NRL Analysis of GPS On-Orbit Clocks

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***Abstract*—The U.S. Naval Research Laboratory (NRL) has collected data and analyzed GPS space vehicle atomic clock performance since the beginning of the GPS Program. These analyses have largely been based on pseudorange observations and precise post-fit ephemerides provided by the National Geospatial-Intelligence Agency (NGA). Observational data and clock comparisons were limited to data collected within the GPS system due primarily to the lack of global tracking resources and effective means of gathering the data. With the successful conclusion of the International GPS Service (IGS) and Bureau International Poids and et Mesures (BIPM) Pilot Project, new capabilities to associate IGS geophysical data to Universal Coordinated Time (UTC), and integration of timing centers to contribute to the determination of UTC are evolving. Data collection from participating timing centers and analysis to form the IGS timescales and Clock Products has established new capabilities for analysis of orbiting precision atomic clocks. NRL leads the IGS Clock Products Working Group and generates the IGS timescales. These efforts joined together with the GPS on-orbit analyses offer new possibilities for analysis and improved performance for both GPS and IGS. This paper will discuss these new resources for analysis and possible improved analytical capabilities.**

I. INTRODUCTION

The resources of the Global Positioning System (GPS) space vehicle clock data available for the Naval Research Laboratory (NRL) on-orbit clock analysis have been improving in the recent years. In March 2004, the National Geospatial-Intelligence Agency (NGA) began providing Carrier Derived Pseudorange (CDP) observations that provide a significant reduction in system measurement noise. The availability of the International GPS Service (IGS) GPS data, which is also derived from carrier phase measurements and produced at intervals of five minutes, was used beginning in April 2004 to observe short- term behavior in space vehicle clocks. The NRL on-orbit clock analysis has referenced clock estimates to the Department of Defense (DoD) Master Clock through the NGA Washington (WAS) ground station located at the U.S. Naval Observatory (USNO) [1]. Referencing to a single ground station results in data loss for all clocks at epochs when the station fails to receive or record a valid measurement. This type of data loss inevitably occurs in all ground stations at some time due to equipment failure, interference, or multi-path signal reception degradation. In 2004 NRL made operational the generation of the IGS distributed timescales to which all IGS Rapid & Final Clock products are now referenced. NRL is investigating the use of such distributed timescales to reference all of its GPS data sources that will lead to improved results of current GPS on-orbit clock analysis.

II. CONSTELLATION AND CLOCK SUMMARY

The GPS constellation is changing as the operating clocks in the older Block II/IIA are changed to maintain acceptable performance or they are replaced by the Block IIR space vehicles. Figure 1 shows changes in the constellation and clock operation that occurred during the last year. There was one Block IIR new launch and two Block IIA clock changes.

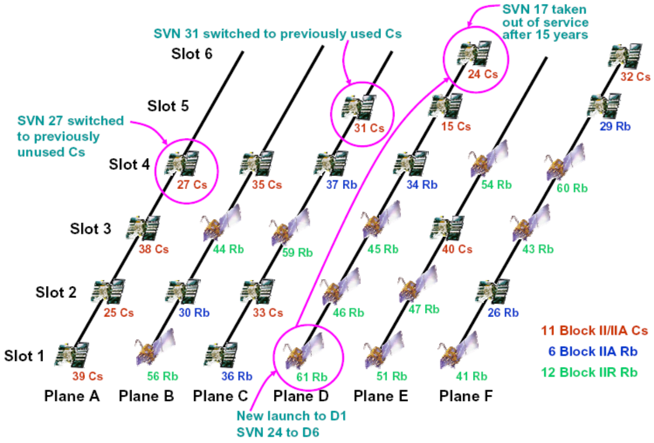

Figure 1. GPS Constellation Status showing satellite plane position and clock type (as of August 2005).

Figure 2 shows the age of each space vehicle clock currently operating and the average age of each clock type. The Block II/IIA cesium clocks are shown as having been operated longer than the rubidium, however, these data reflect the amount of time the units were operating rather than a direct comparison of the individual unit's operating life. This relation is a result of the cesium clocks being the first units to be activated. The Block IIR satellites with three rubidium clocks are replenishing the constellation hence those units show the youngest age.

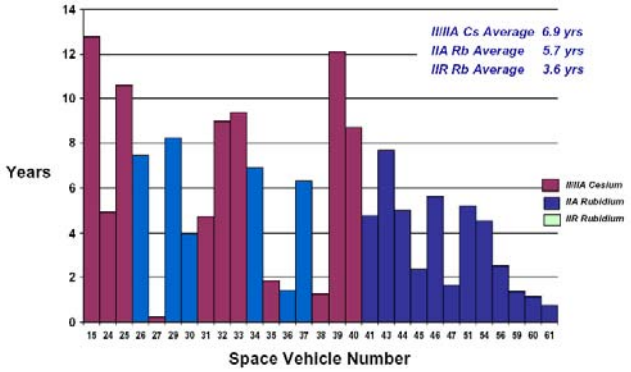

Figure 2. Operating lifetime of current Navstar clocks by clock type as of August 2005

III. Data Sources

The primary data source for NRL on-orbit clock analysis is pseudorange observations and precise satellite ephemerides from NGA. NRL has used NGA data since the beginning of the GPS program [2]. In 1995 the WAS station was added to the NGA network resulting in the ability to maintain a complete record of each clock's performance compared to the DoD Master Clock since that time.

Observations are made from the GPS monitor stations around the world and smoothed to fifteen-minute intervals. These smoothed pseudorange observations are used to compute residuals of the estimated positions derived from the corresponding precise positions of the space vehicles and the surveyed monitor station positions. These residuals are consequently estimates of the phase difference of the space vehicle clocks relative to the ground station clocks.

In the last few years space vehicle clock estimates, carrier phase observations and independently produced precise ephemerides from IGS became available. The IGS is a scientific federation of more than 200 international agencies, universities, and research institutions in more than eighty countries. Each participant contributes to a broad range of expertise in navigation satellite technologies, data acquisition and analysis. The resulting contributions take the form of orbit determination models, analysis techniques, and data archives from a variety of observational programs collected together into a family of IGS products. Regional and global IGS data centers maintain multi-channel, dual-frequency, code and carrier tracking data archives from more than 350 permanent continuously operating GPS tracking stations. To facilitate data exchange, standardized data and analysis protocols have been developed and applied to the different data products and archives.

A significant aspect of IGS data collection and analysis developed in the past ten years was a pilot project between the IGS and the Bureau de Poids et Measures (BIPM) [3]. The project was an investigation of geodetic time/frequency transfer and network clock performance in the GPS satellites and throughout the ground network. The project initiated additional timing-related observations, data collection protocols, and incorporation of hydrogen masers and other precise timing equipment into the network. These activities are now the responsibility of the Clock Products Working Group (CPWG) lead by NRL. The Clock Products produced at NRL include estimates of the GPS space vehicle onboard clocks, ground station clocks and a distributed timescale computed from all the clocks. The IGS Distributed Timescale is the reference for the clock products and produced in two forms, the rapid timescale, denoted IGRT and the final timescale IGST [4]. They provide the stable, common reference for analyzing GPS clock data that is independent of a single ground station clock.

A database of the GPS broadcast ephemeredes is also maintained in order to evaluate clock performance as seen by users. User clock estimates may then be derived using the broadcast ephemeredes and observed pseudorange data from NGA or other data sources recording the satellite signals. Comparing these user estimates to the precise estimates using precise ephemeredes may then be applied to evaluations of actual GPS broadcast performance.

Constellation satellite changes, space vehicle on-orbit maintenance, and GPS ground station maintenance are routinely performed by the Second Space Operational Squadron (2SOPS) to keep GPS operational. These intentional changes also affect the analysis results, especially when performance anomalies are a particular interest. Data concerning these operational factors are provided by 2SOPS. These data form the core of a database of system anomalies such that space vehicle and monitor station clock anomalies may be clearly observed.

A significant data source is provided by the NRL Precise Clock Evaluation Facility (PCEF) [5] developed to evaluate and characterize space qualified atomic clocks. Every GPS type of space clock has been evaluated including several of the latest Block IIR and IIF space clocks. The RAFS Life Test [6] operated two Block IIR rubidium units in environmentally controlled thermal vacuum chambers for over seven and one half years and a similar test is underway to evaluate two Block IIF cesium units [7]. The phase of the test units is compared to any one of several hydrogen masers or other test reference. All phase, frequency and telemetry data for the test clocks is collected and archived. The data are then analyzed in the same manner as the on-orbit clock data. The PCEF data taken under controlled conditions are not subject to additive space and system noise sources and are more representative of the clock performance. The PCEF data are compared to the on-orbit results to assist in overall GPS on-orbit clock performance evaluation. These unique PCEF data have proved invaluable in investigating various anomalous clock behaviors and in improving engineering design.

IV. METHODS OF TIME ESTIMATION

In May 1995 the WAS monitor station at USNO began operation. Methods of comparing the clocks throughout the GPS to a common reference were developed. These methods are known as Linked Common View Time Transfer (LCVTT) [8] and Continuous Coverage Time Transfer (CCTT) that enables the pseudorange observations to be referenced to the DoD Master Clock through the collocated NGA station. Figure 3 shows an example of how these techniques are applied to the links between five satellites and five ground stations.

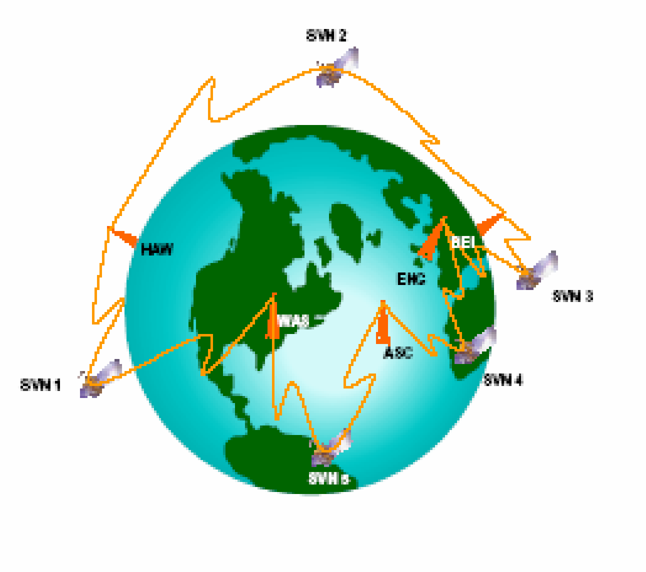

Figure 3. Diagram depicting Linked Common View (LCVTT) and Continuous Coverage Time Transfer (CCTT)

With this technique the procedure is to first use LCVTT to compare the monitor station clocks to the WAS station, as shown in Figure 3. Table I shows the comparisons. Then, using CCTT and the results from Table I, the space vehicle clock can then be compared to the single reference as shown in Table II.

TABLE I. LINKED COMMON VIEW TIME TRANSFER (LCVTT) FOR GROUND STATION CLOCKS

[SVN1 – WAS] – [SVN1 – HAW] = (HAW – WAS)

[SVN2 – HAW] – [SVN2 – BEI] = (BEI – HAW)
(HAW – WAS) + (BEI – HAW) = (BEI – WAS)

[SVN3 – BEI] – [SVN3 – ENG] = (ENG – BEI)
(BEI – WAS) + (ENG – BEI) = (ENG – WAS)

[SVN4 – ENG] – [SVN4 – ASC] = (ASC – ENG)
(ENG – WAS) + (ASC – ENG) = (ASC – WAS)

[SVN5 – ASC] – [SVN5 – WAS] = (WAS – ASC)
(ASC – WAS) + (WAS – ASC) = (WAS - WAS)

TABLE II. CONTINUOUS COVERAGE TIME TRANSFER (CCTT) FOR SPACE VEHICLE CLOCKS

[SVN1 – WAS] = (SVN1 – WAS)
[SVN2 – HAW] + (HAW – WAS) = (SVN2 – WAS)
[SVN3 – BEI] + (BEI – WAS) = (SVN3 – WAS)
[SVN4 – ENG] + (ENG – WAS) = (SVN4 – WAS)
[SVN5 – ASC] + (ASC – WAS) = (SVN5 – WAS)

Since 1995, more NGA stations have been added and in 1999 the LCVTT method was extended to include multiple paths (MPLCVTT) in order to make use of additional data. This method yielded on average 3-6 measurements per epoch that were combined using a least squares filter to get a result with lower noise. The links in the MPLCVTT method are shown in Figure 4.

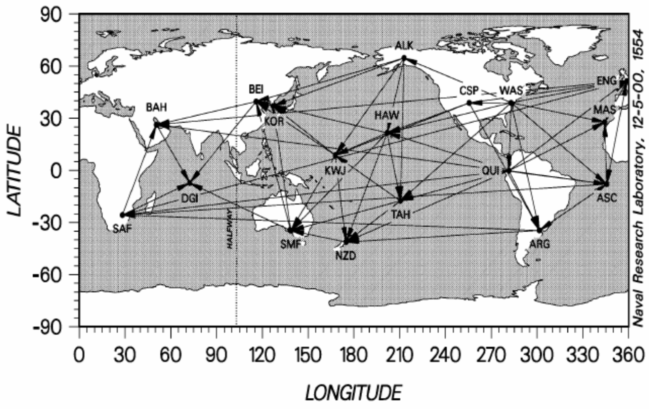

Figure 4. Diagram showing common-view links used in Multiple-Path Linked Common-View Time Transfer (MPLCVTT)

As ground stations are added to improve global coverage, the technique described above using a single reference has significant computation requirements and the problem of dependence on a single point reference. To address these problems a technique of Optimal Network Time Comparison was developed which is based on utilizing all possible measurements.

The problem and its least squares solution may be expressed in the following over-determined linear system,

$$(1) \qquad A \cdot X(t) = Z(t) \text{ and}$$

$$X(t) = (A^T wA)^{-1} Z(t) ,$$

Where each component, $X_i(t)$, of the unknown vector $X(t)$ represents the phase of clock i relative to a chosen reference clock, say $REF(t)$. The ground clocks are ordered first (say $i=1,\ldots,m$), followed by the satellite clocks, (say $i=m+1,\ldots,m+n$). Each component, $Z_i(t)$, of the data vector $Z(t)$ consists of the measurements, which are the pseudorange residuals of each ground station relative to the satellites which are in view at that station. The design matrix A_{ji} then simply relates X to Z by subtractions. Figure 5 depicts an example with $m=3$ and $n=4$. The weight vector w, represent the weights of each of the data elements. Thus, equation (1) relates each clock to a chosen intermediate clock using *all possible* paths to that clock. The chief benefit of this formulation as compared with the older LCVTT and MPLCVTT formulations is that all clock estimates are optimally (with appropriate assumptions on the noise characteristics of the data) determined from the data and any two clocks may be related by a single subtraction (i.e., clock i relative to clock j can be obtained from $X_i(t) - X_j(t)$). Though this method more optimally combines the measurement data into clock estimates, the method still results only in clock-to-clock comparisons.

For a system of three ground stations, ASC, ENG, and WAS, and four space vehicles, SVN1, SVN2, SVN3, and SVN4:

$$\overset{A}{\begin{pmatrix} 1 & 0 & -1 & 0 & 0 & 0 \\ 1 & 0 & 0 & -1 & 0 & 0 \\ 0 & 1 & -1 & 0 & 0 & 0 \\ 0 & 0 & 0 & -1 & 0 & 0 \\ 0 & 0 & 0 & 0 & -1 & 0 \\ 0 & 1 & 0 & 0 & 0 & -1 \\ 1 & 0 & 0 & 0 & 0 & -1 \\ 0 & 1 & 0 & -1 & 0 & 0 \\ 0 & 0 & -1 & 0 & 0 & 0 \end{pmatrix}} \overset{x}{\begin{pmatrix} \text{ASC-WAS} \\ \text{ENG-WAS} \\ \text{SVN1-WAS} \\ \text{SVN2-WAS} \\ \text{SVN3-WAS} \\ \text{SVN4-WAS} \end{pmatrix}} = \overset{z}{\begin{pmatrix} \text{ASC-SVN1} \\ \text{ASC-SVN2} \\ \text{ENG-SVN1} \\ \text{WAS-SVN2} \\ \text{WAS-SVN3} \\ \text{ENG-SVN4} \\ \text{ASC-SVN4} \\ \text{ENG-SVN2} \\ \text{WAS-SVN1} \end{pmatrix}}$$

Figure 5. System of equations showing new optimal network combination with 3 ground stations and 4 satellites.

Both examples discussed above use WAS as the reference, which limits all measurements at each epoch to those where WAS measurements exist.

V. CLOCK ESTIMATE COMPARISONS

To be able to compare the performance of these techniques, each was used to estimate clock performance for the period 1 January 2005 through 1 July 2005 using different data sources and clock references. The data sources were NGA 15-minute observations and IGS 5-minute observations. The NGA data was referenced to each of WAS, IGRT (the IGS Rapid Distributed Timescale), and GPS Time for purposes of this evaluation. The resulting data are presented in graphs of phase, frequency, drift, versus observation times and Hadamard frequency stability in order to evaluate differences of the datasets for these typical types of clock metrics. There are five datasets presented on each graph as follows:

1) NGA carrier derived pseudorange clock estimates referenced to the WAS ground station clock. These estimates are computed using MPLCVTT and CCTT.

2) NGA carrier derived pseudorange clock estimates referenced to the WAS ground station obtained from the Optimal Network Estimate method

3) NGA carrier derived pseudorange clock estimates referenced to IGRT computed from the Optimal Network Estimate method.

4) NGA carrier derived pseudorange clock estimates referenced to the NGA estimate of GPS Time computed from the Optimal Network Estimate method.

5) IGS published clock estimates referenced to IGRT.

Figure 6 shows the one-day frequency offset of SVN 45 signal with a Block IIR rubidium clock driving the on-board Time Keeping System (TKS) [9]. In this example, the pattern of recurring frequency variations significantly changed in May (~MJD=53550). All the datasets are in agreement and show basically the same frequency characteristics of the clock. Figure 7 shows the four-day drift of the same clock. The dataset with the GPS Time reference is seen to differ slightly from the other datasets. This may be explained by the fact that the GPS reference is a smoothed solution and is optimized for precise orbit determination.

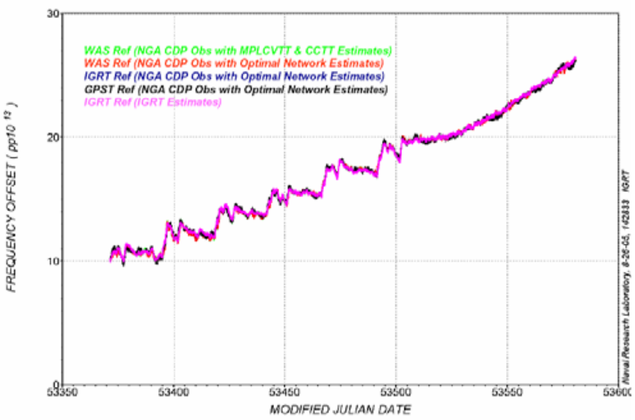

Figure 6. One-Day Frequency Offset of Navstar 45 for the period 1 January to 1 July 2005

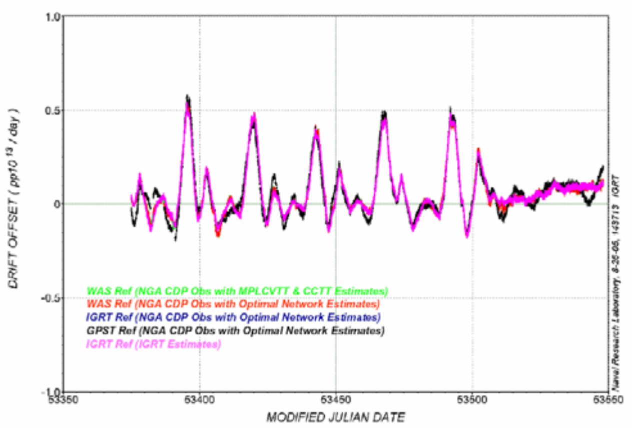

Figure 7. Four-Day Drift Offset of Navstar 45 for the period 1 January to 1 July 2005

The Block IIR rubidium clock on SVN43 has exhibited small phase spikes on occasion. An example of this anomaly is seen as a discontinuity in the phase data shown in Figure 8 over a two-day span. The IGS 5-minute dataset gives a better description of the clock anomaly revealing a higher peak in the discontinuity than is seen in the other datasets.

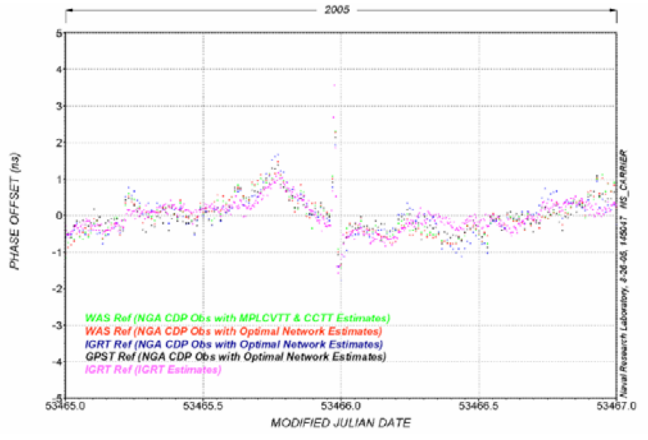

Figure 8. Phase Offset of Navstar 43 tabulated at 15-minute intervals for 4-5 April 2005.

Figures 9-14 are Navstar clock Hadamard stability profiles with samples times of τ ranging from the data basic sample period (15-minutes for NGA and 5-minutes for IGS) to eighteen days (which is equal to approximately 1/10 of the data span from 1 January 2005 to 1 July 2005). All of the datasets are in close agreement in the stability profile of the SVN 15 Block II cesium clock shown in Figure 9. The SVN 38 Block IIA cesium clock Hadamard stability profile is shown in Figure 10. Again, all of the datasets are in close agreement. Figures 11 and 12 are Hadamard stability profiles of Block IIA rubidium clocks, and in these examples, small differences can be seen among the datasets where IGS data show some improvement in stability in the short term.

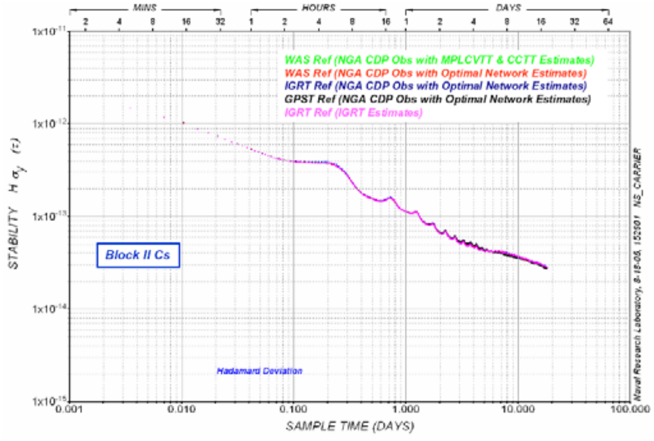

Figure 9. Frequency stability of Navstar 15 (Block II Cesium) using different sources and references, 1 January to 1 July 2005.

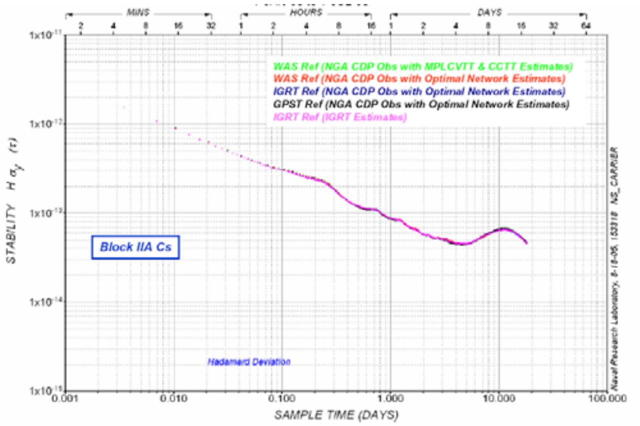

Figure 10. Frequency stability of Navstar 38 (Block IIA Cesium) using different sources and references, 1 January to 1 July 2005.

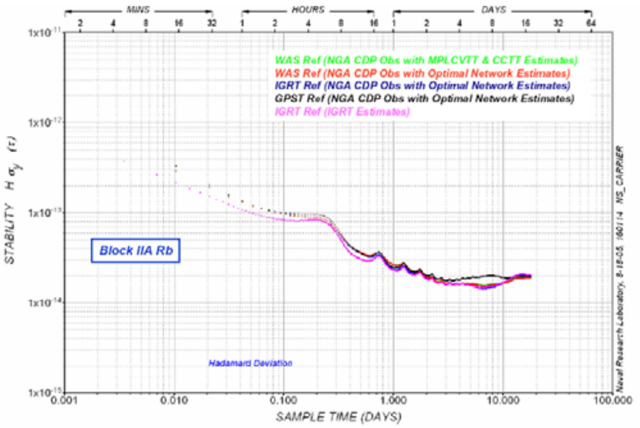

Figure 11. Frequency stability of Navstar 26 (Block IIA Rubidium) using different sources and references,1 January to 1 July 2005.

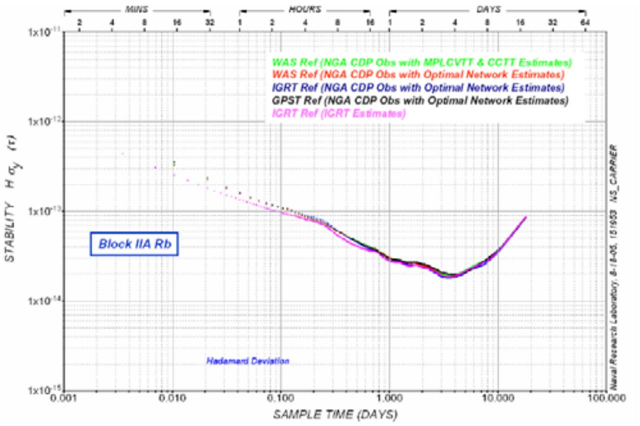

Figure 12. Frequency stability of Navstar 36 (Block IIA Rubidium) using different sources and references, 1 January to 1 July 2005.

Figures 13 and 14 are stability profiles of the lower noise Block IIR timing signals where the datasets show a noticeable difference. The IGS datasets show a significantly reduced stability in the short term. The NGA datasets using the MPLCVTT and CCTT method and the Optimal Network method both with the WAS reference are in close agreement. The NGA data with the IGRT Timescale reference shows an improvement in stability in the mid sample times and follows closer to the IGS data, while the NGA dataset with the GPS time reference shows worse stability in the mid to long-term sample times.

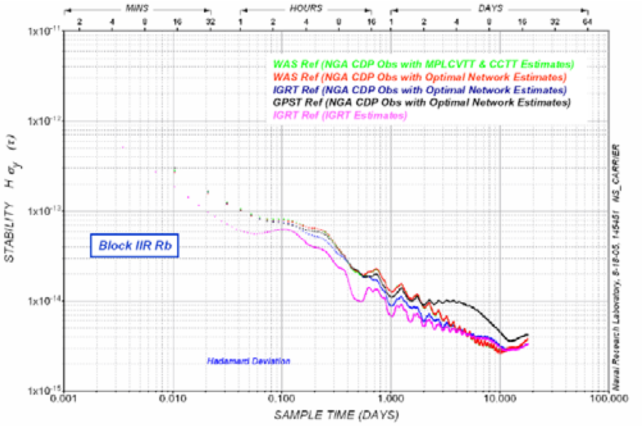

Figure 13. Frequency stability of Navstar 56 (Block IIR Rubidium) using different sources and references, 1 January to 1 July 2005.

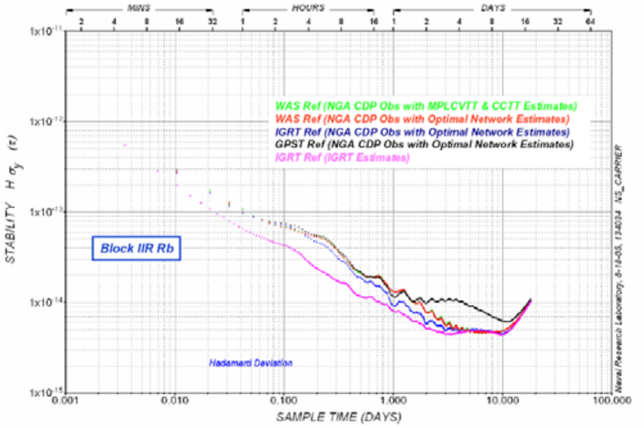

Figure 14. Frequency stability of Navstar 60 (Block IIR Rubidium) using different sources and references, 1 January to 1 July 2005.

Figures 15 and 16 compare all the GPS constellation clock frequency stability profiles as determined by NGA data and IGS data respectively. Figure 15 is derived from the NGA CDP observations referenced to the WAS station using the Optimal Network Estimate method, and the data have a sample period of 15-minutes. The profiles are color coded by Navstar clock type and show the similarity in stability characteristics for each type clock. Figure 16 is derived from IGS clock estimates referenced to the IGRT Timescale and the data have a sample period of 5-minutes. The lower noise of the Block IIA rubidium over the Block IIR timing signal in the very short term is more evident in the IGS data, indicating the NGA data are limited by transfer noise in the very short term.

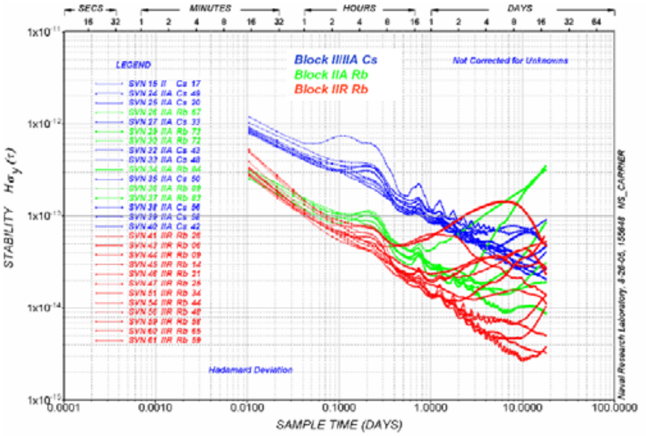

Figure 15. Frequency stability of GPS constellation (colored by Block & clock type) using NGA carrier-derived pseudorange data and the Optimal Network Estimation technique, 1 January to 1 July 2005.

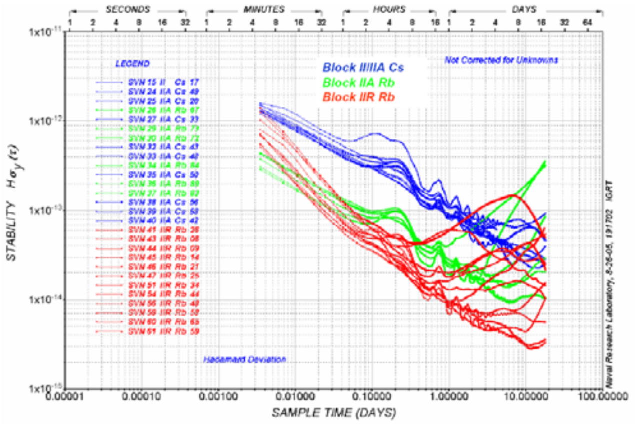

Figure 16. Frequency stability of GPS constellation (colored by Block & clock type) using IGS Rapid data and referenced to the IGS Rapid timescale IGRT for the period 1 January to 1 July 2005.

VI. SUMMARY AND CONCLUSIONS

In comparing the various data sources, the results show that for analysis of GPS clocks for sample times greater than a day, all the data give close to the same results and any of the described datasets can be used. Also, all references analyzed are sufficiently quiet for use as reference except for GPS Time. For the more stable clock types, the IGS data source provides a better result, especially for short-term characterization of GPS clock behavior. Also, the more frequent measurements of the IGS provide the ability to see clock events that might otherwise be missed. In particular, the Optimal Network Estimation recently employed at NRL has greatly reduced our computational burden and has improved the robustness of our NGA clock estimates, though the quality of the resulting estimates is seemingly no better than that of the legacy LCVTT or MPLCVTT techniques. Finally, the IGS distributed timescales IGRT & IGST which NRL has implemented, and to which the IGS Rapid and Final clock products are now referenced, provide a stable and robust reference for analyzing the GPS clocks as well as ground station clocks [10]. NRL will investigate implementing for all its datasets similar distributed timescales to which the GPS clocks may be estimated.

REFERENCES

[1] J. Oaks, M. Largay, J. Buisson, and W. Reid, "Comparative analysis of GPS clock performance using both code-phase and carrier-derived pseudorange observations," Proceedings of the 36th Annual Precise Time and Time Interval Systems and Applications Meeting, 7-9 December 2004, pp. 431–439.

[2] J. Oaks, J. Buisson, "Satellite Time Transfer Past and Present," Proceedings of the 34th Annual Precise Time and Time Interval Systems and Applications Meeting, 3-5 December 2002, pp. 7–18.

[3] Ray J. and Senior K., "IGS/BIPM pilot project: GPS carrier phase for time/frequency transfer and timescale formation", ***Metrologia***, **40**, pp. S270-88., 2003

[4] Ken Senior, Paul Koppang, Demetrios Matsakos, and Jim Ray, "Developing an IGS Timescale", Proc IEEE/EIA International Frequency Control Symposium, June 2001

[5] R.L. Beard, F. Danzy, E. Powers, and J.D. White, "Test and Evaluation Methods at the NRL Clock Test Facility," Proceedings of the 43rd Annual Symposium on Frequency Control, 1 June 1989

[6] R. Beard, J. White, J. Brad, T. Myers, W. Reid, F. Danzy, J. Buisson, "Long Term Ground Test Results for Two GPS Block IIR Rubidium Clocks", Proc. ION National Technical Meeting 26-28 January 2000, Anaheim CA.

[7] Digital Cesium Beam Frequency Standard Evaluation Test Plan, version 5.3, Space Applications Branch, Naval Research Laboratory, Washington, D.C., 1 Sept 2004

[8] W. Reid, "Multiple-Path Linked Common-View Time Transfer," Proceedings of the 31st Annual Precise Time and Time Interval Systems and Applications Meeting, 7-9 December 1999, pp. 43–53.

[9] H.C. Rawicz, M.A. Epstein and J.A. Rajan, "The Time Keeping System for GPS Block IIR, Proceedings of the 24th Annual Precise Time and Time Interval Applications and Planning Meeting,1-3 December 1993 , pp.5-16.

[10] J. Ray and K. Senior, "Geodetic techniques for time and frequency comparisons using GPS phase and code measurements," *Metrologia*, **42**, 2005, pp. 215-232.