GSPM13: An Updated Empirical Model for Solar Radiation Pressure Forces Acting on GPS Satellites

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Abstract

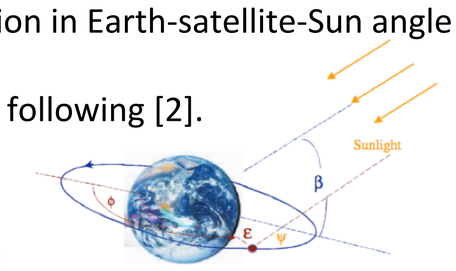
Solar Radiation Pressure (SRP) forces are the largest non-gravitational perturbations acting on Global Positioning System (GPS) satellites that orbit the Earth at an altitude of approximately 20,000 km. Due to the unprecedented levels of precision and accuracy reached in the field of GPS data processing, the effects of SRP mis-modeling have emerged as a limiting error source for GPS precision orbit determination (POD). We present the methodology adopted to generate an updated set of models for SRP forces acting on GPS satellites and evaluate them by way of several metrics. This set of models, referred to as GSPM13, is empirically derived based on over 20 years of orbit solutions, enabling the development of separate models for each GPS family spanning blocks I through IIF. The GSPM13 model performance is evaluated by means of multi-day orbit predictions as well as network solution orbit determination. A wide range of internal and external metrics including orbit precision, solar scale parameter estimation and carrier phase ambiguity resolution are used to validate the models. Use of GSPM13 results in significant improvement for blocks I, IIR and IIF in particular, relative to T10 for block I and prior versions of the GSPM models (e.g., GSPM04 and GSPM10). Fourth-day 3D-RMS orbit prediction errors decrease by about 70%, 3% and 6% for block I, IIR and IIF, respectively, while orbit precision improves by up to 3%.

Highlights

- Iteration on flight-data-based estimation process developed by Bar-Sever and Kuang [1] and refined by Sibthorpe et al. [2].
- Dynamical fit to 5- and 10-day-arc reference trajectories generated by combining daily reprocessed orbits spanning 1992-2013 [3].
- Block specific approach tailored to accommodate outstanding behaviors exhibited by some satellites → separate models specific to individual satellites or subgroups of satellites within a block.
- Most conspicuous improvements in performance seen for blocks I and IIF when comparing to T10 and GSPM10 models, respectively.
- Negligible change in performance wrt. GSPM04/GSPM10 for block II/IIA
- GSPM13 used as a priori model in JPL IGS AC contribution to IGS 2nd reprocessing effort.

Analytical Model

SRP force represented as truncated Fourier expansion in Earth-satellite-Sun angle
SX_n, CY_n, CZ_n: coefficients to be estimated,
with SX_2 and CY_1: β-angle dependent and modeled following [2].



$$F_x = \lambda k \sum_{n=1,2,3,5,7} SX_n \sin(n\varepsilon)$$

$$F_y = mCY_0 + \lambda \sum_{n=1,2} CY_n \cos(n\varepsilon)$$

$$F_z = \lambda k \sum_{n=1,3,5} CZ_n \cos(n\varepsilon)$$

$$where: \lambda = 10^{-5}(AU/r)^2$$

CY_0: Y-bias acceleration
β: <Earth-Sun line, spacecraft orbital plane> angle
ε: Earth-satellite-Sun angle
AU: astronomical unit
k: dimensionless factor
m: spacecraft mass (kg)
r: Sun-spacecraft distance (km)

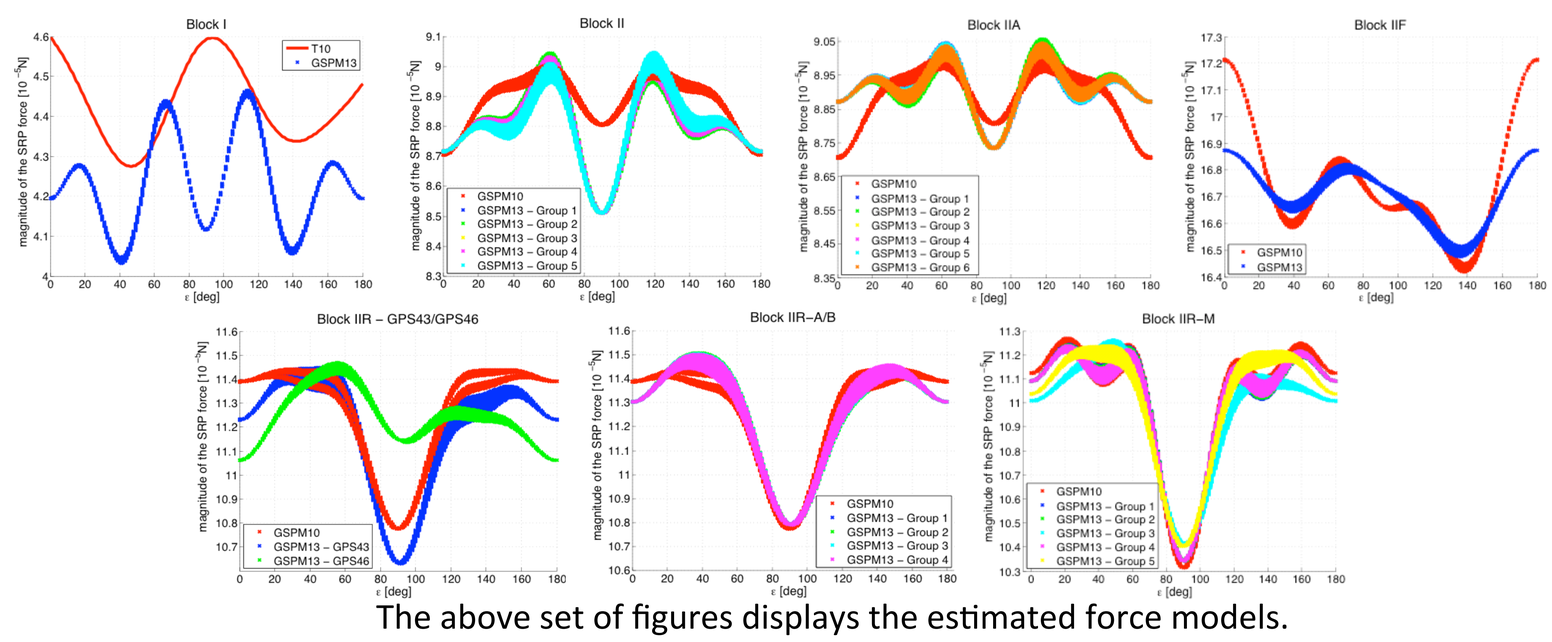
Estimated Force Models and Comparison with GSPM10

Satellites are sorted into different groups based on the parameterization of the SX_2 coefficient.
Custom models are created for each group and a few individual satellites that clearly stand out.

I	One single group					
II	GPS13 GPS14 GPS16 GPS19	GPS15 GPS20	GPS17	GPS18	GPS21	
IIA	GPS23 GPS29 GPS30	GPS24 GPS28 GPS40	GPS25 GPS33 GPS36	GPS26 GPS27	GPS31 GPS32	GPS34 GPS35 GPS37 GPS38 GPS39
IIR-A/B	GPS41 GPS56	GPS44 GPS45 GPS47	GPS51 GPS54 GPS59	GPS60 GPS61	GPS43	GPS46
IIR-M	GPS48 GPS49 GPS50	GPS53 GPS58	GPS52	GPS55	GPS57	
IIF	One single group					

Groups for which models are created

Group 1
Group 2
Group 3
Group 4
Group 5
Group 6

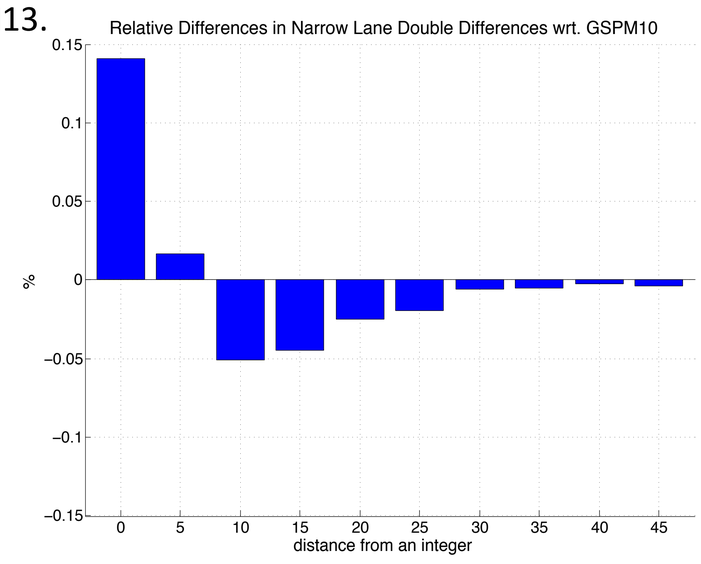


The above set of figures displays the estimated force models.
The thickness of each line is due to β-angle variations.

Performance Analysis

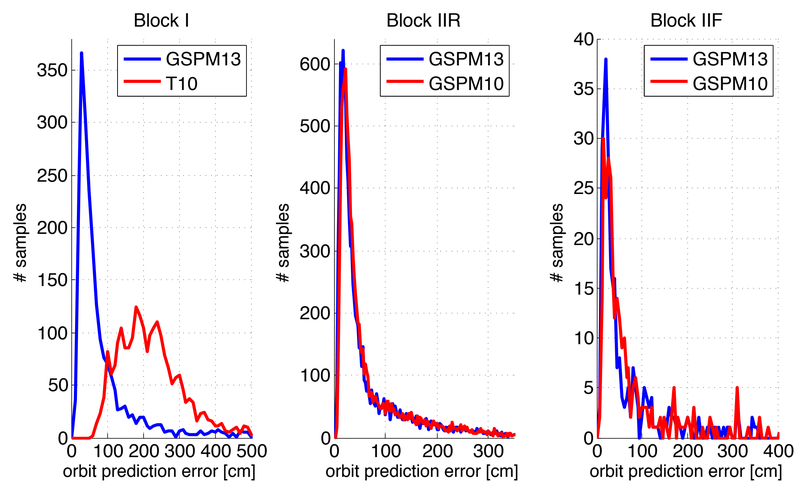
Network POD Solution Analysis:

- One month per year from 1993 to 2013 processed using identical data, estimation strategies and software. Only difference in modeling strategy lies in the SRP model used: GSPM13 vs. T10/GSPM10.
- Small **improvements in orbit precision**, but most noticeably for 1994-1996 due to significant improvements in modeling **Block I** (maximum precision increase = 3.8%).
- **Resolution of phase ambiguities slightly improved** when using GSPM13.



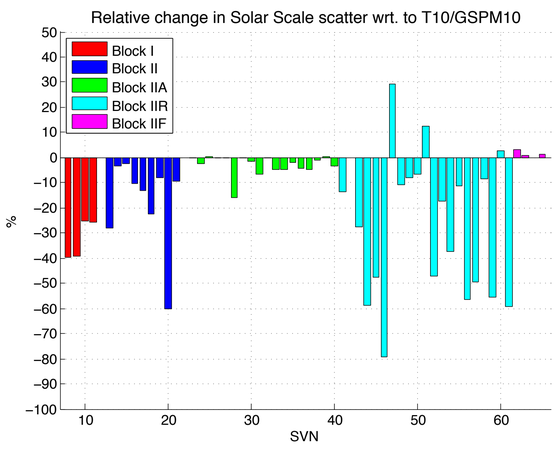
Orbit Prediction Error Analysis:

- Methodology: fit to reference orbits (IGS/JPL final products) over 3 days, predict trajectory for 4 days based on 3-day fit and compare 4th day of prediction to reference orbit.
- Use of GSPM13 leads to **significant reduction in orbit prediction error** for blocks I, IIR and IIF. Negligible change observed for blocks II and IIA (hence not shown here).



Eclipsing and non-eclipsing periods both included when generating the histograms shown here. The orbit prediction data sets consist of weekly solutions spanning 1994-2013.

- **Scatter in solar scale estimates reduced in** GSPM13 solutions relative to GSPM10 solutions (absolute differences of the order of 1e-3)
- Better centering of solar scale estimates around nominal value of 1 for GSPM13 solutions overall (not shown here).



References

1. Bar-Sever, Y. and Kuang, D. (2004), "New Empirically Derived Solar Radiation Pressure Model for GPS Satellites", The Interplanetary Network Progress Report 42-159
2. Sibthorpe, A. et al. (2010), "Empirical Modeling of Solar Radiation Pressure Forces Affecting GPS Satellites", AGU Fall Meeting 2010
3. Desai, S. et al. (2012), "The JPL IGS Analysis Center: Status and Plans", IGS Workshop 2012

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