FORMOSAT / COSMIC Mission --- Taiwan's Efforts to Improve Weather Forecast

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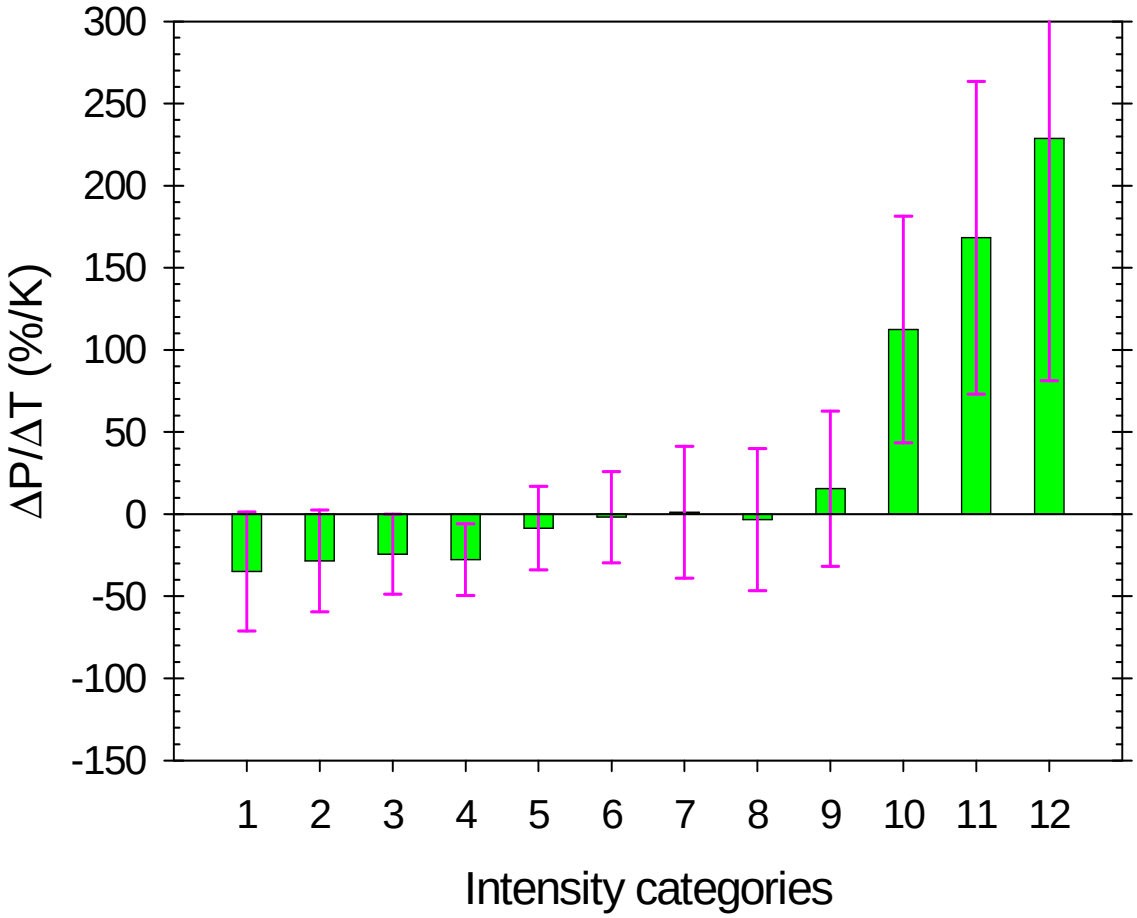
- **There are strong indications that recent increase of the occurrence of extreme weather events is related to global warming. Shaw Liu et al (2009)have studied the rainfall problem quantitatively.**

Changes in Taiwan's rain intensity for each degree warming in global temperature (mm/day)



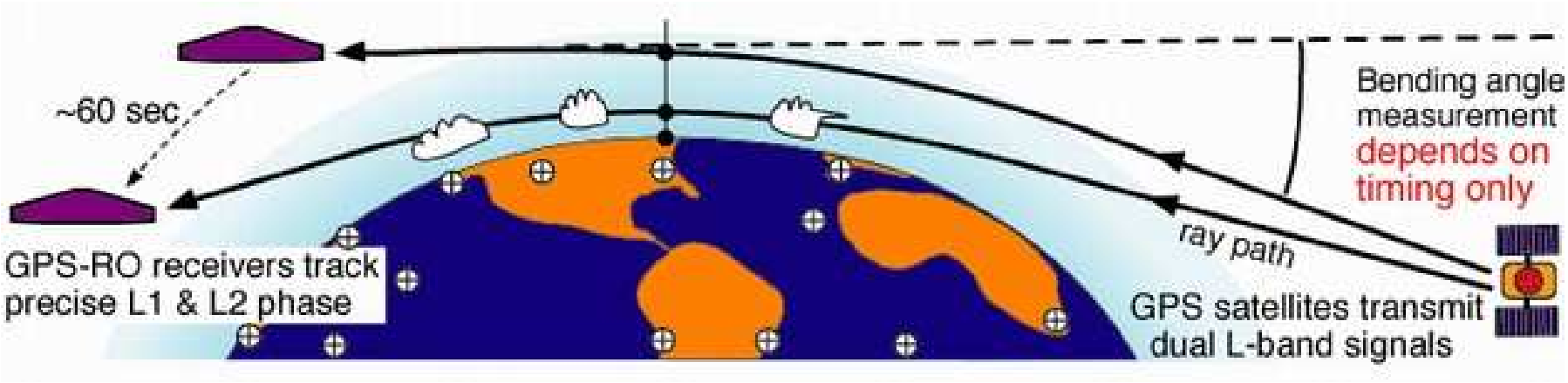
Record-breaking Rain-gauge Data

County	Township	Annual Rainfall (mm)	08/7 (mm)	08/08 (mm)	08/09 (mm)	08/10 (mm)	08/07-08/10 (mm)	08/07-08/10 vs Annual
Chiayi	Alishan	3,910	420	1,161	1,166	218	2,965	76%
Pingtung	Sandimen	3,884	745	1,402	394	332	2,872	74%
Chiayi	Jhuci	3,801	556	1,185	877	156	2,775	73%
Kaohsiung	Taoyuan	4,086	501	1,283	583	423	2,790	68%
Kaohsiung	Liouguei	3,138	236	1,178	696	351	2,461	78%
Chiayi	Fanlu	3,437	708	815	601	79	2,202	64%
Chiayi	Dapu	2,749	482	1,214	458	3	2,156	78%
Kaohsiung	Jiasian	2,861	400	1,072	345	203	2,020	71%
Nantou	Sinyi	3,254	170	717	909	134	1,929	59%
Kaohsiung	Maolin	3,152	252	743	230	179	1,404	45%
Pingtung	Wutai	2,898	206	580	208	165	1,160	40%
Kaohsiung	Cishan	2,365	91	620	128	85	924	39%

- **Need to improve weather forecasting**

  Recently, a new technique known as GPS Radio Occultation has been developed to greatly improve our capability to collect important weather data globally. This in turn helps us to improve weather forecasting, including cases for extreme weather events.

GPS-RO is possible because the GPS system designers in the early 1970s had the vision to extend the transmission beamwidths comfortably beyond the Earth's limb. All we need now is a suitably programmed GPS receiver on a low Earth satellite, pointed at the Earth's limb.



GPS occultation is the only known technique that offers full SI-traceability for atmospheric temperature measurements. What is more, it is the only spaceborne technique that offers the required precision for climate monitoring and an essentially zero bias. GPS-RO temperature profiles averaged for climate analysis achieve an absolute accuracy of about 0.05 deg C between 5 km and 30 km altitude, an order of magnitude better than any other available technique. How does GPS-RO achieve SI-traceability? First, recall that the RO measurement is obtained by precisely counting phase cycles of the received GPS signal to determine the changing path delay through the atmosphere (see RadioOccultation for details). Those cycles are derived from the atomic frequency standards that keep time onboard the GPS satellites. The onboard clocks are continuously tied with great precision to International Atomic Time (IAT) — an SI standard — by the US National Institute of Standards and Technology (NIST).

Obtaining Temperature and Pressure From Refractivity

Dry **Moist** **Ionosphere**

$$N = (n-1)\times 10^{6} = 77.6\frac{P}{T} + 3.73\times 10^{5}\frac{P_w}{T^2} - 40.3\times 10^{-12}\frac{n_e}{f^2}$$

- Equation of state

$$\rho = 0.3484\frac{P}{T}$$

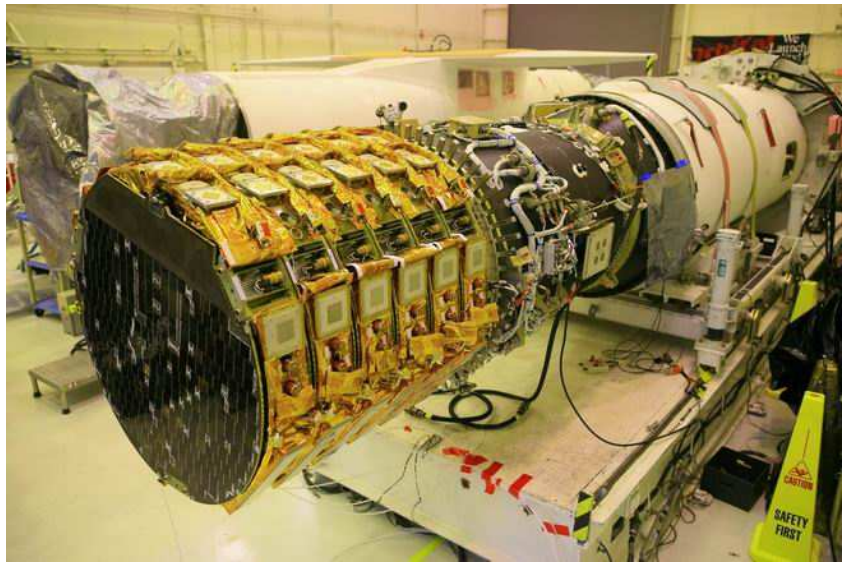
- Hydrostatic equilibrium equation

$$\frac{\partial P}{\partial h} = -g\rho$$

n = index of refraction
N = refractivity
P = pressure
T = temperature
P_w= water vapor pressure
n_e= electron density
f = operating frequency
ρ = density
h = height
g = gravitational acceleration

- **In collaboration with UCAR (University Center for Atmospheric Research), Taiwan's NSPO planned and launched a constellation of six LEO satellites in 2006 to use GPSRO technique to collect atmospheric data for meteorology, space weather and climate investigations**
- **The Constellation is called FORMOSAT 3 / COSMIC**

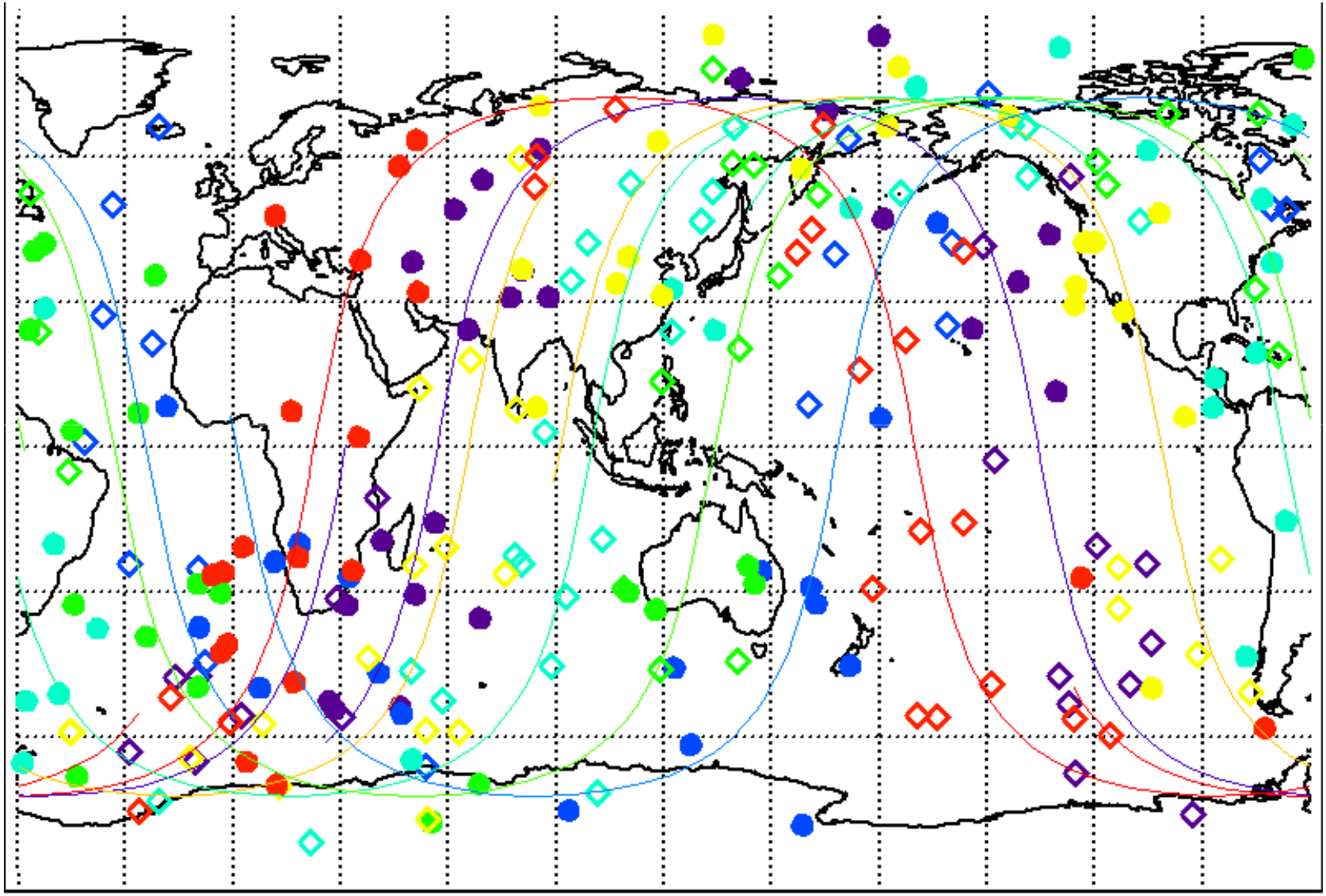
March 2006 at OSC B1555 , Vandenberg
Spacecraft Mating to Minotaur



福衛3號升空的一刻　GPS全球氣象預測新紀元展開

COSMIC Launch - Picture Provided by B. Kuo - Click to view the COSMIC launch footage

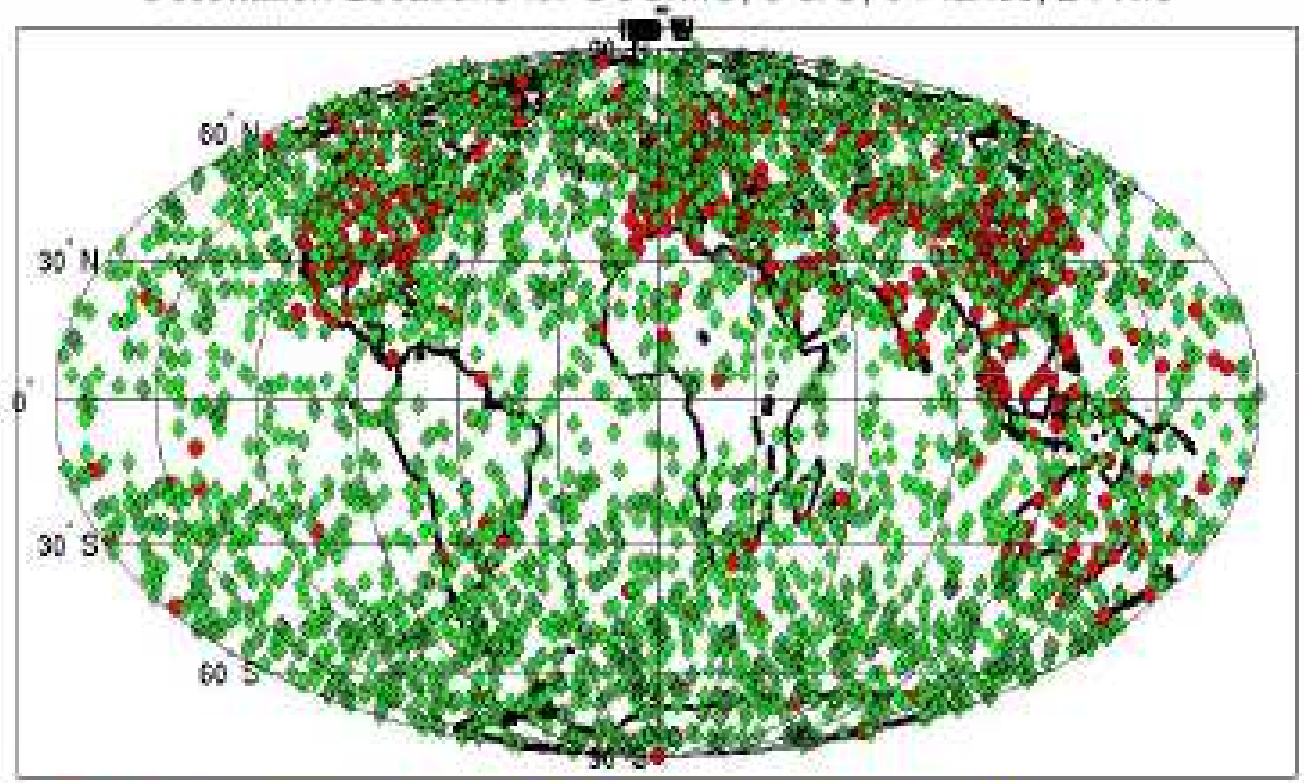
Mission Orbit: 800 km, 30 deg separation



FORMOSAT-3/COSMIC Mission

RO Soundings in a Day

Occultation Locations for COSMIC, 6 S/C, 6 Planes, 24 Hrs

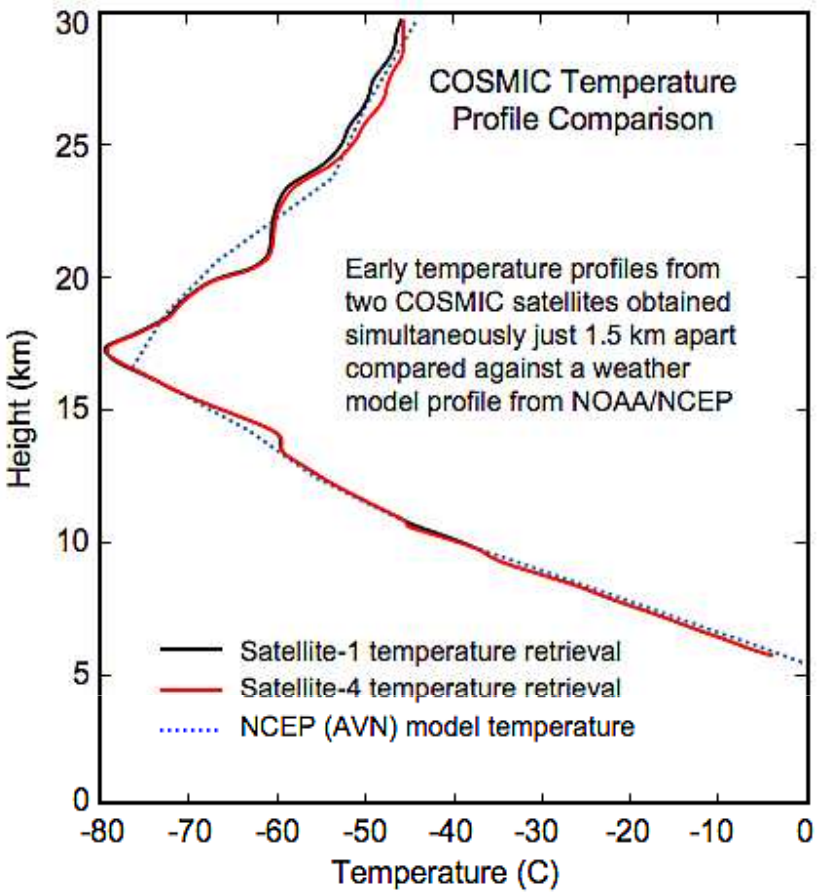


Red dots are current radiosonde sites (900).

Green dots are COSMIC soundings (2500) in a day.

NSPO

The constellation of six FORMOSAT-3/COSMIC satellites monitors as many as 2,500 profiles of the atmosphere each day. In comparison, ground sounding stations provide only 900 profiles of measurements.



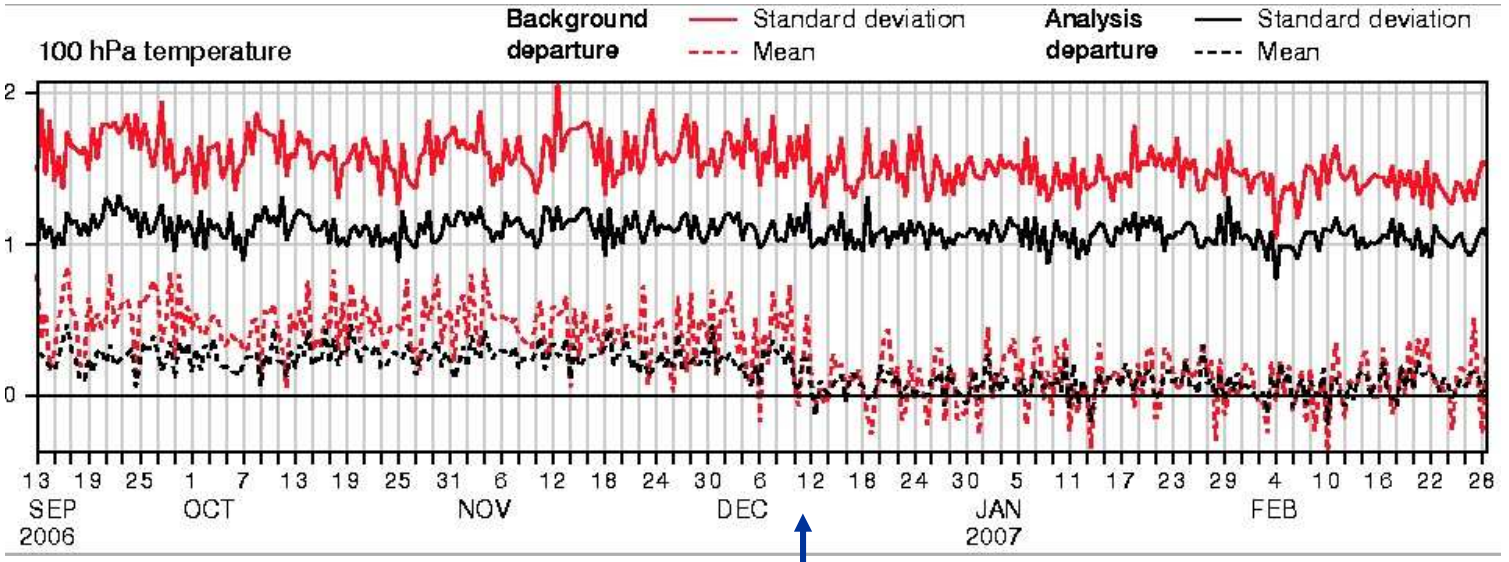
The acid test: These earliest temperature profiles from COSMIC (2006) were taken from two spacecraft looking at the same occulting signal while the spacecraft were still very close together. The occultation tangent points are only 1.5 km apart. No calibration or bias adjustment has been made. As the true temperature difference between the two is negligible, this comparison provides a pure test of measurement precision.

Above about 23 km we see the curves diverge slightly owing to declining precision in the thinning upper atmosphere. Below that altitude the curves are nearly indistinguishable. No other sensing technique, including weather balloons, comes within a factor of five of this precision. A model profile from NOAA/NCEP (National Centers for Environmental Predictions) is shown for comparison.

Characteristics of GPS RO Data

- **Limb sounding geometry complementary to ground and space nadir viewing instruments**
- **Global 3-D coverage 40 km to surface**
- **High accuracy (equivalent to <1 K; average accuracy <0.1 K)**
- **High vertical resolution (0.1 km surface – 1 km tropopause)**
- **Only system from space to resolve atmospheric boundary layer**
- **All weather-minimally affected by aerosols, clouds or precipitation**
- **Independent height and pressure**
- **Requires no first guess sounding**
- **Independent of radiosonde calibration**
- **Independent of processing center**
- **No instrument drift**
- **No satellite-to-satellite bias**
- **Compact sensor, low power, low cost**

Operational implementation of GPSRO



Neutral in the troposphere, but some improvement in the stratospheric temperature scores. Obvious improvement in time series for operations.

Operational implementation represented a quite conservative use of data. No data below 4 km, no rising occultations.

Next set of experiments to investigate increased use of the data.

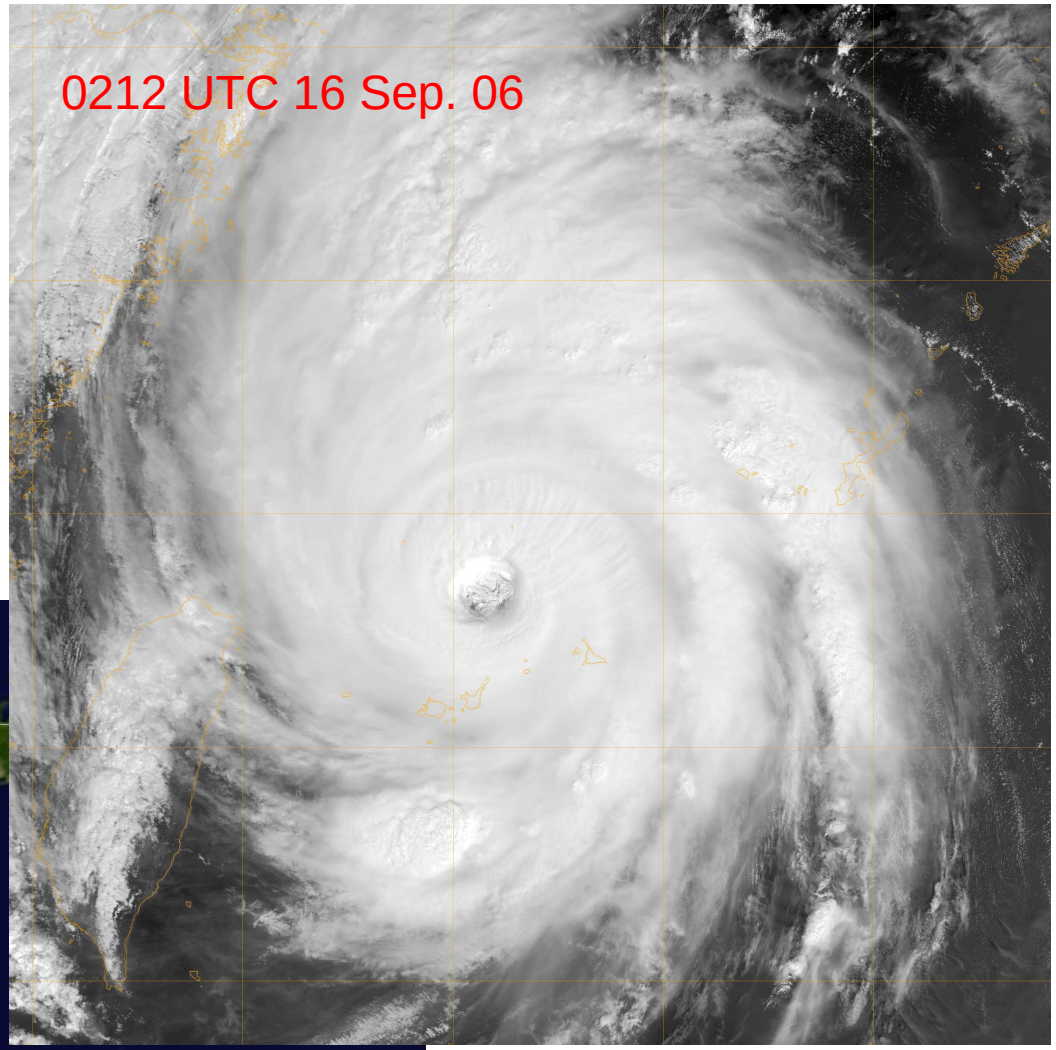
COSMIC operational

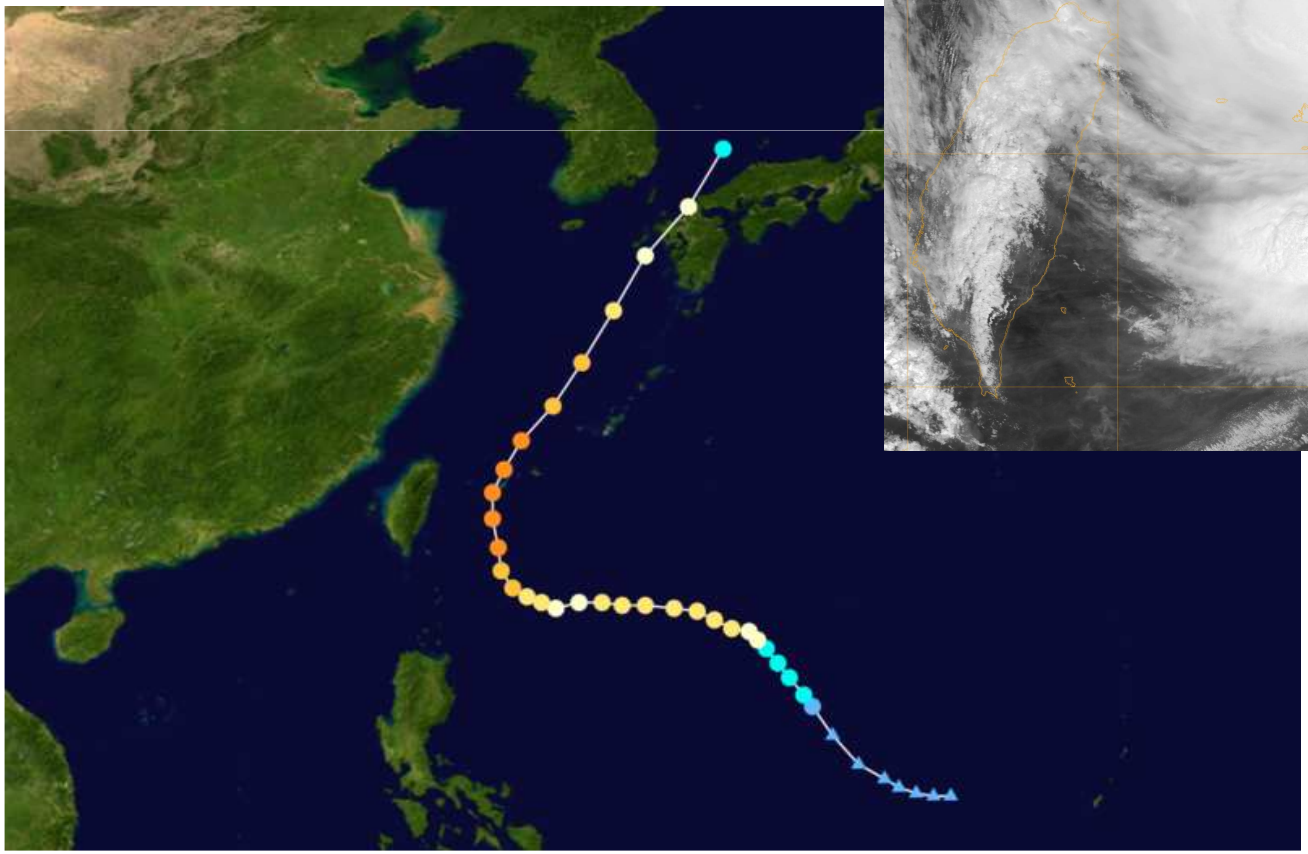
S. Healy, ECMWF

The total observations assimilated by ECMWF in a 12-h period is about 10 million. 90% of these are satellite radiances. For this same time period, the number of GPSRO observations assimilated is less than 300,000, or less than 3% of the total number of observations assimilated. (Sean Healy, ECMWF, personal communication). The first five contributors to forecast error reductions are

- **AMSU-A (4 satellites) 17.2%**
- **IASI-12.0%**
- **AIRS-11.8%**
- **AIRREP (aircraft temperature and winds) 9.3%**
- **GPSRO (bending angles)-8.5%**
- **TEMP (radiosonde winds, humidity, and temperatures)-7.9%**
- **QuikSCAT (scatterometer surface winds over the oceans)-5.2%**

Typhoon Shan Shan 2006





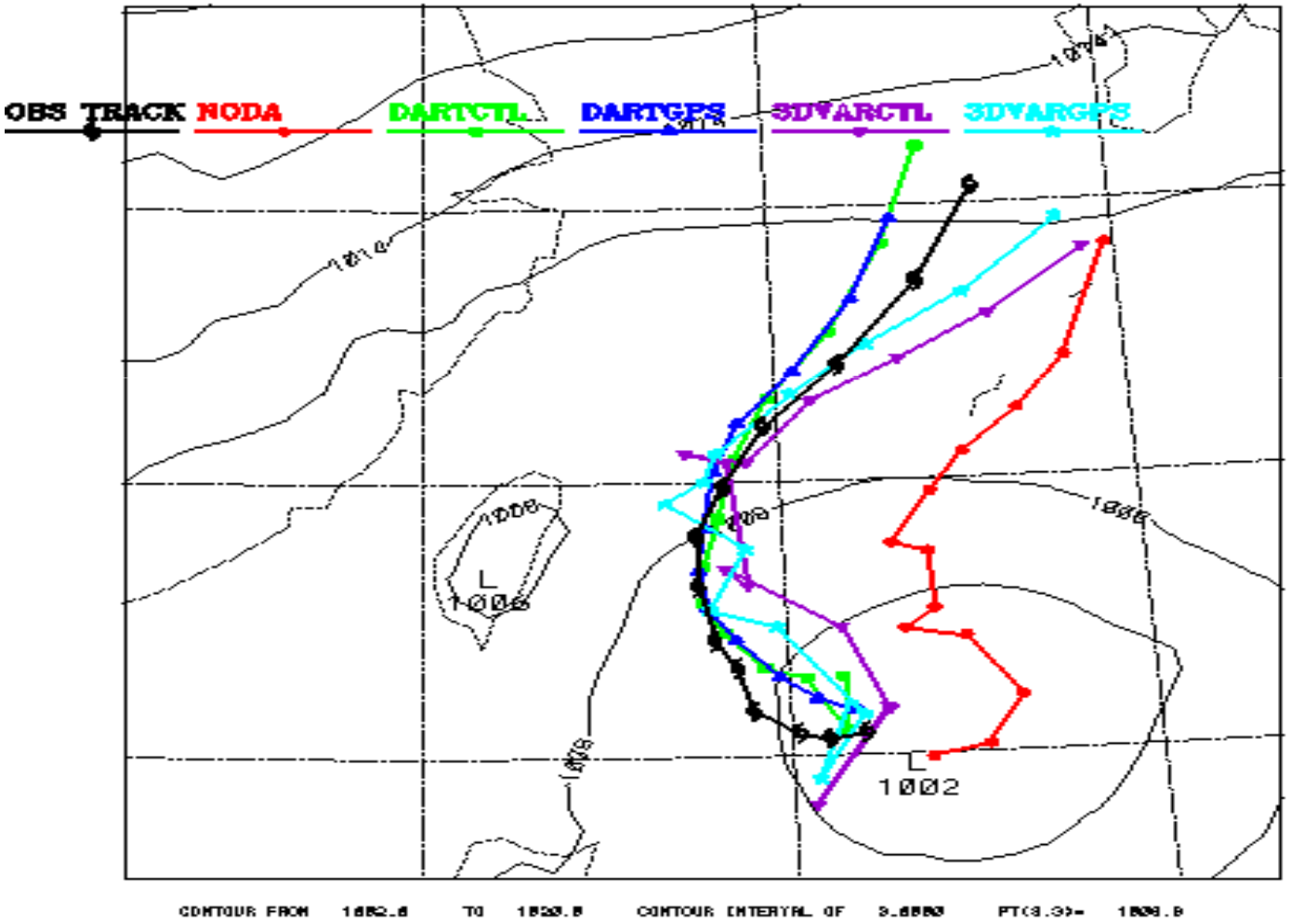
Formed: 9 Sep 06

Dissipated: 19 Sep 06

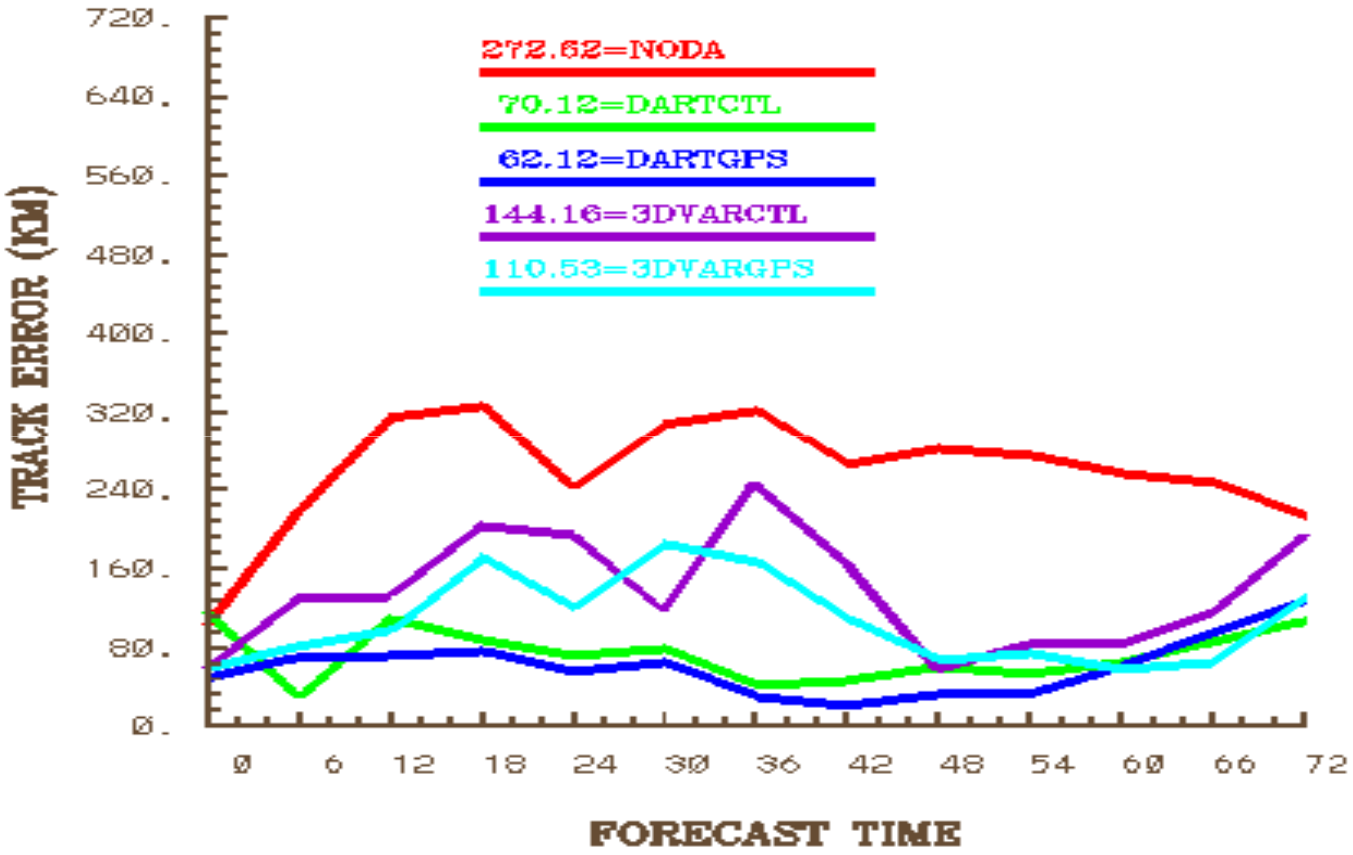
Lowest pressure: 919 mb

Category 4 storm

Track Forecast from 12Z Sep 12 (dots for every 6 hour)



Track forecast error from 00Z Sep 14 (every 6 hour)

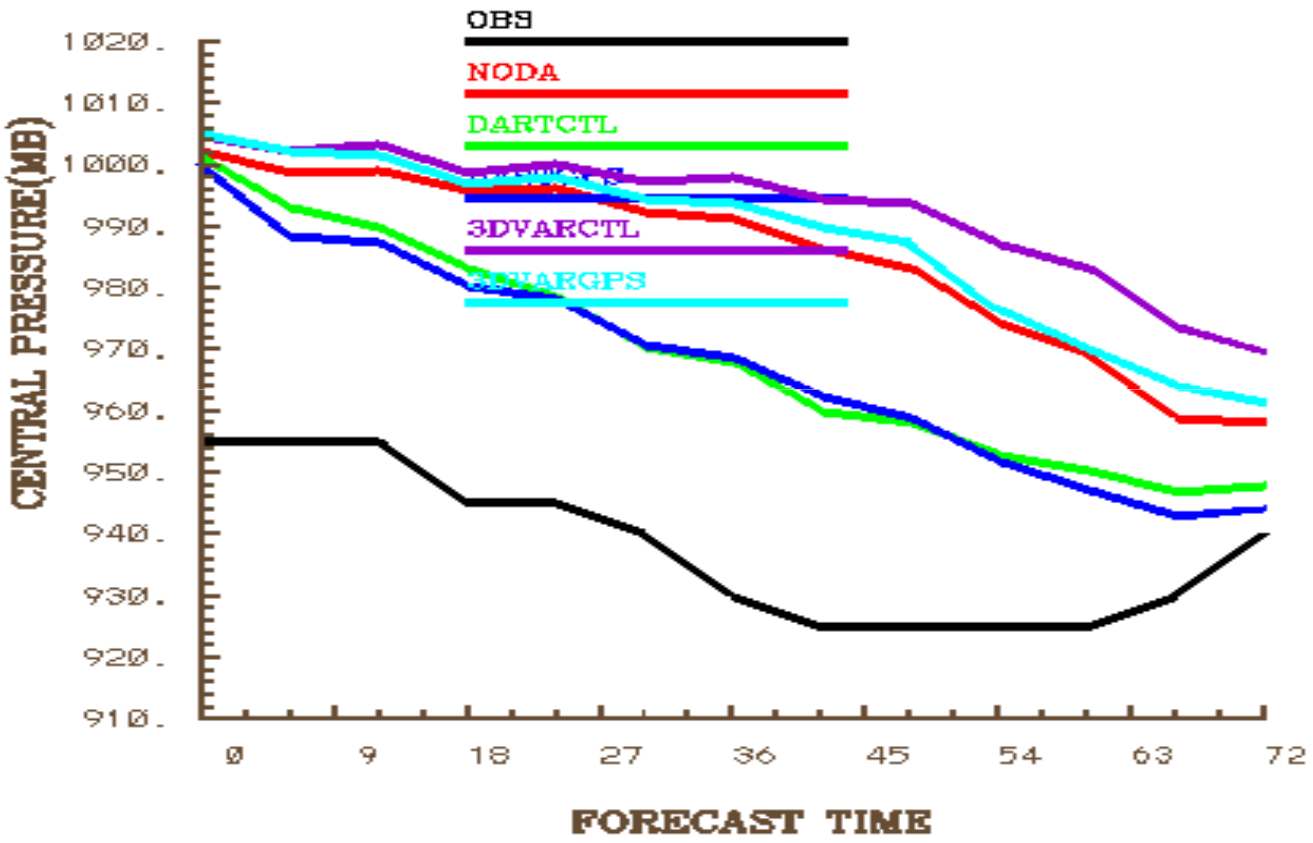


NO TC Bogus for all experiments

GPS data assimilation improves forecast with either WRF-Var or WRF EnKF system

WRF-EnKF system produces better track forecast than WRF-Var

Intensity forecast from 00Z Sep 14 (every 6 hour)



WRF EnKF produces stronger storm than WRF-Var (when both did not use TC bogus)

GPS RO data assimilation improves intensity forecast, particularly for WRF-Var

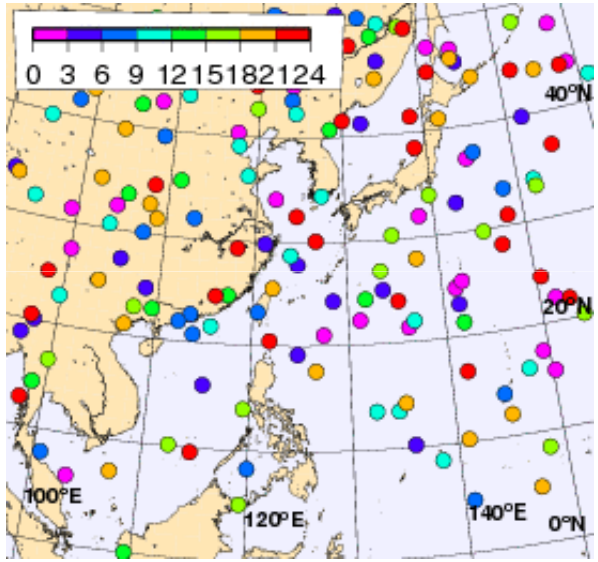
F-3 / COSMIC Follow on

- Option A:
  - 8 satellites placed at 72 degree inclination angle
  - 4 satellites placed at 24 degree inclination angle
- Option B:
  - 12 satellites placed at 72 degree inclination angle

Distribution of RO soundings in a day

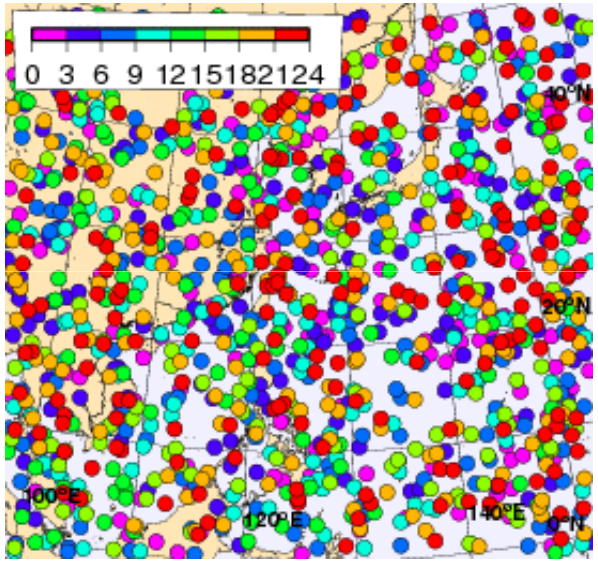
G

FORMOSAT-3/COSMIC



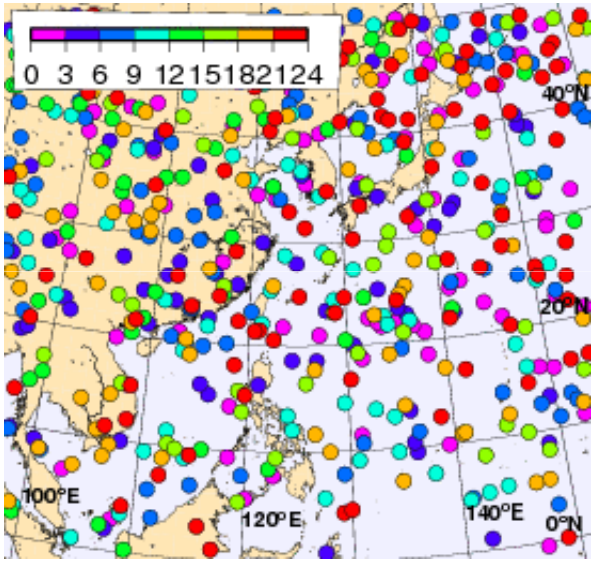
A

COSMIC-IIA



B

COSMIC-IIB



Different color shows availability of RO soundings at different hours of the day.

Typhoon Forecast Improvements

- We perform two-day data assimilation, followed with three-day forecast for FORMOSAT-3, COSMIC-IIA, and COSMIC-IIB.
- Compared with the Control (without RO data) COSMIC-II gives far superior results.

	Intensity forecast	Track forecast
FORMOSAT-3	8.1	25.0
COSMIC-IIA	43.3	79.1
COSMIC-IIB	26.0	39.5

FORMOSAT-7/COSMIC II

- Tentative plan: Two launches, 6 satellites at 72 degree, 500 km; 6 at 24 or 15 degree, 800km
- All satellites will have GPSRO payload that can receive signals from GPS, GALILEO and GLONASS
- 6 will have Radio Beacon and other space weather payloads
- Mission period 2014 to 2021

More GNSS Transmitters for Next Mission

Spacecraft transmitting RO signals in 2012

- *U.S. GPS* *~ 30 in service*
- *Russia GLONASS* *~ 24 in service*
- *China BeDou* *~ 35 will be in service 2010 (?)*
- *Europe Galileo* *~ 32 will be in service 2013*

Occultation Sounding Statistics Per Day

# of LEO's	Transmitters	Total number of soundings/day	Average horizontal spacing [km]	Average number of soundings in 500km/500km box [#]
6	GPS	3112	404.8	1.5
6	GPS+GLO	5959	292.6	2.9
6	GPS+GLO+GAL	9307	234.1	4.6
12	GPS	6267	285.3	3.1
12	GPS+GLO	11954	206.6	5.9
12	GPS+GLO+GAL	18645	165.4	9.1
24	GPS	12506	201.9	6.1
24	GPS+GLO	23905	146.1	11.7
24	GPS+GLO+GAL	37320	116.9	18.3
48	GPS	25012	142.8	12.3
48	GPS+GLO	47761	103.3	23.4
48	GPS+GLO+GAL	74536	82.7	36.5

- It is expected that because of the reliability and low-cost of the system, there will be a number of GPSRO Constellations launched in the near future to be used as one of the main data collecting systems for meteorology, climate and space weather applications.
- Because of F3/COSMIC, Taiwan has established herself as one of the leaders in building and operating GPSRO Constellations. This provides us with potential future scientific, technological and possible business opportunities.

THANK YOU