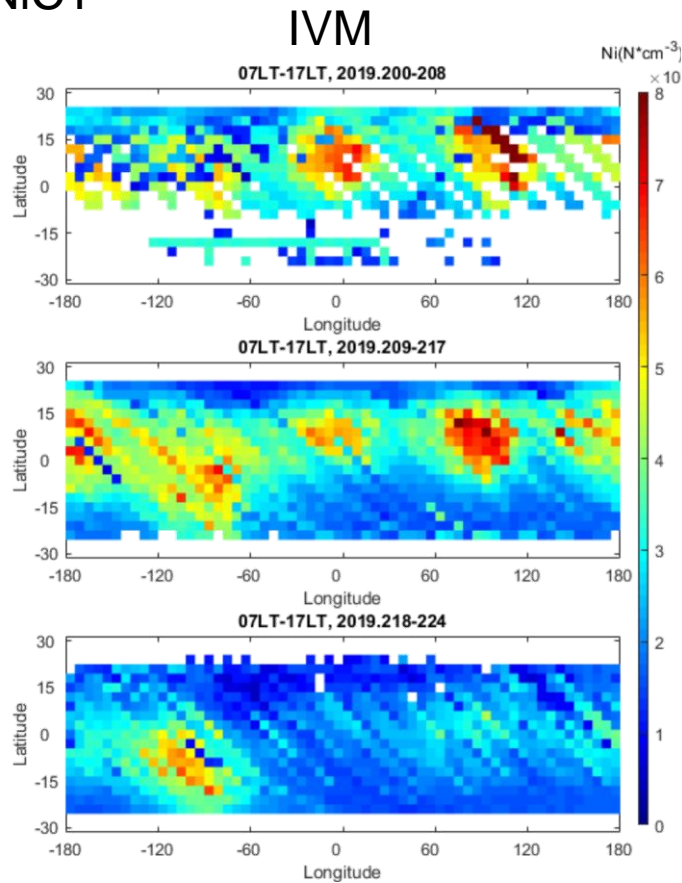
GIS profiles (F7C2-GPS)
2019-08-12; 0000 LT



Credit: Chien-Hung Lin, NCKU

Ionospheric products

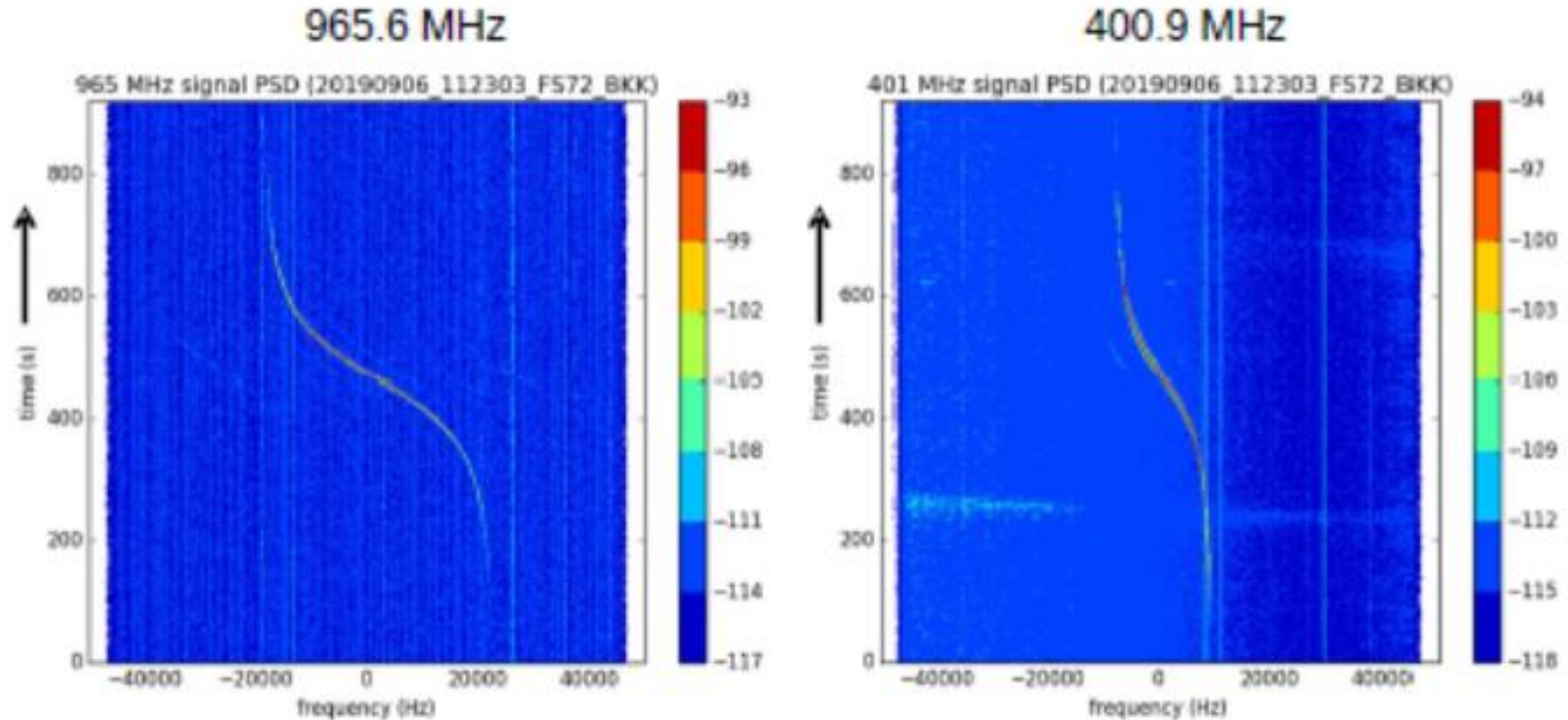
Ionosonde :
Umass Lowell
NiCT



Credit: Chien-Hung Lin, NCKU

1st RF Beacon Signal Observed (1/3)

September 6, 2019 11:23UT-, Bangkok, Thailand

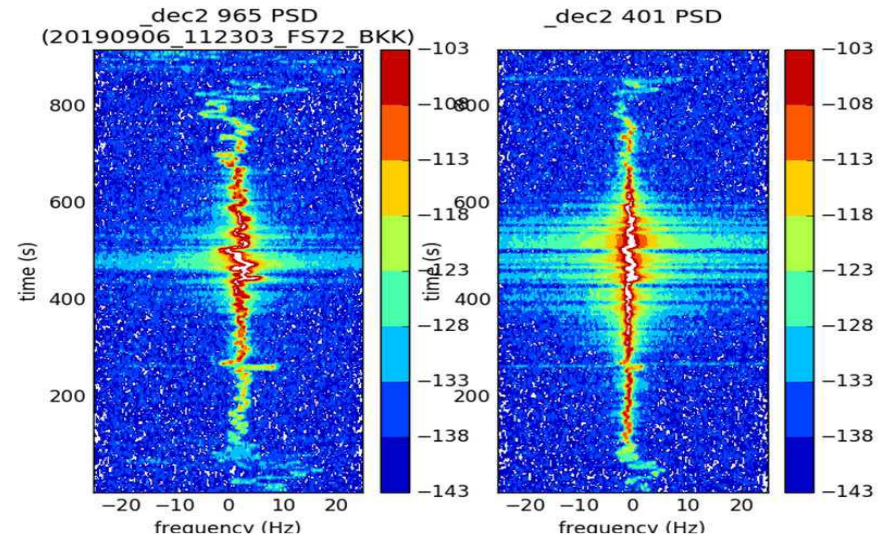
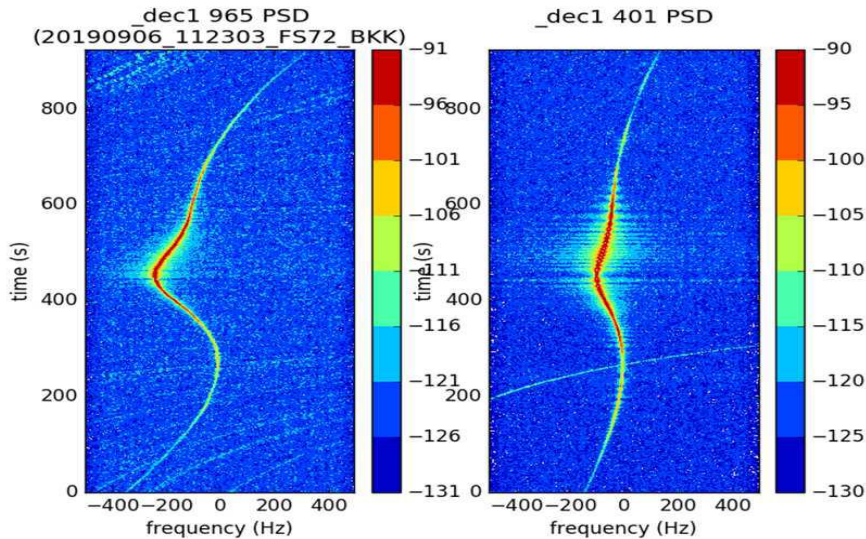


Monitoring 400.9 MHz and 965.6 MHz signal from FORMOSAT-7/COSMIC-2

- Started on September 1, 2019
 - Bangkok (Thailand), BKK, 13.7278 deg N, 100.7724 deg E
 - Ho Chi Minh (Vietnam), HCM, 10.8486 deg N, 106.5598 deg E
 - Kototabang (EAR site, Indonesia), EAR, 0.2044 deg S, 100.3203 deg E
- (Credit: Tung-Yuan Hsiao & Yamamoto Mamoru)

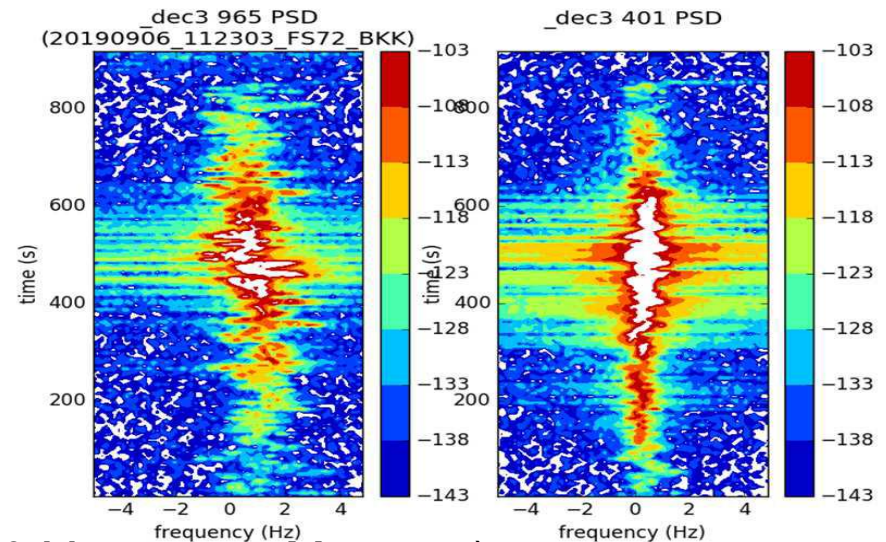
1st RF Beacon Signal Observed (2/3)

September 6, 2019 11:23UT-, Bangkok, Thailand



Signal processing scheme (**ESPRIT**)

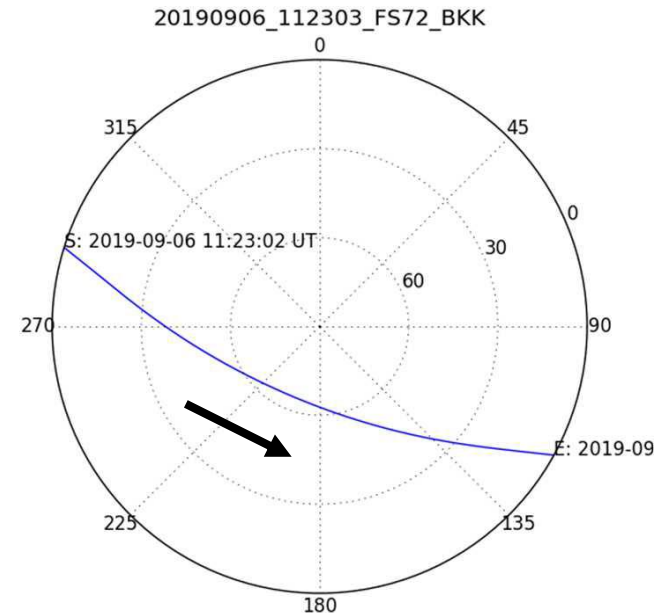
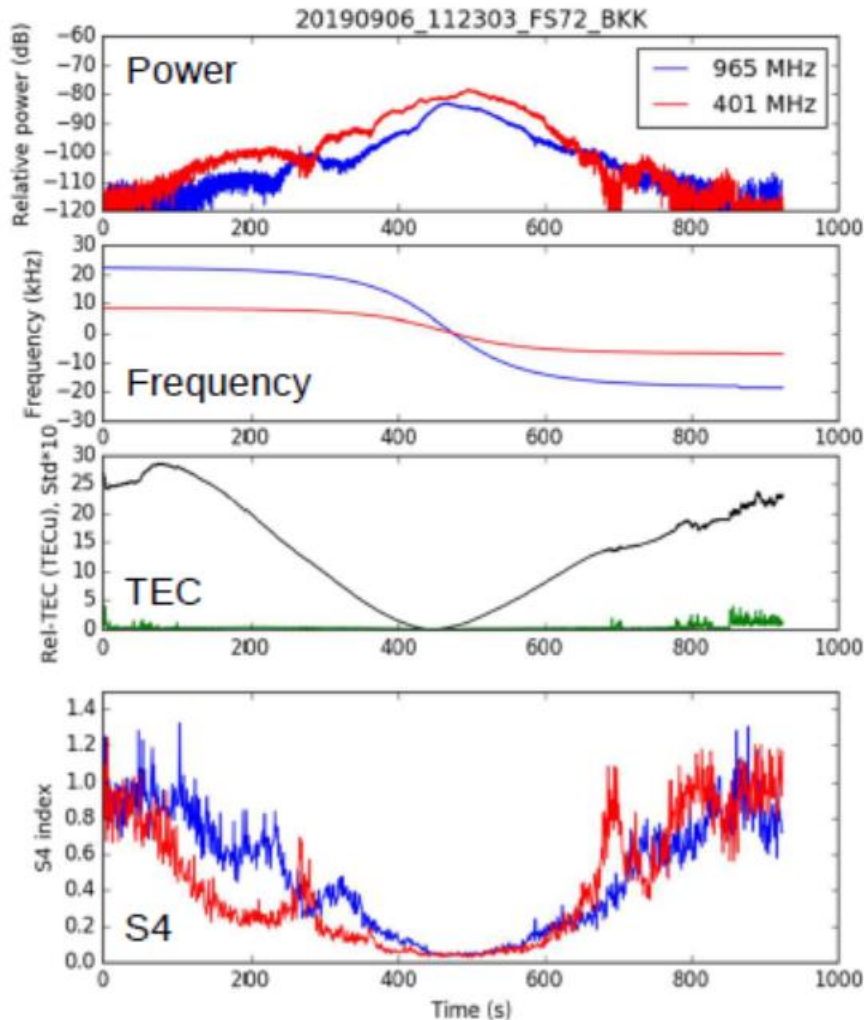
- Frequency finding and down sampling with preserving phase (difference) information. Three-step processing.
- Sampling speed decreases from original 100 kHz (last page)
 - (top left) 1 kHz
 - (top right) 50 Hz ... for S4 index
 - (bottom right) 10 Hz ... for TEC



(Credit: Tung-Yuan Hsiao & Yamamoto Mamoru)

1st RF Beacon Signal Observed (3/3)

September 6, 2019 11:23UT-, Bangkok, Thailand



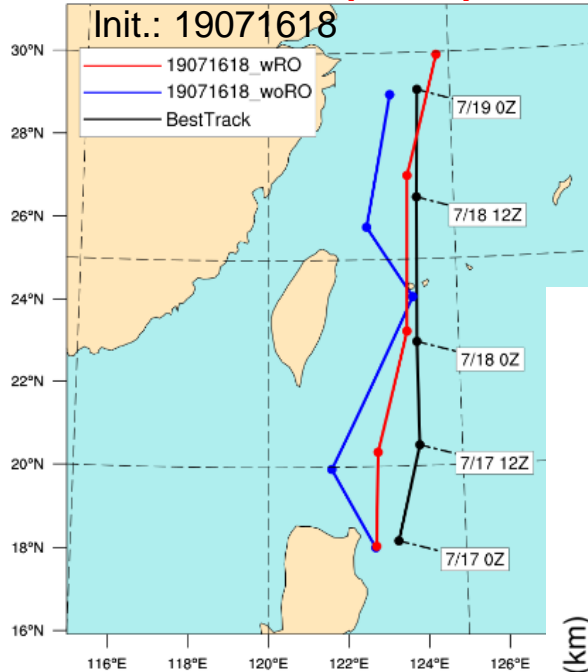
Results of signal processing

- (top) Azimuth/elevation of satellite.
- (left) Signal power, frequency, total electron content (TEC, in TEC unit), and S4 index, from top to bottom.
- TEC is preliminary as we need to resolve 0.1Hz-level frequency offset problem between two signals. Not yet reached the final f-offset.

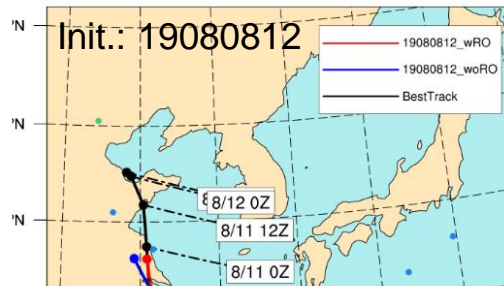
(Credit: Tung-Yuan Hsiao & Yamamoto Mamoru)

Prediction of Three Typhoon Track

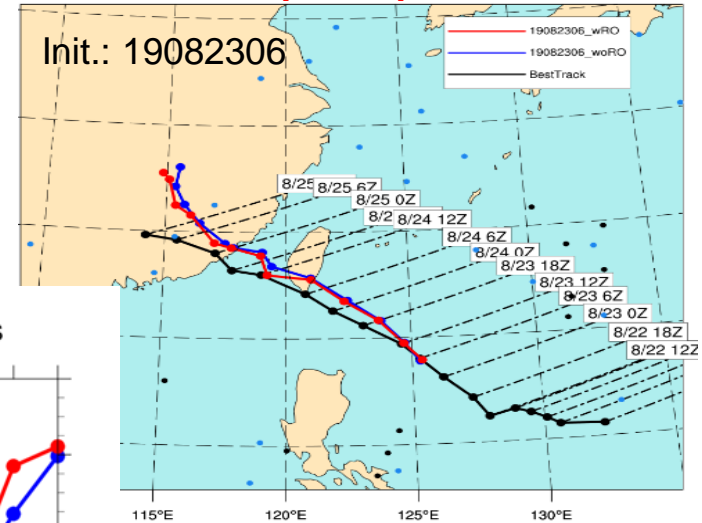
TY DANAS (2019)



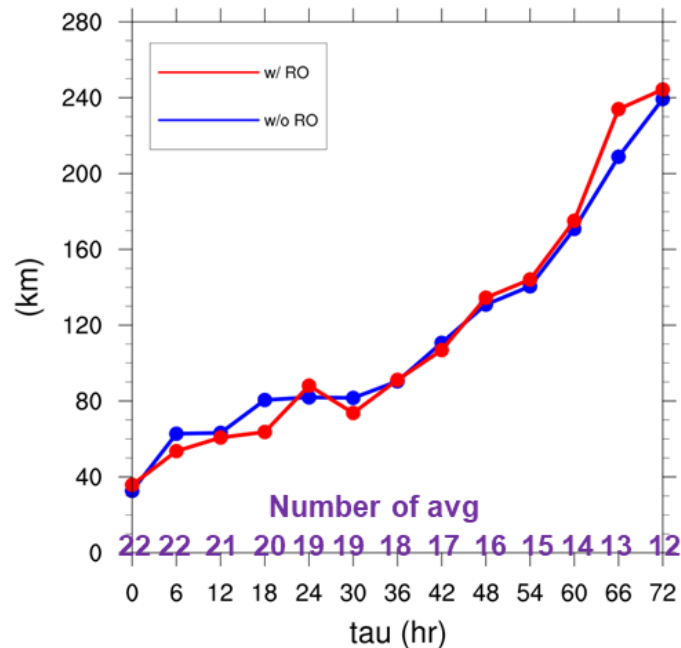
TY LEKIMA (2019)



TY BAILU (2019)



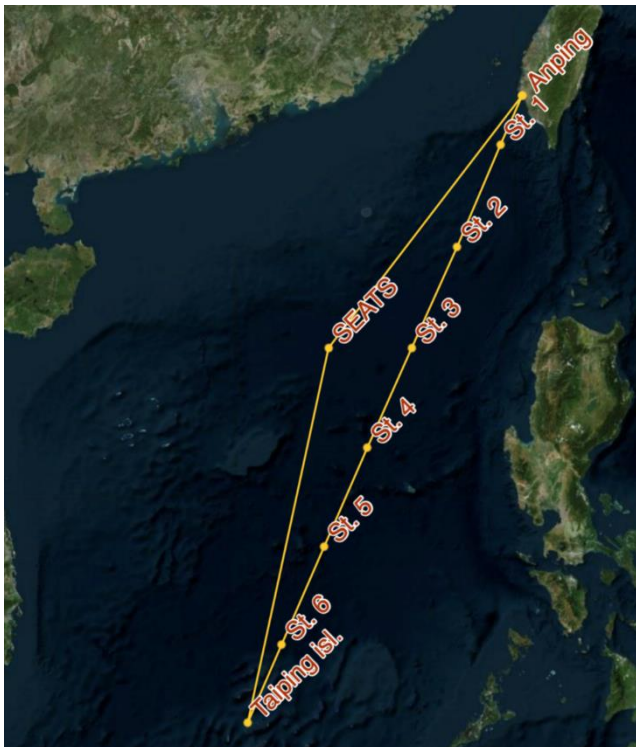
Track Error Avg. of 3 Typhoons



CREDIT: CWB NWP - regional team

South-China Sea Two Island Monsoon Experiment (SCSTIMX)

- The South China Sea Two-Island Monsoon Experiment (SCSTIMX) is the field component of the integrated project “Interaction of convection over the Maritime Continent - SCS with large-scale flow”.
- SCSTIMX campaign are planned between the Taiping Island and Dongsha Island, Surface weather, wind profiler, and upper-air sounding observations are conducted regularly at the two islands.

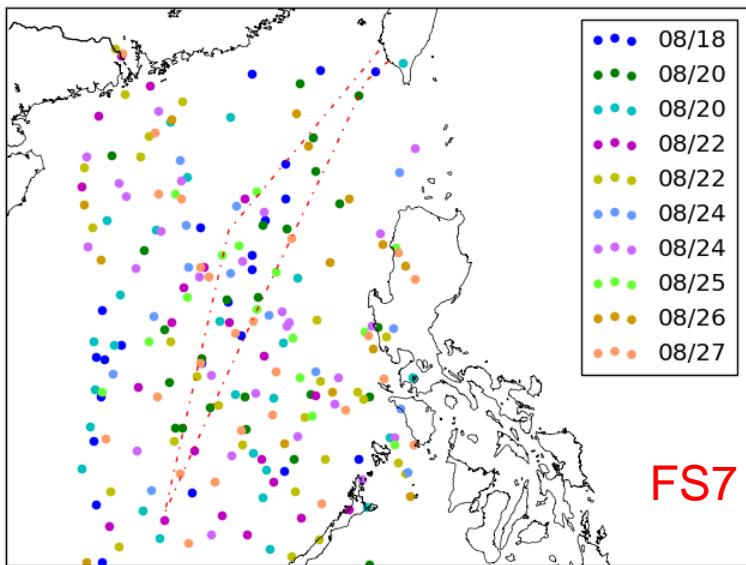


Longitude	Latitude	Station	距離(nm)	船速(節)	航時(hr)	作業時間(hr)	下放深度(m)
120.2981	22.5474	Anping port				0	
119.6799	22	St. 1	63.2	8	7.9	1	300
118.7547	20.0074	St. 2	130.4	8	16.3	1	300
117.7803	17.9989	St. 3	132.7	8	16.6	1	300
116.8311	16.001	St. 4	131.8	8	16.5	1	300
115.907	13.9976	St. 5	131.7	8	16.5	1	300
114.998	12.0011	St. 6	131.1	8	16.4	1	300
114.271	10.3895	Taiping island	105.8	8	13.2	0	
116	18	SEATS	467.9	8	58.5	3.5	3000
120.1483	22.9605	Anping port	378.3	8	47.3	0	

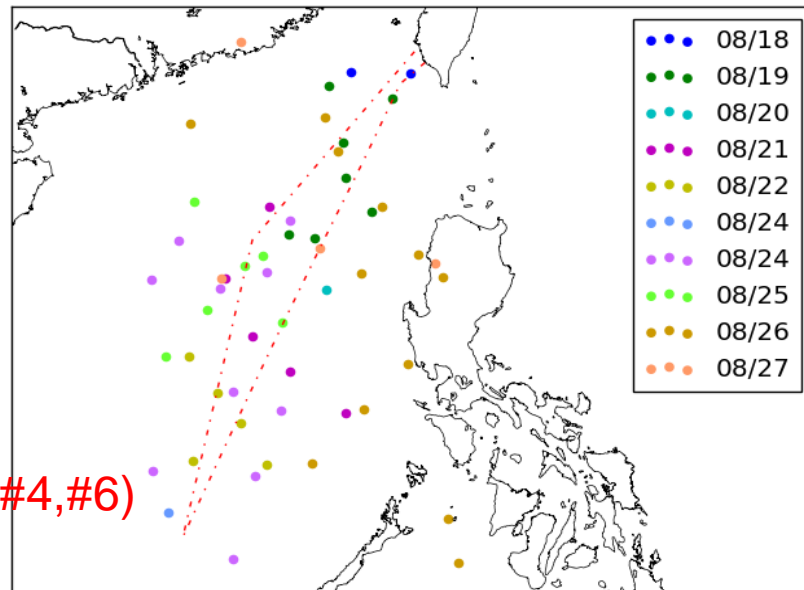
- Radiosonde two times per day on 07:30 & 19:30 LST (2019.08.18-2019.08.27) .
- Additional Radiosonde observation for FORMOSAT-7 occultation profiles.

CREDIT: (勵進號研究船, Prof. Lin林博雄. NTU)

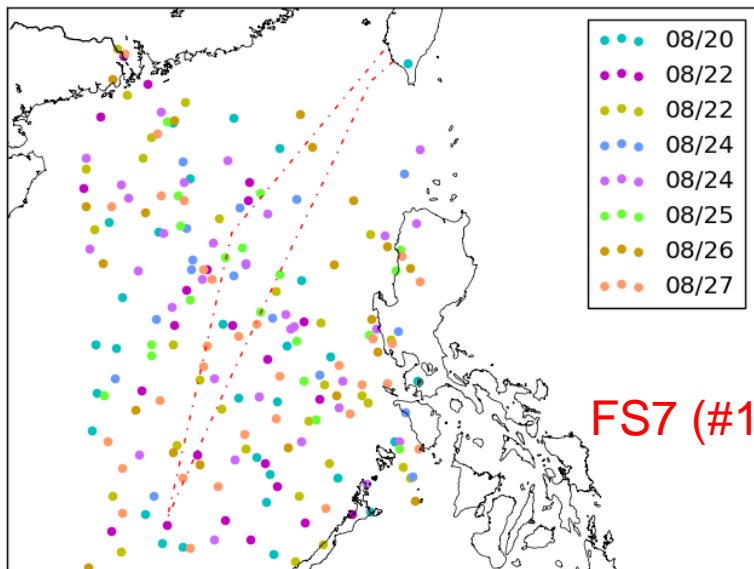
Total RO during Exp. Period. (8/13) Co-observation RO events during Exp. Period.



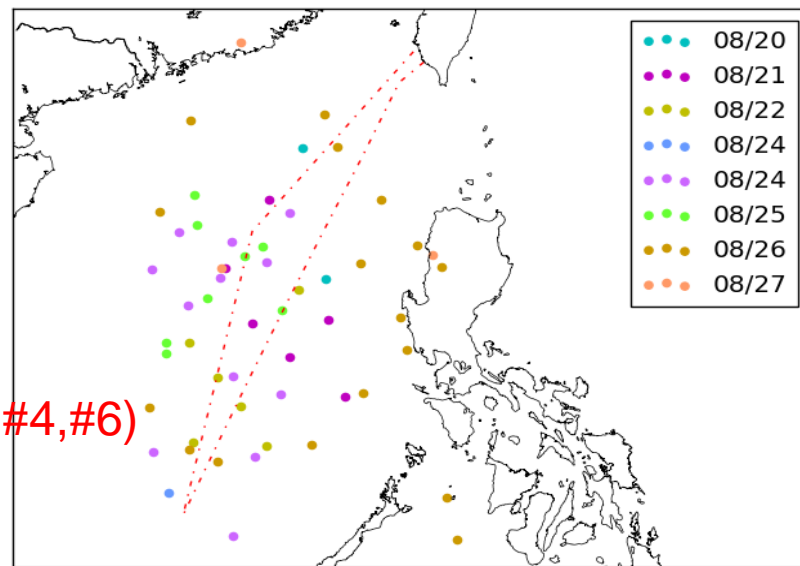
FS7 (#2,#3,#4,#6)



Total RO during Exp. Period. (8/20) Co-observation RO events during Exp. Period.



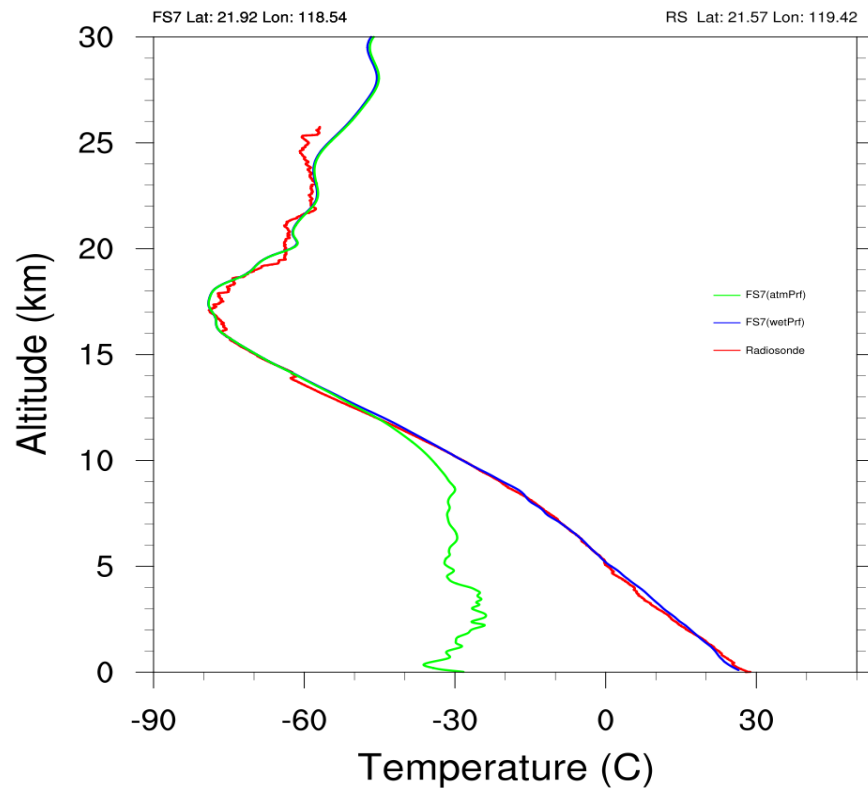
FS7 (#1,#2,#3,#4,#6)



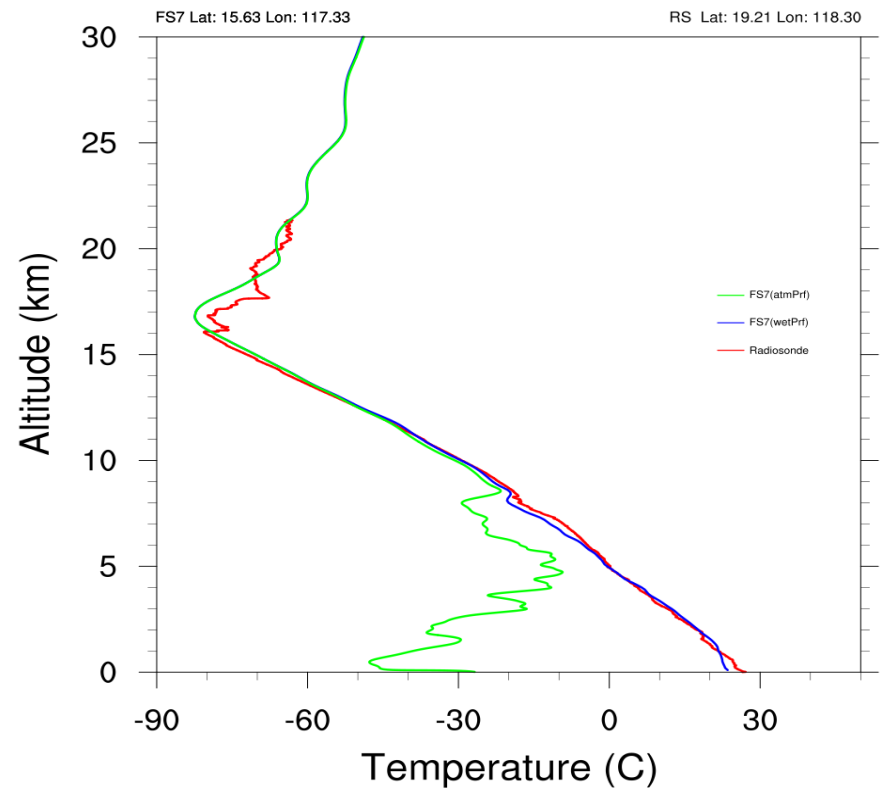
South-China Sea Two Island Monsoon Experiment (SCSTIMX)

■ South-China Sea Two Island Monsoon Experiment

Profile 2019081812(C2E2.2019.230.12.09.G13)



Profile 2019081909(C2E6.2019.231.09.19.G30)



Conclusion

- As the world's first GPSRO constellation, FORMOSAT-3/COSMIC has clearly demonstrated the advantages and utilities of a GPS RO constellation and has fulfilled all the promises and more
- Constellation Radio Occultation Measurement has become a powerful Earth Observation System.
- NSPO and NOAA have recognized the need and the opportunity and jointly implemented the FORMOSAT-7/COSMIC-2 mission, and it will continue the legacy of FORMOSAT-3.
- An overview of the FORMOSAT-7 mission, L&EO Satellite checkout, and preliminary results of the satellites was presented.
- The Satellite Initial Operational Capability (IOC) is target at end October 2019.
- The Neutral Atmospheric IOC is targeted for early 2020.

FORMOSAT-7/COSMIC-2 Major Collaboration Partners

U.S.A.



Taiwan



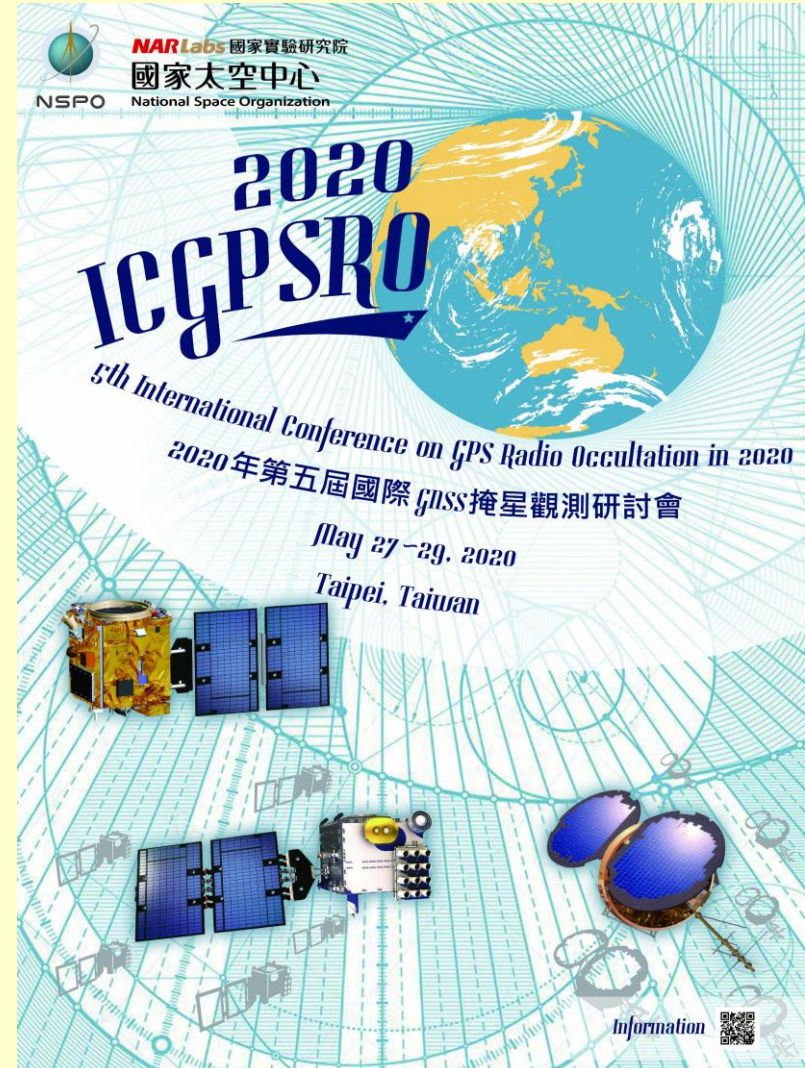
Europe



Australia



5th ICGPSRO 2020 Conference Announcement





*Launch Taiwan Into Higher Orbits
And Beyond*

Thanks for Your Attention