Low-frequency gravity change from GPS data of COSMIC and GRACE: potential enhancement from COSMIC-2's GPS and SLR data

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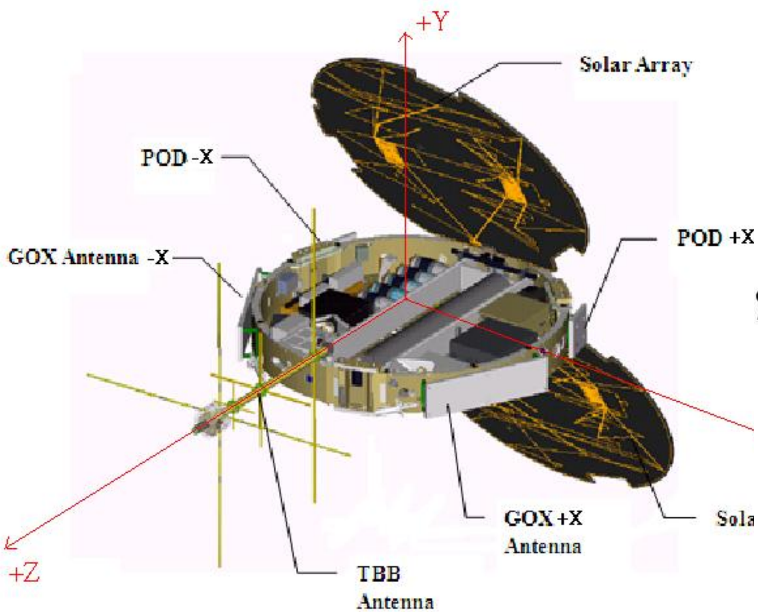
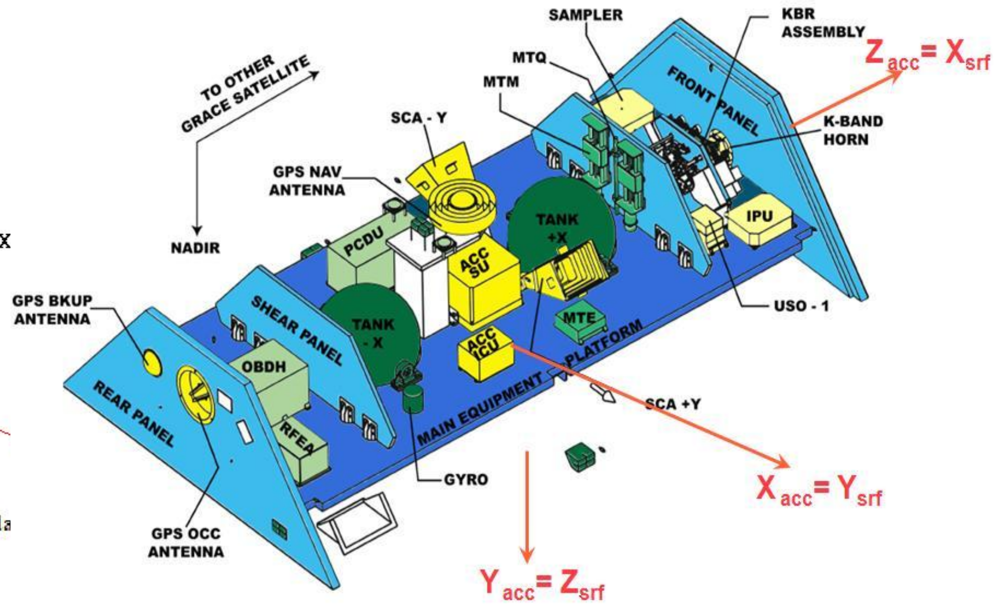
COSMIC and GRACE GPS payloads

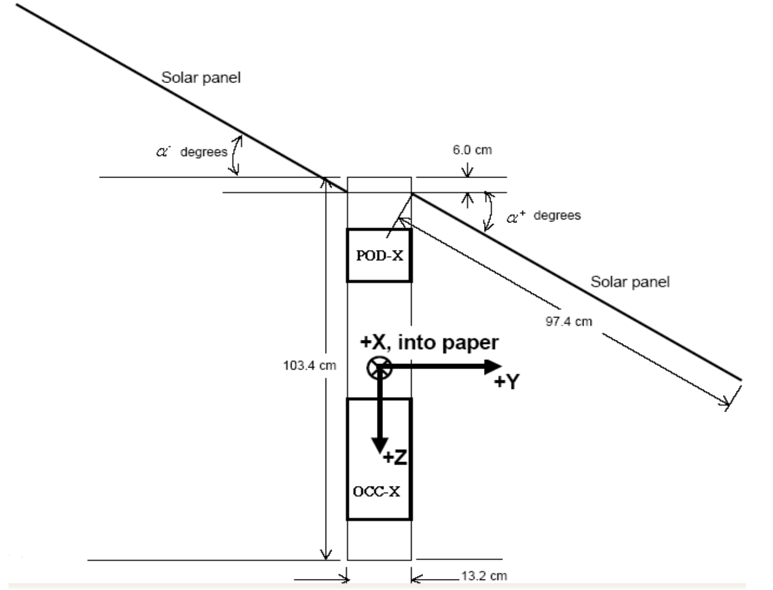




JPL blackjack receiver; patch antenna, not directed to zenith

JPL made, but USO controlled GPS receiver; performs better than COSMIC receivers

Spacecraft geometry of COSMIC satellite



- The geometry and dimension of a COSMIC satellite. The GPS antenna of GRACE is mounted 0.45 m above the COM along the radial direction.
- The table shows the coordinates of the two POD antenna centers of FM1 in the spacecraft coordinate frame.
- The angle between the line of coordinate origin- physical center of POD antenna and the +X or -X axis is 30°. The angle between the normal to the antenna patch and the +X or –X axis is 15°.

Coordinates	POD +X	POD -X
x	0.472	-0.472
y	0.000	0.000
z	-0.269	-0.279

Estimation of time-variable gravity harmonic coefficients from GPS: residual orbit and the two-step approach

Residual orbit: Kinematic orbit – dynamic orbit

Observation equation:

$$\Delta x_i = \sum_{k=1}^{6} c_k^i \Delta s_k(\Delta \bar{C}_{nm}, \Delta \bar{S}_{nm}) + \Delta r_i + \varepsilon_i, \quad i = 1, 2, 3$$

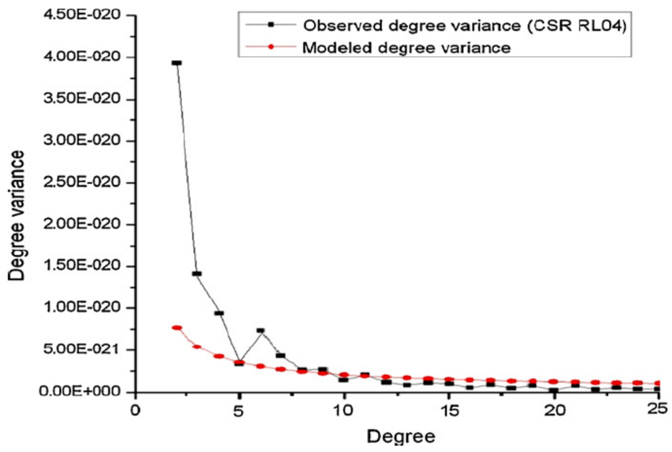
Least-squares solution for GMM with constraint

$$\hat{X} = (A^T P_l A + P_x)^{-1} A^T P_l L$$

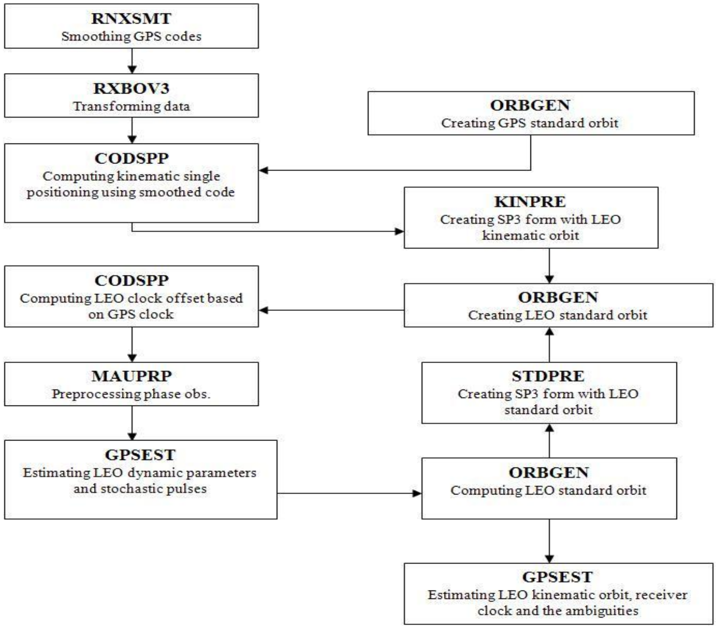
Modified Kaula's Rule for time-variable harmonics

$$P_X = diag(\frac{1}{\sigma_n^2})$$

$$\bar{\sigma}_n^2 = \frac{1}{2n+1} \sum_{m=0}^{n} (\bar{J}_{nm}^2 + \bar{K}_{nm}^2) = \alpha \cdot n^{\beta} \approx 5.04 \times 10^{-21} n^{-1.7130}$$



Precise kinematic orbit determination using GPS data



- The kinematic approach estimates the kinematic parameters of an orbit arc, including epoch coordinate components, receiver clock errors and phase ambiguities.

- Bernese 5.0 uses the reduced dynamic orbit as a priori orbit for the kinematic orbit.

- The zero-differenced ionosphere-free GPS measurements are used

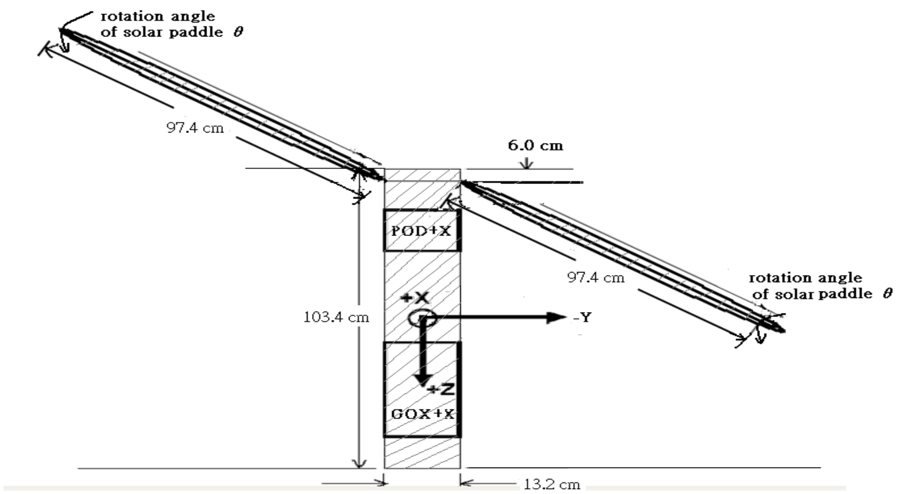
The overlapping arc differences of COSMIC dynamic orbits, based on data from Day 214 to 239, 2006 (cm)

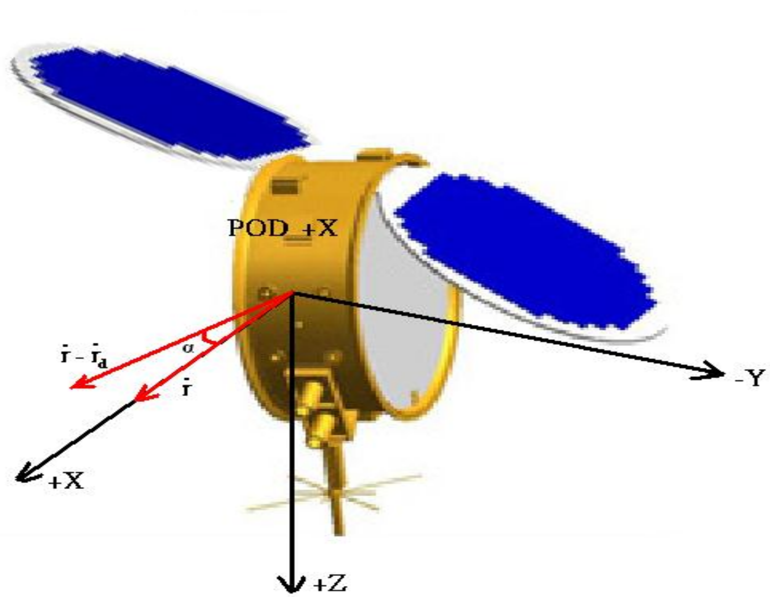
	Radial	Along-track	Cross-track
FM1	2.62	2.23	2.74
FM2	1.83	1.63	1.50
FM3	2.45	2.45	2.62
FM4	2.25	2.77	2.79
FM5	1.98	2.21	2.99
FM6	2.10	2.06	2.86

Reference dynamic orbits for COSMIC and GRACE using GEODYN II

Model/parameter	Standard
Conventional inertial reference frame	J2000
N-body	JPL DE-403
Earth gravity model	GGM03S
Polar motion	IERS standard 2000
Reference ellipsoid	a_e =6378136.3m , f =1/298.257
GM	396800.4415 km^3s^{-2}
Ocean tides	GOT00.2
Solid Earth tides	IERS standard 2000
Atmosphere density	Mass Spectrometer Incoherent Scatter (MSIS) Empirical Drag Model
Earth radiation pressure	Second-degree zonal spherical harmonic model
Solar radiation pressure	one coefficient every 1.5 hours
Atmosphere drag	one coefficient every 1.5 hours
General accelerations	9 parameters every 1.5 hours

Dimensions of the main part and solar panels of a COSMIC LEO (top), velocity vector $\dot{\mathbf{r}}$ and LEO-to-atmosphere vector $(\dot{\mathbf{r}} - \dot{\mathbf{r}}_\mathbf{d})$





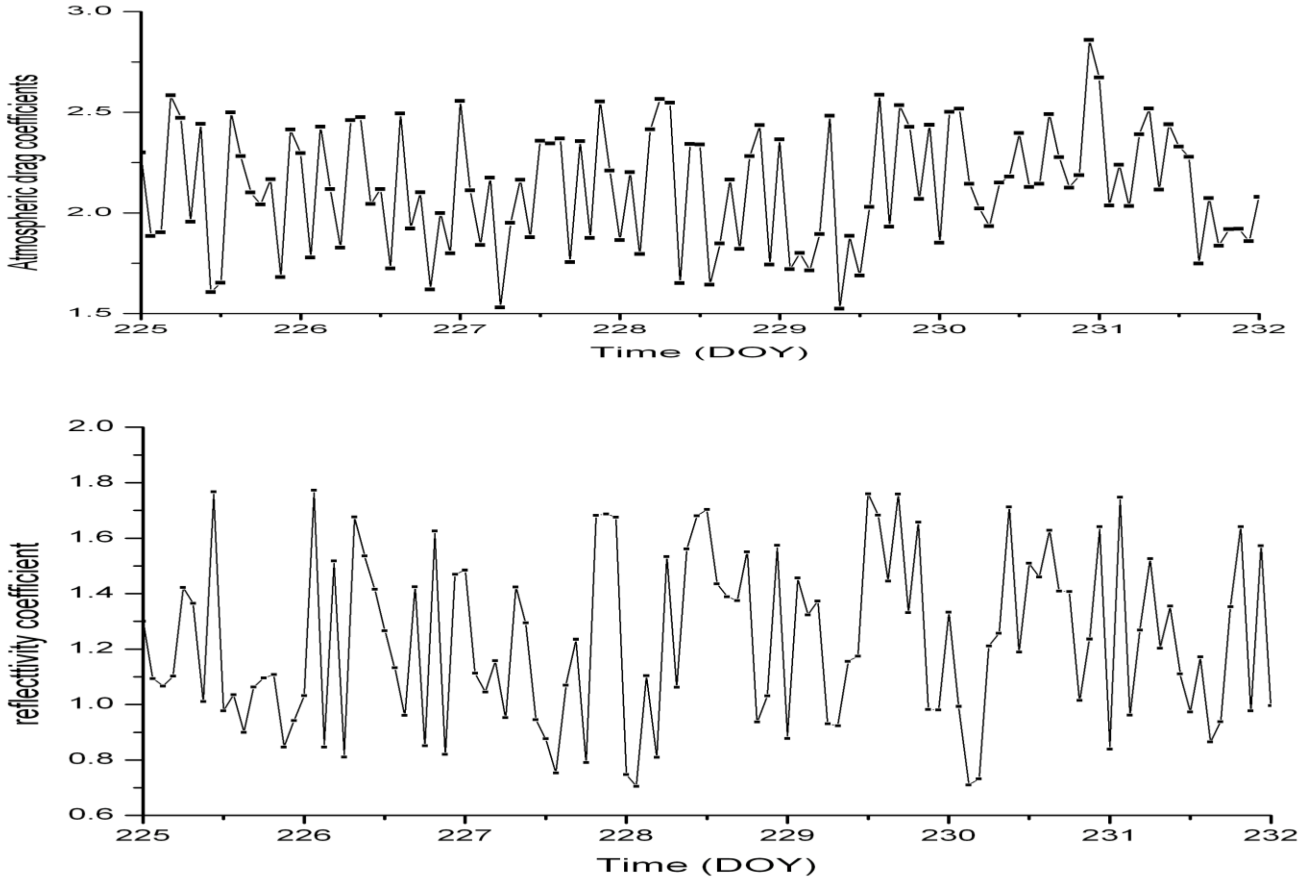
A COSMIC spacecraft travels in a manner that the POD+X antenna points to the flight direction. The total area in the flight direction is

$$A_T = A_{main} + A_{panel}$$

The effective area is computed by

$$A_d = A_T \cos^{-1}(\dot{\mathbf{r}} \cdot (\dot{\mathbf{r}} - \dot{\mathbf{r}}_\mathbf{d}) / |\dot{\mathbf{r}}| |\dot{\mathbf{r}} - \dot{\mathbf{r}}_\mathbf{d}|)$$

Estimated atmospheric drag coefficients (top) and solar reflectivity coefficients of FM 5 from Day 225 to 232, 2006.



These estimated coefficients vary over time, and the mean values/standard deviations of the drag and reflectivity coefficients are 2.12/0.29 and 1.23/0.30, respectively.

Numbers of daily observation files and daily usable kinematic orbit files from September 2006 to December 2007 for GPS-only gravity recovery

Numbers of daily observation files and daily usable kinematic orbit files from September 2006 to December 2007.

Month	FM1	FM2	FM3	FM4	FM5	FM6	GRA	GRB
2006.9	26[a]/26[b]	15/14	26/26	27/27	29/29	23/23	30/30	30/30
2006.10	27/24	30/27	27/27	28/25	28/28	25/24	31/31	31/31
2006.11	28/28	16/16	30/29	29/29	28/27	29/25	30/30	30/30
2006.12	27/27	26/26	26/26	29/29	29/29	22/21	31/31	28/28
2007.1	29/29	30/29	27/27	29/29	29/28	20/20	31/31	31/31
2007.2	26/26	27/27	28/27	28/28	28/28	16/14	28/28	28/28
2007.3	29/29	6/6	31/31	28/23	30/30	30/30	31/31	31/31
2007.4	30/29	13/13	30/29	23/18	29/29	20/20	30/30	30/30
2007.5	31/30	12/10	30/28	23/21	30/29	31/31	31/31	31/31
2007.6	30/30	22/21	25/25	30/30	30/30	26/26	30/30	30/30
2007.7	30/30	29/29	16/14	30/30	31/27	31/31	31/31	30/30
2007.8	31/31	18/18	17/17	30/29	31/30	29/28	31/31	31/31
2007.9	28/27	8/8	7/7	30/30	29/28	7/7	30/30	30/30
2007.10	28/15	27/27	21/21	31/31	31/31	0/0	31/31	31/31
2007.11	29/28	13/13	7/4	30/30	28/26	12/12	30/30	30/30
2007.12	27/27	27/27	23/23	31/29	29/27	28/27	31/31	30/30

[a] Number of daily observation files.
[b] Number of daily usable kinematic orbit files.

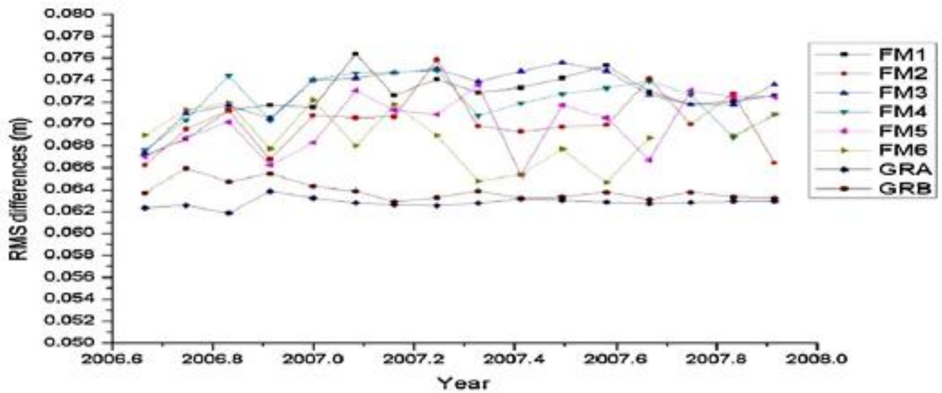
RMS differences between reference and kinematic orbits

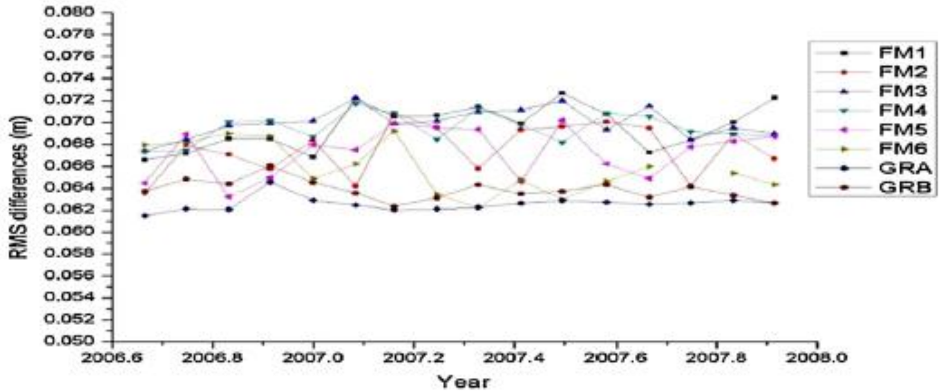
Monthly RMS differences between reference and kinematic orbits from September 2006 to December 2007 (unit: cm).

Satellite	Radial	Alone-track	Cross-track
FM1	7.24	6.96	6.66
FM2	7.02	6.76	6.46
FM3	7.30	7.00	6.78
FM4	7.25	6.95	6.68
FM5	7.00	6.73	6.31
FM6	6.88	6.59	6.33
GRA	6.28	6.26	5.01
GRB	6.38	6.38	5.42

Residual orbits reveal time-varying gravity

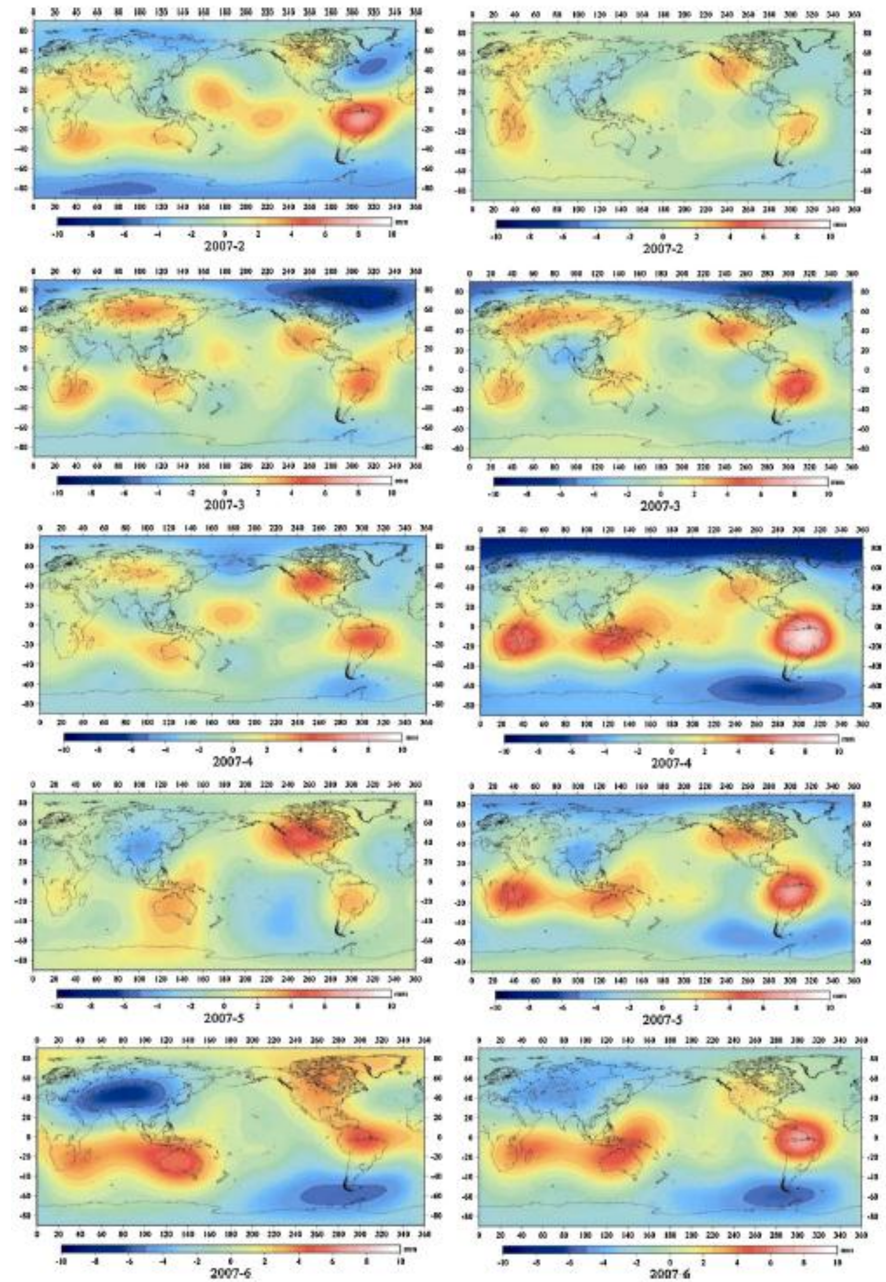
- Dynamic orbits includes a static gravity effect and all other forces
- Variations in radial (top), along-track and cross-track (bottom) directions are affected by time-varying gravity, plus un-modeled effects and ill-modeled effects





Geoid change (mm) to degree 5 from GRACE KBR (left) and GPS (Sep 2006-June 2007)

- Estimated coefficients below degree 10 may achieve >1 in signal-to-noise ratio
- The gravity variation from GPS is relative to GGM03 S
- Active hydrological changes found from both GPS and GRACE solutions
- Seasonal pattern from GPS is consistent from on year to another
- J2 from GRACE may contain biases from its polar orbit and long-period tidal aliases; this contributes partly to the difference between the GRACE and GPS solutions



Changes in J2, J3 and J4: a comparison between COSMIC GPS (NCTU), GRACE KBR (CSR) and SLR

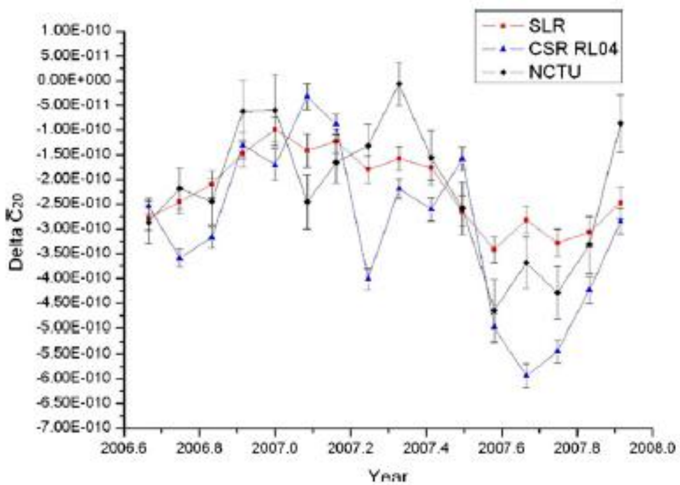


Fig. 4. Time series of $\Delta\bar{C}_{20}$ (change of second zonal coefficient) from NCTU, SLR, and CSR RL04 from September 2006 to December 2007.

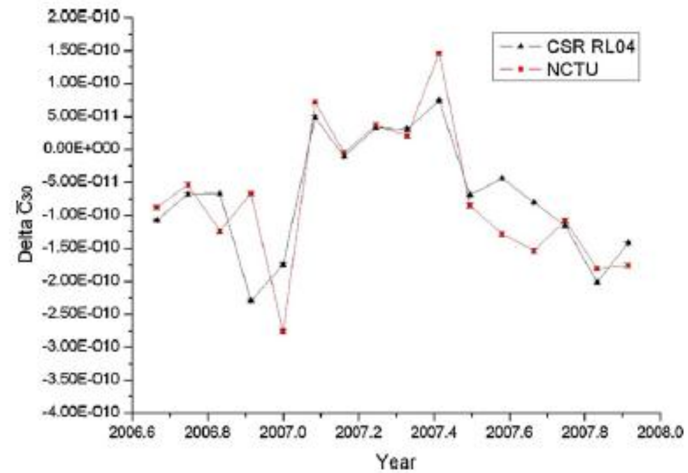


Fig. 6. Time series of $\Delta\bar{C}_{30}$ (change of third zonal coefficient) from NCTU and CSR RL04 from September 2006 to December 2007.

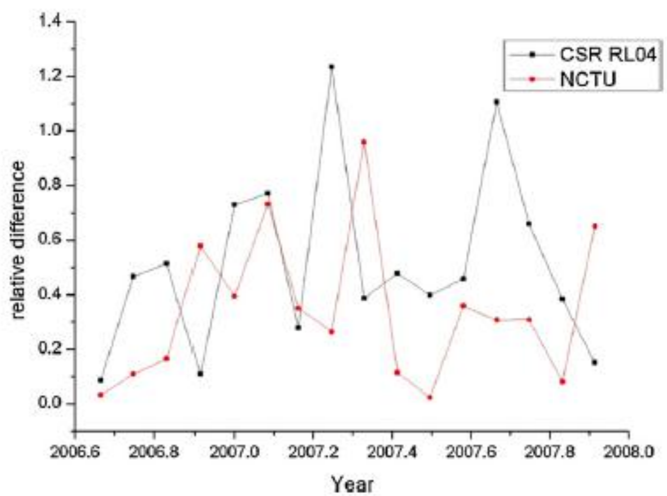


Fig. 5. Relative differences of $\Delta\bar{C}_{20}$ of the NCTU and CSR RL04 coefficients with respect to the SLR-derived coefficients from September 2006 to December 2007.

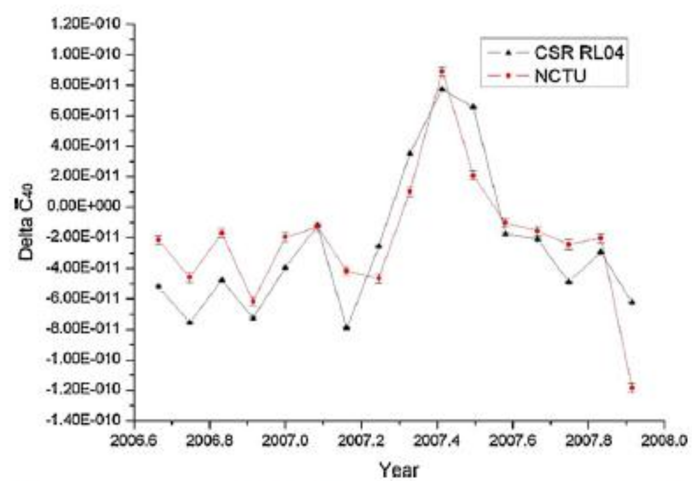


Fig. 7. Time series of $\Delta\bar{C}_{40}$ (change of fourth zonal coefficient) from NCTU and CSR RL04 from September 2006 to December 2007.

Correlations be tween gravity solutions from GPS, SLR and GRACE KBR

Correlation coefficients between zonal harmonic coefficients from two solutions.

Coefficient	NCTU-GRACE	NCTU-SLR	SLR-GRACE
$\Delta\bar{C}_{20}$	0.64	0.82	0.76
$\Delta\bar{C}_{30}$	0.81	N/A	N/A
$\Delta\bar{C}_{40}$	0.82	N/A	N/A

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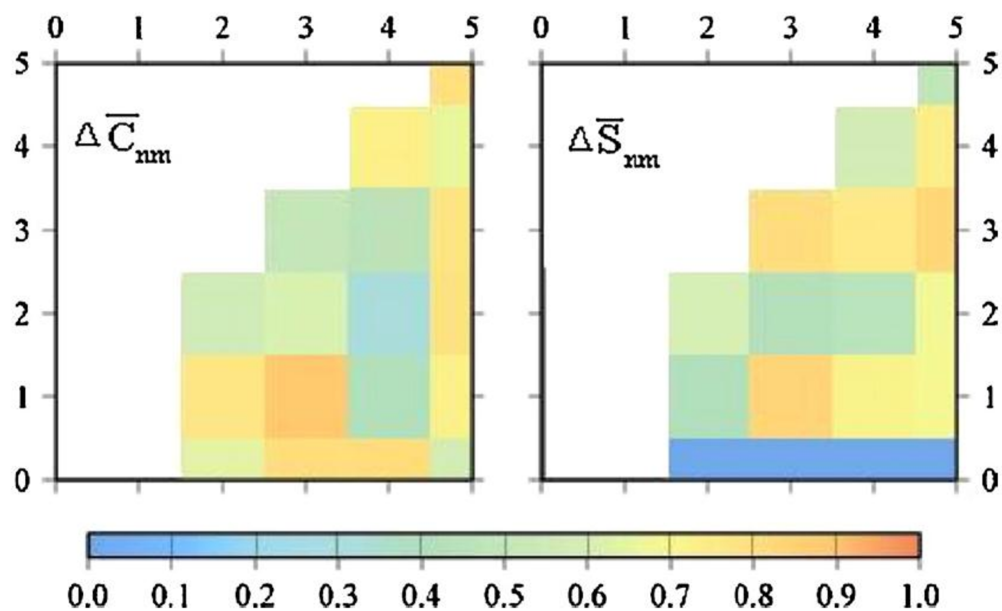
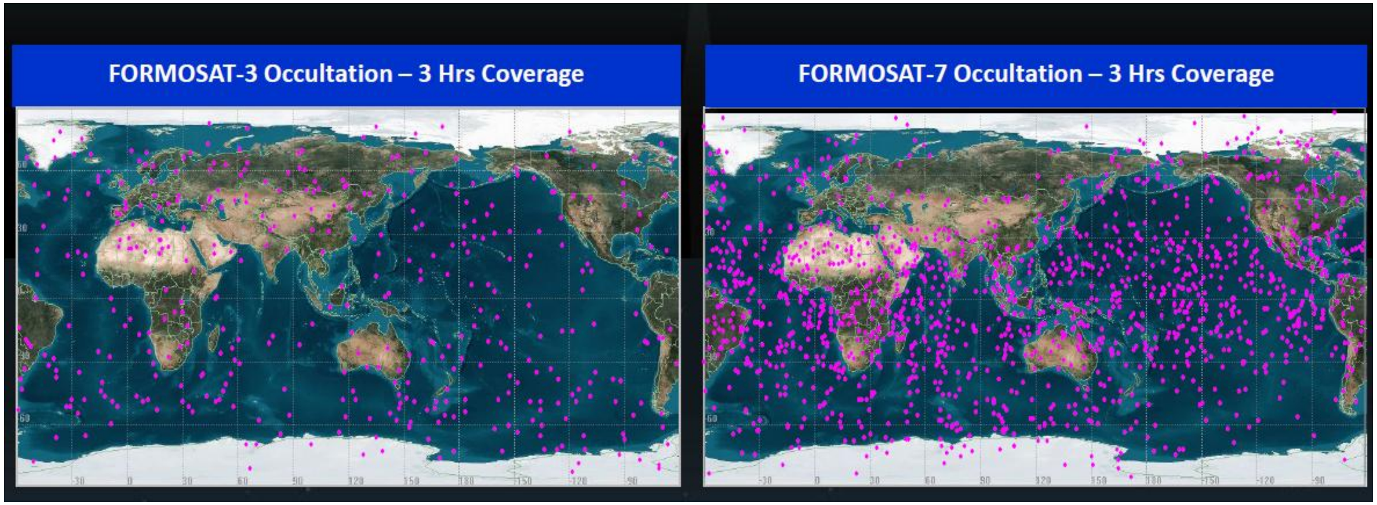
Correlation coefficients between harmonic coefficients from GRACE KBR and from GPS

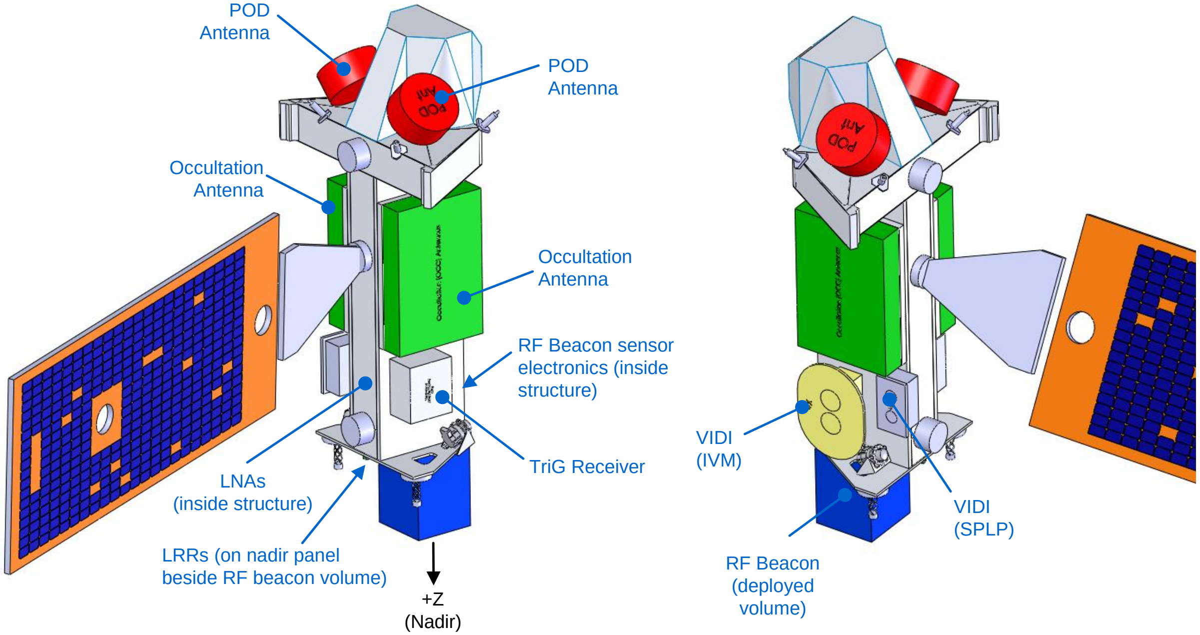


COSMIC-2: a follow-on mission of COSMIC for RO to atmosphere and ionosphere

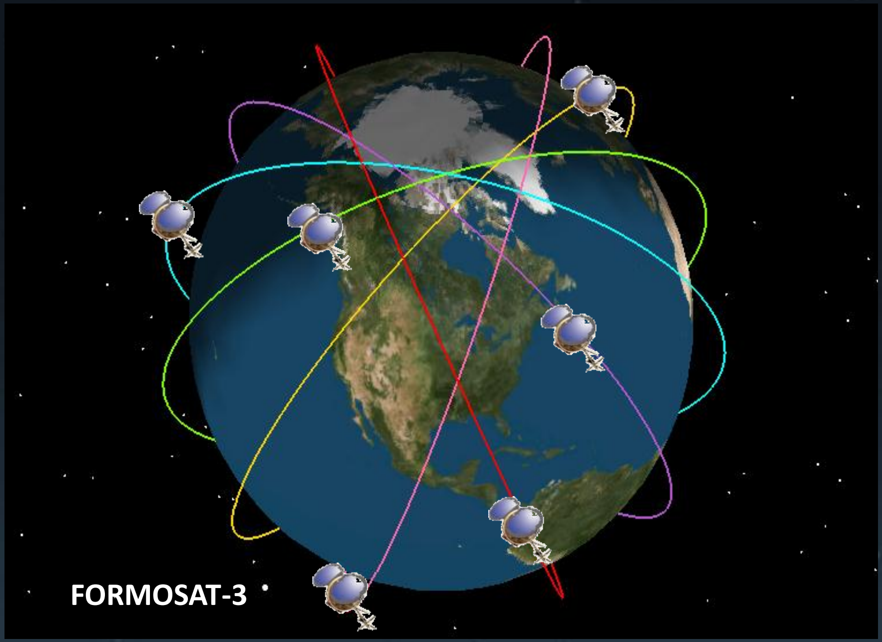
(see http://www.nspo.narl.org.tw/2011/tw/projects/FORMOSAT-7/program-description.html)

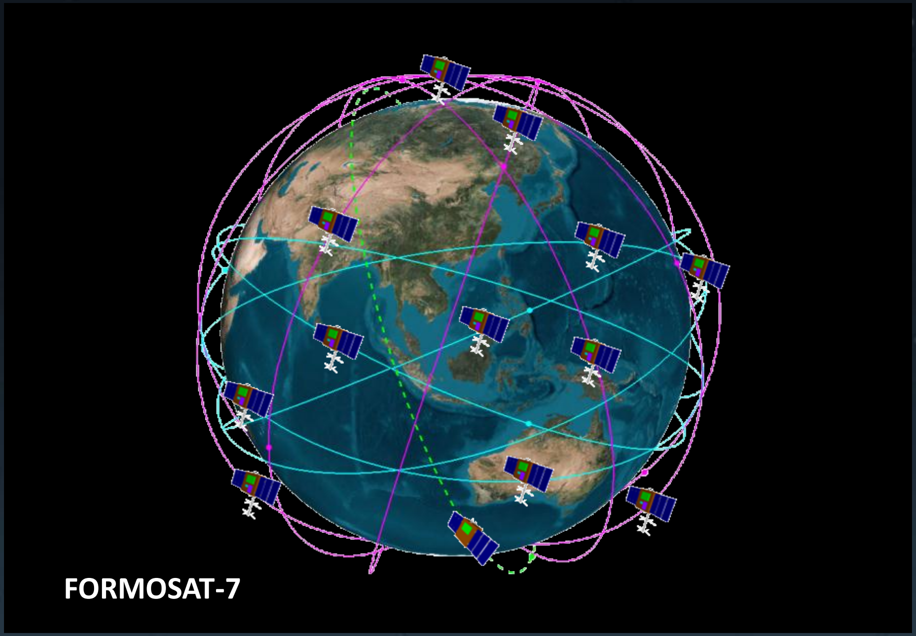


- TriG GNSS receiver
- Laser retroreflector
- Low inclination (24 deg) high inclination (72 deg), 13 satellites

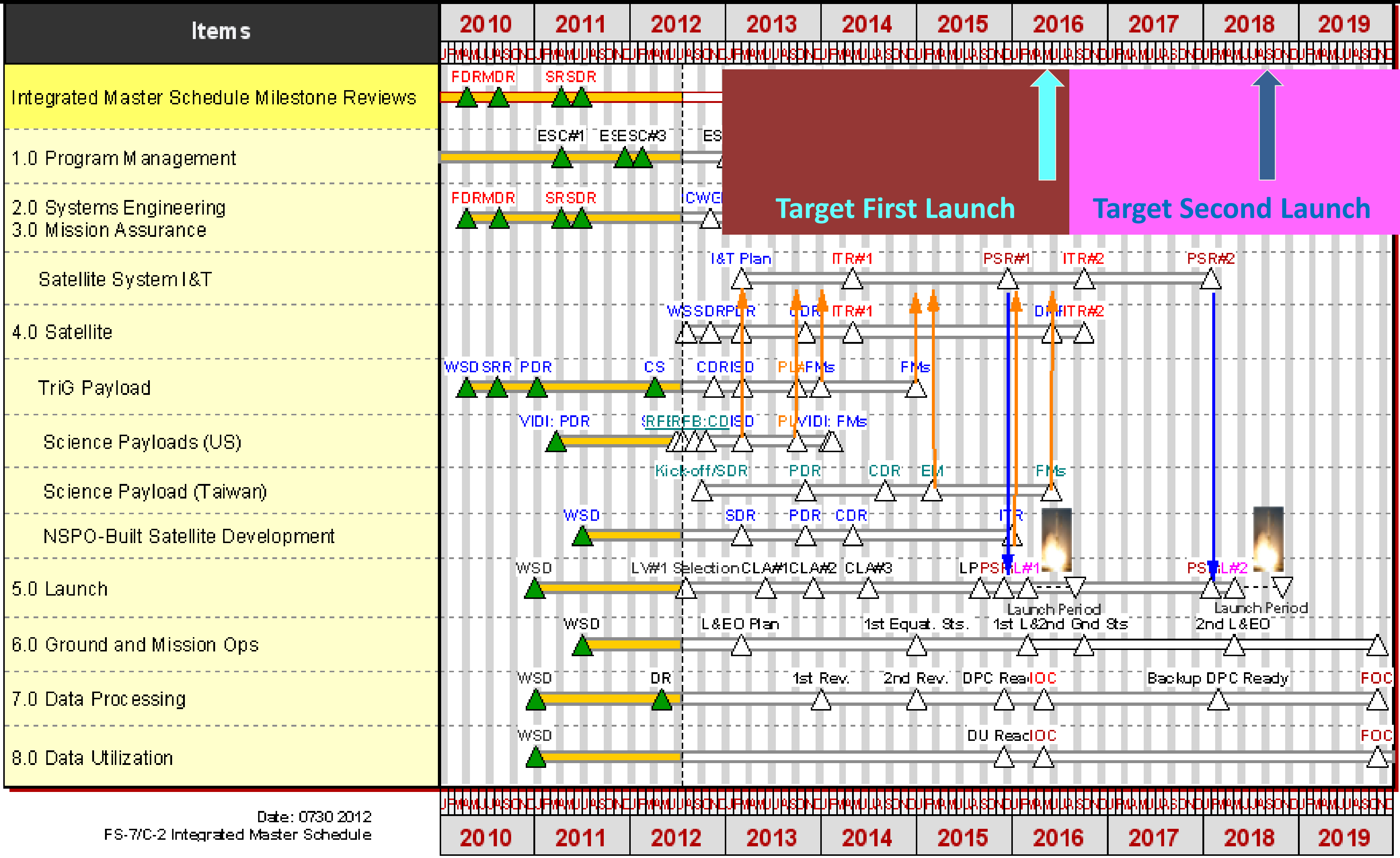


COMPARISON OF COSMIC AND COSMIC-2 ORBIT CONFIGURATIONS





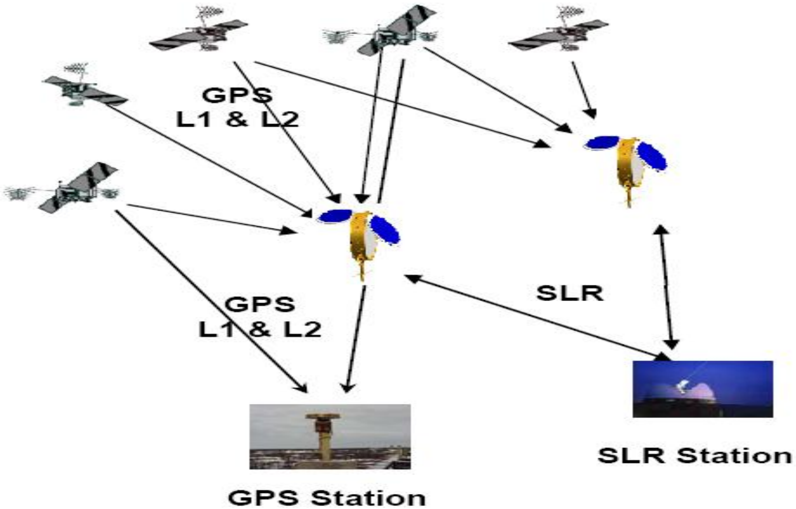
FORMOSAT-7 / COSMIC-2 mission schedule



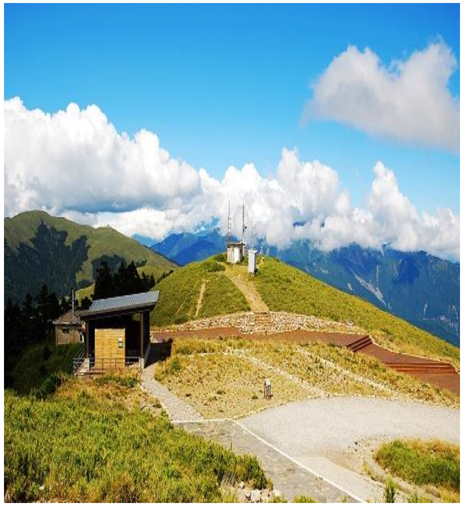
The role of COSMIC-2 SLR data in gravity recovery

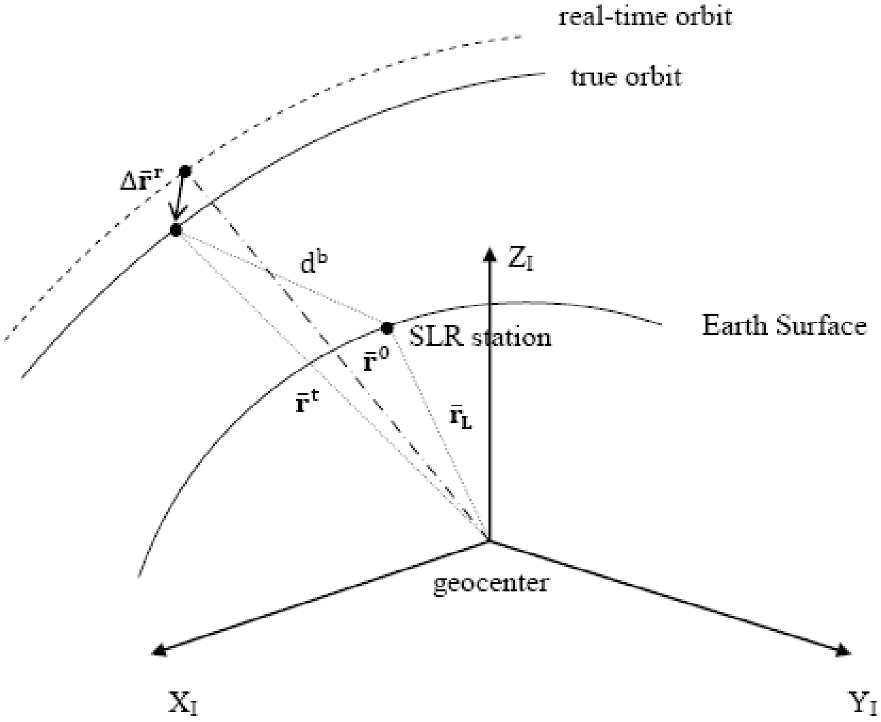
- The key data of COSMIC-2 for gravity recovery are still GPS
- Current COSMIC satellites use GPS receivers and antennae less accurate than those on GRACE satellites, yielding degraded orbits
- The SLR data of COSMIC-2 can validate and improve COSMIC-2 orbits from GNSS signals, and determine problems in COSMIC-2 satellite attitudes
- Combine normal equations from GPS (COSMIC-2) and SLR (Lageos-1 and-2 and other geodetic satellites) for improved time-varying gravity solutions

Improving real-time orbit of COSMIC-2 using SLR



Candidate SLR site in Taiwan





For real-time GPS reflection needing cm orbit accuracy

Conclusions and future work

- The kinematic orbits and dynamic orbits (a static gravity field is included) of COSMIC and GRACE result in time-varying low-frequency gravity consistent with GRACE KBR result
- J2 change from GPS is correlated with the SLR result at 0.82 . J3 and J4 changes are consistent with GRACE KBR result
- Extension of gravity time series using GPS data from CHAMP, COSMIC and GRACE from 1999 to present.
- Simulations will be made to see the result of COSMIC-2 GPS and SLR data in gravity recovery