The FORMOSAT-3/COSMIC Five Year Mission Achievements: Atmospheric and Climate

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Outline

• FORMOSAT-3/COSMIC: The world’s first GPSRO constellation system with open-loop tracking
• FORMOSAT-3/COSMIC five-year mission achievements in
  – Global NWP
  – High-impact weather
  – Climate applications
  – Instrument calibration
  – Atmospheric study from boundary layer to stratosphere
• Outlook
FORMOSAT-3/COSMIC: The first GPSRO constellation system

- Open-loop tracking allowed sounding of the atmosphere close to the surface;
- A constellation of six satellites provided global uniform observations across all local times;
- Early phase of COSMIC constellation provided unique opportunity to study the precision of GPSRO technique

These attributes have significant implications for weather and climate studies
Open Loop Tracking in COSMIC

Comparison with ECMWF

COSMIC much better than CHAMP due to open-loop tracking

~80% of COSMIC soundings can penetrate to below 1 km, and can be used to measure boundary layer height and moisture.
Distribution of COSMIC RO sounding in Jan 2008

From Pirscher et al. (2010)
Characteristics of GPS RO Data

- Limb sounding geometry complementary to ground and space nadir viewing instruments
- Global coverage
- Profiles ionosphere, stratosphere and troposphere
- Only observing system from space that can profile the ABL
- High accuracy (equivalent to <1 K; average accuracy <0.1 K)
- High precision (0.02-0.05 K)
- High vertical resolution (0.1 km near surface – 1 km tropopause)
- Only system from space to observe atmospheric boundary layer
- All weather-minimally affected by aerosols, clouds or precipitation
- Independent height and pressure
- Requires no first guess sounding
- No calibration required
- Independent of processing center
- Independent of mission
- No instrument drift
- No satellite-to-satellite bias
- Compact sensor, low power, low cost
- Complements IR and microwave sounders
- Calibrates and reduces biases of IR and microwave sounders

All of these characteristics have been demonstrated in peer-reviewed literature
COSMIC: Major Accomplishments:

• COSMIC data routinely used in all major global operational centers; significant positive impacts demonstrated in global NWP.
• Significant impacts on the analysis and prediction of typhoons, atmospheric rivers, Mei-Yu system, heavy rainfall events….
• Calibrate AMSU, SSM/I, AIRS, and radiosonde measurements.
• Study diurnal tide, stratospheric sudden warming, QBO, stratospheric-tropospheric interaction, Kelvin waves, gravity waves, …
• Drive space-weather assimilation and forecast systems.
• Study ionospheric events and phenomena (e.g., Wendell Sea anomaly)
• Approximately 100 papers per year being published, world-wide.

From H. Liu, J. Anderson, C. Snyder

Lei et al. (2007), HAO
FORMOSAT-3/COSMIC
Achievement: Weather Prediction
• COSMIC data are routinely used in all major global operational centers; significant positive impacts have been demonstrated in global NWP:
  – Despite the relatively small number of observations, COSMIC is ranked #3~5 on its impacts among all observing systems
  – COSMIC data can be assimilated without bias correction and provide “anchor” for variational bias correction for other types of satellite observations
  – COSMIC provide 8 hours of gain in forecast skills in Day 4 forecast
  – Improved global analyses and forecasts contribute to improved regional forecast through initial and boundary conditions.
Positive impact at ECMWF and NCEP when COSMIC data assimilated

Impact of COSMIC on the reduction of forecast errors for the 100 mb temperature over Southern Hemisphere.

0.12 means 12% improvement.
COSMIC Impact on NWS/NCEP forecast accuracy

AC scores (the higher the better) for forecast days 1-8 40-day experiments:

- expx (NO COSMIC)
- cnt (operations - with COSMIC)
- exp (updated RO assimilation code - with COSMIC)

COSMIC provides 8 hours of gain in model forecast skill at day 4. This is a very significant impact for a single observing system.

Courtesy Lidia Cucurull, NWS NCEP
Operational ECMWF system September to December 2008. Averaged over all model layers and entire global atmosphere. % contribution of different observations to reduction in forecast error.

GPS RO has significant impact (ranked #5 among all observing systems) in reducing forecast errors, despite the small number of soundings.

Forecast error contribution (%)

Courtesy: Carla Cardinali and Sean Healy, ECMWF
Impact of Various Observing Systems

GEOS-5.6.1  28 Jan – 05 March 2010 00z

FORMOSAT-3
Ranked #3 in Impact Per Observation

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

From Ron Gelaro, NASA, GMAO
FORMOSAT-3/COSMIC
Achievement: High-impact weather

- COSMIC demonstrated significant impacts on the analysis and prediction of typhoons, atmospheric rivers, Mei-Yu system, and heavy rainfall events:
  - Ability to sound the atmosphere in all weather conditions demonstrated
  - COSMIC data provide valuable information on the three-dimensional water vapor distribution
  - COSMIC data improved model’s skill in forecasting hurricane genesis
  - COSMIC reduced hurricane track forecast errors by 10~15%
  - COSMIC improved the analysis and prediction of atmospheric rivers
NCAR 4-Day Ernesto (2006) Forecasts

The Actual

Forecast with

Forecast without

54 hrs

78 hrs

102 hrs
Typhoon Prediction During T-PARC

Assimilation of GPSRO data from COSMIC improved the quality of regional analysis and typhoon track errors. For four storms in T-PARC 2008, the average improvement is 13%.

From H. Liu and Jeff Anderson
12 COSMIC soundings used to construct X-section along NW-SE axis through the AR
The COSMIC soundings yield cross-sectional thermodynamic structures comparable in character and detail to previous aircraft-based dropsonde surveys.

From Neiman et al. (2008)
Forecast: Verification with GPS Refractivity

Ma et al. (2011) assimilated COSMIC data using the NCEP regional GSI system for three days, and demonstrated improvement in forecasting atmospheric river (shown are Bias and Standard Deviation of 24h forecast fit to GPS Refractivity over the 36-km model domain). CTRL – No COSMIC, LOC – Assimilation with local refractivity operator, NLOC – Assimilation with nonlocal excess phase operator.
Forecast: Verification with SSM/I

Valid at 0200 UTC 7 November 2006 on 36-km domain
From Ma et al. (2011)
F3/C Achievement: Calibration of other observing systems

• Because of high accuracy of GPS RO technique, COSMIC data have been used to calibrate AMSU, SSM/I, AIRS, radiosonde and ground-based GPS measurements:
  – Precision of GPSRO (through CHAMP-COSMIC comparison) in simulated AMSU brightness temperature is ~0.06°C
  – COSMIC GPSRO data revealed bias, instrument drifts, and diurnal heating/cooling of AMSU and AIR sounders
  – COSMIC data revealed day time and night time biases of different radiosonde systems
  – COSMIC data assessed the performance of different SSM/I retrieval algorithms
The precision of using GPS RO data to inter-calibrate other satellite is about 0.06 K

NOAA 18 AMSU Ch9 Brightness Temperature

Shu-peng Ben Ho, UCAR/COSMIC
COSMIC data to calibrate AMSU on NOAA satellites

200609 NOAA 15 AMSU Channel 9

\[ Y = 0.9846X + 3.707 \]
Corr = 0.99
Mean(NOAA15-COSMIC) = 0.44
Stddev(NOAA15-COSMIC) = 0.97
Total number = 789

200609 NOAA 16 AMSU Channel 9

\[ Y = 0.975X + 5.5 \]
Corr = 0.999
Mean(NOAA16-COSMIC) = 0.83
Stddev(NOAA16-COSMIC) = 0.94
Total number = 557

200609 NOAA 18 AMSU Channel 9

\[ Y = 0.96X + 6.68 \]
Corr = 0.998
Mean(NOAA18-COSMIC) = 1.13
Stddev(NOAA18-COSMIC) = 0.95
Total number = 587
Use of RO Data to Identify the Location/local-time Dependent Brightness Temperature Biases for Climate Studies

Because RO data are not affected by temperature variations of the satellite, they are very useful to identify the microwave brightness temperature anomalies due to the heating or cooling of the satellite.
COSMIC data used to calibrate SSM/I retrieval algorithm

COSMIC data are used to evaluate four different SSM/I algorithms during two atmospheric river events: 1-16 Nov, 1-8 Dec, 2006.
From Wick et al. (2009)
**COSMIC-Radiosonde**

**Russia**

Day

Mean Bias from 10 to 30km = 0.719
Abs(Mean) Bias from 10 to 30km = 0.719
MeanSD Bias from 10 to 30km = 1.875

Night

Mean Bias from 10 to 30km = -0.102
Abs(Mean) Bias from 10 to 30km = 0.187
MeanSD Bias from 10 to 30km = 2.036

**USA**

Day

Mean Bias from 10 to 30km = 0.130
Abs(Mean) Bias from 10 to 30km = 0.207
MeanSD Bias from 10 to 30km = 1.950

Night

Mean Bias from 10 to 30km = 0.526
Abs(Mean) Bias from 10 to 30km = 0.566
MeanSD Bias from 10 to 30km = 2.011
COSMIC simulated AIRS
Tbs vs. AIRS observed Tbs

Y = 1.0X - 0.29
Corr = 0.995
Mean(COSMIC-AIRS) = 0.17 K
Stddev(COSMIC-AIRS) = 1.37 K
Total = 68

Dif COSMIC-AIRS Time < 2 hours
Dif COSMIC-AIRS Location < 200 km
AIRS viewing angle < 15 degree
FORMOSAT-3/COSMIC
Achievement: Climate

• “GPS-RO observations and derived products have some unique properties and potentials that are very appealing from a climate perspective” – consensus of NOAA ad hoc GPS-RO Climate Workshop Group
  – Error characterization – comprehensive and well-documented (e.g., Kursinski, 1997)
  – Low structural error – different processing centers produced essentially the same results.
  – High vertical resolution, global uniform sampling
  – High precision and accuracy in the upper troposphere-lower stratosphere
  – These attributes are well demonstrated in COSMIC
Precision of COSMIC Profiles

- Collocated COSMIC soundings (FM3 - FM4)
- 2006.150-2006.300
- Tangent point separation (TPS) < 10 km
- Precision of Refractivity (N) < 0.2% between 10 and 20 km altitude
- For TPS < 5 km, N precision ~0.1% (~0.25°C precision for temperature)
- For TPS < 1 km, N precision ~0.02% (~0.05°C precision for temperature)
- Post-Processed products more precise than real-time products

Temporal Evolution of Cold Point Tropopause

Borsche, Foelsche, Pircher and Kirchengrast, 2008
Quantify the Reproducibility of RO data:
Estimates of Structural Uncertainty of RO data

Comparison of RO data processed by GFZ, JPL, UCAR, and WegC

Fractional Refractivity Anomalies

(Ho et al. JGR, 2009)

Independent of processing procedures: the trend from GPS RO data processed by different centers < 0.03%/5yrs
F3/C Achievement: Atmospheric studies from boundary layer to stratosphere

- GSPRO is the only technique that can study the atmospheric boundary layer (ABL) from space:
  - COSMIC demonstrated the ability to determine ABL height and their geographical, seasonal, and diurnal variations
  - Comparison with global models revealed systematic differences

- COSMIC data used to study diurnal tide, stratospheric sudden warming, QBO, stratospheric-tropospheric interaction, Kelvin waves, gravity waves, ENSO, MJO … etc.
Variability of the ABL depth from 3 years of COSMIC GPS RO data

ABL height is determined from BA lapse variations over land are larger than over the oceans the phase of the diurnal variation over the ocean is inverse to that over land

From Sergey Sokolovskiy
ABL detection frequency

ABL height

Comparison of COSMIC and ECMWF on PBL analysis

ABL height information obtained from COSMIC can be used to evaluate global models.
Looking for the ENSO signal in COSMIC RO data

Difference between Feb 2010 – Feb 2008 in total column water vapor (TCWV)

The ENSO signal is clearly visible in total column water vapor differences between 2010/2 – 2008/2.

Time-longitude section of tropopause height, tropopause temperature, and TCWV difference shows the evolution of the event.

From Barbara Scherllin-Pirscher and Ben Ho
Summary

• As the world’s first GPSRO constellation, FORMOSAT-3/COSMIC has clearly demonstrated the advantages and utilities of a GPS RO constellation in:
  – Global operational numerical weather prediction
  – Prediction of tropical cyclones and other high-impact weather systems
  – Calibration of other observing systems
  – Climate trend analysis
  – Study of atmospheric circulation systems from boundary layer to stratosphere

• FORMOSAT-3/COSMIC has fulfilled all the promises and more
Outlook

• For operational NWP, climate monitoring, and atmospheric studies, there are many advantages of having a well designed RO constellation:
  – WE MUST PUSH FORWARD WITH FORMOSAT-7/COSMIC-2

• We must maintain the number of RO soundings available for operational use, through collaboration with international RO missions

• There is still room for improvements:
  – Improve tracking, retrieval algorithm, data processing, and data assimilation