Performance Assessment and Improvements for the FORMOSAT-5 Onboard Orbit Propagator Using GPS Ephemeris

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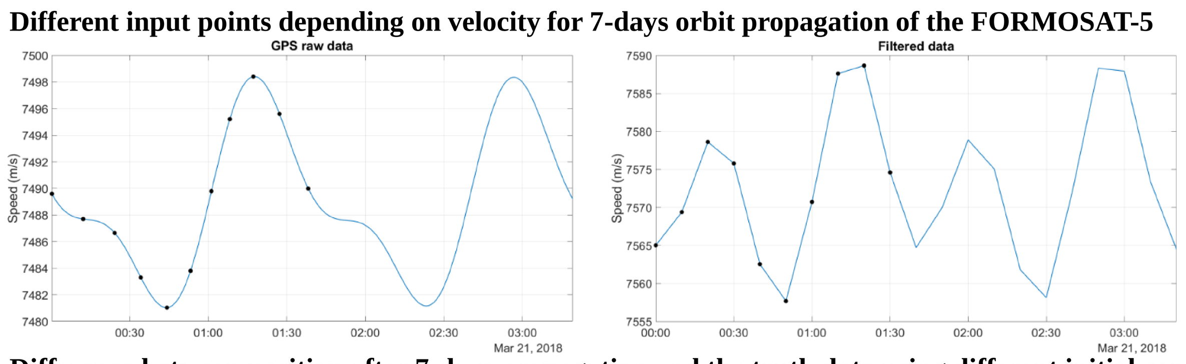
ABSTRACT

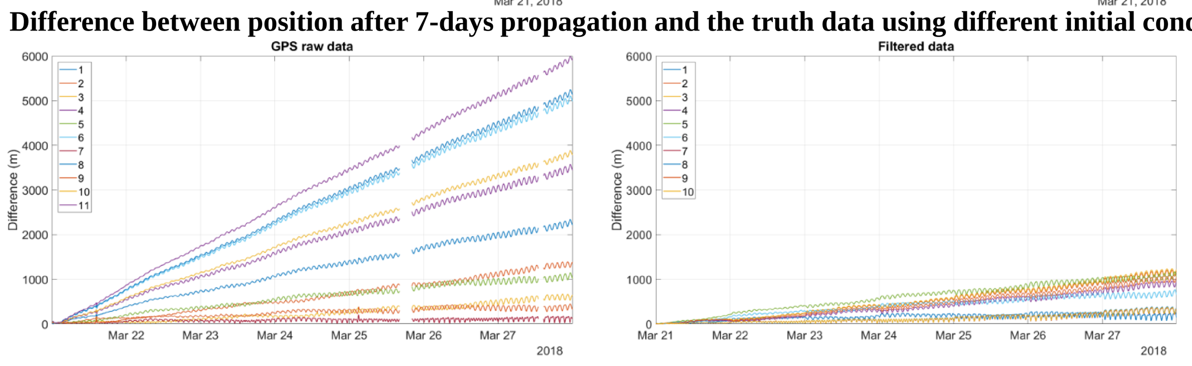
Launched in 2017, FORMOSAT-5 is a spacecraft located on a 720 km Sun synchronous orbit carrying indigenously developed payloads for Earth observation and in-situ ionospheric measurements. The FORMOSAT-5 attitude and orbit control subsystem (AOCS) contains a navigation filter utilizing a numerical orbit propagator to provide estimates of spacecraft inertial position and velocity when the onboard GPS receiver is not available. Times during which the onboard GPS is available provide an unique opportunity to assess the performance of the orbit propagator. In this paper, we report the variation of the FORMOSAT-5 orbit propagation error due to different orbit perturbations by using the built-in High Precision Orbit Propagator (HPOP) in the Systems Tool Kit (STK) and our self-made MATLAB orbit propagator. The effects on orbit propagation error by introducing drag effects from various empirical thermospheric models is also explored. The results will be used to improve navigation and tracking functions for future Taiwanese satellites and also provide insight into the neutral density modeling capability of current empirical thermosphere models, which are also a key tool for understanding thermosphere and ionosphere variability.

DIFFERENCES IN INITIAL CONDITIONS

Different input points depending on velocity for 7-days orbit propagation of the FORMOSAT-5



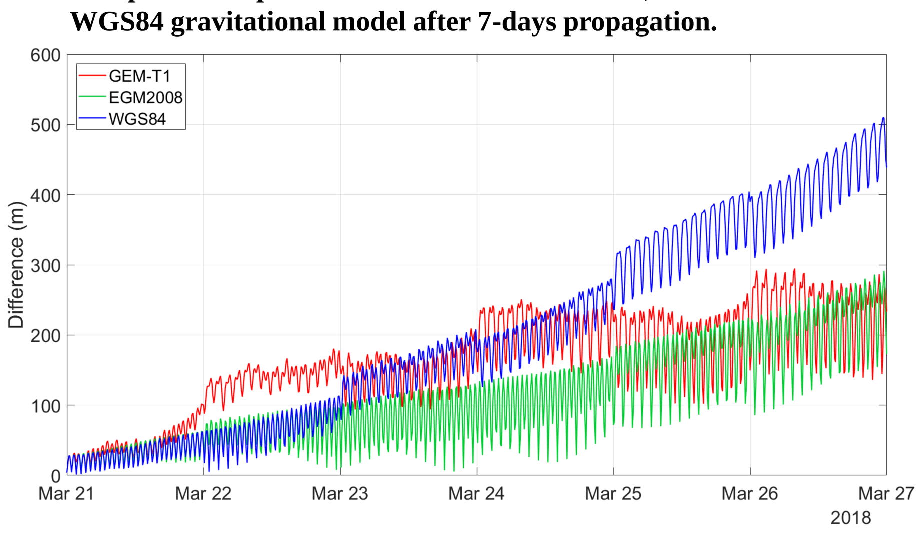
Difference between position after 7-days propagation and the truth data using different initial conditions



- The spacecraft speed varies considerably between the raw onboard GPS data (left) and batch least-squares filtered (right) ephemeris.
- The maximum position error at the end of 7 days propagation reach nearly 6 km when using the raw GPS data (left). The error is much lower when the filtered data (right) is used as truth and for the initial condition.

EFFECT OF GRAVITATIONAL MODELS

Comparison of position error between GEM-T1, EGM2008 and WGS84 gravitational model after 7-days propagation.



- The uneven mass distribution of the Earth will cause asymmetries in the gravitational force applied on the satellite.
- Numerical orbit propagators use spherical harmonic gravitational models to simulate the distribution of gravity.
- We compare three kinds of the gravitational models over 7-days of orbit propagation: Goddard Earth Model T1 (GEM-T1), Earth Gravitational Model 2008 (EGM2008), World Geodetic System 1984 (WGS84).

All of the models are run using 21 degrees and orders by using HPOP. The integrator is 4th order Runge-Kutta with 1.2096 sec step size. The effect of gravitational model selection is few hundreds meters of position error.

EFFECT OF DRAG

- One of the most significant but sophisticated orbit perturbation in LEO.
- Equation of drag:

$$\vec{a}_{drag} = -\frac{1}{2}\rho\frac{c_D A}{m}v_{rel}^2\frac{\vec{v}_{rel}}{|\vec{v}_{rel}|}$$

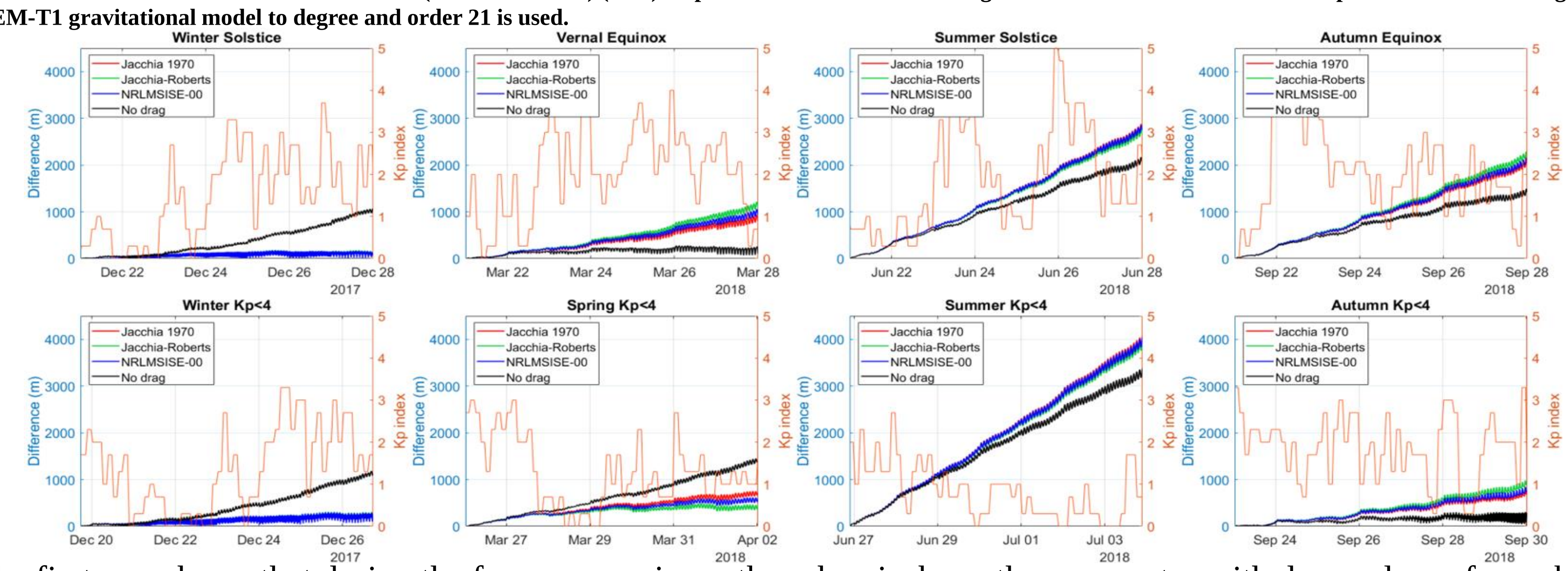
ρ : atmospheric density, estimated by empirical atmospheric models. The estimation of the models will depend on the input of the F10.7 solar radio flux index, geomagnetic indices and the way of processing them.

c_D : coefficient of drag, should consider the reaction between molecules and the satellite's surface using real gas dynamics simulations for the highest accuracy in the density of thermosphere. This calculation is too complicated for onboard or operational use, and a simplified estimate is usually used.

$\frac{A}{m}$: area to mass ratio, area is defined as the cross-section of the satellite, which is dependent upon spacecraft attitude. Mass will also change if there is consumption of propellant.

$\vec{v}_{rel}$: relative velocity between the satellite and atmosphere, not only the velocity of the satellite but also the wind in upper atmosphere and the corotation of the atmosphere with the earth.

Comparison between propagation position error with drag calculated using the Jacchia 1970 (red), Jacchia-Roberts (green), and Naval Research Laboratory Mass Spectrometer Incoherent Scatter Model 2000 (NRL MSISE-00) (blue) empirical models. 4th order Runge-Kutta method with 1.2096 sec step size is chosen as integrator. GEM-T1 gravitational model to degree and order 21 is used.

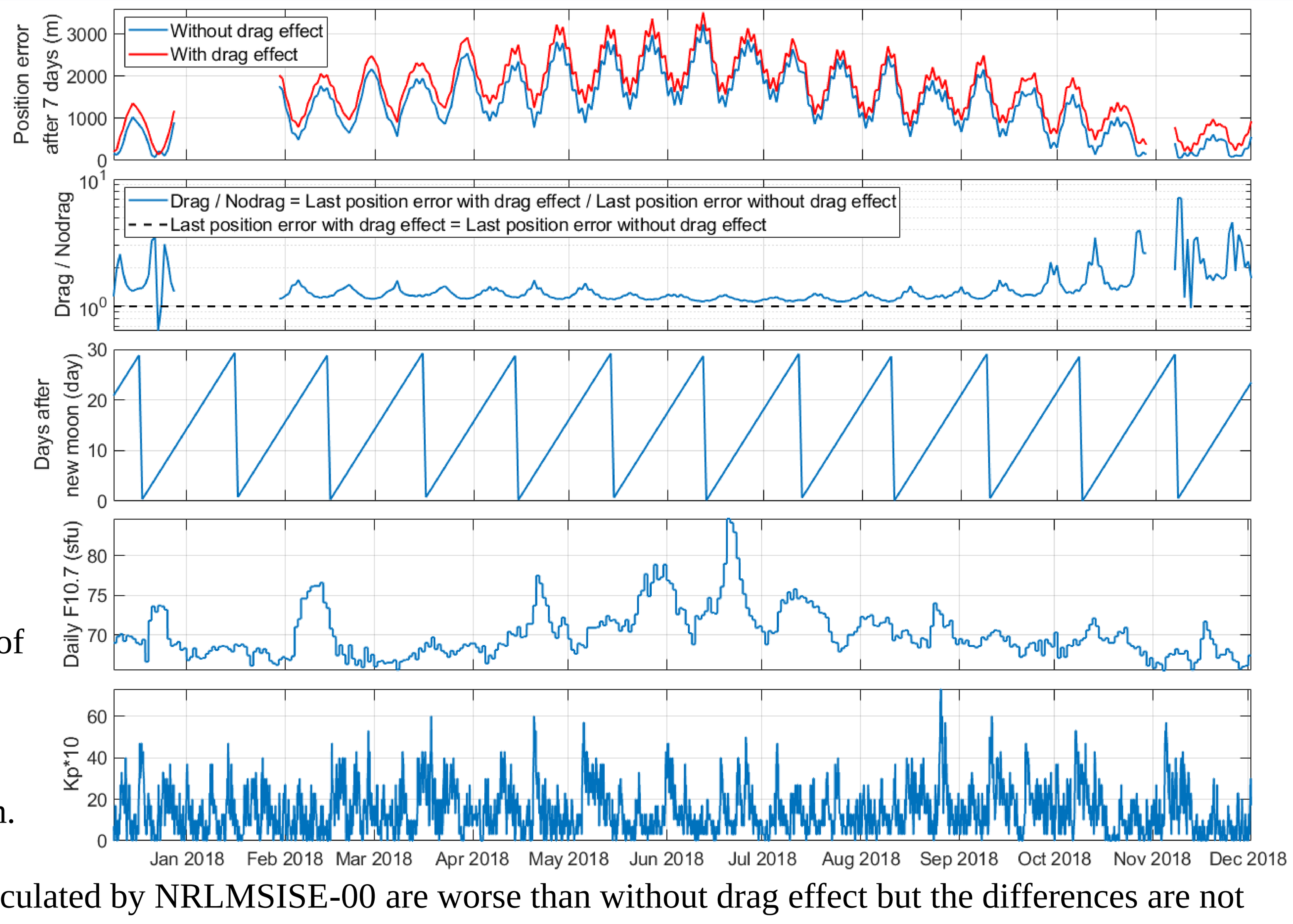


The first row shows that during the four seasons in northern hemisphere, the propagator with drag only performs better during winter solstice. In the second row, the propagation epochs are all during geomagnetic quiet-times. The relative performance is similar to the storm time case studies, with the exception of during vernal equinox.

UPPERAIR-OP ORBIT PROPAGATOR

UPPERAIR-OP Orbit Propagator

- Truth data: based on the flight data of FORMOSAT-5
- Language: MATLAB
- Integrator: ode45 variable step size solver, based on Dormand-Prince method
- Gravitational model: EGM2008 to degree and order 100 maximum
- Atmospheric model: NRLMSISE-00
- Accuracy: position error lower than 4 km after 7-days of propagation



Results

- Results of UPPERAIR-OP compared with space weather proxies and lunar cycle.
- 7-days of propagation in every beginning of day from Dec 9th 2017 to Dec 1st 2018.
- Compared the last position error after 7-days of propagation with and without drag and calculated the ratio between them. Ratio > 1 indicates larger error with drag.
- Most of the results of considering drag calculated by NRLMSISE-00 are worse than without drag effect but the differences are not greater than 500 m.
- There's a 15-days cycle no matter what force model we used. After compared with lunar cycle, we can speculate it as the third-body effect from the moon due to lunar liberation (eccentricity).
- The difference between integrators may also be a factor.

CONCLUSIONS & FUTURE WORKS

- Uncertainties of the initial conditions will greatly influence the resulting propagation error.
- The effect of drag is on the orbit of FORMOSAT-5 is larger than the differences between gravitational models of the same degree and order.
- Propagation using drag calculated from empirical atmospheric models is still variable and does not always yield position errors lower than propagation without drag in the orbit of FORMOSAT-5.
- Third-body effect from the moon cause a 15-days cycle of propagation precision.
- Assess thermospheric density by using different empirical models of physical model.
- The density estimation precision in this orbit may related to the solar cycle and need more analysis.
- Same kind of propagation method can be used for other satellites in the future (e.g. FORMOSAT-7/COSMIC-2) for more thermosphere assessments.

ACKNOWLEDGMENTS

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