FORMOSAT-7/COSMIC-2 Mission Status and Initial Results

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ROM-SAF IROWG Workshop
Helsingør, Denmark

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Outline

• Mission overview and status
• Initial neutral atmosphere results
• Initial ionosphere results
• Neutral atmosphere cal/val
• Summary
Mission Overview

• FORMOSAT-7/COSMIC-2 (COSMIC-2, C2) follows on the successful COSMIC-1 mission launched in 2006
• Six satellite constellation around the equator (24 degree inclination low Earth orbit)
• 5 year mission life to provide 4000+ radio occultation soundings per day for improved numerical weather prediction, space weather monitoring, trending of climate change
• All weather, uniform coverage over oceans and land with 30 min median data latency
• Each satellite has 3 payloads provided by USAF
  – Tri GNSS Radio-occultation System (TGRS) – primary payload
  – Ion Velocity Meter (IVM) – secondary payload
  – RF Beacon – secondary payload
COSMIC-2 Instruments

**Mission Payload**
- **TGRS (Tri-GNSS Radio occultation System)**
  - To measure the amplitude and phase/group delay of GNSS signals

**Science Payload**
- **IVM (Ion Velocity Meter)**
  - To measure in-situ ion density, drifts (Electric fields), temperature & composition
- **RFB (Radio Frequency Beacon)**
  - To measure total electron content and ionospheric scintillation.
COSMIC-2 on STP-2 Stack

[ Photo courtesy of SpaceX ]
Satellite Overview and STP-2 Launch

- COSMIC-2 launched June 25, 2019 as part of the USAF Space Test Program-2 (STP-2) mission

<table>
<thead>
<tr>
<th>Power Supply</th>
<th>2-axis drive solar array</th>
</tr>
</thead>
<tbody>
<tr>
<td>Body dimensions</td>
<td>100 x 125 x 125 cm³</td>
</tr>
<tr>
<td>Mass</td>
<td>&lt;300 kg (per satellite)</td>
</tr>
<tr>
<td>Communications Capabilities</td>
<td>S band, upload speed 32kbps, download speed 2 Mbps</td>
</tr>
<tr>
<td>Payload Support</td>
<td>Data storage capacity 2Gbits, mass 39.4 kg, power supply 95W</td>
</tr>
</tbody>
</table>

- Integrated Payload Stack (IPS)
  - Six COSMIC-2 Spacecraft
  - Demonstration and Science Experiment (DSX)
  - Six Auxiliary Payloads
  - Dispensers plus ballast
  - Eight PPODs with Twelve Cubesats

Falcon Heavy STP-2 launched from CCAFS LC-39A (Photo credit: NASA)
Ground Station Architecture

- Nine downlink stations enable rapid delivery of data to data processing centers (US DPC and Taiwan DPC)
US Data Processing Center

- Redundant, geographically separate processing centers
- Modular framework with broad capabilities in GNSS RO/R processing, POD, atmospheric retrievals, science analysis
- Extensive data management system
  - Coordinates downlink scheduling, telemetry data transfer, payload commanding
- FISMA IT security
- Low latency processing to meet 30 minute median requirement
- Ion velocity meter processing and product generation (with UT Dallas)
- Redundant archive systems at UCAR/NCAR HPSS and NOAA NCEI
- Direct product delivery to operational weather/space weather centers
- In use for operational KOMPSAT-5 and PAZ RO processing
Mission Status

- Spacecraft checkout June 25 – July 15: complete
- Satellite payload activation/checkout July 16 – 21: complete
- Early-orbit checkout of all 18 instruments: complete
- No hardware issues on TGRS and IVM
- RF Beacon checkout is complete and all units are undergoing commissioning with Kwajalein ground station
- Orbit phasing July 22 – 23: complete
- Satellite FS701 lowering to mission orbit (~550 km) July 24 – Aug 16: complete
- Payload commissioning July 24 – Oct 15: in progress
## Spacecraft/Instrument Status

<table>
<thead>
<tr>
<th>FM1</th>
<th>FM2</th>
<th>FM3</th>
<th>FM4</th>
<th>FM5</th>
<th>FM6</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Orbit Altitude</strong></td>
<td>Final 550 km orbit as of August 16</td>
<td></td>
<td></td>
<td></td>
<td>725 km initial orbit</td>
</tr>
<tr>
<td><strong>Spacecraft Status</strong></td>
<td>Currently nominal operation</td>
<td>Currently nominal operation (2 safe mode events)</td>
<td>Currently nominal operation (2 safe mode events)</td>
<td>Currently nominal operation (3 safe mode events)</td>
<td>Currently nominal operation (1 safe mode event)</td>
</tr>
<tr>
<td><strong>TGRS</strong></td>
<td>v4.3.2 Software</td>
<td>v4.3.2 Software</td>
<td>Commissioning</td>
<td>Commissioning</td>
<td>Commissioning</td>
</tr>
<tr>
<td><strong>IVM</strong></td>
<td>Commissioning</td>
<td>Commissioning</td>
<td>Commissioning</td>
<td>Commissioning</td>
<td>Commissioning</td>
</tr>
<tr>
<td><strong>RFB</strong></td>
<td>Transmit mode enabled</td>
<td>Transmit mode enabled</td>
<td>Transmit mode enabled</td>
<td>Transmit mode enabled</td>
<td>Transmit mode enabled</td>
</tr>
</tbody>
</table>

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**All Spacecraft currently nominal**  
Instruments in commissioning  
Flight s/w for TGRS 1 updated  
Remaining TGRS updates in progress  
RFB transmit mode on
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July 16, First COSMIC-2 Profiles

- Doug Hunt produced ~110 neutral atmospheric occultations within 3 hours of receiving the first level 0 data from FM 1 and 3!
  - Ended up with > 200 profiles that day

[ Results as obtained on July 16 shown ]
Occultations Counts

• Showing post-QC counts since instrument activation on July 16
• Level 1 requirement is 4000, should have no issues meeting this when all instruments stable

CDAAC COSMIC-2 Good QC Neutral Atm Occ Counts

Trending towards > 4000 occ per day

Orbit phasing
Simulated C2 RO Coverage

- Simulated C2 occultations in this figure
Actual C2 RO Coverage by Day

CDAAC COSMIC-2 Good QC Neutral Atm Occs [ 2019-07-16 ]
Actual C2 RO Coverage

• Occultation locations on Aug 22, 2019
  – 4115 total after QC from 5 satellites, highest count so far
Average Occultation SNRs

- L1 on left, L2 on right (includes L2C and L2P)
  - Significantly higher than average L1 SNR of ~800 V/V for COSMIC-1
STDV Statistics

• STDV is the standard deviation of the difference between climatological bending angle and RO bending angle between 60-80 km
  – This altitude range is chosen to avoid both atmospheric and ionospheric effects to measure the inherent noise of the RO data
• Results for constellation shown below
  – Per satellite results consistent with overall statistics

Overall mean: 1.3 microrad
STDV for Low/High SNR

• Higher SNR clearly improves STDV
• STDV mean ratios for low/high SNR
  – GPS 1.7, GLO 1.2 (high freq transmitter clock variations dominate)

Average L1 SNR < 600 V/V

Average L1 SNR > 1800 V/V
Bending Angle Comparison to ECMWF

- All data for recent week
  - Results very reasonable

<table>
<thead>
<tr>
<th>Altitude (km)</th>
<th>Avg Mean All (%)</th>
<th>Avg Std Dev All (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>0 - 10</td>
<td>-0.6</td>
<td>9.4</td>
</tr>
<tr>
<td>10 - 20</td>
<td>-0.1</td>
<td>1.7</td>
</tr>
<tr>
<td>20 - 30</td>
<td>0.1</td>
<td>1.6</td>
</tr>
<tr>
<td>30 - 40</td>
<td>0.6</td>
<td>2.3</td>
</tr>
</tbody>
</table>
Bending Angle Comparison to ECMWF

- GPS, GLONASS data separately for recent week
  – Results very similar for both GNSS

<table>
<thead>
<tr>
<th>Altitude (km)</th>
<th>GPS Avg Mean (%)</th>
<th>GPS Avg Std Dev (%)</th>
<th>GLO Avg Mean (%)</th>
<th>GLO Avg Std Dev (%)</th>
</tr>
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<tbody>
<tr>
<td>0 - 10</td>
<td>-0.5</td>
<td>9.4</td>
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<td>0.6</td>
<td>2.2</td>
<td>0.6</td>
<td>2.4</td>
</tr>
</tbody>
</table>
• Radiosonde data
  – NCEP PrepBufr
  – Quality control, respect NCEP QC (few steps specific to NCEP or DA overturned)
  – Additional (OMB-based and physical) QC applied [e.g., spikes (superadiabatic), supersaturation (> 120%), hydrostatic consistency between T and Z reports]
• Comparison period: 2019.197-240 (Jul 16 – Aug 28)
• Drifts of both balloon and tangent point are fully taken into account (level-wise collocation)
• Robust to outliers (excludes largest 2% departures at each level)
• Minimum sample size is set to 50
1D-Var Retrieval Comparison to Radiosondes

- **Highlights**
  - St. dev. keeps decreasing with decreasing separation (e.g. temp. near tropopause)
  - Rough C2 error estimates are 0.5-1.5 K in temperature and 5-10% of observed moisture

Courtesy T.-K. Wee
RO Penetration Depth Comparison

- C2 vs. KOMPSAT-5/ Metop-AB/PAZ for collocated profiles (300 km, 3 hrs, 10133 pairs)

Mean = 0.65 km
Median = 0.25 km
Rms = 1.10 km

Mean = 1.80 km
Median = 0.84 km
Rms = 2.28 km

Courtesy Z. Zeng
Three Cornered Hat (3CH) Method

- Derives random error characteristics using 3+ datasets
  - Includes measurement, representativeness, random errors
  - Assumes no correlation between datasets
- Refractivity error estimates shown

Tropopause not captured as well by GFS lower resolution

Courtesy J. Sjoberg
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Initial C2 Relative TEC Data

Two GPS TEC Arcs

Two GLONASS TEC Arcs
C2 Relative TEC Precision

- We use closely collocated observations from 2 COSMIC-2 satellites from the initial stages of the mission to estimate precision of the LEO relative TEC observations.
- We determine the relative TEC by subtracting the TEC value from each arc at the time they initially overlap.
- The std dev for GPS relative TEC for COSMIC-2 pairs is 0.14 TECU for GPS, and 0.15 TECU for GLONASS.
- A similar analysis for COSMIC-1 yields ~0.16 TECU std. dev. for GPS.

COSMIC-2 GPS Relative TEC
Mean = -0.01
Std Dev = 0.14

COSMIC-2 GLONASS Relative TEC
Mean = -0.05
Std Dev = 0.15

Courtesy N. Pedatella
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Neutral Atm Cal/Val and Plans

- Cal/val team from UCAR/COSMIC, CWB, JCSDA, NSPO, NOAA/STAR began work mid-August
- Multiple validation approaches, e.g. comparisons between C2 FMs, C2 vs. other missions and measurement techniques, NWP (O-B, O-A, impacts)
- TGRS v4.3.2 software patch in progress during September
- October dataset should be close to operational instrument configuration
- First public data/product release planned in November
  - External NWP centers get data at this time
- Validated products planned Feb 2020
  - Actual date will be driven by TGRS v4.4 software (space weather updates) schedule
Neutral Atm Cal/Val Schedule

Launch: Jul 16
Instrument Activation
Aug 16: Initial Products
Nov 2019: Provisional Data Release (Public)
Feb 2020: Validated Data Release / IOC
Mar 2021: Constellation FOC

Launch and early orbit operations
Checkout and commissioning
Weather cal/val
Weather operations

L = Launch
d = days
m = months
IOC = Initial Operational Capability
FOC = Full Operational Capability
Summary

• COSMIC-2 launched successfully on June 25, 2019
  – Spacecraft/instrument checkout complete
  – Instrument commissioning in progress
• COSMIC-2 processing is going well
  – Significant effort on mission simulations and experience with prior missions is paying off
  – Neutral atmosphere profile quality good
    • Further detailed comparisons coming throughout cal/val
    • TGRS software update in progress to address some issues
  – Initial ionosphere results positive
  – Team continues to work on instrument commissioning and cal/val
  – On track for first public data/product release in November 2019
Acknowledgements

• Thanks to the FORMOSAT-7/COSMIC-2 Program partners!
Upcoming IROWG C2 Presentations

• Schreiner, Performance Assessment and Requirement Verification of COSMIC-2 Neutral Atmospheric Radio Occultation Data, Th 13:00
• Meehan, The TriG Radio Occultation System on COSMIC-2 Early Performance Assessment, Th 13:20
• Sjoberg, Estimates of Errors in Radio Occultation and Multiple Reanalyses, Fri 10:20
• Braun, COSMIC-2 Early Orbit Space Weather Data Assessment and Validation Activity, Mon 11:00
• Sokolovskiy, Initial Assessment of the First Results of Sensing the Lower Troposphere with COSMIC-2, Tue 14:30
• Ho, NESDIS RO Science Studies and Quality Assurance through the STAR Integrated Cal/Val System, Tue 15:50
• Cao, The Significant Roles of COSMIC2 GNSS RO in NOAA Integrated Calibration/Validation System for NWP, Tue 16:10