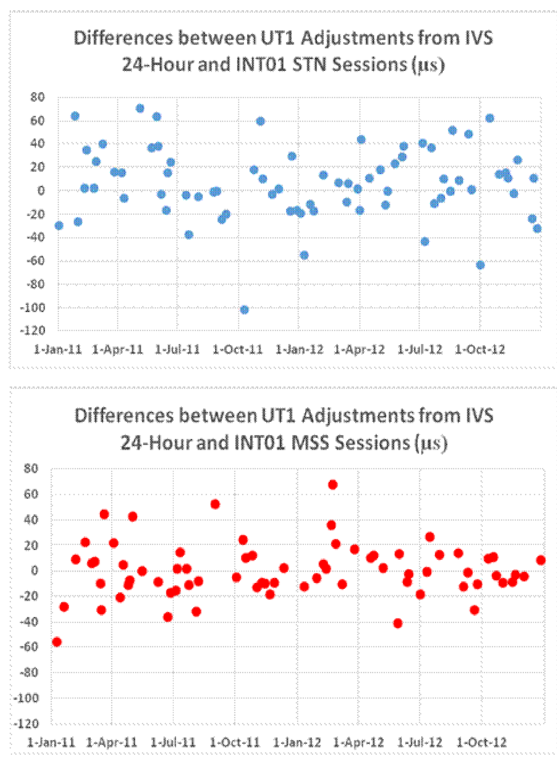
# Improvement of the IVS INT01 Sessions through Bayesian Estimation

**John Gipson and Karen Baver**

NVI, Inc.

## Introduction

UT1 is an important product. IVS-INT01 sessions deliver more rapid, but less precise, UT1 estimates than the larger IVS 24-hour sessions. The IVS tries to improve IVS-INT01 UT1 estimates, e.g., by improving its accuracy with respect to the 24-hour sessions. In December 2015, Gipson, Strandberg, and Azhirnian demonstrated the effect of polar motion, nutation, and atmospheric gradient changes on the UT1 estimate from the 2011-2012 INT01 sessions. This work also applied polar motion and nutation values from IVS 24-hour sessions to INT01 sessions in an effort to improve the UT1 estimates as a proof-of-concept. Here we extend the work by applying gradients and by using nutation and polar motion values from external series that should be available for real-time operational processing of INT01s. We divide the 2011-2012 INT01 sessions into two sets: 74 STN sessions, which were scheduled with a small set of sources that are strong but have uneven sky coverage, and 70 MSS sessions, which were scheduled with a large set of sources that are on average weaker but have good sky coverage. Our measure of accuracy is the difference between the UT1 estimate from an INT01 session and the UT1 estimate from a concurrent 24-hour session extrapolated to the epoch of the INT01's UT1 estimate. When we apply a priori information in the INT01 analysis, the UT1 estimate will change. If this change reduces the distance to the estimate from the 24–hour session, we have improved the INT01 estimate.




Agreement of the 2011-2012 INT01 sessions with concurrent 24-hour sessions' UT1:
STN STDEV: 30.68 µs
MSS STDEV: 21.04 µs

## Our Approach

**Background:** VLBI measures τ, the time delay between when a signal reaches two stations. Many parameters contribute to τ. Least squares processing solves the equation $A = N^{-1}B$, where

$$N_{jk} = \Sigma_{obs} \frac{f_j f_k}{\sigma^2_{obs}} \qquad B_j = \Sigma_{obs} \frac{f_j OC}{\sigma^2_{obs}} \qquad OC_{obs} = \Sigma_j A_j f_{j\_obs} = \tau_{obs} - \tau_{theo} \qquad f_j = \frac{\partial\tau}{\partial parm_j}$$

A = estimated parameter vector

INT01 sessions have few observations and only allow estimation of a few parameters. But we can insert estimates of other parameters from the larger 24-hour sessions into the least squares equation as constraints (extra "observations"). This a priori information simulates Bayesian estimation.

**Method:**

1. Use the Solve package to estimate a parameter that is non-standard for INT01s, e.g., gradients, polar motion, or nutation, and save the normal equations to a file.
2. Use a local program to add estimates and their σ values from a 24-hour session to the corresponding INT01 by adding *estimate*/$\sigma^2$ to the B vector and $1/\sigma^2$ to the N matrix. Invert the modified normal equations and extract the INT01 UT1 estimate.
3. Subtract each pair of 24-hour and default INT01 UT1 estimates and find the standard deviation of the differences. Repeat for the 24-hour and modified INT01 UT1 estimates. The new standard deviation should be less than the default one if use of the 24-hour parameter estimate improves the least squares process.

**Measures:**

1. Default StDev is the standard deviation of 24-hour session UT1 estimates minus UT1 estimates from default solutions of concurrent INT01 sessions.
2. Parameter (Gradient, IGS PM, or FCN) StDev is the standard deviation of 24-hour session UT1 estimates minus UT1 estimates from solutions of concurrent INT01 sessions with the given parameter applied. If this is less than default StDev, application of the parameter has brought the INT01 UT1 estimates closer to the 24-hour UT1 estimates and therefore improved the accuracy of the INT01 UT1 estimates.
3. Predicted effect is the standard deviation of the UT1 estimates from parameter-applied INT01 solutions minus UT1 estimates from default INT01 solutions.
4. Measured difference is the square root of the square of the default StDev minus the square of the parameter StDev. This measures the amount of reduced noise.

**Plots:**

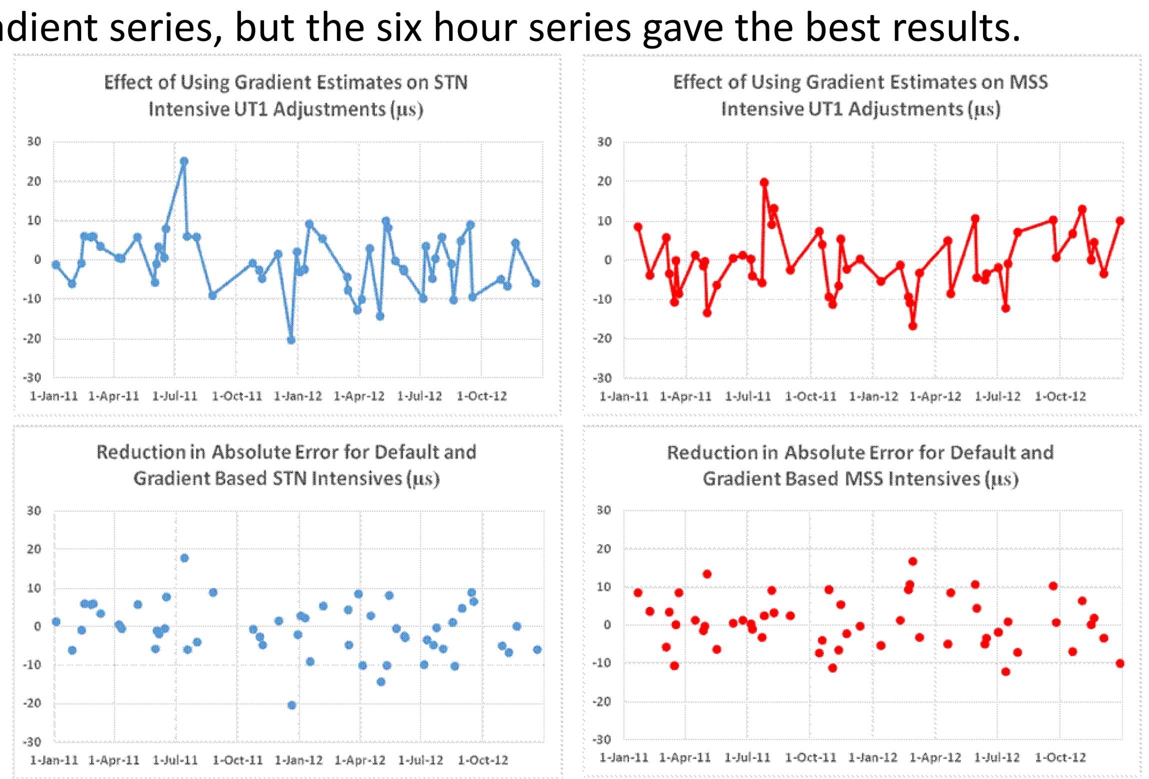
1. "Reduction in absolute error" plots show the absolute value of the differences between the 24-hour and default INT01 UT1 estimates minus the absolute value of the differences between the 24-hour and parameter-applied INT01 UT1 estimates.
2. "Effect of using" plots show the parameter-applied INT01 UT1 estimates minus the default INT01 UT1 estimates. This corresponds to the predicted effect measure.

## Gradient A priori Values

We introduced east and north atmospheric gradients from the standard INT01 stations, Kokee and Wettzell, into the least squares processing. Each standard 24-hour solution produces five gradients spaced six hours apart, so we interpolated the gradient series to the epochs of INT01 UT1 estimation. We only used gradients from concurrent 24-hour sessions to avoid the growth of interpolation errors. We also rejected concurrent sessions that did not observe Kokee or Wettzell. So only 54/74 STN and 53/70 MSS INT01 sessions were included in the gradient study. We also generated one hour and one day gradient series, but the six hour series gave the best results.

Using 24-hour gradient estimates makes the INT01 UT1 estimates more accurate (in the STN case by 0.8 µs, and in the MSS case by 1.92 µs). Gradients remove 6.6 µs of STN noise and 9 µs of MSS noise.

| (µs) | STN | MSS |
|---|---|---|
| Default StDev | 27.20 | 21.94 |
| Gradient StDev | 26.40 | 20.02 |
| Predicted Effect | 7.46 | 7.62 |
| Measured Diff. | 6.55 | 8.98 |




Avg. reduction in absolute error: STN = 0.77 µs MSS = 0.58 µs

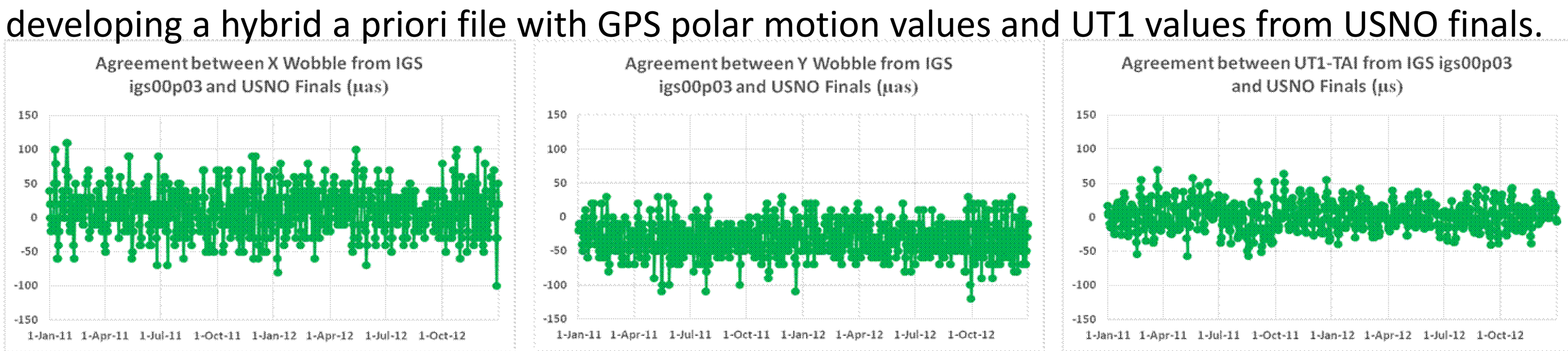
## External Data for Operational Processing

The use of Solve estimates is proof-of-concept but not usable operationally because data from 24-hour sessions will not become available until at least two weeks after an INT01 is analyzed. External data with better latency must be used for operational INT01 Bayesian estimation. We tested external polar motion and nutation data. The next step should test external gradients, e.g. from IGS.

### Polar Motion

**Source:** GPS (IGS cumulative Earth Rotation Parameter file (version 00 since w1412) , ftp://cddis.gsfc.nasa.gov/gps/products/igs00p03.erp) (few day latency)

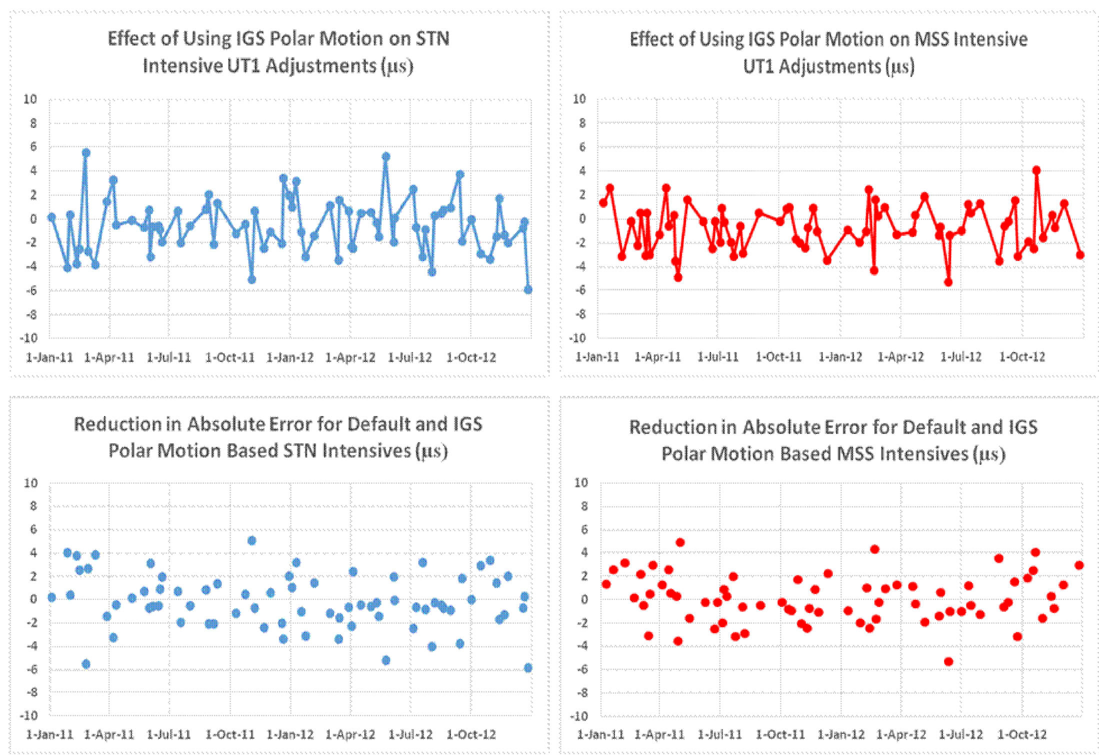
We interpolated polar motion (GPS) and accompanying UT1 values at noon epochs to the midnight epochs needed by Solve. Except for a Y-wobble offset, the values agree with our operational EOP a prioris, which are derived from USNO finals values. Future steps are investigating the offset and developing a hybrid a priori file with GPS polar motion values and UT1 values from USNO finals.




The IGS data makes the STN more accurate by 0.04 µs and removes 1.57 µs of noise. It makes the MSS more accurate by 0.22 µs and removes 3.10 µs of noise.

| (µs) | STN | MSS |
|---|---|---|
| Default StDev * | 30.88 | 21.90 |
| IGS PM StDev | 30.84 | 21.68 |
| Predicted Effect | 2.26 | 1.92 |
| Measured Diff. | 1.57 | 3.10 |

*from a 24-hour solution that used IGS a prioris

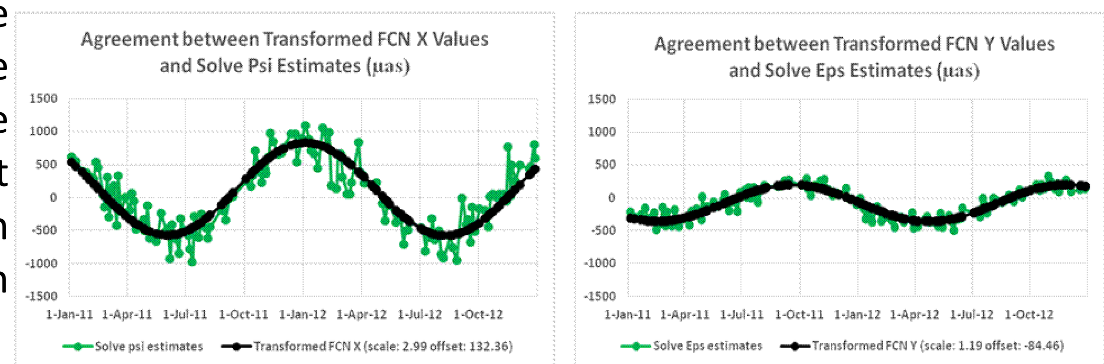



Avg. reduction in absolute error: STN = -0.20 µs MSS = 0.06 µs

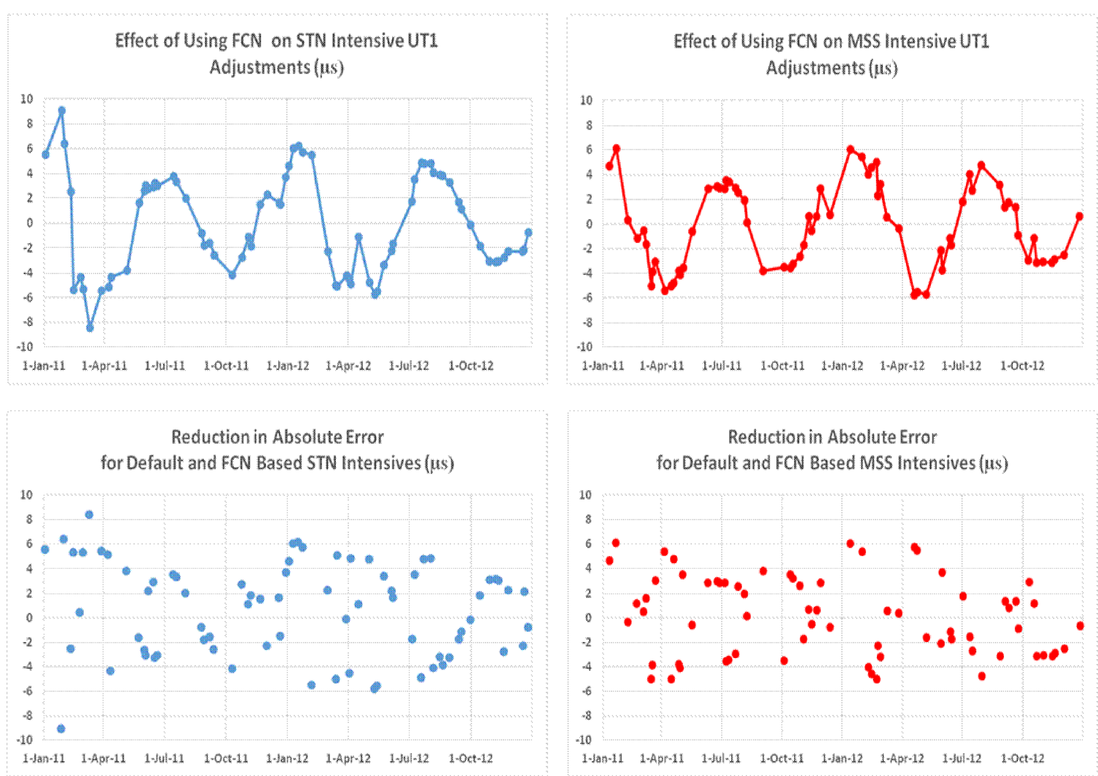
### Nutation

**Source:** VLBI data (XY free core nutation from an empirical model obtained by a least squares fit to the IERS EOP 08 C 04 series). Author: Sébastien Lambert (Syrte). Available at syrte.obspm.fr/~lambert/fcn. Latency: immediate.

Solve uses ψ and ε nutation, so the free core nutation had to be transformed from X and Y. These two plots show the agreement between the transformed nutation and Solve nutation estimates from the same time frame.




| (µs) | STN | MSS |
|---|---|---|
| Default StDev | 30.68 | 21.04 |
| FCN StDev | 30.50 | 20.75 |
| Predicted Effect | 3.80 | 3.32 |
| Measured Diff. | 3.30 | 3.49 |




The FCN data makes the STN more accurate by 0.18 µs and removes 3.30 µs of noise. It makes the MSS more accurate by 0.29 µs and removes 3.49 µs of noise. The frequencies of the effect signals are approximately twice those of the input signals.

Avg. reduction in absolute error: STN = 0.66 µs MSS = 0.12 µs

Nutation changes slowly. So it should be feasible to use it for operational Bayesian estimation.

## Conclusions

- The use of gradients gives the largest improvement. But this is only proof-of-concept. An external gradient source (e.g., IGS) must be tried next.
- The use of free core nutation from Lambert gives the next largest improvement.
- The use of IGS polar motion and UT1 gives some improvement, but an offset must be investigated, and a hybrid GPS/VLBI a priori file must be tested. Also, the INT01 latency recently became as little as a few hours, so a source with corresponding latency (e.g., IGS file igu00p01.erp) should be tested.

## References

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Lambert, S., Empirical Modeling of the Earth's Free Core Nutation, syrte.obspm.fr/~lambert/fcn/notice_fcn.pdf.

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***Contact author:*** *John Gipson, john.m.gipson@nasa.gov*
*NVI, Inc.*
*7257D Hanover Parkway*
*Greenbelt, MD 20770, USA*