Combining and Predicting Earth Orientation Parameters Using a Kalman Filter

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Geodesy, Astronomy and Geophysics in Earth Rotation

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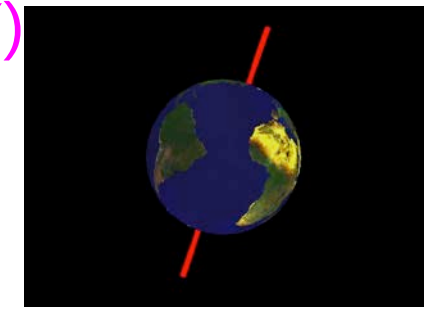
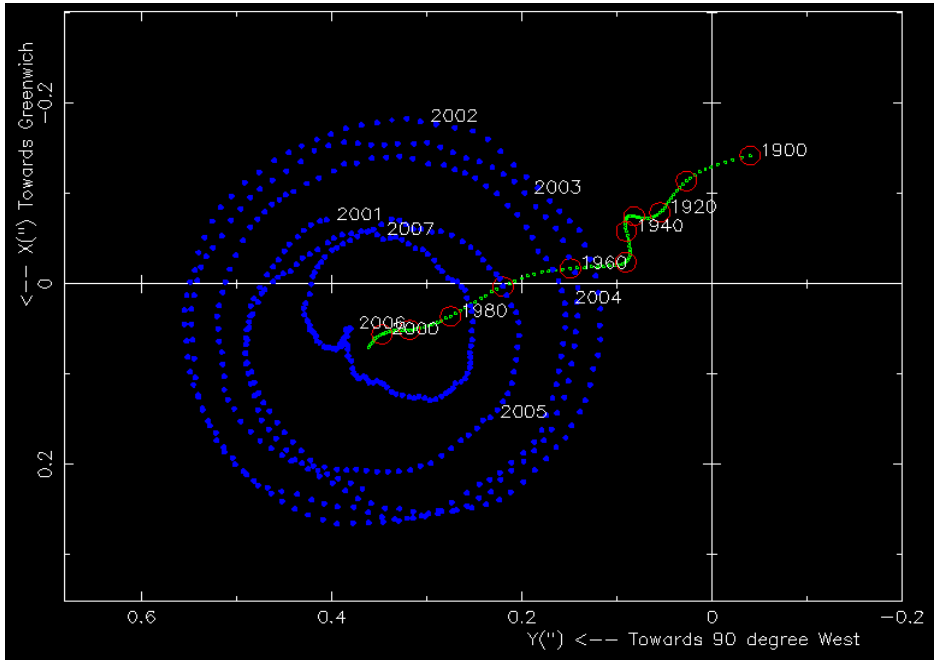
Introduction

- 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 ($\Delta\psi$, $\Delta\varepsilon$; X, Y)
    - Specifies location of spin axis in *celestial* reference frame
  - 2 polar motion parameters (PMX, PMY)
    - Specifies location of spin axis in t*errestrial* reference frame
  - 1 spin parameter (UT1)
    - Specifies angle through which Earth has rotated about spin axis

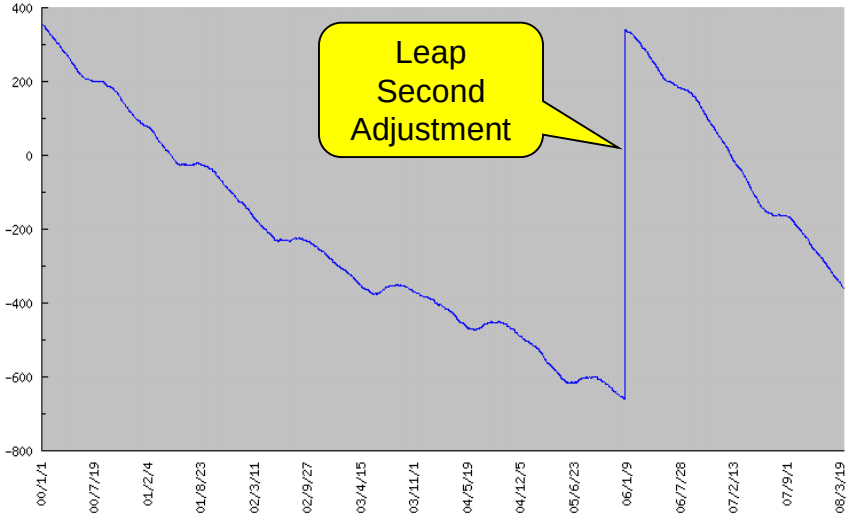


Observed Earth Rotation Variations

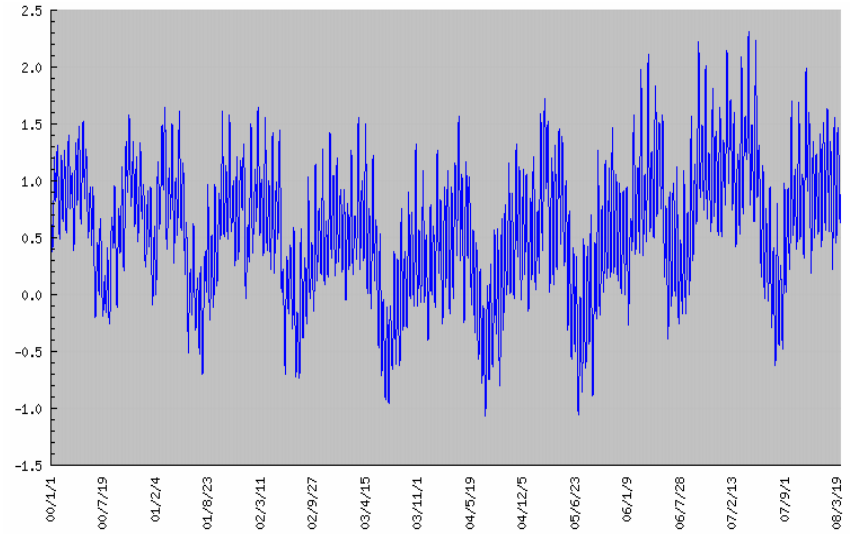
Polar Motion
2001-2007 and
mean pole since 1900



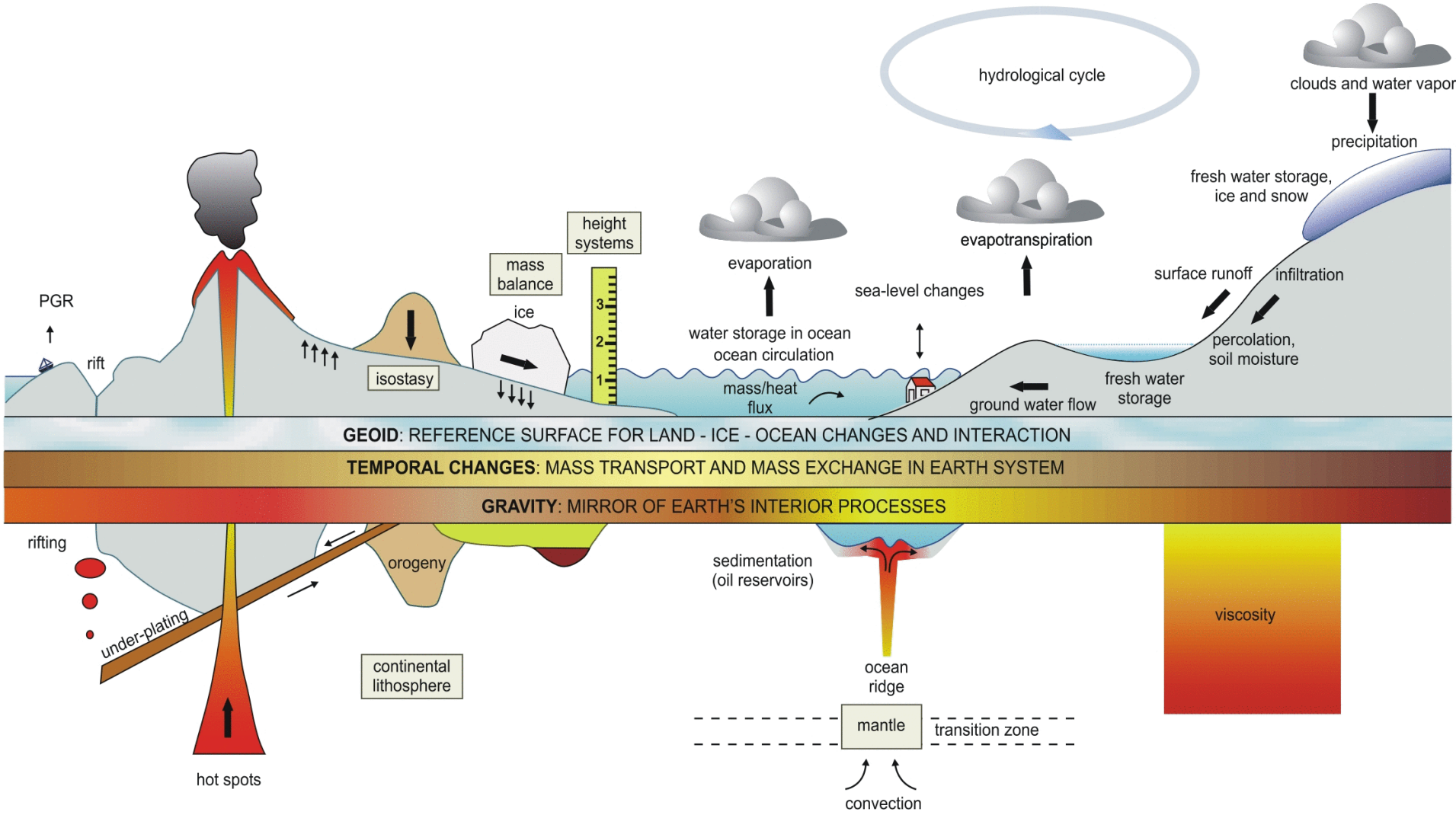
ms UT1-UTC (1/1/00-3/31/08)



Length of Day Offset (1/1/00-3/31/08)



Mass Transport in the Earth System

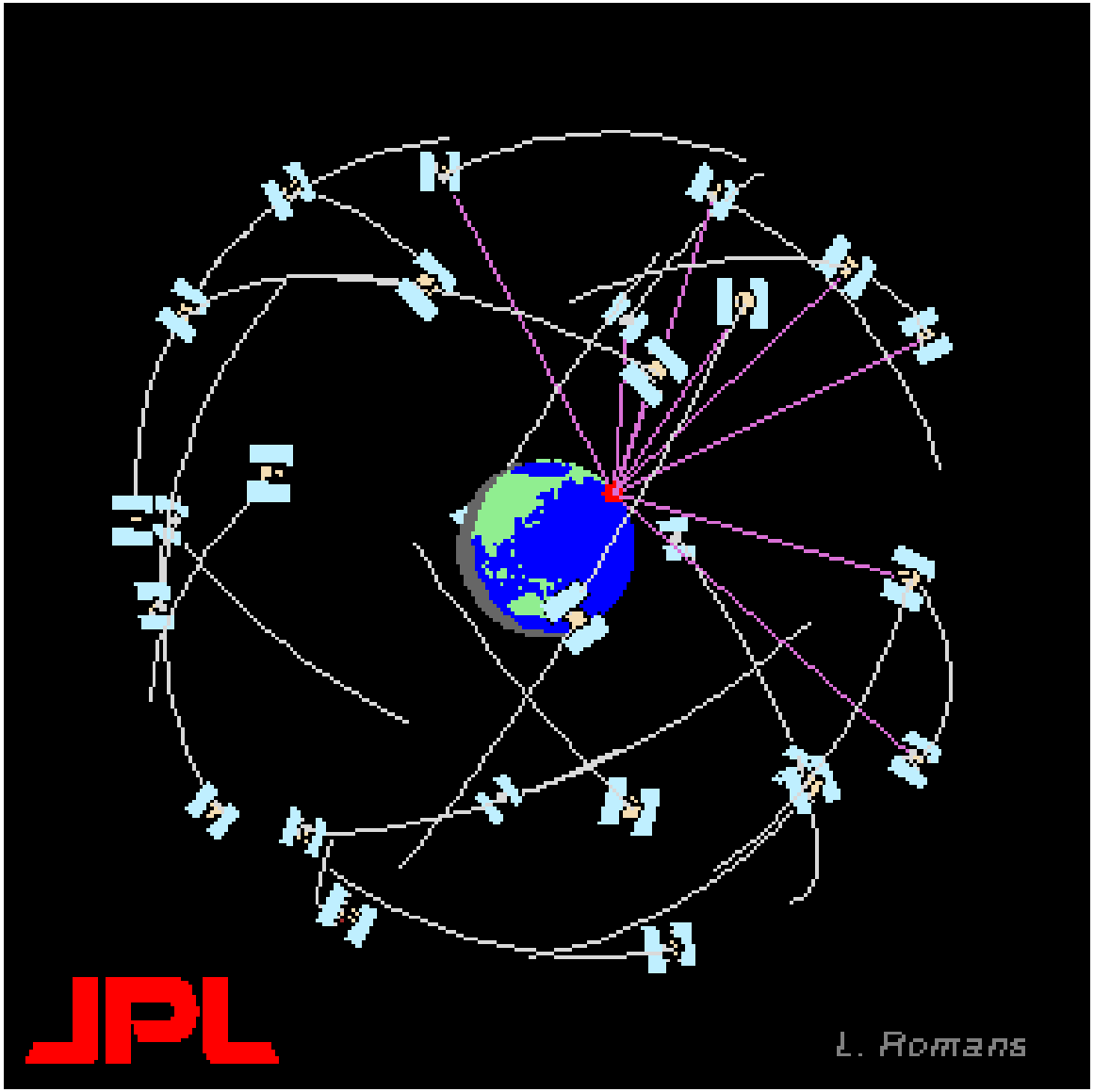


Ilk et al. (2005)

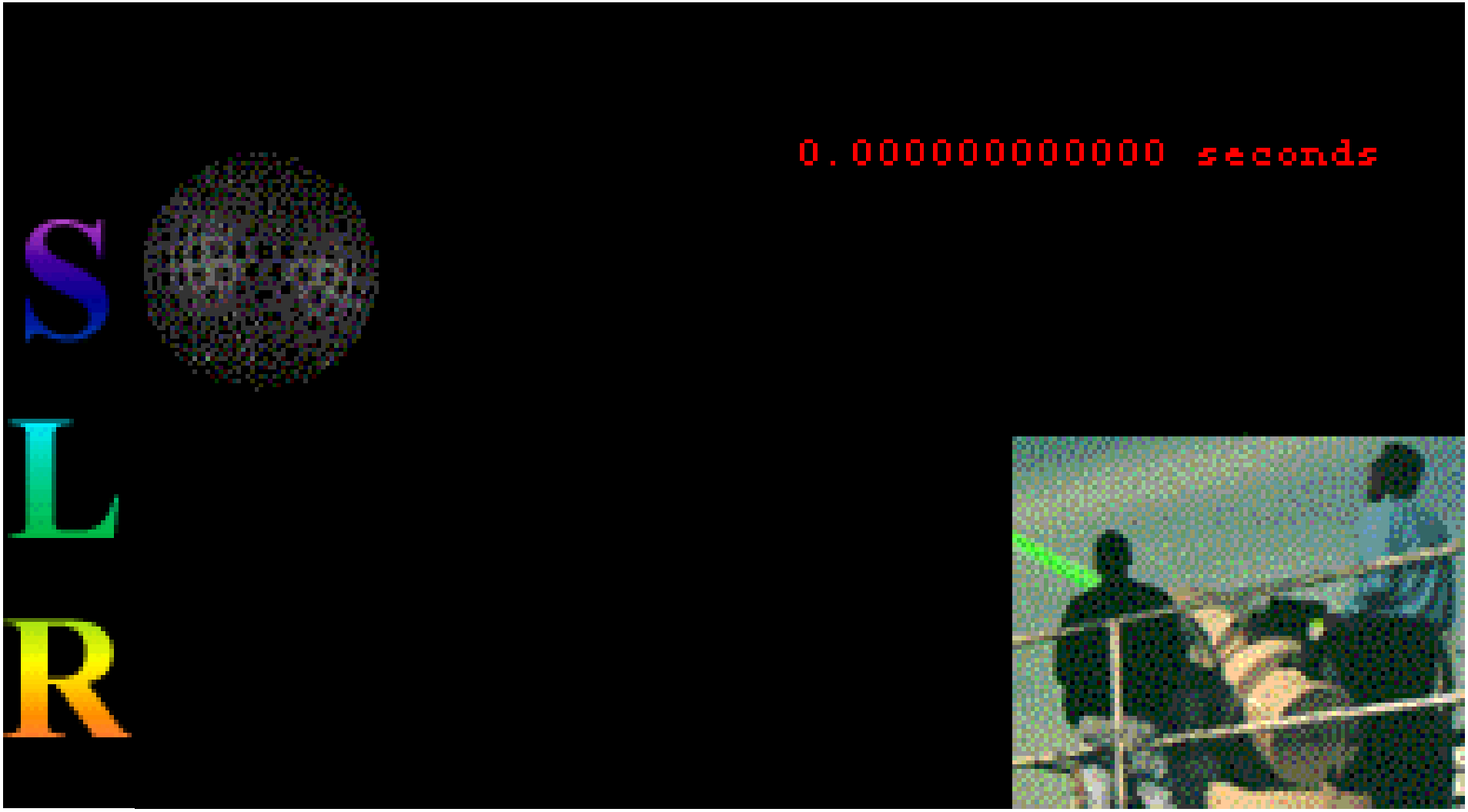
Introduction, cont.

- 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 tighter accuracies
    - 2 cm real-time polar motion and 5 cm real-time UT1 for Phoenix

Global Navigation Satellite Systems



Satellite Laser Ranging



VERY LONG BASELINE INTERFEROMETRY

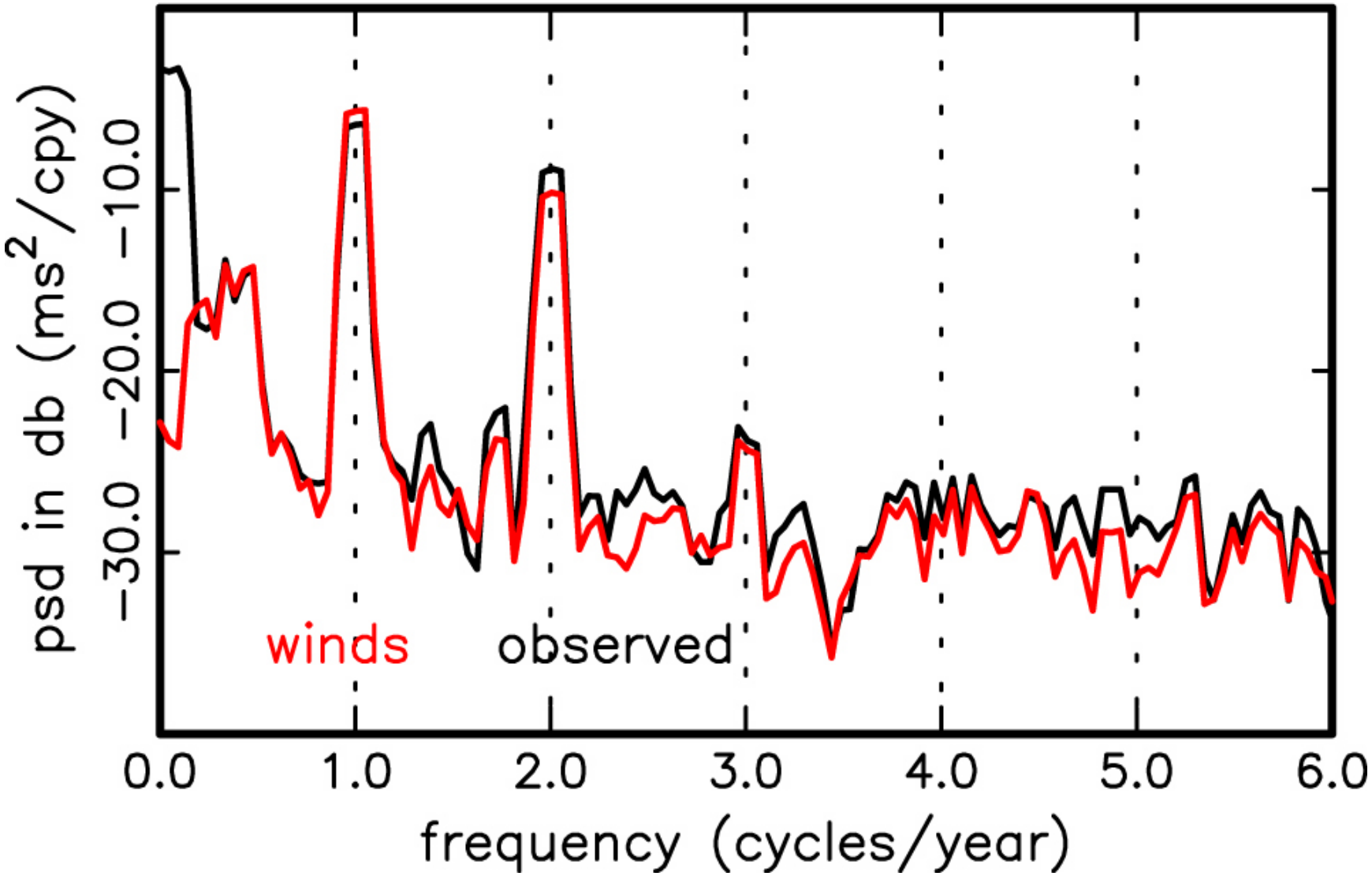
Earth Orientation Measurements

- Determine the full set of UT1 and polar motion
  - Multibaseline VLBI
- Determine a subset of UT1 and polar motion
  - Single baseline VLBI (Intensives)
- Determine linear combinations of UT1 and PM
  - Single baseline VLBI determines transverse, vertical
  - Single station LLR determines UT0, variation-of-latitude
- Are irregularly spaced in time, vary in accuracy, and may be corrupted by systematic errors
  - GPS LOD measurements include errors arising from motion of GPS satellite constellation
- Design of KEOF dictated by these characteristics of the Earth orientation measurements

Earth Orientation Data

- 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
- 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, 7.5 days into future)

LOD VARIATIONS



(Gross et al., 2004)

Kalman Filter

- A Kalman filter is well-suited to combining irregularly spaced, incomplete and/or degenerate measurements of varying accuracy subject to systematic errors
- Information matrix approach allows use of measurements spanning arbitrary subspace of UTPM parameter space
  - Information matrix is zero for that subspace of UTPM space not spanned by the measurements
  - Measurements do not need to be of only polar motion and/or UT1
- State vector is propagated to arbitrary time of measurement
  - Measurements do not need to be taken at the same time
- Measurement vector is combined with propagated state vector by vector-weighted average
  - Measurement uncertainties used as weights when combining data
  - Measurement correlations are taken into account
- Stochastic models of process and measurement noise are included
  - Allows systematic errors to be modeled
    - Such as effect of GPS satellite constellation motion on GPS LOD measurement
  - Enables use of proxy measurements such as AAM

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:**

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

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:

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

F and 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:

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

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

- 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

Single Baseline VLBI

- **Single baseline VLBI measurements are sensitive to:**
  - Transverse component of Earth orientation
    - Arising from rotation of Earth about baseline vertical direction, thereby perturbing baseline in the baseline transverse direction
  - Vertical component of Earth orientation
    - Arising from rotation of Earth about baseline transverse direction, thereby perturbing baseline in the baseline vertical direction
- **Single baseline VLBI measurements are not sensitive to a rotation of the Earth about the baseline vector**
  - Such a rotation of the Earth does not change the orientation of the baseline with respect to the radio source
- **An orthogonal transformation matrix relating the transverse and vertical components to polar motion and UT1 can be defined by:**

$$\begin{pmatrix} T(t) \\ V(t) \\ D(t) \end{pmatrix} = \begin{pmatrix} -v_y & -v_x & v_z \\ \tau_y & \tau_x & -\tau_z \\ b_y & b_x & -b_z \end{pmatrix} \begin{pmatrix} x_p(t) \\ y_p(t) \\ U(t) \end{pmatrix}$$

where: $\hat{\mathbf{b}} = \dfrac{\mathbf{r}_2 - \mathbf{r}_1}{\| \mathbf{r}_2 - \mathbf{r}_1 \|}$; $\hat{\boldsymbol{\tau}} = \dfrac{\mathbf{r}_1 \times \mathbf{r}_2}{\| \mathbf{r}_1 \times \mathbf{r}_2 \|}$; $\hat{\mathbf{v}} = \hat{\mathbf{b}} \times \hat{\boldsymbol{\tau}}$

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

$U(t) \equiv UT1(t) - TAI(t)$

$T(t)$, $V(t)$ are the transverse, vertical components

$D(t)$ is the degenerate component not determinable from single baseline VLBI measurements

- **Above transformation matrix is used to transform the measurement vector and its covariance matrix between the TVD and UTPM components**

Single Baseline VLBI

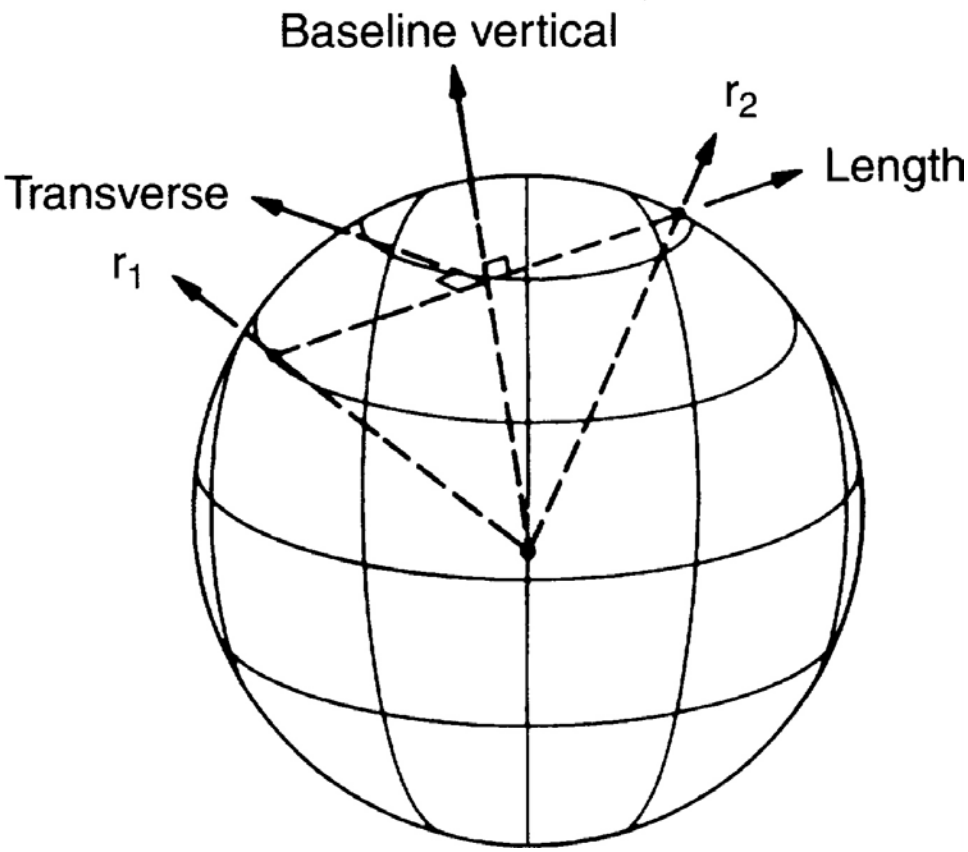


Illustration of the definition of the baseline transverse $\hat{\tau}$, vertical $\hat{\mathbf{v}}$, length $\hat{\mathbf{b}}$ coordinate reference frame. The positions within some rotating, body-fixed conventional terrestrial reference frame of the VLBI observing telescopes (that are located at either end of the baseline) are given by the position vectors $\mathbf{r_1}$ and $\mathbf{r_2}$.

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: λ_i, ϕ_i are the nominal station latitude and longitude

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

$U(t) \equiv UT1(t) - TAI(t)$

$\Delta\phi_i(t)$ 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 $\cos\phi_i$

Stochastic Model of AAM

- **Excess length-of-day $\Lambda(t)$ is related to UT1 by:**

$$\frac{dU(t)}{dt} = -\frac{\Lambda(t)}{\Lambda_o}$$

where: $U \equiv UT1 - TAI$; Λ_o is the nominal length-of-day (86400 s)

- **Axial component of AAM analyses $A(t)$ is related to excess length-of-day $\Lambda(t)$ by:**

$$\Lambda(t) = A(t) + \mu_a(t)$$

where: $$\frac{dA(t)}{dt} = \omega_A(t) \quad ; \quad \frac{d\mu_a(t)}{dt} = \omega_{\mu_a}(t)$$

  - Since $\omega_A(t)$ and $\omega_{\mu_a}(t)$ represent zero-mean white noise stochastic processes, $A(t)$ and $\mu_a(t)$, and hence $\Lambda(t)$, behave as random walks (integrated white noise)

- **Axial component of AAM forecast $F(t)$ is related to axial component of AAM analyses $A(t)$ by:**

$$F(t) = A(t) + \mu_f(t) + b$$

where: $$\frac{d\mu_f(t)}{dt} = -\frac{\mu_f(t)}{\tau_f} + \omega_{\mu_f}(t) \quad ; \quad b \text{ is a constant bias term}$$

  - Thus, $\mu_f(t)$ is modeled as an exponentially decaying term excited by white noise (an AR1 process)

- **Within KEOF, τ_f and the power spectral densities Q of the zero-mean white noise processes ω are set to:**

Q_A = 0.0036 ms²/day $\qquad$ Q_{μ_a} = 0.0007 ms²/day

Q_{μ_f} = 0.00258 ms²/day $\qquad$ τ_f = 5 days

- **These models have been empirically determined from LOD and AAM data**

Stochastic Model of GPS LOD

- **Excess length-of-day $\Lambda(t)$ is related to UT1 by:**

$$\frac{dU(t)}{dt} = -\frac{\Lambda(t)}{\Lambda_o}$$

where: $U \equiv UT1 - TAI$; Λ_o is the nominal length-of-day (86400 s)

- **GPS measurements of LOD $G(t)$ are related to LOD $\Lambda(t)$ by:**

$$G(t) = \Lambda(t) + \mu_{grw}(t) + \mu_{gar1}(t)$$

where: $\frac{d\mu_{grw}(t)}{dt} = \omega_{\mu_{grw}}(t)$; $\frac{d\mu_{gar1}(t)}{dt} = -\frac{\mu_{gar1}(t)}{\tau_g} + \omega_{\mu_{gar1}}(t)$

  - Since $\omega_{\mu_{grw}}(t)$ represents a zero-mean white noise stochastic process, $\mu_{grw}(t)$ behaves as a random walk (integrated white noise)
  - Since $\omega_{\mu_{ar1}}(t)$ represents a zero-mean white noise stochastic process, $\mu_{gar1}(t)$ is modeled as an exponentially decaying term excited by white noise (an AR1 process)

- **Within KEOF, τ_g and the power spectral densities Q of the zero-mean white noise processes ω are set to:**

$Q_{\mu_{grw}}$ = 0.000005 ms^2/day $\qquad$ $Q_{\mu_{gar1}}$ = 0.0005 ms^2/day

τ_g = 2.27272727 days

- **This stochastic model for GPS LOD measurements has been empirically determined from LOD and JPL GPS LOD data**
  - This model and/or the parameter settings may not be valid for GPS LOD measurements determined at a different GPS analysis center

Kalman Earth Orientation Filter

- A Kalman filter is used to
  - Combine the available Earth orientation data
  - Predict future changes in the Earth's orientation
    - Out to 78 days in advance
- Input data are corrected prior to combination
  - Data are placed within same terrestrial reference frame
    - ITRF93, the frame consistent with the navigation system
  - UT1 corrected to be consistent with the equation of equinoxes used by the navigation system
  - Stated uncertainties are adjusted to reflect accuracy, not precision, of measurement
    - Adjusted uncertainties are used as weights by Kalman filter
- Combined and predicted EOPs are delivered
  - Daily by automated procedures

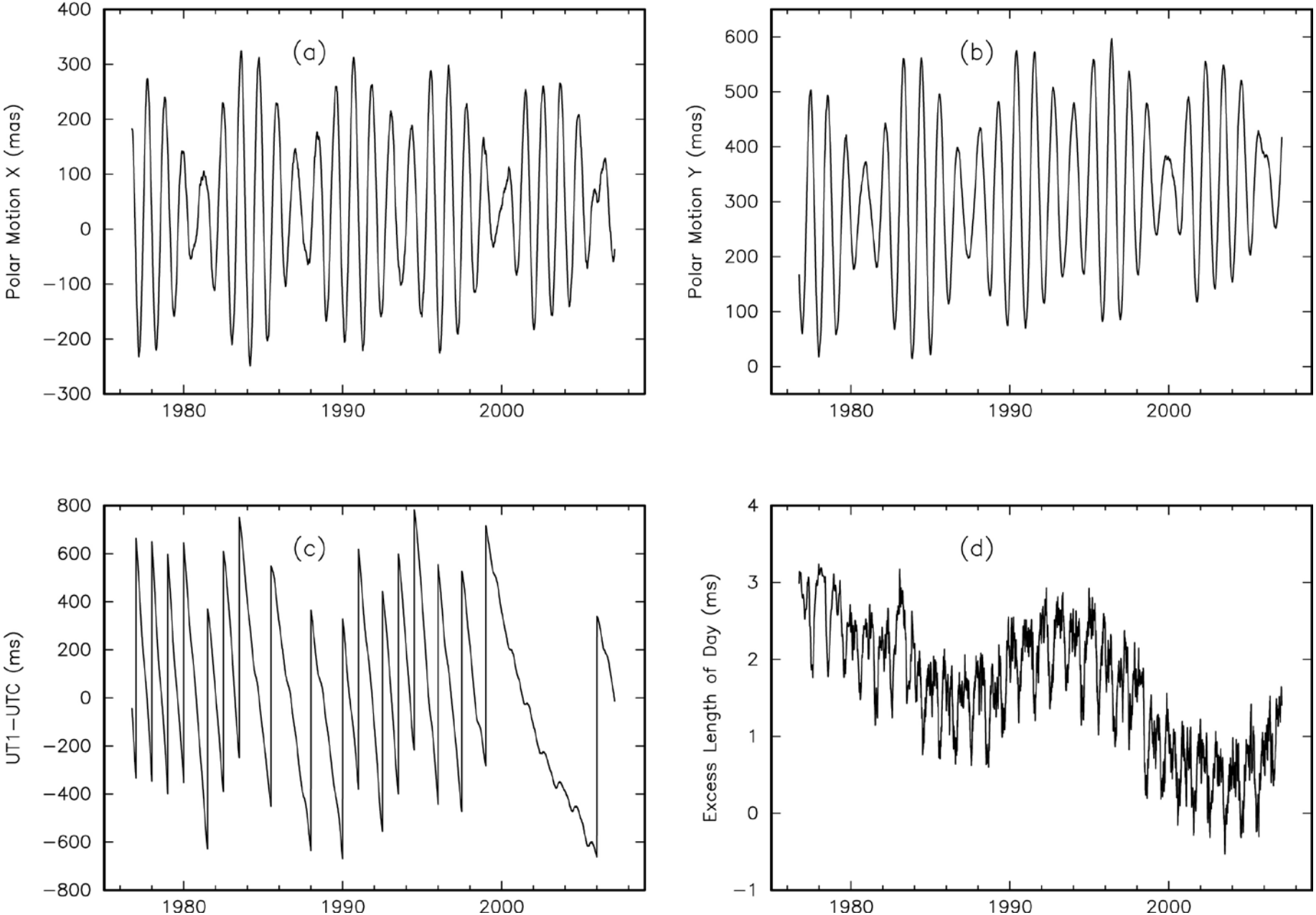
KEOF Products

- **Earth Orientation Parameter (EOP) file**
  - **Contains calibrations for polar motion and UT1–UTC**
    - **Long version spans 1962.0 to present at daily intervals (at 5-day intervals before July 1, 1969)**
    - **Short version spans past year at daily intervals**
    - **Consistent with the terrestrial reference frame used by the spacecraft navigation teams (ITRF93)**
    - **UT1 does not include "new" 18.6- and 9.3-year lunar nodal terms**
  - **Also contains precession-nutation parameters necessary to determine station locations in celestial reference frame at the few-centimeter level**
  - **Allows for arbitrary number of calibrations**
    - **Greater temporal resolution of calibrations means smaller interpolation error when interpolating between calibration values**
  - **Produced daily**
- **Export file**
  - **Consists of values and short-term predictions of polar motion, UT1–UTC, and their rates**
    - **EOP values span 1994.0 to the present at daily intervals**
    - **EOP predictions extend 35 days into the future at daily intervals**
    - **Available in versions time-tagged at midnight or at noon**
    - **Consistent with the current IERS terrestrial reference frame (ITRF2005) and definition of UT1 (UT1 includes "new" 18.6- & 9.3-year terms)**
  - **Produced daily**
  - **Web site currently under development**

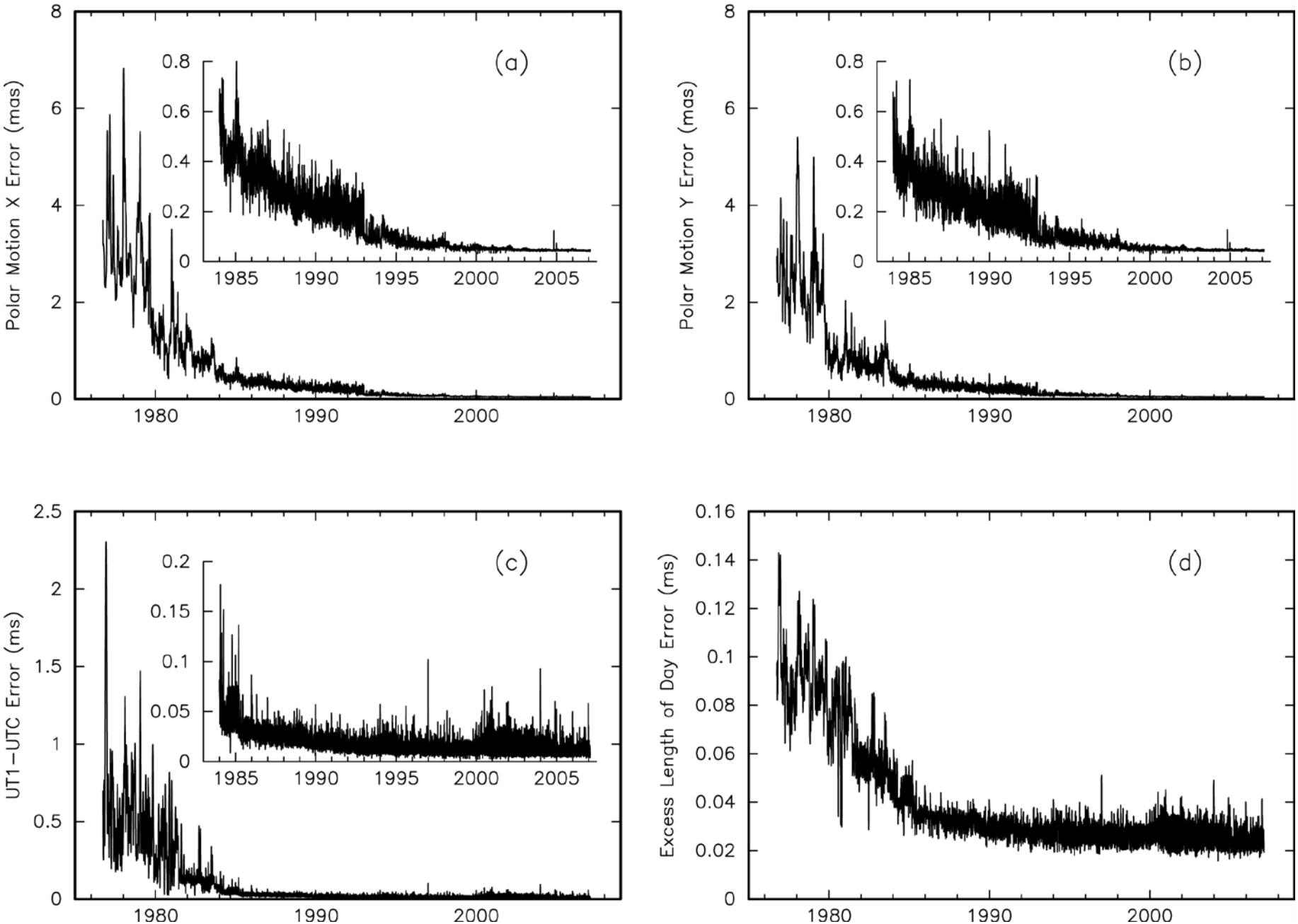
KEOF Products, cont.

- **Annual smoothings (SPACE2014, COMB2014, POLE2014)**
  - **SPACE series of annual smoothings formed by using KEOF to combine the most accurate space-geodetic Earth orientation measurements available**
    - **DSN and other VLBI, lunar laser ranging, satellite laser ranging, and GPS measurements are combined**
    - **Resulting Earth orientation estimates (polar motion, UT1–UTC, and their rates) span 1976 to the present at 1-day intervals**
  - **COMB series of annual smoothings additionally incorporate BIH optical astrometric measurements**
    - **Resulting Earth orientation estimates (polar motion, UT1–UTC, and their rates) span 1962 to the present at 1-day intervals**
  - **POLE series of annual smoothings additionally incorporate ILS optical astrometric measurements**
    - **Resulting Earth orientation estimates (polar motion and its rate) span 1900 to the present at 30.4375-day intervals**
  - **These annual smoothings are generated as part of the procedure employed when annually determining the corrections (to the series' bias, rate and stated uncertainties) that must be applied to the Earth orientation series used in the daily operations**
    - **The required corrections are determined by comparing each operational series to an independent reference series**
    - **The independent reference series must be created since no existing Earth orientation series is entirely independent of the data being corrected**
    - **The independent reference series are created by combining subsets of the series used to form the SPACE series**
    - **Combining all series then yields the SPACE series**
  - **Available once-per-year on or about May 1**

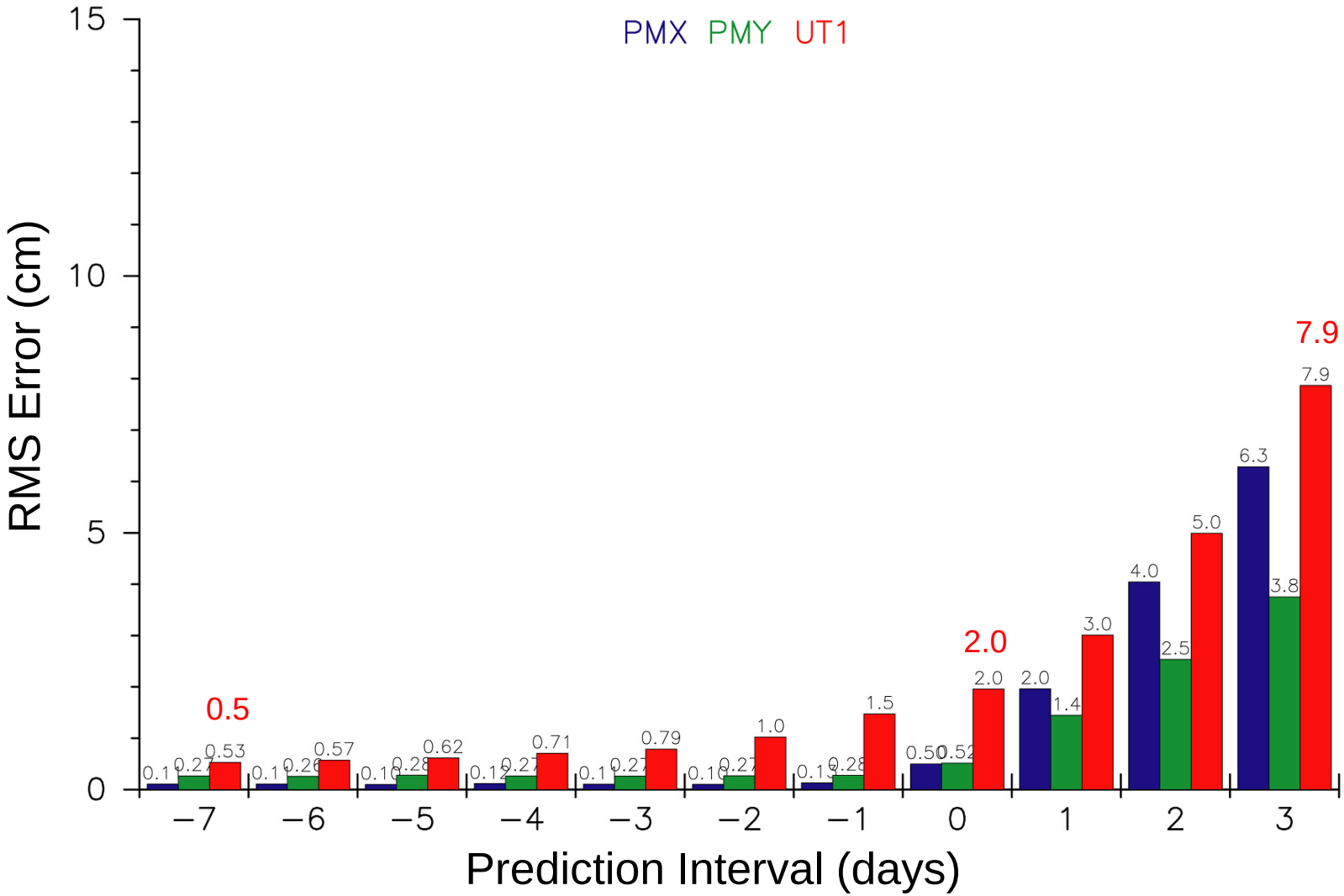
A COMBINED EARTH ORIENTATION SERIES : SPACE2006



A COMBINED EARTH ORIENTATION SERIES : SPACE2006



Earth Orientation Prediction Error



Prediction day 0 is epoch of file generation and delivery
61 Deliveries Spanning October 1, 2006 to March 31, 2007

Evolving Requirements

- Phoenix (2008)
  - Allocation to Earth orientation in support of Delta-DOR
    - 5 cm real-time UT1 ; 2 cm real-time polar motion
- Navigation Tracking-Metrics Requirements
  - 2010
    - 5 cm real-time UT1 and polar motion
    - 3 cm after-the-fact UT1 and polar motion reconstructions (older than 1 day)
  - 2020
    - 3 cm real-time UT1 and polar motion
    - 2 cm after-the-fact UT1 and polar motion reconstructions (older than 1 day)
  - 2030
    - 2 cm real-time UT1 and polar motion
    - 0.5 cm after-the-fact UT1 and polar motion reconstructions (older than 1 day)

Pathways to Meeting Requirements

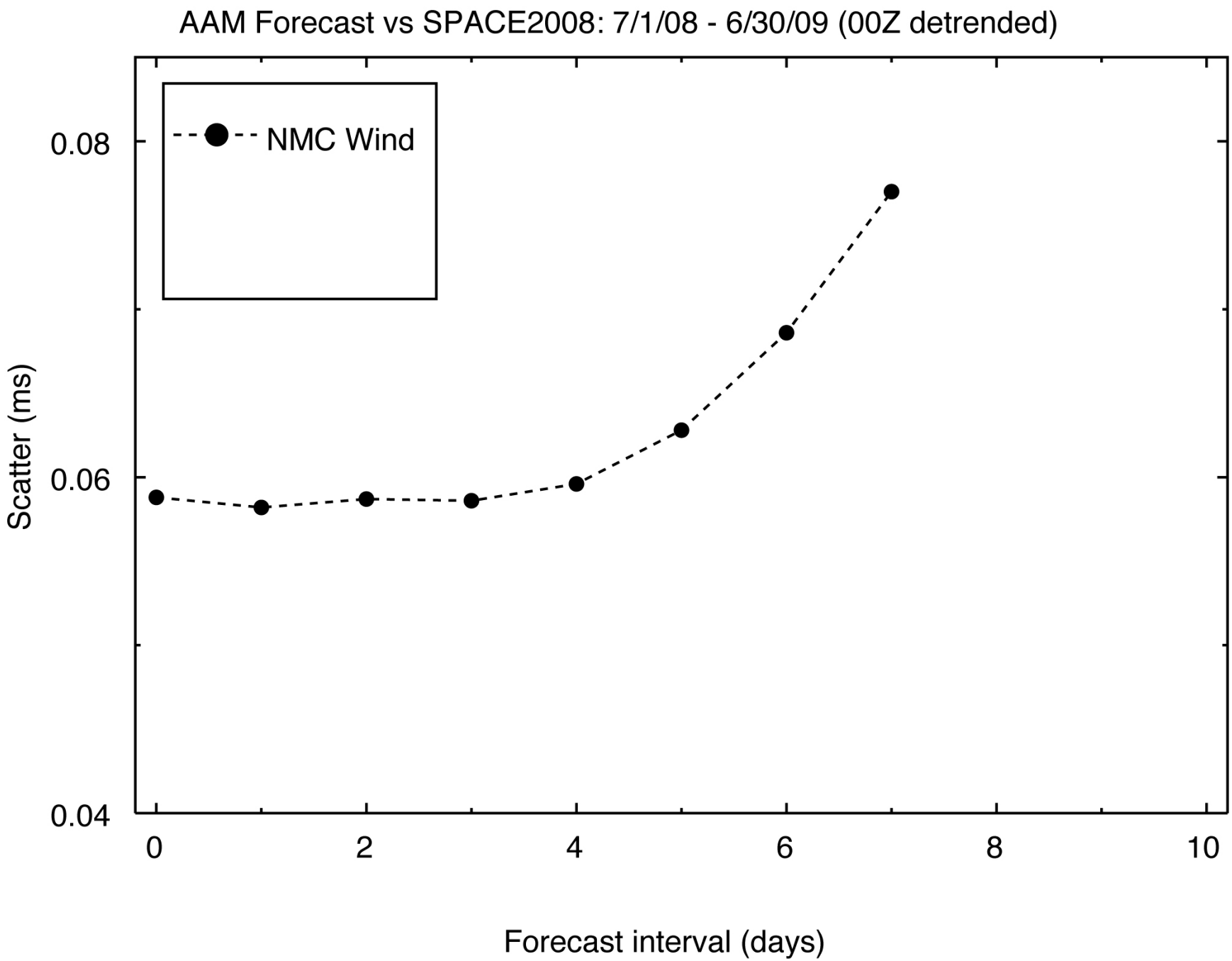
- Focus needs to be on improving real-time UT1
- Better measurements
  - Need more accurate and *timely* VLBI measurements
- Better combination procedures
  - Use additional measurements
    - Ultra-rapid (real-time) GPS measurements
    - Polar motion rate measurements
  - Improve stochastic models
- Better predictive capabilities
  - Use additional forecast data
    - Atmospheric angular momentum forecasts at different lead times
    - Oceanic angular momentum forecasts (when available)
  - Improve prediction algorithms

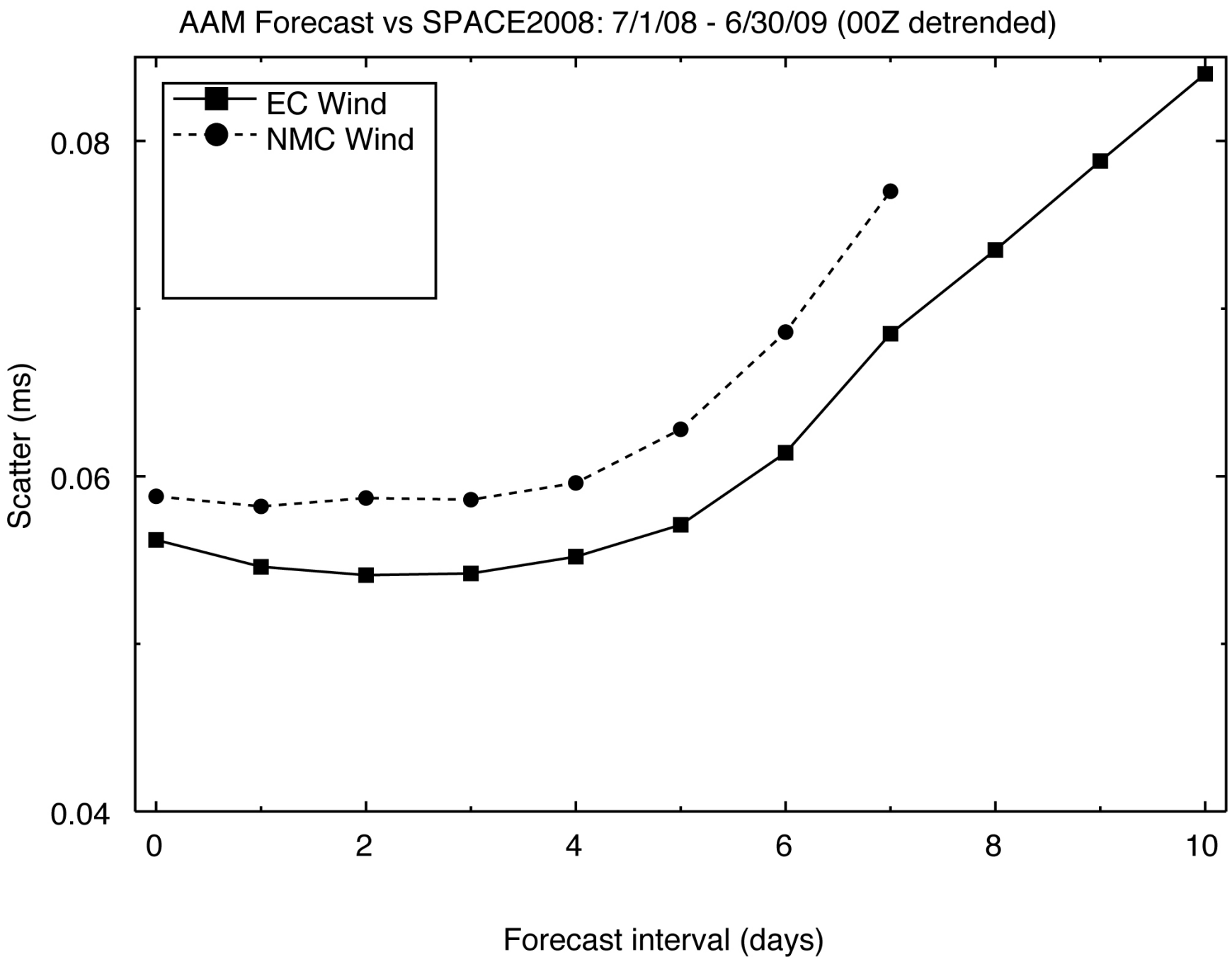
Combining EOP Measurements

- Garbarge in, garbage out
  - Combined product is only as good as the data being combined
    - Accuracy of input series is of paramount importance
- Consistency
  - Input series need to be consistent with each other before being combined
    - Input series must be given, or placed, within same reference frame
    - Values must be interpolated to same epoch
    - Values must be assigned appropriate weights
- Method of combining measurements
  - Weighted average, Kalman filter, etc.
  - Combine full values or residuals
- Retrospective, real-time, or predictions
  - Require different approaches

Improved Predictions using OAM?

- Earth's rotation varies rapidly and unpredictably
  - Universal Time (UT1) variations 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
- Atmospheric angular momentum (AAM)
  - Exchanged with angular momentum of solid Earth
    - Axial component causes length-of-day (UT1-rate) variations
    - Equatorial components contribute to causing the Earth to wobble as it rotates
  - Computed by operational numerical weather forecast models
    - NCEP, ECMWF, NOGAPS, …
  - AAM forecasts used to improve accuracy of UT1 predictions
- Oceanic angular momentum (OAM)
  - Can OAM forecasts improve accuracy of UT1 predictions?


AAM Forecast vs SPACE2008: 7/1/08 - 6/30/09 (00Z detrended)
NMC Wind
Scatter (ms)
0.08
0.06
0.04
0
2
4
6
8
10
Forecast interval (days)


AAM Forecast vs SPACE2008: 7/1/08 - 6/30/09 (00Z detrended)
EC Wind
NMC Wind
0.08
0.06
0.04
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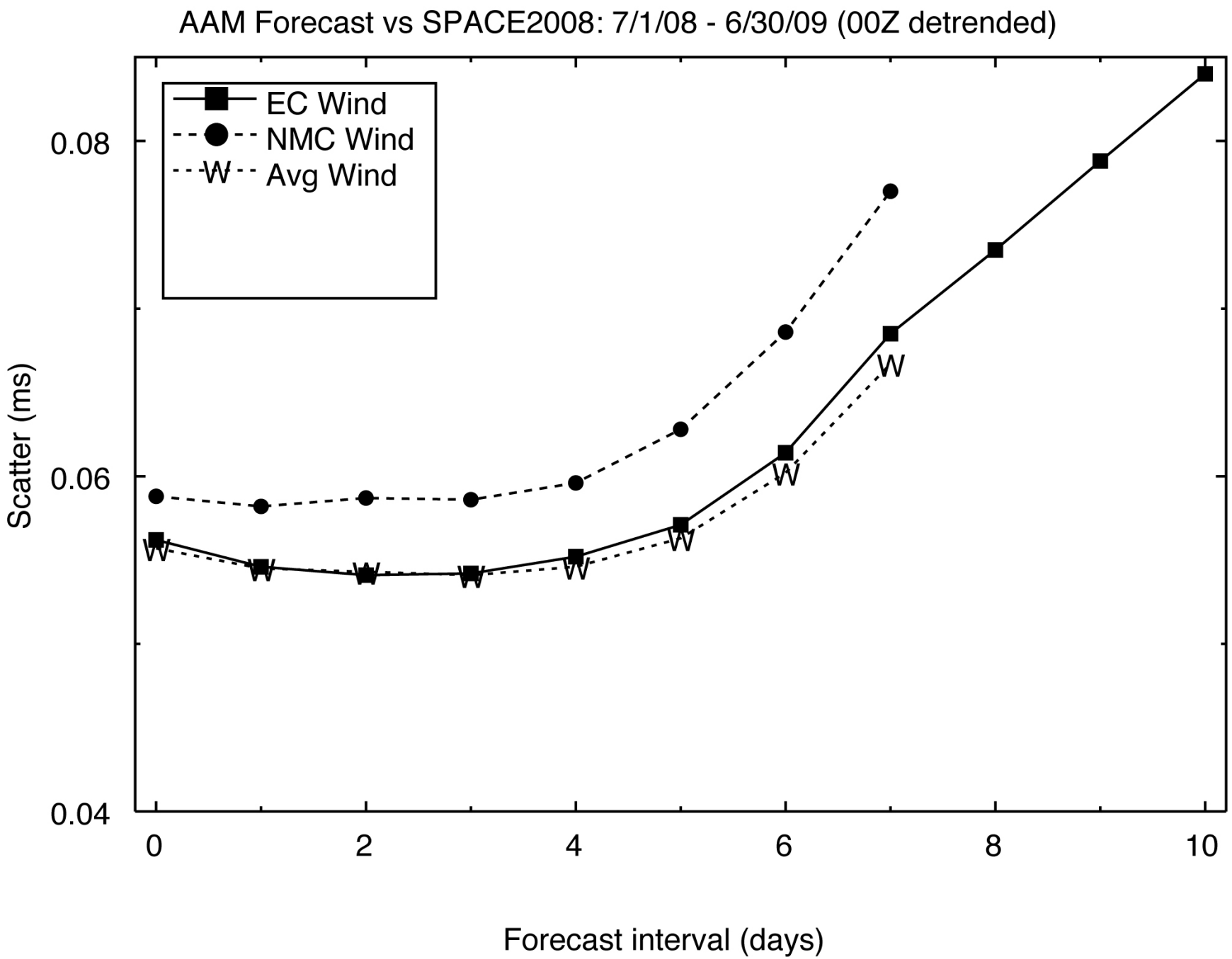
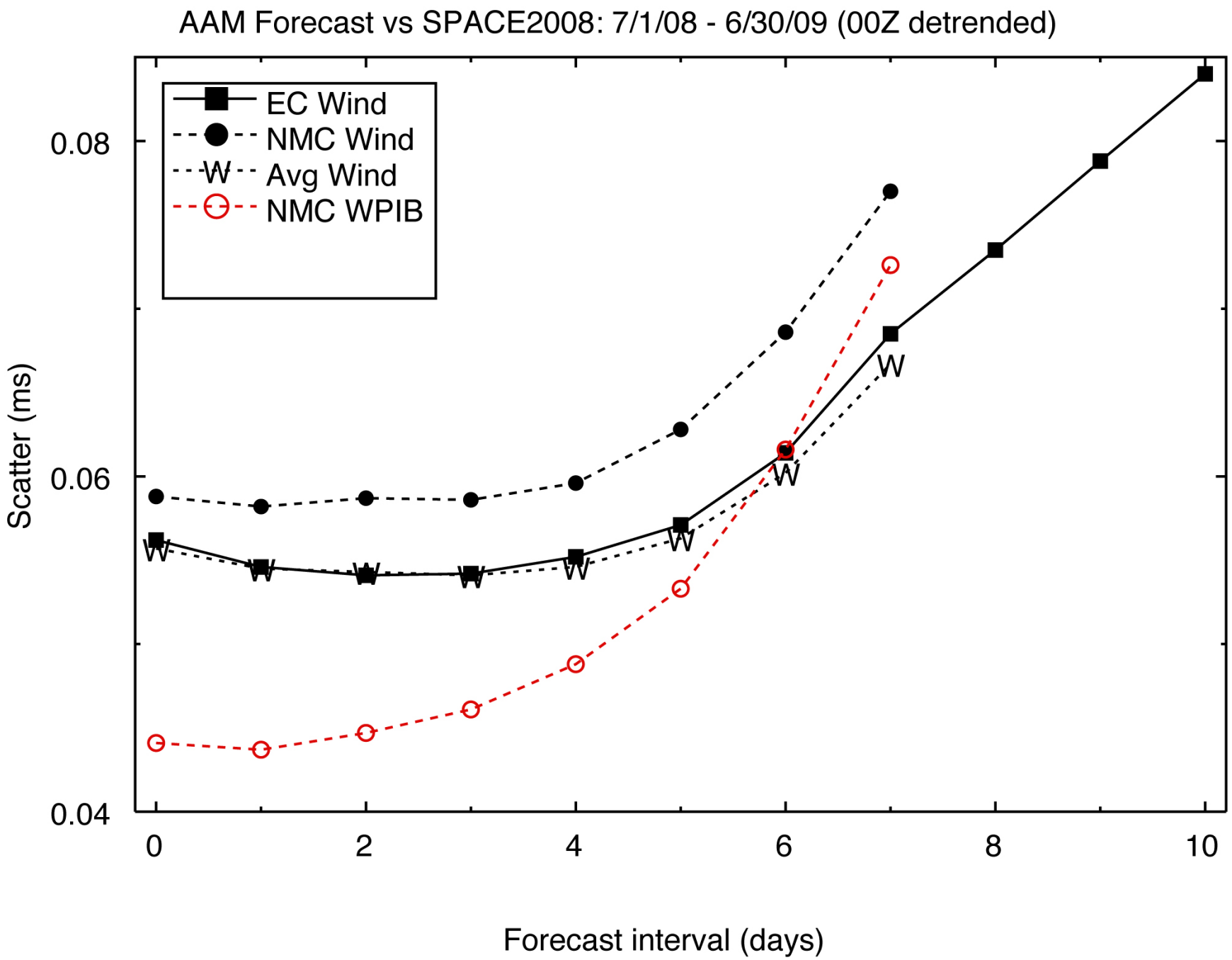
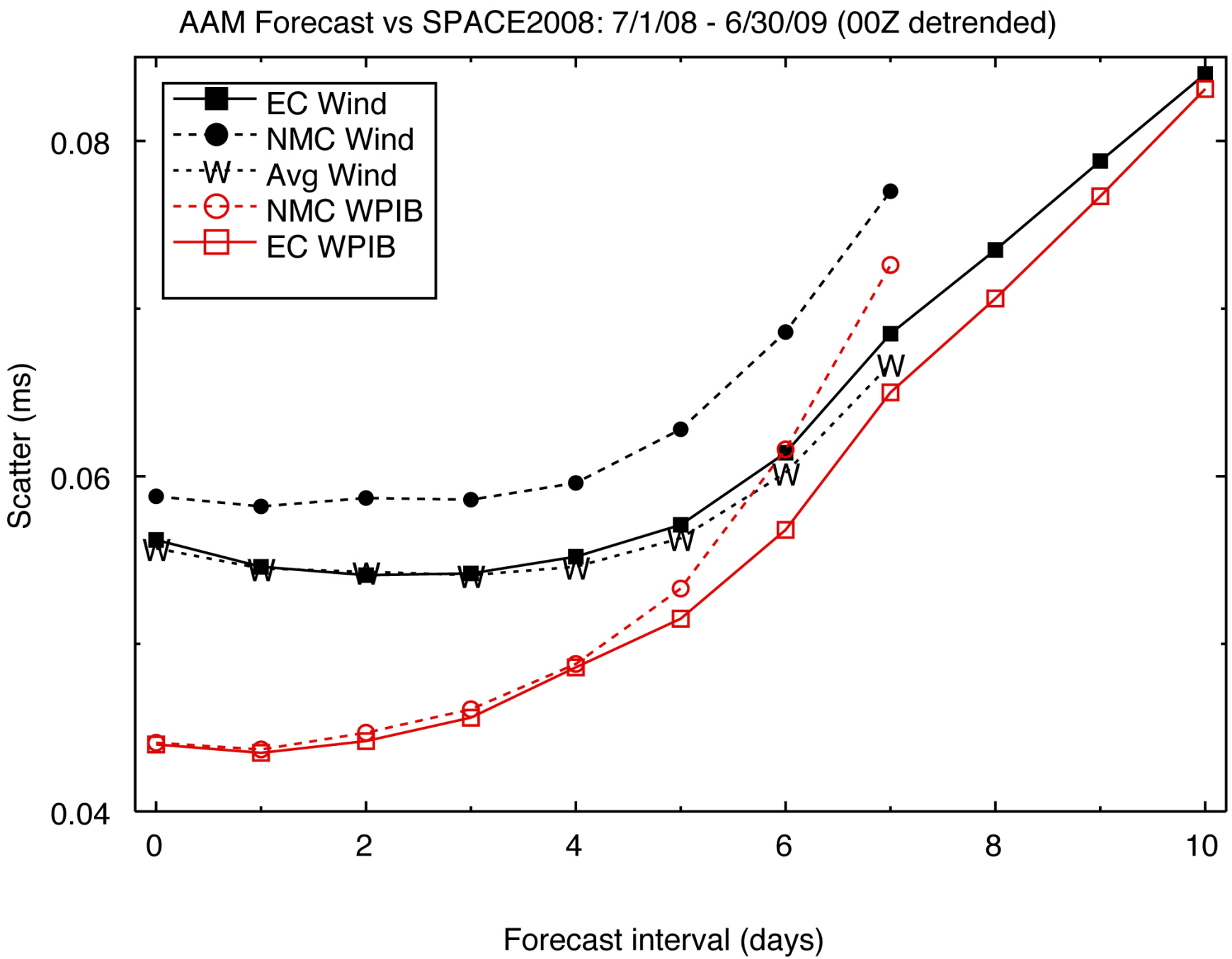
Forecast interval (days)


AAM Forecast vs SPACE2008: 7/1/08 - 6/30/09 (00Z detrended)
EC Wind
NMC Wind
Avg Wind
Scatter (ms)
0.08
0.06
0.04
0
2
4
6
8
10
Forecast interval (days)


AAM Forecast vs SPACE2008: 7/1/08 - 6/30/09 (00Z detrended)
EC Wind
NMC Wind
Avg Wind
NMC WPIB
Scatter (ms)
0.08
0.06
0.04
0
2
4
6
8
10
Forecast interval (days)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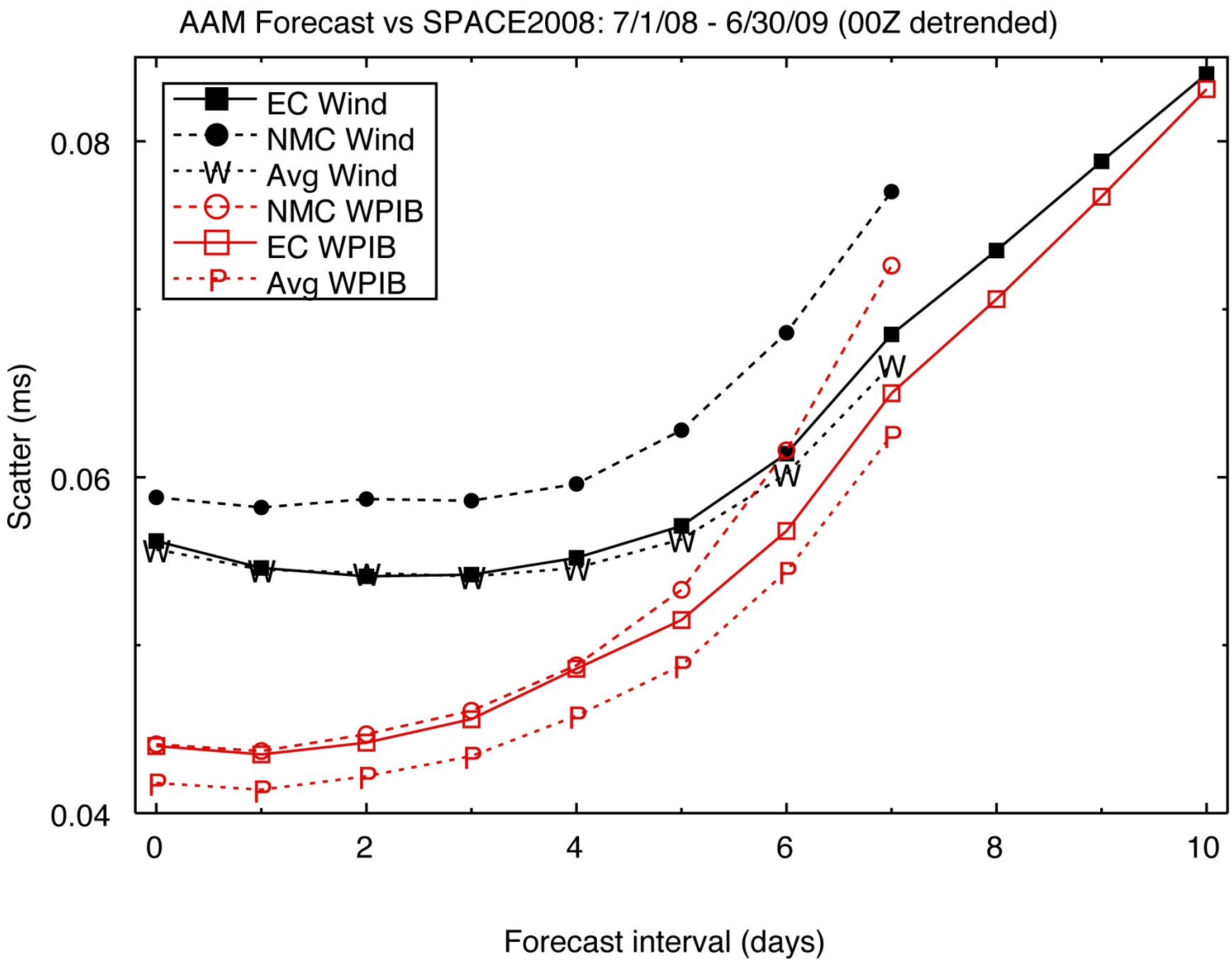
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Forecast interval (days)

Approach

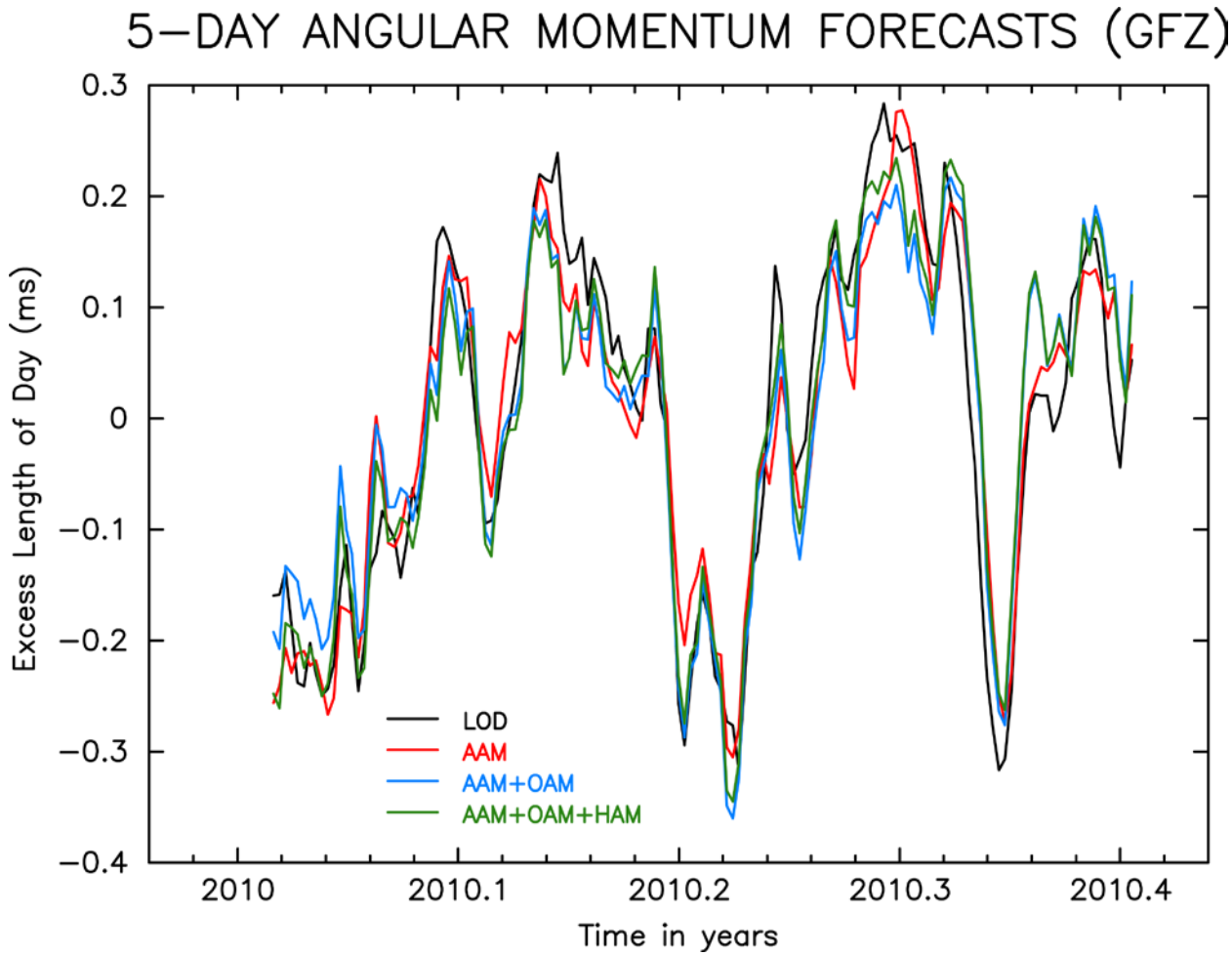
- Evaluate impact of AAM, OAM & HAM forecasts on accuracy of UT1 predictions
  - Using JPL's Kalman filter approach to predicting UT1
    - NCEP 5-day wind AAM forecasts currently used at JPL
- Test cases
  - Reprocess 143 operational filter runs spanning January 1, 2010 to May 28, 2010 using
    - No AAM forecasts
    - 5-day wind AAM forecasts from NCEP (reproducing operational results)
    - 5-day wind + inverted barometer pressure AAM forecasts from NCEP
    - 5-day wind AAM forecasts from ECMWF/GFZ
    - 5-day wind + inverted barometer pressure AAM forecasts from ECMWF/GFZ
    - Average of 5-day wind AAM forecasts from NCEP & ECMWF/GFZ
    - Average of 5-day wind+ib pressure AAM forecasts from NCEP & ECMWF/GFZ
    - Consistent 5-day OAM and HAM forecasts from GFZ

Data Sets

- Helmholtz Centre Potsdam – GFZ
  - Consistent estimates of AAM, OAM, & HAM computed at GFZ
    - AAM computed from European Centre for Medium-Range Weather Forecasts
    - OAM computed from Ocean Model for Circulation and Tides (OMCT)
    - HAM computed from Land-Surface Discharge Model (LSDM)
    - Ocean and hydrology models driven by ECMWF fields
    - Global atmosphere/oceans/hydrology mass conservation imposed
    - Analyses and forecasts to 10 days into future; only 5-day forecasts used here
    - Forecasts start January 1, 2010
- US National Centers for Environmental Prediction
  - Atmospheric angular momentum only
    - Angular momentum of winds and surface pressure variations
    - Analyses and forecasts to 7.5 days into future; only 5-day forecasts used here
- UT1 predictions
  - Generated using JPL's Kalman Earth orientation filter

Kalman Earth Orientation Filter

- A Kalman filter is used operationally at JPL to
  - Combine available Earth rotation measurements
    - Including NCEP AAM forecasts (5-day winds only)
  - Predict future changes in the Earth's rotation
    - Out to 78 days in advance
- Input data are corrected prior to combination
  - Data are placed within same terrestrial reference frame
    - Current ITRF (e.g., ITRF2008)
  - Stated uncertainties are adjusted to reflect accuracy, not precision, of measurement
    - Adjusted uncertainties are used as weights by Kalman filter
- Used here to generate UT1 predictions
  - No AAM; AAM only; AAM+OAM; AAM+OAM+HAM
    - Predictions generated 143 times during January 1, 2010 to May 28, 2010



Forecast Series	LOD Variance Explained	Correlation
ECMWF/GFZ 5-day wind	84.311%	0.9215
ECMWF/GFZ 5-day wind+ib	88.566%	0.9426
GFZ 5-day AAM+OAM (mass+motion)	86.093%	0.9294
GFZ 5-day AAM+OAM+HAM (mass+motion)	87.625%	0.9361

UT1 Prediction Error, cm

AAM Forecast Series	Prediction Interval, days							
	0	1	2	3	4	5	6	7
No AAM forecasts	1.2	2.6	5.7	10.1	15.5	21.5	28.0	34.9
NCEP 5-day wind	1.2	2.2	4.3	7.0	10.1	13.3	16.7	20.7
NCEP 5-day wind+ib	1.2	2.2	4.1	6.7	9.7	12.8	16.2	20.3
ECMWF/GFZ 5-day wind	1.2	2.2	4.2	6.8	9.7	12.8	16.2	20.2
ECMWF/GFZ 5-day wind+ib	1.2	2.1	4.1	6.5	9.4	12.4	15.9	19.9
Average NCEP+ECMWF/GFZ wind	1.2	2.2	4.2	6.9	9.8	12.9	16.3	20.2
Average NCEP+ECMWF/GFZ wind+ib	1.2	2.1	4.1	6.6	9.4	12.5	15.9	19.9
GFZ 5-day AAM+OAM (mass+motion)	1.2	2.0	3.6	5.7	8.1	10.7	13.8	17.6
GFZ 5-day AAM+OAM+HAM (mass+motion)	1.2	2.0	3.7	5.8	8.2	11.0	14.1	18.0

Tabulated UT1 prediction error is the rms with respect to an accurate UT1 reference series of the 143 predictions given at the stated lead time.

Prediction day 0 is the epoch of the last length-of-day measurement. The epoch of the last UT1 measurement is typically a few days earlier.

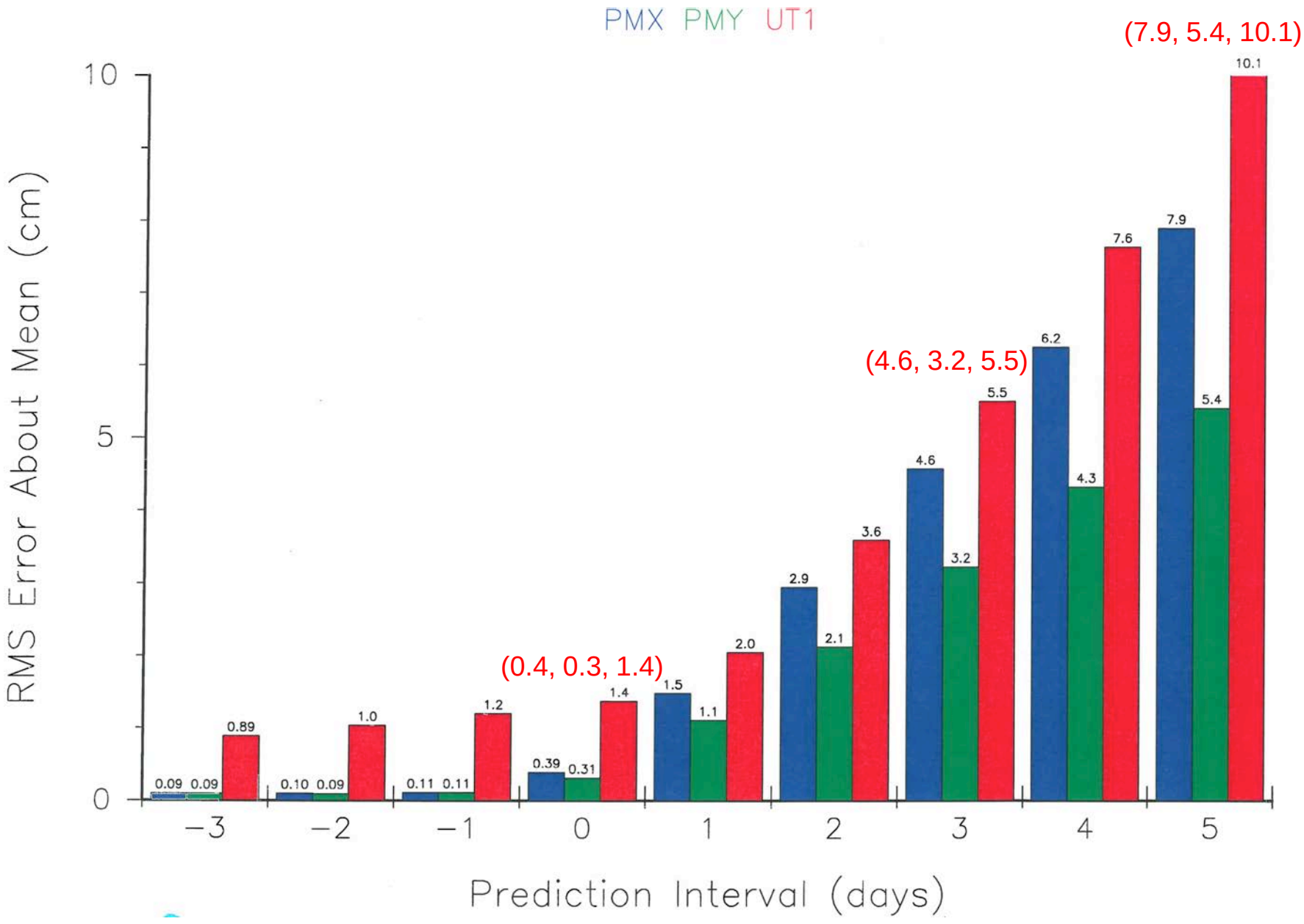
A change in rotation equivalent to a 1 millisecond change in time corresponds to a 46.3 centimeter displacement of the Earth's surface at the equator.

Include IGS Ultra-Rapids

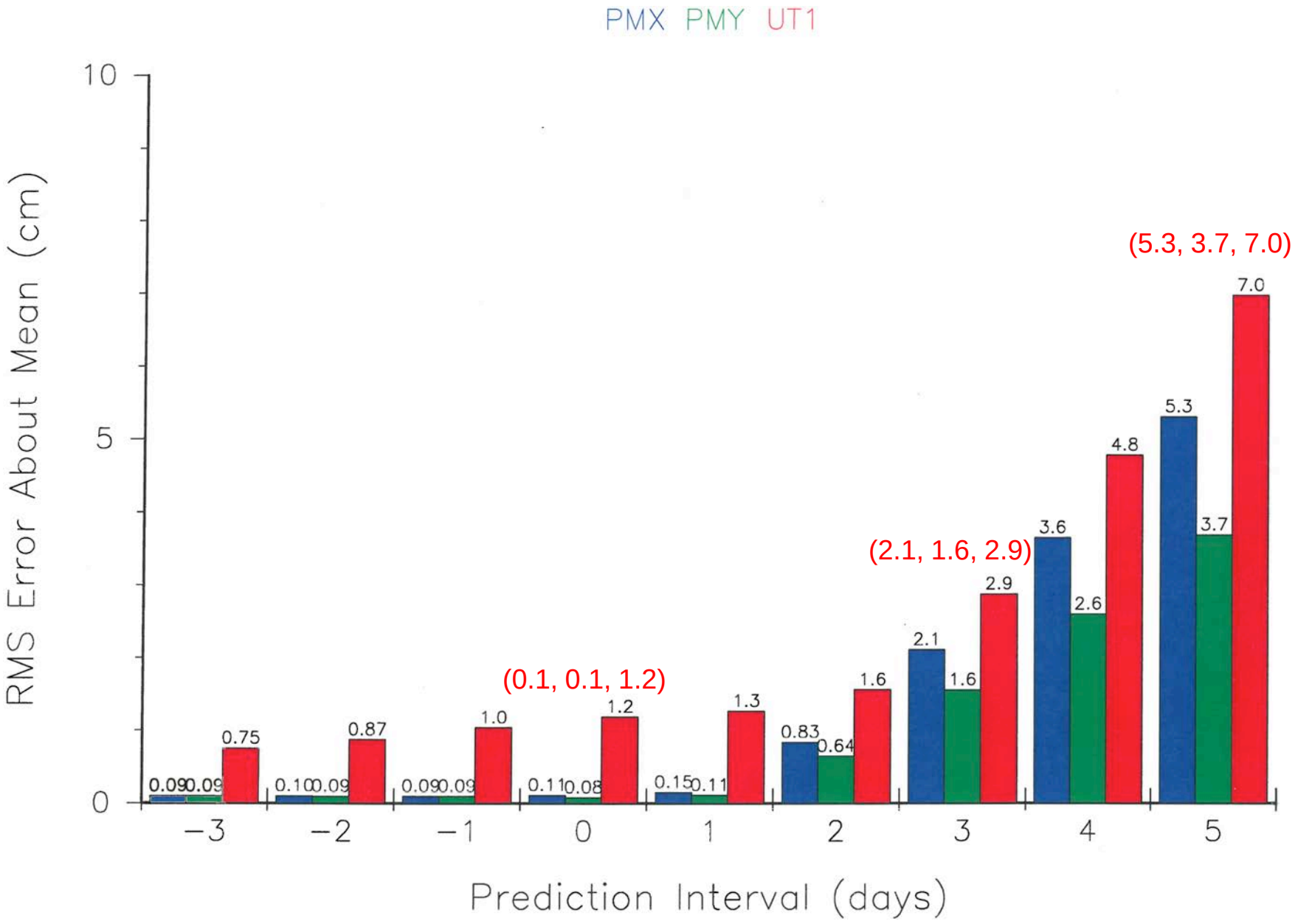
- IGS Ultra-Rapid polar motion and length-of-day
  - Observed half
    - Latency of 3 to 9 hours; available at 03, 09, 15, 21 UTC
    - Polar motion accurate to about 50 microarcseconds
    - Length-of-day accurate to about 10 microseconds
  - Predicted half
    - Real-time
    - Polar motion accurate to about 200 microarcseconds
    - Length-of-day accurate to about 50 microseconds
- Include IGS Ultra-Rapids in KEOF
  - Polar motion and length-of-day; observed & predicted halves
    - Reduces 0-day (PMX, PMY, UT1) from (0.39, 0.31, 1.4) to (0.11, 0.08, 1.2) cm
    - Reduces 3-day (PMX, PMY, UT1) from (4.6, 3.2, 5.5) to (2.1, 1.6, 2.9) cm
    - Reduces 5-day (PMX, PMY, UT1) from (7.9, 5.4, 10.1) to (5.3, 3.7, 7.0) cm

(Statistics based on re-processing operational KEOF runs during last half of 2014)

Control Run (No IGS Ultra-Rapids)



With IGS Ultra-Rapid PM & LOD



Summary

- Impact of AAM, OAM, and HAM forecasts on accuracy of UT1 predictions has been evaluated
  - AAM wind forecasts greatly improve UT1 predictions
    - 7-day UT1 prediction accuracy improves from 34.9 cm to 20.2 cm (EC/GFZ)
  - Including i.b. improves UT1 prediction accuracy only slightly
    - 7-day UT1 prediction accuracy improves from 20.2 cm to 19.9 cm (EC/GFZ)
  - EC/GFZ AAM forecasts are slightly better than NCEP
  - Averaging EC/GFZ & NCEP AAM forecasts has no effect
  - Including OAM improves UT1 prediction accuracy only slightly
    - 7-day UT1 prediction accuracy improves from 19.9 cm to 17.6 cm (EC/GFZ)
  - Including HAM degrades UT1 prediction accuracy slightly
    - 7-day UT1 prediction accuracy changes from 17.6 cm to 18.0 cm (EC/GFZ)
- IGS Ultra-Rapid polar motion and length-of-day
  - Greatly improves polar motion and UT1 predictions
    - By about 30% at 5-day lead time

Summary

- Navigating spacecraft in deep space requires accurate 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 tighter accuracies
    - 2 cm real-time polar motion and 5 cm real-time UT1 for Phoenix
- These requirements are met at JPL by
  - Measuring Earth orientation variations with GPS and VLBI
  - Combining these in-house measurements with other, publicly available, measurements using a Kalman filter
- Meeting future requirements with only in-house data will be an ongoing challenge