Laser Ranging Contributions
to
Earth Rotation Studies

Richard S. Gross

Jet Propulsion Laboratory
California Institute of Technology
Pasadena, CA 91109–8099, USA

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Introduction

- Laser ranging has been used to routinely determine EOPs for more than 3 decades
  - Lunar laser ranging measurements since 1970
  - Satellite laser ranging measurements since 1976
- Laser ranging-derived EOPs span longer time interval than do those from any other space-geodetic technique
  - Required for investigating long-period variations
  - Provides backbone for EOP combinations
- Lunar laser ranging measurements determine UT0
Decadal Polar Motion Variations

Gross and Vondrák (1999)
Combining EOP Series (1/3)

- Individual Earth orientation series are determined within a particular realization of some terrestrial, body-fixed reference frame (such as ITRF2005)
  - TRF defined operationally by specifying positions and linear motions of a set of ground-based observing stations
- Different realizations of the same TRF may differ by being offset from each other, and/or by drifting (rotating) with respect to each other
  - Different realizations of the reference frame are based upon different subsets of the defining stations
  - The different station subsets are likely to be located on different subsets of the tectonic plates
  - Errors in modeling tectonic plate motions, and hence motions of stations located on them, cause the different station subsets to drift with respect to each other
Combining EOP Series (2/3)

• Thus, individual Earth orientation series determined within different realizations of the terrestrial reference frame can be expected to drift with respect to each other.

• Changes in the Earth's orientation are degenerate with rotations of the terrestrial reference frame.

• These drift (rate) differences exhibited by individual Earth orientation series must be accounted for prior to their combination.
Combining EOP Series (3/3)

- Determining bias-rate corrections
  - Accomplished by comparing individual series to a reference
- Reference series should be internally consistent and of long duration
  - Internally consistent so that bias-rate corrections are unaffected by inconsistencies in the reference series
  - Long duration so that all the other series can be corrected using the same reference and hence be placed within the same realization of the terrestrial reference frame
- These two criteria (internal consistency and long duration) are met by the SLR series
  - SLR series forms the backbone to which shorter duration series are attached when generating combined EOP series
Difference of IERS 05 C 04 with COMB2006

- Polar Motion X (mas)
- Polar Motion Y (mas)
- UT1 (ms)
- Excess Length of Day (ms)

Graphs showing the differences over time from 1970 to 2000.
Earth Orientation Data

• **Sources of available EOP 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)
Single Station LLR

- Single station LLR measurements are sensitive to:
  - Variation of station latitude
  - UT0

- Single station LLR measurements are not sensitive to a rotation of the Earth about station position vector
  - Such a rotation of the Earth does not change the position of the station with respect to the Moon

- An orthogonal transformation matrix relating variation of latitude and UT0 to polar motion and UT1 can be defined by:

\[
\begin{pmatrix}
\Delta\phi_i(t) \\
UTF_i(t) \\
D_i(t)
\end{pmatrix}
= \begin{pmatrix}
\cos\lambda_i & -\sin\lambda_i & 0 \\
\sin\lambda_i \sin\phi_i & \cos\lambda_i \sin\phi_i & \cos\phi_i \\
-\sin\lambda_i \cos\phi_i & -\cos\lambda_i \cos\phi_i & \sin\phi_i
\end{pmatrix}
\begin{pmatrix}
x_p(t) \\
y_p(t) \\
U(t)
\end{pmatrix}
\]

where: \(\lambda_i, \phi_i\) are the nominal station latitude and longitude

\(x_p, y_p\) are the \(x\)- and \(y\)-components of polar motion

\(U(t) = UT1(t) - TAI(t)\)

\(\Delta\phi_i(t)\) is the variation of station latitude

\(UTF_i(t) = \cos\phi_i [UT0_i(t) - TAI(t)]\)

\(D_i(t)\) is the degenerate component not determinable from single station LLR measurements

- UTF must be introduced so above matrix is orthogonal

- Above transformation matrix is used to transform measurement vector and its covariance matrix between VUD and UTPM components
  - Uncertainties of measured UT0 must be converted to uncertainties of UTF by multiplying them by \(\cos\phi_i\)
Real-Time Earth Orientation (1/2)

- 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

- 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

- Measurements of UT1 and polar motion must be taken frequently and processed rapidly to maintain a real-time knowledge of the Earth’s orientation
Real-Time Earth Orientation (2/2)

- 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

- Accurate prediction of satellite orbits requires accurate predictions of Earth’s orientation
  - GNSS satellites
Near-Real-Time UT1 from LLR

- Lunar laser ranging observations
  - Can be processed rapidly
    - Small size of observation files $\Rightarrow$ rapid dissemination to analysis centers
    - Analysis centers can rapidly reduce observations for EOPs
- LLR has potential of providing near-real-time UT0
  - Within hours of data acquisition
- LLR has potential of providing near-real-time UT1
  - LLR near-real-time UT0 can be transformed to UT1
    - Using near-real-time polar motion from GPS
Summary

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