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STATUS AND PROSPECTS FOR COMBINED GPS LOD AND VLBI UT1 MEASUREMENTS

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ABSTRACT. A Kalman filter was developed to combine VLBI estimates of UT1-TAI with biased length of day (LOD) estimates from GPS. The VLBI results are the analyses of the NASA Goddard Space Flight Center group from 24-hr multi-station observing sessions several times per week and the nearly daily 1-hr single-baseline sessions. Daily GPS LOD estimates from the International GNSS Service (IGS) are combined with the VLBI UT1-TAI by modeling the natural excitation of LOD as the integral of a white noise process (i.e., as a random walk) and the UT1 variations as the integration of LOD, similar to the method described by Morabito et al. (1988). To account for GPS technique errors, which express themselves mostly as temporally correlated biases in the LOD measurements, a Gauss-Markov model has been added to assimilate the IGS data, together with a fortnightly sinusoidal term to capture errors in the IGS treatments of tidal effects. Evaluated against independent atmospheric and oceanic axial angular momentum (AAM + OAM) excitations and compared to other UT1/LOD combinations, ours performs best overall in terms of lowest RMS residual and highest correlation with (AAM + OAM) over sliding intervals down to 3 d. The IERS 05C04 and Bulletin A combinations show strong high-frequency smoothing and other problems. Until modified, the JPL SPACE series suffered in the high frequencies from not including any GPS-based LODs. We find, surprisingly, that further improvements are possible in the Kalman filter combination by selective rejection of some VLBI data. The best combined results are obtained by excluding all the 1-hr single-baseline UT1 data as well as those 24-hr UT1 measurements with formal errors greater than 5 μs (about 18% of the multi-baseline sessions). A rescaling of the VLBI formal errors, rather than rejection, was not an effective strategy. These results suggest that the UT1 errors of the 1-hr and weaker 24-hr VLBI sessions are non-Gaussian and more heterogeneous than expected, possibly due to the diversity of observing geometries used, other neglected

systematic effects, or to the much shorter observational averaging interval of the single-baseline sessions. UT1 prediction services could benefit from better handling of VLBI inputs together with proper assimilation of IGS LOD products, including using the Ultra-rapid series that is updated four times daily with 15 hr delay.

Keywords: UT1, length of day, VLBI, GPS, Kalman filter

1. INTRODUCTION

Variations in the rotation rate of the Earth occur on all observable timescales and are caused by both external and internal processes. Gravitational interactions with the Sun and Moon, primarily, give rise to tidal features with narrow spectral characteristics. Deviations in the length of day (LOD) from exactly 86,400 s of atomic time due to the tides reach about 2 ms. Because the external forcing potentials are very accurately known, the observed rotational response of the Earth can be used to infer subtle features of the planet's viscoelastic properties (Yoder et al., 1981, and many later works). The internal excitations are related to redistributions of the Earth's fluid components, namely atmosphere, ocean, surface hydrology, and fluid outer core, which mostly have broadband effects with atmospheric and oceanic variations especially evident at shorter periods (less than a few years) and deep interior processes detectable only over longer periods (e.g., Hide and Dickey, 1991). These non-tidal changes in LOD amount to about 1 ms over the course of a typical year. Rotational changes are effected through both mass (moment of inertia) and motion (angular momentum) mechanisms. For a comprehensive review of Earth orientation variations and their geophysical interpretation, refer to Eubanks (1993).

As UT1 refers to the axial rotation angle (normally expressed in time units) of the Earth relative to the conventional celestial (inertial) reference frame, now realized by the astrometric coordinates of a set of extragalactic radio sources, only Very Long Baseline Interferometry (VLBI) is able to measure UT1 variations directly (see IERS Conventions 2003, edited by McCarthy and Petit, for details). Observations of near-Earth satellites are also sensitive to spin rate changes, but all such techniques lack the ability to distinguish UT1 from a uniform rotation of the satellite orbit nodes in inertial space. Thus it is generally not possible to estimate satellite orbits and UT1 jointly without additional constraints. On the other hand, LOD (equivalent to the negative discrete time derivative of UT1 over 24 hr) is routinely estimated in satellite data reductions. A time series of continuous LOD measurements of this type can be integrated to yield UT1-like variations relative to some initialized value. However, any unmodeled motions of the orbit nodes will contaminate the LOD estimates and hence the inferred UT1 variations. Ray (1996) found significant time-varying biases in the LOD results from all analysis centers of the International GNSS Service (IGS) derived from Global Positioning System (GPS) observations, compared to derivatives of simultaneous VLBI UT1. The biases were temporally correlated and differed widely among the centers, though inter-center similarities were also evident. Ray suggested that a Gauss-Markov process could describe the GPS LOD biases with a time constant of about 0.75 d. LOD results from Satellite Laser Ranging (SLR) to the two LAGEOS satellites have been less thoroughly studied but the errors are evidently larger (Eanes and Watkins, 1994), probably due mostly to the much weaker constellation.

The International Earth Rotation and Reference Systems Service (IERS) and other groups provide regularized tabulations of UT1-UTC and LOD variations derived from multi-technique combinations of VLBI and satellite observations. These products are required for a broad range of practical and scientific applications to relate the Earth's instantaneous orientation to a local inertial frame. The treatment of LOD biases has been handled variously in the different combined series. The IERS 05C04 series, maintained by the Observatoire de Paris, uses VLBI, GPS, and SLR inputs and removes the low-frequency satellite LOD variations (99% at a 19-d period) by a Vondrák (1969, 1977) filter of their LOD differences compared to differentiated VLBI UT1 values; see C04_05.guide.pdf at hpiers.obspm.fr/iers/eop/eopc04_05. However, the 05C04 input UT1 and LOD series are combined quasi-independently of each other (D. Gambis, private communication 2008) rather than enforcing the physical condition that

$$d(UT1 - TAI)/dt = -LOD$$

where TAI is the far more stable International Atomic Time and the time differential is conventionally 1 d. This leads to some level of internal inconsistency on short timescales, as seen in the results below.

IERS Bulletin A is prepared at the U.S. Naval Observatory (USNO) and is intended for near real time uses. Several VLBI UT1 series are included together with a unique UT1-like series generated at USNO from axial rotations of the IGS orbits and the most recent IGS integrated LOD values (Luzum et al., 2001). Biases in the GPS results are removed by applying a high-pass Gaussian filter to the differences with spline-interpolated VLBI UT1. Signals in the GPS series with periods less than 10 d are supposed to be fully transmitted while attenuating those at 26 d by about 50%.

The Jet Propulsion Laboratory (JPL) generates an updated Earth orientation parameter (EOP) series each year as the basis for its operational EOP prediction service, which is important for deep space navigation and for scientific investigations. The SPACE2006 combination (Gross, 2007) departed from earlier versions by omitting satellite-based LOD estimates altogether due to problems coping with the orbit-related errors, so only VLBI UT1 measurements were included. As we will see below, while this expedient avoids spurious signals entering the combination, it also limits the high-frequency fidelity of SPACE2006. Previously a GPS-based LOD series determined at JPL had been included by stochastically modeling its biases with random walk, first-order autoregressive, and white noise components (Gross, 2006). (GPS-based LOD contributions have been restored in more recent SPACE combinations.) In addition to the annual SPACE series, JPL also produces a continuously updated prediction series that is intended for operational purposes. Due to its importance for UT1 predictions, the JPL operational series assimilates AAM at noon epochs in addition to geodetic inputs. Both product sets are available at ftp://euler.jpl.nasa.gov/keof.

A few other combination approaches have been tested but not utilized for routine EOP services. The method of "combined smoothing," developed at the Astronomical Institute in Prague (Vondrák and Cepek, 2000), permits a time series of values and a second series of time derivatives of those values to be fit jointly using an analytic minimization condition with two coefficients of smoothness that must be set. This method has been applied by Vondrák and Ron (2005) to a combination of VLBI UT1 and GPS LOD values, providing a product with improved accuracy and resolution compared to VLBI alone, although all signals shorter than 1.5 d have been removed. Vondrák and Ron relied only on the coarse LOD bias calibration applied within the IGS internal combination (based on sliding-window differences with past Bulletin A series;

see Mireault et al., 1999) and did not consider any residual biases, which are significant as shown below.

Contrary to all other combinations known to us, Thaller et al. (2007) combined two weeks of simultaneous VLBI UT1 and GPS LOD values at the normal equation level while making no provision for LOD biases. Deficiencies in the GPS observations of the Earth's spin are presumably accommodated in the satellite orbit parameters to agree with the unbiased VLBI rotation rate. While this method might yield improved GPS (inertial) orbits, that possibility was not examined and the utility for UT1/LOD combination was only tested by finding a reduction in RMS differences with the IERS C04 series from 15 to 11 µs. Since the IERS series itself relies upon the same main data inputs, the reasoning is circular. In addition, any effective smoothing in the procedures of Thaller et al. could lead to better agreement with C04 due to its being strongly smoothed at the highest frequencies (see results below and 05C04 documentation cited above, which indicates strong smoothing of periods less than 2 d). Previously we have shown (Ray et al., 2005) that injecting very accurate GPS-based polar motion values into a VLBI-GPS combination improves the VLBI-only UT1 estimates, another factor which could account for the Thaller et al. results. At a practical level, their approach requires strictly continuous VLBI and GPS observations and so it was evaluated over just the 14 d of a special VLBI observing campaign.

In this study the GPS LOD biases are explicitly modeled using a Kalman filter assimilation with VLBI UT1 measurements. Apart from the combined product itself, this approach permits us to examine the nature of the byproduct GPS biases and consider possible underlying causes. Our inter-technique UT1/LOD combination is performed separately from a "rigorous" processing of terrestrial frame coordinates and Earth orientation parameters (EOPs), as in ITRF2005 (Altamimi et al., 2007) for instance. Such a separation is justified for LOD because the frame-related biases are nil, noting that a LOD offset of 1 µs over 1 d corresponds to an equivalent frame rotational velocity of about 170 mm/a. Realistic frame misalignments are smaller than this by more than an order of magnitude. Ideally, however, the input UT1 values should be previously aligned in a joint frame-EOP combination (Ray, 2009). Previous results from this work have been reported previously (Senior et al., 2008a, 2008b).

2. KALMAN FILTER COMBINATION MODEL

Our Kalman filter implementation follows closely the development by Morabito et al. (1988) where LODR (the suffix "R" indicating that corrections for zonal tidal variations have been applied; see Yoder et al., 1981, and McCarthy and Petit, 2004) follows a random walk process and UT1R (tidally corrected UT1) is an integrated random walk:

$$- d^2\,\mathrm{UT1R} / dt^2 = (1/86400)\, d\mathrm{LODR}/dt = w_L$$

where w_L is a white noise process. The white noise power spectral density was determined empirically from the power spectrum of actual UT1R variations from VLBI and found to agree with the Morabito et al. value of 3600 $\mu s^2/d^3$ derived from atmospheric wind angular momentum.

To accommodate possible LODR technique biases, two additional states have been added to the Kalman model. One state considers a first-order Gauss-Markov process (Ray, 1996) driven by white noise, w_M, where the LODR biases, B_M, are modeled as

$$d B_M / dt = -(B_M / T) + w_M$$

This has an auto-correlation for the lag interval, τ, of

$$R(\tau) = \sigma^2 \exp(-|\tau|/T)$$

where the parameters σ and T are related to the Kalman gain, Q, for the Gauss-Markov process by

$$Q = \sigma^2 [1 - \exp(-2\tau/T)]$$

By computing IGS LOD residuals from a filter combination where they receive no weight, we found empirically that the decay time constant, T, equals about 1.8 d and that the coefficient of the auto-correlation exponential, σ^2, is $(29.6\ \mu s)^2$. In deriving these values, we found that it was crucial to first fit and remove a fortnight wave from the LOD residuals, else the time constant will be seriously underestimated, as was the case when Ray (1996) estimated a time constant of 0.75 d.

A second bias state has also been included to capture effects of mismodeled tides near fortnightly periods. Kouba (2003) showed that any errors in the subdaily EOP model for ocean tidal effects (McCarthy and Petit, 2004) for the O1 wave (period of 25.82 hr) will beat against a 24-hr analysis period to yield alias signals at 14.19 d. Smaller effects might also be expected near 9.3, 9.6, 14.75, 181.3, 364.6, and 368.2 d. In addition to being largest, the O1 alias has been previously detected in IGS EOP products (Kouba, 2002; see also more recent results at acc.igs.org/erp-repro1.html).

3. INPUT DATA SETS

From the beginning of routine VLBI observations in 1984 there have been two basic observing configurations. Multi-baseline networks run for 24-hr sessions at various, sometimes irregular intervals for a mix of different objectives. Those networks primarily devoted to EOP monitoring (currently the R1 and R4 series coordinated by the International VLBI Service, IVS; see ivscc.gsfc.nasa.gov/program for details) operate weekly and include up to about eight stations reasonably well distributed globally. However, the VLBI network is much sparser than the IGS GPS distribution and is very weak in the southern hemisphere especially. Since 2002, the weekly R1 (Monday-Tuesday) and R4 (Thursday-Friday) EOP sessions together account for about 67% of all 24-hr VLBI sessions. The remaining 24-hr observations involve a very diverse mix of stations, some of which are only used infrequently, for a wide variety of objectives. Some are very poorly suited to EOP observations.

The second basic VLBI configuration uses only one pair of VLBI stations widely separated longitudinally to give good sensitivity to UT1 variations (Robertson et al., 1985). Each so-called “Intensive” session usually observes for about 1 hr and nearly daily. The mutual visibility of celestial radio sources is limited for these long east-west baselines, so a unique observing strategy was adopted to optimize UT1 determinations. The design of this program, which currently interleaves several station pairs throughout the week, represents a balance between the natural variability of UT1 being greater than for polar motion by a factor of about five to six and efficient use of VLBI resources. The positions for the Intensive stations and *a priori* knowledge of the other components of Earth orientation must be determined from the 24-hr sessions or other sources, and interpolated to the Intensive session epochs, which introduces errors in the UT1 results (Robertson et al, 1985; Ray et al. 1995). Modeling tropospheric delay fluctuations and non-point-like structure in the radio sources are probably the leading residual sources of UT1 error.

While the IVS does form a multi-center combined EOP product series for the R1 and R4 multi-baseline sessions, a comparable combination for the single-baseline Intensives is not yet available. Since it is critical that the data from both types of configurations be analyzed fully consistently, we have used solutions of the NASA Goddard Space Flight Center (GSFC) VLBI group, available at gemini.gsfc.nasa.gov/solutions. Specifically, the solution IDs “2007c” and “int21”, respectively, were downloaded. According to the GSFC group, the overlapping 24-hr and Intensive sessions during 1991-2006 have weighted mean and RMS UT1 differences of -0.72 and 22.47 μs, respectively, with a χ^2 per degree of freedom of 2.58 for 1244 points. Our Kalman filter has assimilated VLBI UT1 results between 21 February 1997 and 18 July 2007. In doing so, the reported formal errors have been scaled by a conservative factor of 2. For uniformly optimistic and Gaussian errors, the GSFC χ^2 value is consistent with a smaller error rescaling factor of 1.61 assuming no common-mode VLBI errors shared by the two UT1 series. But Malkin (2009) has recently examined VLBI polar motion precision and accuracy, relative to the IGS multi-center estimates, and found inaccuracies for the most sensitive networks that are larger than the formal errors by 1.6 to 1.9 times. So we opt for a rescaling factor of 2.

Note that the input VLBI UT1 values should have been previously frame-aligned, as in ITRF2005 (Altamimi et al., 2007), but we do not have 24-hr and 1-hr series available that have been treated in this way and are also consistent with each other, which is a critical requirement. Also, the VLBI UT1 accuracy could be improved a bit by adding GPS polar motion and terrestrial reference frame information in the data reduction, probably especially for the Intensive results (Ray et al., 2005). This aspect has not been studied here, however.

GPS LOD values come from the IGS multi-center combination “igs00p03.erp” produced at the Natural Resources Canada (NRCan). The processing follows the strategy described by Mireault et al. (1999) which partially removes LOD biases from each analysis center submission based on a sliding 21-d window comparison to IERS Bulletin A UT1 derivatives. As we will see below, this IGS calibration procedure is only approximate; significant biases remain. Values, each averaged over 24 hr during the range from 23 February 1997 to 18 July 2007 and all centered at noon epochs, were used and the formal errors were also inflated by a factor of 2 initially. Considering the time-varying systematic bias errors it is less clear how best to weight the GPS contributions at this stage. In a later section this question will be re-examined and alternative weights considered.

It should be noted that the GSFC and IGS analysis methods differ significantly in their modeling of tidal EOP variations near 12 and 24 hr periods. The IGS uses the IERS Conventions geophysical model (McCarthy and Petit, 2004) whereas GSFC uses an empirical model estimated from the VLBI data, a procedure that could alias other periodic errors into their tidal model coefficients.

4. VALIDATION OF KALMAN COMBINATION RESULTS

The post-fit UT1 residuals from the Kalman filter combination have weighted RMS (WRMS) values of 15.9 and 20.3 µs, respectively, for the 24-hr and 1-hr VLBI sessions. The minority of 24-hr sessions not dedicated to EOP monitoring dominate the former WRMS statistic. Mean (unscaled) 24-hr formal errors are 5.2 µs but the standard deviation is 9.3 µs because uncertainties for individual sessions range up to 127 µs. The mean formal error for the Intensives is 14.1 µs with 10.0 µs standard deviation. Power spectra are reasonably white for residuals of both session types. The IGS LODs have a post-fit WRMS of 2.84 µs overall (3.90 µs RMS unweighted), but the scatter became visibly smaller and more uniform after spring of 2002. That period corresponds to large improvements in the quality of the GPS orbits by the NRCan analysis center. The mean LOD formal error is 9.25 µs (unscaled). The IGS LOD residuals are so small compared to their uncertainties because of the adjusted bias model. The estimated Gauss-Markov bias ranges between about ±40 µs with an RMS of 8.9 µs whereas the amplitude of the 14.19-d bias varies between 5 and 11 µs. The phase of the fortnightly term increases approximately linearly with time, which we interpret as the accommodation of a slight offset in the assumed value of the fortnightly bias period. The effective period is closer to 14.12 d overall but does drift slightly. This could occur due to other error contributions besides just aliasing of subdaily O1 tidal mismodeling, such as IGS orbit errors which exhibit a broad fortnightly feature (Griffiths and Ray, 2009) and variations in analysis procedures. However, the important 13.63-d and 13.67-d zonal tides are outside the sensitivity range of our Kalman filter fortnightly model.

To provide an independent validation of the quality of our Kalman filter combination, the results have been compared to geophysical LOD excitation based on models for atmospheric and oceanic axial angular momentum (AAM and OAM) variations. The methodology is that of Kouba and Vondrák (2005). The combined LOD geodetic series is first corrected for zonal tides, "LODS", using models of Yoder et al. (1981) and Kantha et al. (1998); see also McCarthy and Petit (2004). AAM values, computed four times daily, are from the NCEP Reanalysis model (Salstein et al., 1997) where the inverted barometer assumption has been applied. Daily averaged values are formed around the middle epochs 00:00 and 12:00 to match the respective geodetic LOD series epochs. OAM values come from the ECCO_kf049f_6hr model (Gross et al., 2005), also with four values daily; the same noon and midnight averaging has been applied. The LODS and (AAM + OAM) time series were compared over the period 21 August 2000 to 31 March 2006.

In forming the time series of LODS – (AAM + OAM) differences, a few parameters are adjusted to account for imperfections in the geophysical zonal tide model and other systematic effects (Kouba and Vondrák, 2005). These include: annual and semi-annual differences; monthly (27.56 d) ocean tide correction; fortnightly (13.63 and 13.66 d) ocean tide corrections; the k/C core-mantle coupling constant (see Yoder et al., 1981); long-term drift differences; and an AAM transfer function scale factor. The post-fit residuals are computed and compared for various different combination series, as well as cross-correlations over a range of sliding windows. Fig. 1 shows the RMS residuals for the IERS 05C04 ("C04") and Bulletin A ("BuA"), the JPL SPACE2006 ("Spc") and operational ("JPo"), and our Kalman filter ("KF") combinations, as well as for the single-technique IGS series. Reported values from 05C04 and Bulletin A are for midnight epochs only, for noon epochs only from IGS, and for noon and midnight from JPL and our Kalman filter.

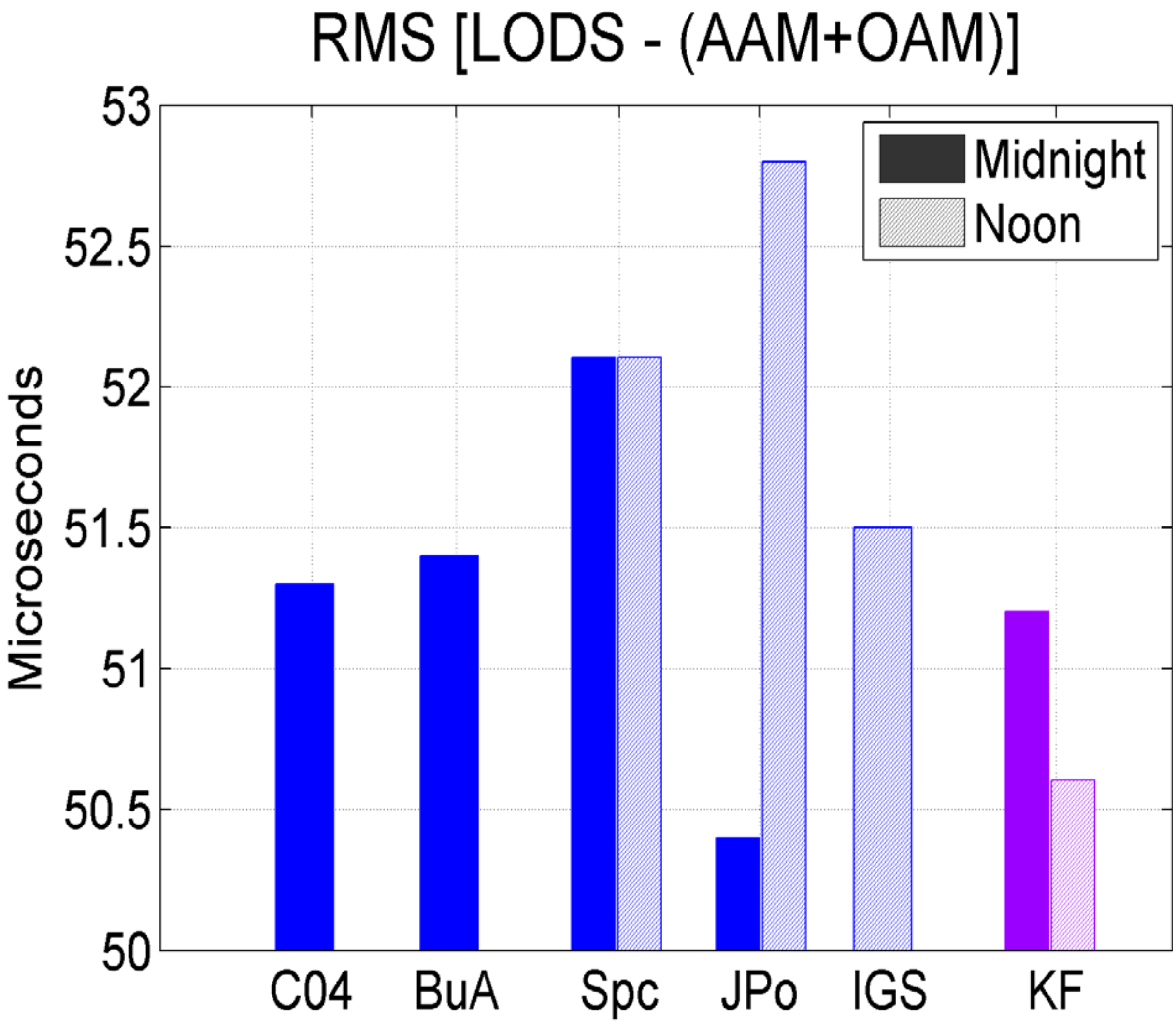

Fig. 1. RMS residuals of LODS and (AAM + OAM) differences for various UT1/LOD combinations and the IGS-only series. The abbreviations are: C04 = IERS 05C04; BuA = IERS Bulletin A; Spc = JPL SPACE2006; JPo = JPL operational predictions; KF = our Kalman filter combination. Smaller RMS differences imply better agreement.

The JPL operational midnight series has the lowest residual compared to (AAM + OAM) but this is because it assimilates AAM data at 00:00 epochs, but its comparison at noon epochs is worst overall. Of the independent series, our Kalman filter has the lowest residuals. The IGS alone performs rather well. Its value in multi-technique combinations is demonstrated by the relative performance of the SPACE2006 series, which did not include any GPS-based LOD contribution and suffers accordingly, compared to the other combinations that did use IGS LODs.

To evaluate which spectral ranges are most important in explaining the variations seen in Fig. 1, cross-correlations are plotted in Fig.2 for four intervals. Sliding windows from 3 d to 5.6 years have been considered but only the four shortest intervals are plotted because there is almost no difference over the full span (99.0% for all series except 99.1% for JPo(00:00) and KF(12:00)). The KF noon series has the highest correlation coefficients over all intervals. The JPL operational series also has high correlations for midnight epochs but this is because of its AAM assimilation; its noon correlations are correspondingly poor due to lack of GPS-based LOD inputs, which is also true for the SPACE2006 series. The IGS-only LOD series performs as well or better than either IERS combination, and is much better than Bulletin A over shorter spans. This indicates that the IGS information content has been under-utilized in those combinations.

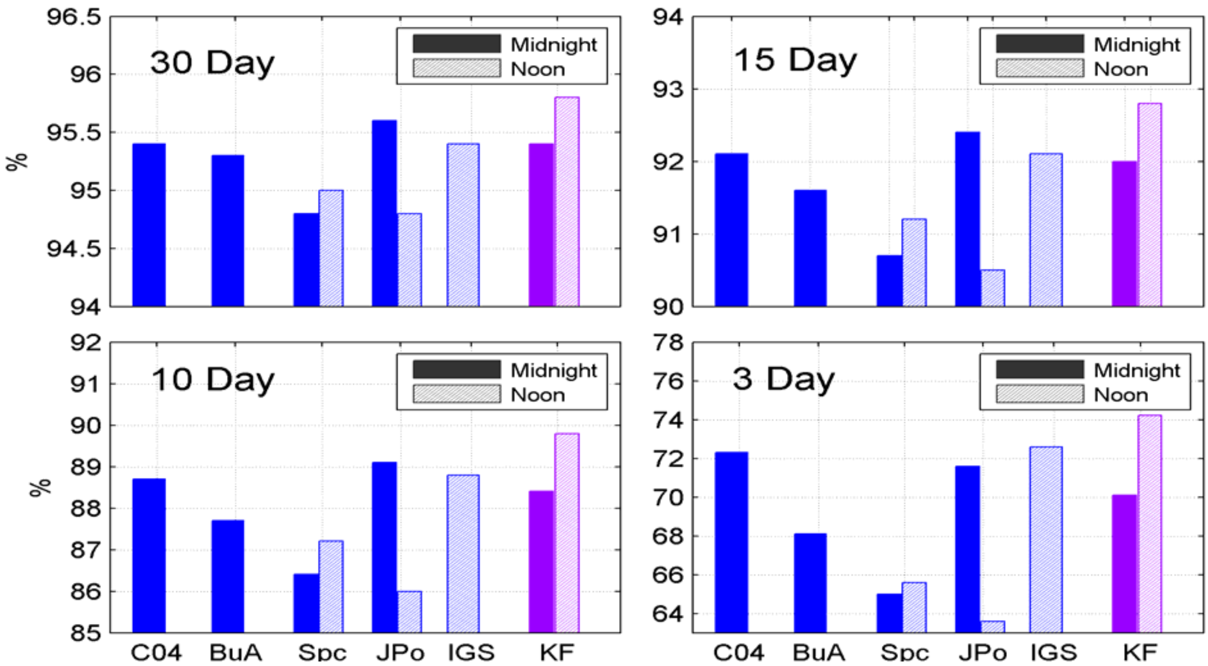

Fig. 2. Cross-correlation coefficients over 30 d, 15 d, 10 d, and 3 d sliding windows between LODS and (AAM + OAM) for various UT1/LOD combinations and the IGS-only series. Abbreviations are given in the Fig. 1 caption. Higher correlations imply better consistency with (AAM + OAM).

Some insight into the different high-frequency performances of the various combination methodologies can be gained by examining the power spectra for each, shown in Fig. 3. The expected power laws for LOD as a random walk and for UT1 as an integrated random walk are also illustrated in Fig. 3 (lower right corner). Departures by the two IERS series are clearly seen, compared to the other combinations and the power law models, for intervals shorter than a few days down to the Nyquist period of 2 d. The 05C04 series shows strong high-frequency LOD smoothing but accompanied by excess UT1 noise. The Bulletin A UT1 values are less noisy but its LOD smoothing is even steeper near the Nyquist limit, probably because the LODs are derived from adjacent UT1 values by numerical differentiation. In view of these results, the differences among series in Figs. 1 and 2 can probably be attributed mostly to over-smoothing in the IERS combinations and an under-utilization of the IGS contribution. The JPL series have the expected attributes but less high-frequency content due to omitting GPS-based inputs.

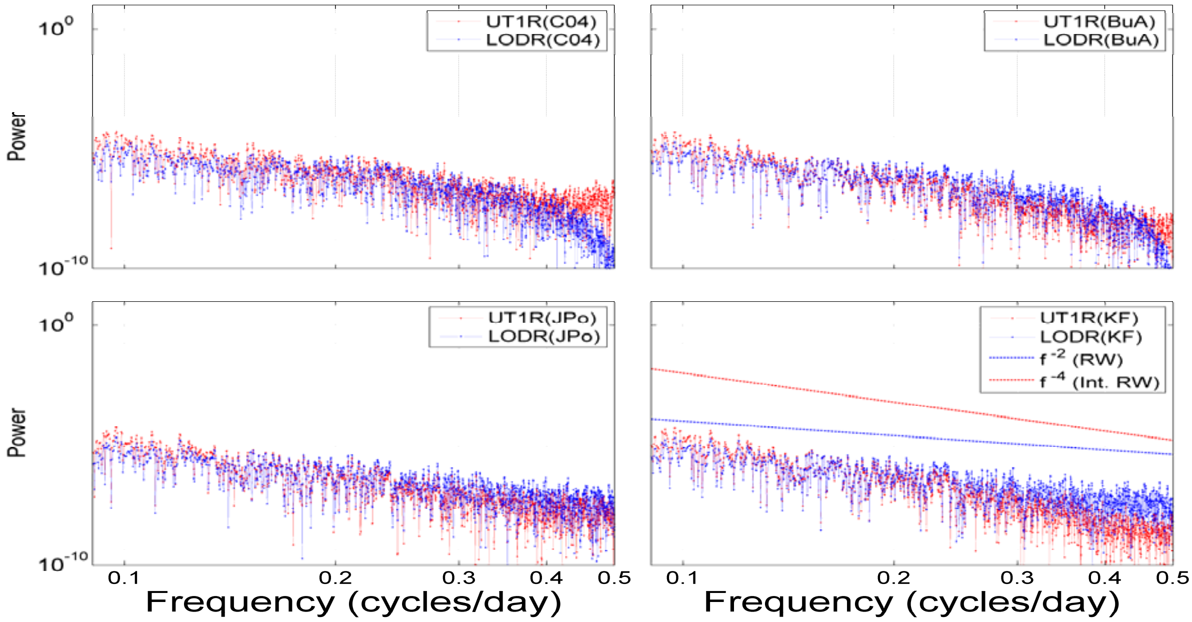

Fig. 3. Sub-fortnightly power spectra for combined UT1 and LOD series, each tidally corrected. IERS 05C04 is in the upper left, IERS Bulletin A in the upper right, JPL operational series in the lower left, and our Kalman filter in the lower right. The JPL SPACE2006 series is not shown because it is very similar to KF. The power laws for random walk (RM) and integrated RM processes are also indicated by the lines on the lower right KF plot.

In addition to these general smoothing features, a closer examination of the spectra of series differences with respect to (AAM + OAM) shows other problems in some bands. As described previously, the IGS LOD estimates are subject to aliased O1 errors in the fortnightly band. The IERS 05C04 combination shares this spurious peak, indicating that insufficient mitigation of the IGS error has been implemented in that combination. More subtle signal distortions are seen in the IGS residuals near monthly periods, but these are not inherited by any of the combinations.

A final comment concerns the different performances of our KF for the noon and midnight epochs. The noon epochs have smaller (AAM + OAM) residuals as well as higher correlations, and the fractional differences increase for shorter intervals. One might attribute this to the IGS values being reported at noon. But the KF combined noon performance is considerably better than IGS alone. Instead, most of this difference in behavior is probably caused by errors in some VLBI inputs, as will be seen in the next section from tests excluding certain VLBI data.

5. TESTS USING DECIMATED VLBI DATA

At the request of the U.S. National Research Council (NRC) panel studying "National Requirements for Precision Geodetic Infrastructure" (T. Herring, private communication 2008), Kalman filter test combinations were made to quantify the impact of reduced VLBI UT1 data. Compared to the nominal combination described above, two variations were proposed: remove all the 1-hr Intensive data (but retain all the remaining 24-hr VLBI UT1 and IGS LOD inputs); remove all VLBI UT1 data except a single once-per-week 24-hr VLBI series (but retain the IGS LOD input). All other aspects of the KF combination and (AAM + OAM) comparisons remained unchanged. For the second test using only one VLBI UT1 value per week, we selected the IVS R1 series because its formal errors are usually slightly better than the parallel weekly R4 series. Because the R1 observations began on 8 January 2002, the comparisons below with (AAM +OAM) covered the period from then to 31 March 2006, which is about 1.37 years shorter than the comparisons reported in the previous section.

RMS differences for the test combinations compared to (AAM + OAM) are shown in Fig. 4. The overall level of the residuals is lower than in Fig. 1 because older, poorer quality data (21 August 2000 – 7 January 2002) were not included here. As seen before, the KF combinations always fit the angular momentum data better than IGS alone. This again confirms that the inclusion of VLBI UT1 data is important. However, the tests to exclude progressive amounts of the lower-quality VLBI results steadily improve the combination agreement with (AAM + OAM). The degree of improvement is greater for the midnight epochs than for noon. Adding just the once-weekly R1 VLBI series to the IGS LODs gives the best overall agreement and best consistency between the midnight and noon epochs.

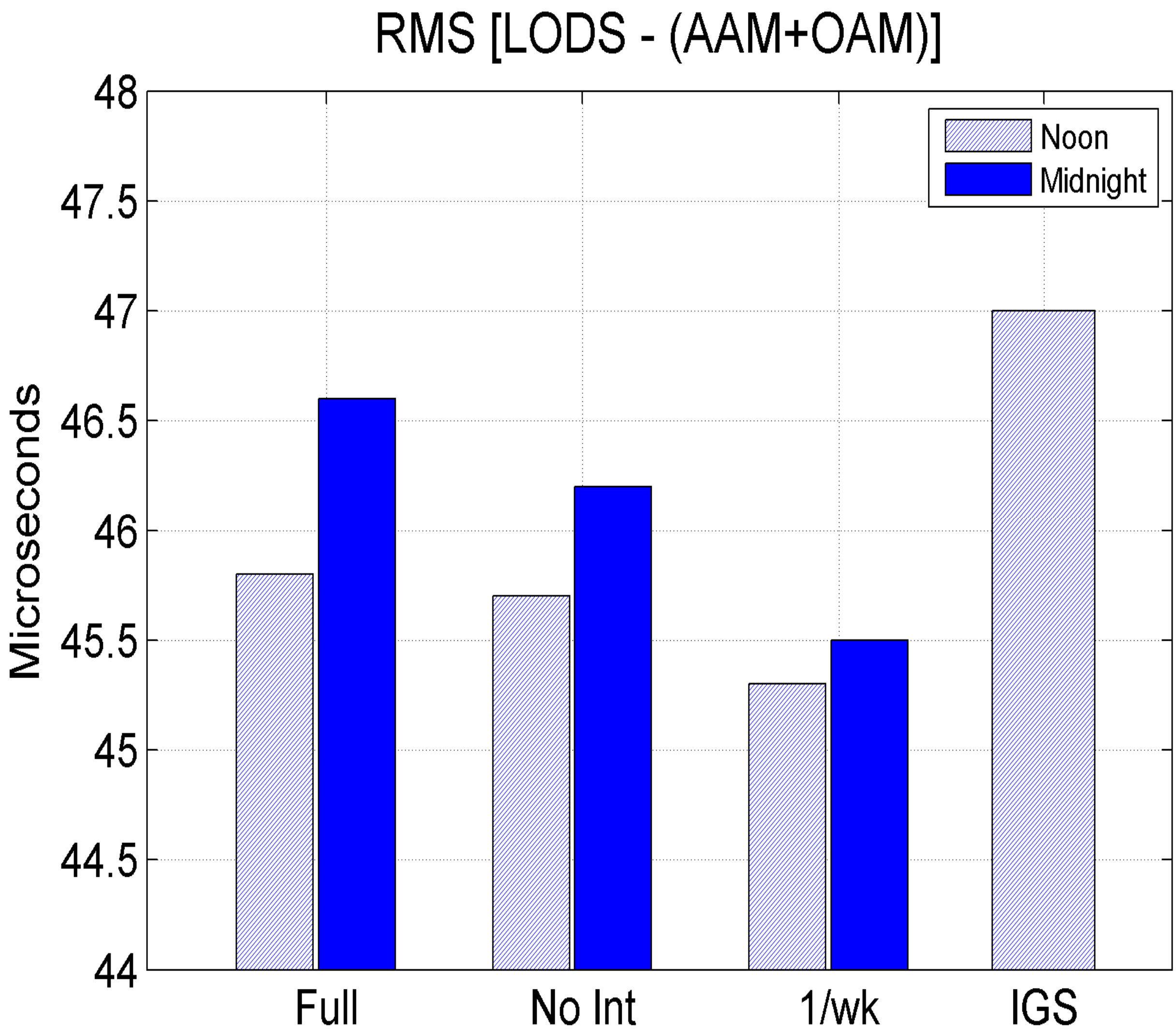

Fig. 4. RMS residuals of LODS and (AAM + OAM) differences when variable amounts of VLBI UT1 data are combined in the KF, plus the IGS-only series. The abbreviations are: Full = all VLBI data included; No Int = exclude 1-hr VLBI UT1; 1/wk = only VLBI UT1 from R1 series. All KF combinations also include the IGS LOD data. Smaller RMS differences imply better agreement.

Fig. 5 shows the corresponding cross-correlation results for the same test and IGS series. Over the full data span, all series yield a correlation of 99.2%. The biggest change seen as progressive amounts of VLBI UT1 data are dropped is a steady increase in the high-frequency correlations for the midnight epochs. This trend is accompanied by a much smaller drop in noon correlations. It should be noted that the middle epoch of the R1 VLBI sessions is near 05:00 UTC so their impact is presumably a bit greater for the midnight epochs than for noon points.

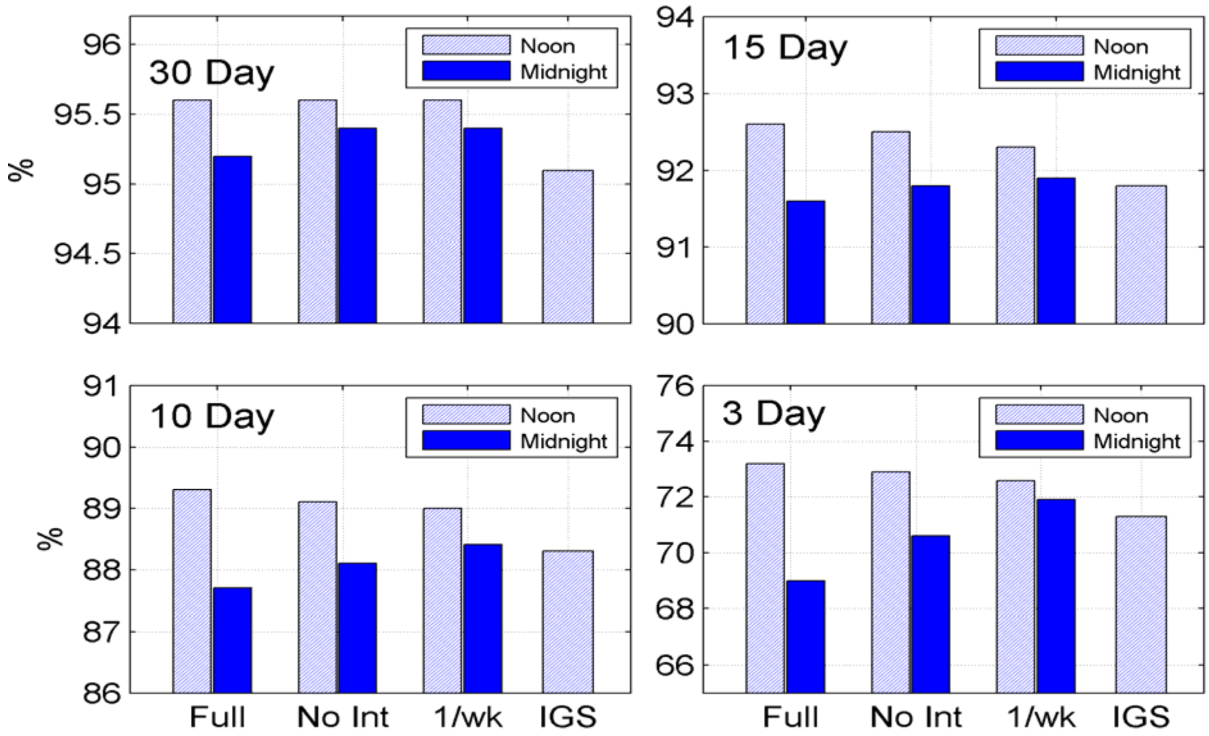

Fig. 5. Cross-correlation coefficients over 30 d, 15 d, 10 d, and 3 d sliding windows between LODS and (AAM + OAM) for when variable amounts of VLBI UT1 data are combined in the KF, plus the IGS-only series. All KF combinations also include the IGS LOD data. Abbreviations are given in the Fig. 4 caption. Higher correlations imply better consistency with (AAM + OAM).

Taken together, these results most likely imply the presence of excess noise in at least some of the non-R1 VLBI UT1 estimates, including both 24-hr and 1-hr sessions. The continuous, daily IGS LOD values are apparently able to allow more accurate interpolation between the weekly VLBI measurements than are the non-R1 UT1 data. However, it should be stressed that the GPS fortnightly bias cannot be modeled with less frequent VLBI data than weekly, so further VLBI exclusions would not be feasible. In addition, for near real time operations it is still beneficial to include the single-baseline Intensive UT1 values because of the considerably greater processing delay for 24-hr data; the extrapolation of IGS LODs alone without any VLBI UT1 information would be ill-advised for much longer than the Gauss-Markov bias time constant (about 1.8 d).

Fig. 6 shows the VLBI Intensive UT1 residuals when they are not included in the KF. The main individual Intensive baselines are indicated separately by color and statistics given in the plot. Systematic patterns are readily apparent, especially for the Tsukuba (Ts)-Wettzell (Wz) baseline. It should be a priority for the IVS community to understand better the UT1 error sources and develop measures to mitigate them (e.g., Ray et al., 1995; Böhm et al., 2010).

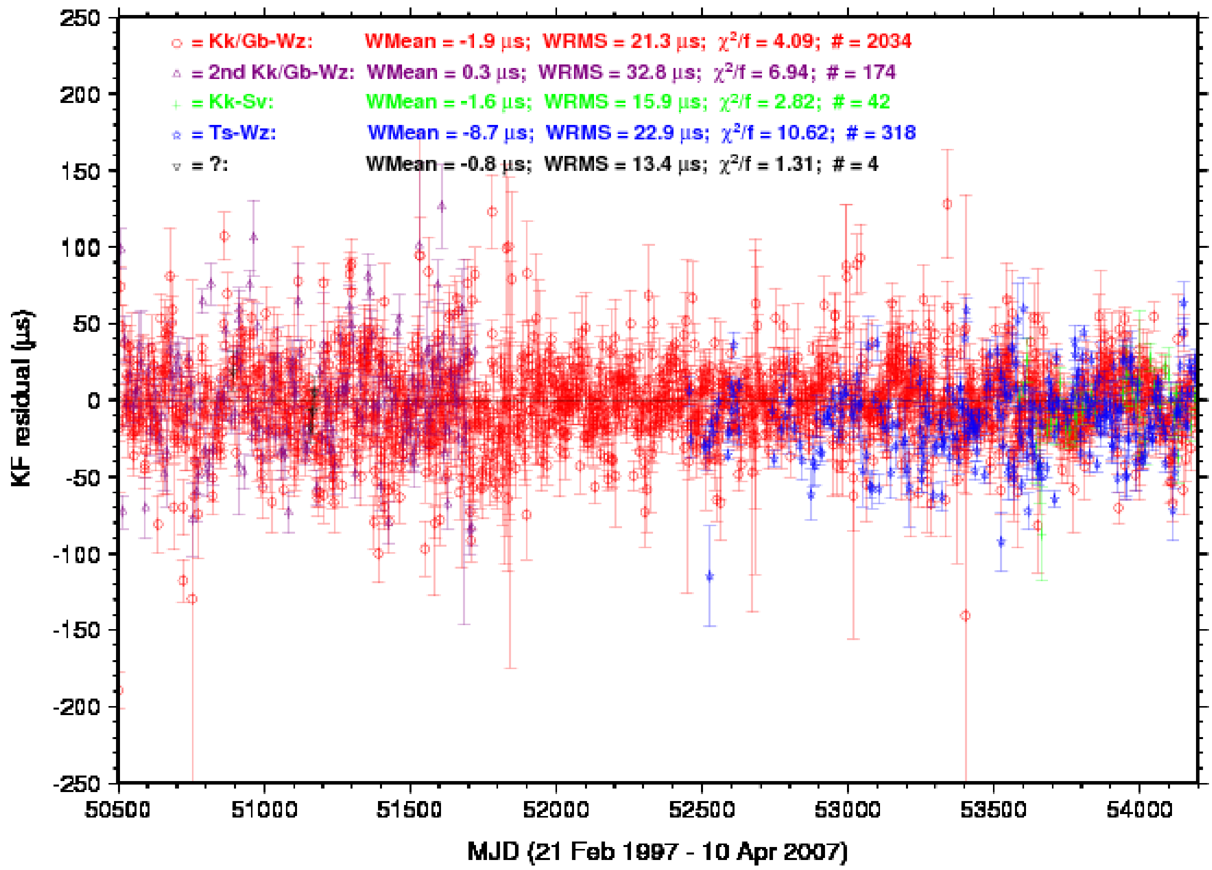

Fig. 6. UT1 residuals for the 1-hr VLBI Intensive sessions, which are not included in the KF combination. Note the obvious systematic patterns evident, especially for certain baselines.

Prompted by the NRC tests, we have tried further combinations of VLBI data editing and observation reweighting. Using independent (AAM + OAM) as the standard for improved UT1/LOD combinations, we find that the best overall results are obtained when: 1) all 1-hr Intensive data are rejected; 2) 24-hr VLBI UT1 data are included when their formal error is no worse than 5 µs and the modeled sigma is scaled by a factor of two; 3) all IGS LOD values are included with modified sigmas equal to 3.9 µs when the formal error, σ, is no worse than 9.25 µs (the overall mean formal error) and equal to 3.9 µs * (σ / 9.25 µs) otherwise. The second criterion excludes about 18% of all 24-hr VLBI data, but these are often highly problematic.

6. DISCUSSION AND CONCLUSIONS

By extending the Kalman filter combination method of Morabito et al. (1988) to include GPS-based LOD measurements together with time-correlated and harmonic bias estimates, we have shown that combinations with VLBI UT1 can be improved significantly, especially in the high-frequency domain. Analytic combination methods perform less satisfactorily because they inevitably introduce unnecessary smoothing in their attempts to reduce the satellite biases and they are not immune to inherited spurious signals. This is the case for the IERS EOP series. Further combination improvements can be realized by judicious editing of input VLBI data. Our tests using (AAM + OAM) excitation as an independent standard indicate that the best Kalman filter combinations of VLBI UT1 and GPS LOD exclude all results from the 1-hr, single-baseline VLBI sessions and from 24-hr, multi-baseline VLBI observations with formal errors greater than 5 μs. Systematic errors in these weaker VLBI measurements degrade interpolation of UT1 from the better (but sparser) VLBI 24-hr sessions more than biases in the IGS LOD data, which can be modeled successfully in the Kalman filter.

Combinations already routinely use LOD products from the IGS Final and Rapid series, which are available with about two weeks and 29 hr delay, respectively. To minimize latency for near real time services, the IGS Ultra-rapid observed LODs (first day of each 2-d update) should also be assimilated. These are available with a delay of 15 hr and are issued four times daily.

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