Improving Near Real-Time and Predicted Earth Orientation Parameters Using IGS Ultra-Rapid Polar Motion and Length-of-Day Measurements

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Abstract. It has been recognized since the early days of interplanetary spaceflight that accurate navigation requires taking into account changes in the Earth's rotation. In the 1960s, tracking anomalies during the Ranger VII and VIII lunar missions were traced to errors in the Earth orientation parameters. As a result, Earth orientation calibration methods were improved to support the Mariner IV and V planetary missions. Today, accurate Earth orientation parameters are used to track and navigate every interplanetary spaceflight mission. The approach taken at JPL to provide the interplanetary spacecraft tracking and navigation teams with the Earth orientation parameters that they need is based upon the use of a Kalman filter to combine past measurements of the Earth orientation parameters and predict their future evolution. Changes in the Earth's orientation can be described as a randomly excited stochastic process; consequently, between measurements, the uncertainty in our knowledge of the Earth's orientation grows and rapidly becomes much larger than the uncertainty in the measurements. Thus, measurements of the Earth's orientation must be taken frequently and processed rapidly in order to meet the demanding accuracy requirements of the spacecraft navigation teams. Here, the improvement in the accuracy of JPL's near real-time and predicted EOPs when the IGS Ultra-Rapid polar motion and length-of-day measurements are included in the Kalman filter is discussed. A 30% improvement in the accuracy of the short-term predicted PMX, PMY, and UT1 estimates delivered to the interplanetary spacecraft navigation teams at JPL is obtained when the IGS Ultra-Rapid polar motion and length-of-day measurements are included in the solution.

Kalman Earth Orientation Filter

Introduction

- Accurate navigation of interplanetary spacecraft requires accurate knowledge of Earth's orientation
  - Must know Earth's orientation in space to know spacecraft's position in space from Earth-based tracking measurements
    - Uncertainty in Earth's orientation can be a major, if not the dominant, source of error in spacecraft navigation and tracking (Estefan and Folkner, 1995)
    - Error in UT1 of 0.1 ms (4.6 cm) produces an error of 7 nrad in spacecraft right ascension, corresponding to a position error at Mars of 1.6 km
- Earth's orientation in space given by 5 parameters:
  - 2 precession-nutation parameters ($\Delta\psi$, $\Delta\varepsilon$)
    - Specifies location of spin axis in *celestial* reference frame
  - 2 polar motion parameters (PMX, PMY)
    - Specifies location of spin axis in *terrestrial* reference frame
  - 1 spin parameter (UT1)
    - Specifies angle through which Earth has rotated about spin axis

Introduction, cont.

- Earth's orientation varies rapidly and unpredictably
  - UT1 variations are particularly difficult to predict
    - Rapid UT1 variations caused mainly by changes in angular momentum of winds
    - Predicting UT1 is as challenging as predicting the weather
  - In contrast, precession-nutation can be accurately modeled
    - Precession-nutation caused by gravitational attraction of Sun, Moon, & planets
    - Model predictions rely upon past measurements
- Measurements of UT1 and polar motion must be taken frequently and processed rapidly to maintain a real-time knowledge of the Earth's orientation:
  - Tracking and Navigation Service Requirements
    - 30 cm (1 sigma) in real time
    - 5 cm (1 sigma) for a posteriori reconstructions after 14 days
  - Demanding missions request much higher accuracies
    - Highest accuracy possible

Earth Orientation Data

- EOP prediction accuracy controlled by timeliness and accuracy of most recent measurement
  - UT1 varies rapidly and randomly
    - UT1 uncertainty grows from epoch of last measurement:
      as $t^{3/2}$ if last measurement is of UT1 and UT1-rate (length-of-day)
      more rapidly than $t^{3/2}$ if last measurement is of UT1 only
- Internal data
  - GPS Quick-Look measurements (PMX, PMY, UT1 rate)
    - Acquired daily, subdaily latency
  - TEMPO single baseline VLBI measurements (UT0)
    - Acquired twice-per-month, 1-week latency

Earth Orientation Data, cont.

- External data
  - Inertial sources
    - Very long baseline interferometry (Intensive UT1 – acquired daily, 2-day latency)
    - Very long baseline interferometry (Multibaseline – few times/wk, 2-week latency)
    - Lunar laser ranging (acquired irregularly, subdaily latency)
  - Non-inertial sources
    - Satellite laser ranging (ILRS Combined – acquired daily, 1-week latency)
    - Global positioning system (IGS Rapids – acquired daily, subdaily latency)
    - Global positioning system (IGS Finals – acquired daily, 2-week latency)
  - Proxy length of day (UT1 rate) data
    - Atmospheric angular momentum analyses (acquired daily, subdaily latency)
    - Atmospheric angular momentum dynamical forecasts (daily, 5 days into future)

Kalman Filter Theory

- Kalman filters are commonly used to estimate parameters of some system when a stochastic model of that system is available and the input data contain noise
- For the purpose of combining Earth orientation series, the system consists of the Earth orientation parameters, their excitations, and full covariance matrices
- The linear, first order differential equation to be solved can be written as:

$$\frac{d\mathbf{x}_s(t)}{dt} = \mathbf{F}\,\mathbf{x}_s(t) + \mathbf{G}\,\omega(t)$$

where: $\mathbf{x}_s$ is the state vector of parameters to be estimated:

$$\mathbf{x}_s(t) = (x_p, y_p, \mu_1, \mu_2, S, \dot{S}, U, A, \mu_a, b, \mu_f, \mu_{grw}, \mu_{gar1})^T$$

x_p, y_p are the *x*- and *y*-components of polar motion

$\chi_1 = \mu_1$; $\chi_2 = \mu_2 + S$; S is the annual wobble excitation (modeled as an AR2 process)

$U \equiv UT1 - TAI$; $\Lambda = A + \mu_a$ (LOD = AAM + residual)

b, μ_f are parameters of the AAM forecast model

μ_{grw}, μ_{gar1} are parameters of the GPS LOD model

ω is a white noise, zero-mean stochastic excitation process vector:

$$\omega(t) = (0, 0, \omega_{\mu_1}, \omega_{\mu_2}, 0, \omega_S, 0, \omega_A, \omega_{\mu_a}, 0, \omega_{\mu_f}, \omega_{\mu_{grw}}, \omega_{\mu_{gar1}})^T$$

$\mathbf{F}$ and $\mathbf{G}$ are constant coefficient matrices

Kalman Filter Theory, cont.

- The measurement vector $\mathbf{x}_m(t)$ is related to the state vector $\mathbf{x}_s(t)$ by:

$$\mathbf{x}_m(t) = \mathbf{H}\,\mathbf{x}_s(t) + \mathbf{n}_m(t)$$

where $\mathbf{H}$ is the design matrix & $\mathbf{n}_m(t)$ represents measurement noise

- In the absence of a measurement, the state vector $\mathbf{x}_s(t_o)$ and its error covariance matrix $\mathbf{C}_s(t_o)$ at some initial time t_o is propagated to some future time t by:

$$\mathbf{x}_s(t) = \Phi(t-t_o)\,\mathbf{x}_s(t_o)$$

$$\mathbf{C}_s(t) = \Phi(t-t_o)\,\mathbf{C}_s(t_o)\,\Phi^T(t-t_o) + \int_{t_o}^{t} \Phi(t-\tau)\,\mathbf{G}\,\mathbf{Q}\,\mathbf{G}^T\,\Phi^T(t-\tau)\,d\tau$$

where: $\Phi(\Delta t)$ is the transition matrix defined by:

$$\Phi(\Delta t) = e^{\mathbf{F}\Delta t} = \sum_{k=0}^{\infty} \frac{\mathbf{F}^k \Delta t^k}{k!}$$

$\mathbf{Q}$ is the diagonal process noise matrix whose elements are the power spectral densities of the assumed white noise excitations

- In the presence of a measurement, the state vector and its covariance matrix are propagated to the time t of the measurement, and the measurement is incorporated by forming:

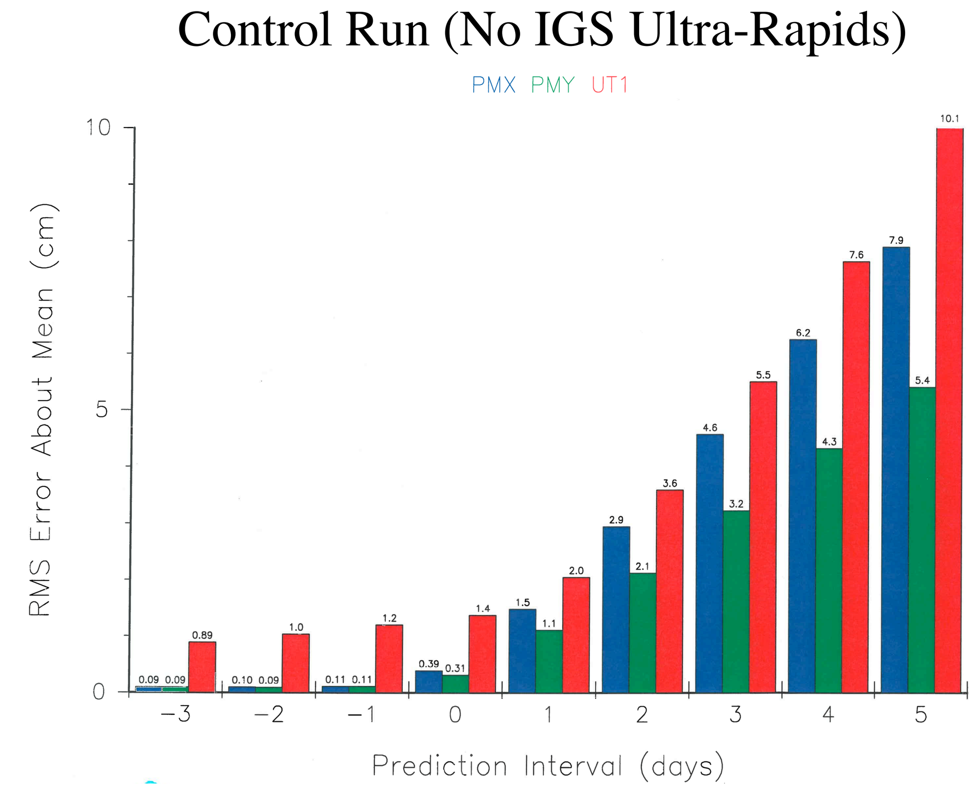
$$\mathbf{x}_s(t) = \frac{{}_i\mathbf{C}_s^{-1}(t)\;{}_i\mathbf{x}_s(t) + \mathbf{H}^T\mathbf{C}_m^{-1}(t)\,\mathbf{x}_m(t)}{{}_i\mathbf{C}_s^{-1}(t) + \mathbf{H}^T\mathbf{C}_m^{-1}(t)\,\mathbf{H}}$$

$$\mathbf{C}_s(t) = [\,{}_i\mathbf{C}_s^{-1}(t) + \mathbf{H}^T\mathbf{C}_m^{-1}(t)\,\mathbf{H}\,]^{-1}$$

- A smoothed series is obtained by running the Kalman filter forward in time, backward in time, and taking the vector weighted average of the results

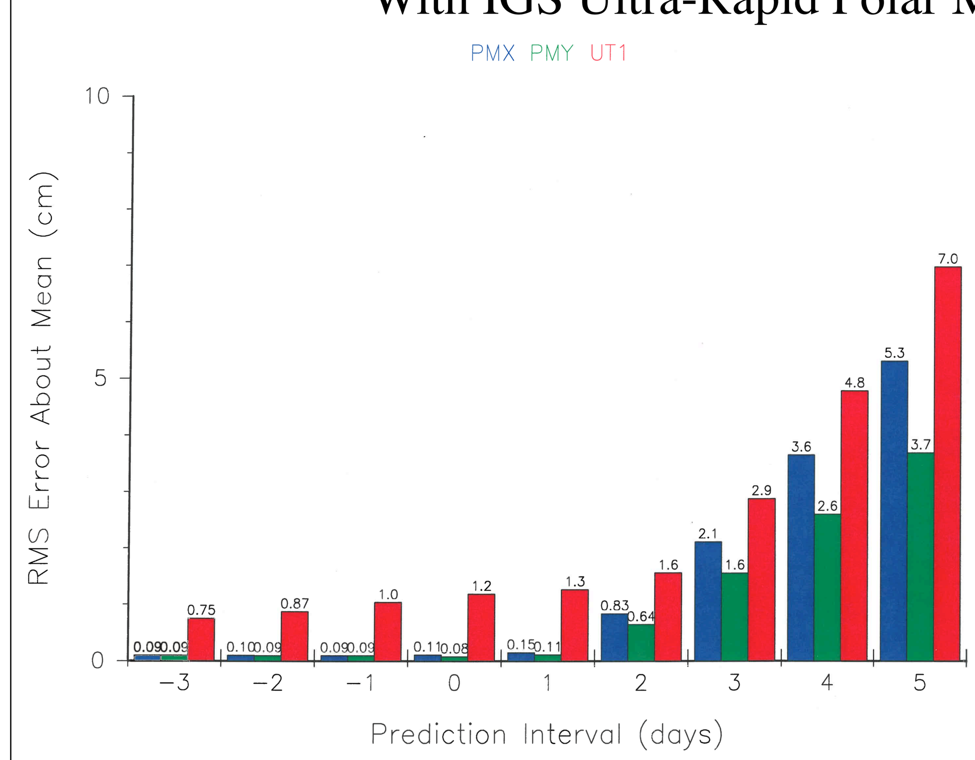
Impact of IGS Ultra-Rapids

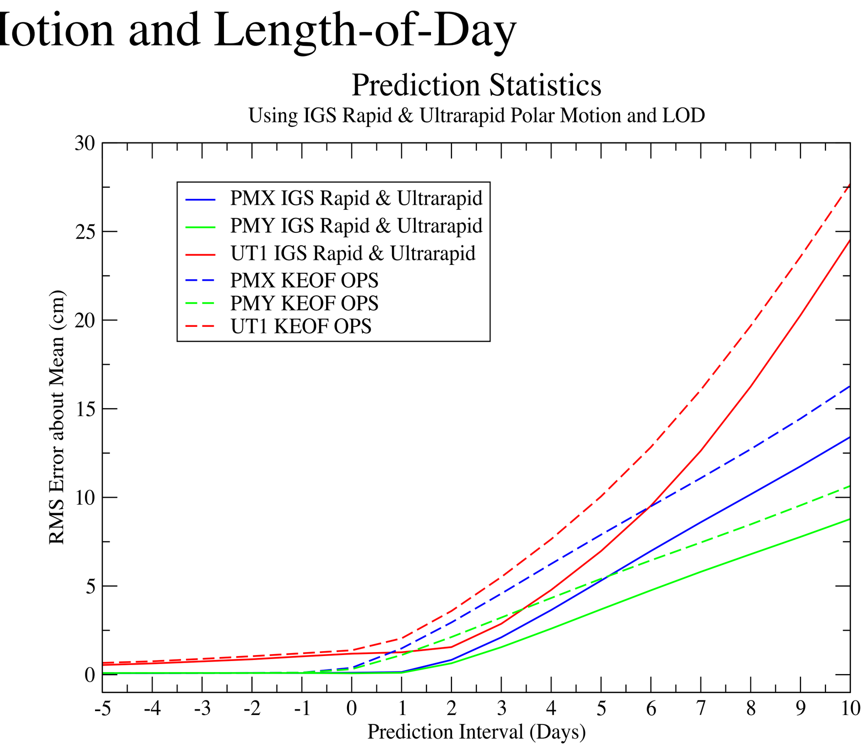
Control Run (No IGS Ultra-Rapids)



Measurements of the Earth's changing orientation in space acquired by the space-geodetic techniques of very long baseline interferometry (VLBI), satellite and lunar laser ranging (SLR and LLR), and global navigation satellite systems (GNSS) including the IGS Final and Rapid combined series are merged using a Kalman filter to provide the interplanetary spacecraft navigation teams at JPL with the near real-time and short-term predicted EOPs that they need. The accuracy of the near real-time and predicted EOPs is determined by comparing them to a more accurate reference series. The rms over the last 6 months of 2014 of the difference of the daily operational solutions with a more accurate reference series is shown above. During this time period, the most timely EOP measurements included in our solutions were the IGS Rapid polar motion and length-of-day measurements. The real-time (prediction day 0) accuracy of (PMX, PMY, UT1) delivered to the navigation teams during the last half of 2014 was (0.39, 0.31, 1.4) cm, respectively. This grew to (7.9, 5.4, 10.1) cm at prediction day 5.

With IGS Ultra-Rapid Polar Motion and Length-of-Day





When the IGS Ultra-Rapid polar motion and length-of-day measurements were additionally included in our solutions during the last six months of 2014, the real-time (prediction day 0) accuracy of (PMX, PMY, UT1) was reduced to (0.11, 0.08, 1.2) cm, respectively, growing to only (5.3, 3.7, 7.0) cm at prediction day 5. This is a 30% improvement in the accuracy of our delivered short-term predicted PMX, PMY, and UT1 estimates. This improvement is achieved because the IGS Ultra-Rapid polar motion and length-of-day measurements are more timely than the Rapids, but are still quite accurate.