Performance assessment of GPS IGOR receiver onboard FORMOSAT-3 / COSMIC satellite mission

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Outline

- Introduction
- Precise orbit determination
- Antenna gain pattern, phase center variation (PCV) and phase residual
- Receiver clock correction and error
- Allan deviation
- Frequency stability analysis of IGOR receiver
- Conclusions
3cm accuracy of COSMIC POD has been demonstrated for post-processed scenario
- Hwang et al., 2009 (J of Geodesy) & 2010 (GPS Solutions)
- using 1 month and ~1 yr data

Potential POD error sources mainly came from the effects of
- limited FOV (POD antenna location),
- PCV, and
- attitude control.

Quite different from how the GPS antennas deployed with GRACE satellites

FOV is one of the reasons that the orbit accuracy of COSMIC is less accurate than that of GRACE (1 cm)
Precise orbit determination (POD)

- Reduced dynamic approach (DYN), the parameters to be determined
  - 6 Kepler parameters
  - 9 dynamic parameters
  - Pseudo-stochastic pulses (~240)
- Kinematic approach (KIN), the parameters to be determined (4)
  - Kinematic coordinates for each epoch
  - receiver clock correction

GPS final orbit, GPS high-rate clock and the earth rotation parameters from CODE are used in orbit determination.
- **Pre-flight calibration**
  - L1 and L2 gain pattern analysis
- **PCV related to gain pattern analysis**
  - L3 PCV
  - L3 in-flight post-fit phase residual
- **Performance comparisons between COSMIC and GRACE**
  - L3 PCV
  - L3 in-flight post-fit phase residual
Antenna gain pattern, phase center variation (PCV) and phase residuals

(a) pre-flight calibration (b)

L1 phase gain pattern with the SAD of 0 degree (SAD- solar array drive)

L2 phase gain pattern with the SAD of 0 degree
Antenna gain pattern, phase center variation (PCV) and phase residual

(a) L3 PCV

(b) L3 in-flight post-fit phase residual of FM1 (DOY 194, 2007)
Antenna gain pattern, phase center variation (PCV) and phase residual

(a) GRACE-A L3 PCV based on phase observations over 362 days in 2007 (Jaggi et al. 2009) (b) L3 phase residual of GRACE-A (DOY 214, 2008)
Receiver clock correction

(a) FM1 on DOY 125, 2008
(second generation BlackJack)
Micro-second level

(b) GRACE-A on DOY 174, 2007
(first generation)
Nano-second level
The receiver clock errors of
- FM1 on DOY 125, 2008
- GRACE-A on DOY 174, 2007

as a typical behavior/example

Average RMS of clock errors based on the dynamic (DYN) and kinematic (KIN) solutions over 10 days for

<table>
<thead>
<tr>
<th></th>
<th>FM1</th>
<th>FM2</th>
<th>FM3</th>
<th>FM4</th>
<th>FM5</th>
<th>FM6</th>
<th>GA</th>
</tr>
</thead>
<tbody>
<tr>
<td>DYN(ns)</td>
<td>0.055</td>
<td>0.041</td>
<td>0.050</td>
<td>0.031</td>
<td>0.055</td>
<td>0.026</td>
<td>0.014</td>
</tr>
<tr>
<td>KIN(ns)</td>
<td>0.066</td>
<td>0.078</td>
<td>0.067</td>
<td>0.062</td>
<td>0.087</td>
<td>0.075</td>
<td>0.024</td>
</tr>
</tbody>
</table>

1. Solutions from dynamic approach are much better than those from kinematic
2. For GRACE-A, ~0.01ns clock error presented in the DYN solution and 0.02ns clock error in the KIN solution respectively.
3. For COSMIC, on average, ~0.04 ns clock error presented in the DYN solution and 0.07 ns in the KIN solution respectively.
4. This translates into a POD error of ~1cm for COSMIC
5. This behavior is typical
for the IGOR receiver performance, temperature variation factor is also taken into account. Apparently, during the period of 10-15 hour, the temperature in the receiver is not stable and this results to the increased clock error and the less number of GPS satellites tracked in the receiver. For this F4 case, the temperature in FM4 varies from 38 to 44 degrees.
A normal case of FM1 as another example. Periodical - 14 circles each day (14 peaks)
The temperature in FM1 receiver varies from 37 to 39 degrees and the performances of both
clock error and number of GPS satellites tracked are much better than that of FM4.

Therefore, the temperature control in IGOR receiver will influence the outcome of POD
Allan deviation

In order to assess the performance of IGOR receiver, Allan Variance is used. A phase voltage output of an oscillator can be expressed as (Allan, 1987)

\[ V(t) = V_0 \sin(2\pi\omega_0 t + \phi_0(t)) \]

\( V_0 \) is the voltage amplitude and \( \omega_0 \) is a nominal fundamental frequency and \( \phi_0(t) \) is phase noise at the initial epoch.

For GPS satellite, \( \phi_0(t) \) term is relatively small compared to LEO satellite due to the high performance of atomic oscillator. Thus, the phase measurement between an LEO oscillator and a GPS oscillator can be obtained by

\[ 2\pi\omega_{LEO}(t)[t - t_0] = 2\pi\omega_{GPS}^0 [t - t_0] + [\phi_{LEO}^0(t) - \phi_{GPS}^0(t)] \]
then, the frequency measurement can be given by

\[ \omega^{LEO}(t) = \omega_0^{GPS} + \frac{1}{2\pi} \cdot \frac{d\phi}{dt} \]

A dimensionless quantity \( y(t) \) can be defined as

\[ y(t) = \frac{1}{2\pi\omega_0^{GPS}} \cdot \frac{d\phi}{dt} = \frac{\omega^{LEO}(t) - \omega_0^{GPS}}{\omega_0^{GPS}} = \frac{dx}{dt} \]

For the time domain, \( x(t) \) can be simply given by integrating \( y(t) \)

\[ x(t) = \int_{0}^{t} y(t) \cdot dt \]
Allan deviation can be determined by the frequency domain \( y(t) \) or time domain \( x(t) \)

\[
\sigma_y(\tau) = \left[ \frac{1}{2(M - 1)} \sum_{i=0}^{M-1} (y_{i+1} - y_i)^2 \right]^{1/2} = \left[ \frac{1}{2(N - 2)\tau^2} \sum_{i=1}^{N-2} (x_{i+2} - 2x_{i+1} + x_i)^2 \right]^{1/2}
\]
The frequency stability of FM1 is about 10^{-8}-10^{-7}.

The standard Allan deviation presents white noises in the period of τ(tau) 10^3 -10^4 and the overlapping solution removes such noises and the modified solu is used to separate the white noise and flicker noise in the frequency modulation.
The frequency stability of FM4 is about $10^{-7}$-$10^{-6}$. The frequency stability of FM4 is more unstable than that of FM1, this might be due to the temperature effects in this case.
At the beginning of the kinematic solution, it might be caused by the white noise resulted from the temperature in receiver.
Allan variance of the GRACE oscillator calibrated before the satellite was launched (Ko and Tapley, 2010)

Ko and Tapley (2010) demonstrated that the Allan deviation of $10^{-13}$ for the frequency stability of USO onboard GRACE satellites using KBR measurements was achieved.

USO – Ultra Stable Oscillator,  KBR – K/Ka Band Ranging instrument
Summary

- This study assesses the performance of IGOR receiver in terms of the gain pattern of the POD antenna, receiver clock correction and error, and the frequency stability of the receiver oscillator.
- The frequency stability is used to assess the frequency noise of the oscillator signals.
- The performance of the IGOR receiver is critical for the quality of the GPS signals reception and receiver clock error determination. It is also closely associated with receiver temperature.
- The frequency instability of IGOR receiver might contribute 1-cm orbit error based on the receiver clock error as compared to GRACE satellite (see table).
- GPS-calibrated frequency stability of LEO receiver oscillator is successfully implemented by this study and such self-calibrated method can verify the performance of the receiver oscillator during the in-flight phase.
- This study might be served as a reference for a new receiver onboard COSMIC-2 satellite mission.
Thank you

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