COMPARATIVE ANALYSIS OF GPS CLOCK PERFORMANCE USING BOTH CODE-PHASE AND CARRIER-DERIVED PSEUDORANGE OBSERVATIONS

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Abstract

The Naval Research Laboratory (NRL) has, for many years, determined the GPS space vehicle clock offsets by differencing the pseudorange observations and the post-fit orbit provided by the National Geospatial-Intelligence Agency (NGA). On 14 March 2004, NGA put into production a new class of pseudorange observations called carrier-derived pseudorange observations (CDP). Because the measurement noise of the new CDP observations is much lower than that of the code-phase pseudorange observations, NRL has begun to use the newer CDP observations in its analysis of GPS clock performance. A number of differences between the two types of data are pointed out, and a comparative analysis of clock performance with respect to frequency stability is reviewed. This work was performed under the sponsorship of the GPS Joint Program Office.

INTRODUCTION

The Naval Research Laboratory analyzes the performance of the Navstar space vehicle clocks and monitor station ground reference clocks using observations from the monitor stations and the post-fit precise satellite orbits provided by the National Geospatial-Intelligence Agency (NGA). This continuing work is sponsored by the GPS Joint Program Office and is done in cooperation with the GPS Master Control Station. The measurement observations were collected from the network consisting of U.S. Air Force (USAF), NGA, and International GPS Service (IGS) monitor stations. The NGA Washington, D.C., monitor station, located at the United States Naval Observatory (USNO), uses the Department of Defense (DoD) Master Clock as the time reference. The NRL analyses uses the observations obtained at the Washington, D.C. monitor station to reference the space vehicle and monitor station clocks to the DoD Master Clock. The results are used by the GPS Master Control Station to set parameters in the Kalman filter, thereby improving navigation and time transfer performance **[1]**.

CONSTELLATION OVERVIEW

A summary of the operational Navstar clocks in the GPS constellation as of 1 November 2004 is presented in Figure 1. Each Block II/IIA/IIR space vehicle is shown by plane, position in the plane, and type of clock that was operating on each space vehicle. Changes during the last year are noted. The current constellation consists of twenty-nine space vehicles, nine operating with Block II/IIA cesium atomic frequency standards (CAFS), nine operating with Block II/IIA rubidium atomic frequency standards (RAFS), and eleven operating with Block IIR RAFS. The total operating time for each of the Navstar space vehicles since the space vehicle was inserted into the constellation is shown in Figure 2. Twenty-seven space vehicles have met or have exceeded the required Block II/IIA mean mission duration of 6 years. Twenty-five space vehicles have exceeded 8 years of operation, twenty-two have exceeded 10 years of operation, and nine have exceeded 12 years of operation. Ten Block II/IIA space vehicles, SVN 13, 14, 16, 18, 19, 20, 21, 22, 23, and 28, have been decommissioned. Navstar 28 was the only space vehicle that did not meet the required mean mission duration before being decommissioned. The average operating time of the Block II/IIA space vehicles is 11.1 years, while that of the more recently launched Block IIR space vehicles is 2.8 years. The number of clocks that have been placed in operation on each of the active space vehicles is shown in Figure 3. Of the active space vehicles, eleven are on the first clock, nine are on the second clock, four are on the third clock, and five, Navstars 17, 24, 31, 32, and 36, are on the fourth clock. While Navstar 43 shows two clocks placed into operation, one was turned on for test purposes and then switched off. It was a good clock and can be reactivated when the need arises. The Block IIR space vehicles are equipped with only three clocks, all RAFS. The Block II and IIA space vehicles each have four clocks, two CAFS and two RAFS. The operating lifetime, or length of service, of the clocks that were operating as of 1 November 2004 is shown in Figure 4. Five clocks, all cesium atomic frequency standards, have exceeded 8 years of continuous operation. One of the Block IIR rubidium clocks, on Navstar 43, has exceeded 6 years of continuous operation. The average age of the currently active CAFS is 7.1 years compared to an average age of 4.0 years and 3.0 years respectively for the Block IIA and Block IIR RAFS.

MONITOR STATION CLOCK OFFSET

The network of monitor stations, depicted in Figure 5, consists of six USAF, eleven NGA, and three IGS monitor stations. Since 28 May 1995 when the NGA Washington, D.C., monitor station—collocated with the DoD Master Clock at the U.S. Naval Observatory—became operational, the offset of each monitor station clock with respect to the DoD Master Clock has been computed using Multiple-Path Linked Common-View Time Transfer (LCVTT) **[2]**. The advantages of using multiple paths are (1) that the absence of measurements at one station does not result in the loss of time transfer data for the remaining stations in the network and (2) that the averaging of multiple, independent measurements results in a reduction of the measurement noise. The time reference at each of the NGA monitor stations was an HP5071. The HP5061 time references at the USAF monitor stations are being replaced with the more stable HP5071. This has already been done at the Kwajalein Island (KWJ) and at the Hawaii (HAW) monitor stations. The dramatic reduction in the noise of the 6-hour frequency after the replacement can be seen in Figures 6 and 8. The corresponding improvement in the stability profiles of the two monitor stations can be seen in Figures 7 and 9 to obtain for all sample periods evaluated.

SPACE VEHICLE TIMING SIGNAL OFFSET

For the space vehicles, the phrase “timing signal” is used rather than “clock” because the output of the atomic frequency standard is further modified by the electronics before being broadcast by the space vehicle. The output signal from the atomic frequency standard is fed to the Frequency Standard Distribution Unit (FSDU) for the Block II/IIA space vehicles and to the Time Keeping System (TKS) **[3]** for the Block IIR space vehicles. The TKS provides the additional capability of adjusting the frequency and drift of the timing signal. Where this capability has been employed, the offset of the frequency and drift from the DoD Master Clock have been adjusted to less than 3 pp10^{12} and to less than 2 pp10^{14}/day respectively. The offset of each monitor station clock from the DoD Master Clock is combined with the offset of the space-vehicle timing signal from the appropriate monitor station to produce the offset of each timing signal from the DoD Master Clock. This process results in multiple measurements of the timing signal offset at each 15-minute epoch. The measurements are then averaged at each epoch to get continuous coverage of each timing signal with respect to the DoD Master Clock **[4]**. Continuous coverage data are available for the timing signals from the 77 space vehicles that have been active since 28 May 1995. Including measurements gathered prior to 28 May 1995, the current active database includes timing signal measurements for the 91 Block II/IIA/IIR clocks that have been activated out of the 145 clocks on 39 space vehicles. Archived data are maintained for the timing signals from 35 of the 37 Block I clocks on 10 space vehicles.

CARRIER-DERIVED PSEUDORANGE MEASUREMENTS

On 14 March 2004, NGA put into production low-noise carrier-derived pseudorange (CDP) measurements in addition to the code phase pseudorange measurements previously used in analyses of clock performance by NRL. A comparison of the noise in the 15-minute frequency for the two measurement types for the Block II/IIA/IIR timing signals is shown in Figures 10 to 12. The improvement from using the low-noise CDP measurements is more pronounced for the timing signals originating with the rubidium clocks, which have better short-term stability than the cesium clocks. In Figures 13 to 15 are shown the frequency-stability profiles for the timing signals from a Block IIA CAFS, a Block IIA RAFS, and a Block IIR RAFS using both code-phase and CDP measurements. For the CAFS, the improvement is minor and disappears after about 3 hours. For the Block IIA RAFS, the improvement is significant at short sample times, but again it disappears after about 4 hours. For one of the best Block IIR RAFS, the improvement is significant and is sustained out to about 3 days, indicating that measurement noise in the code-phase measurements was masking the performance of the timing signal.

In Figures 16 and 17 are shown a comparison of the noise in the 15-minute frequency for the two measurement types for the six USAF and nine NGA monitor station clocks. During the time period shown, Hawaii and Kwajalein Island were still using an HP5061. All monitor stations show a reduction in the noise with the use of the CDP measurements. Interestingly, the Colorado Springs (CSP) monitor station in Figure 16, which had the largest measurement noise, now is the quietest. It had previously been thought that the large measurement noise was due to multi-path reflections inside the dome protecting the antenna, since none of the other monitor stations utilized a dome. In Figure 17, there was no explanation at this time for the high noise level at the Alaska monitor station from 14 March to 26 April.

In Figures 18 and 19 are shown the frequency-stability profiles for the HP5061 at the Ascension Island monitor station and for the HP5071 at the Alaska monitor station using both code-phase and CDP measurements. The more stable HP5071 shows slightly better improvement in the short-term stability, with both clocks showing improvement that disappears after 16 hours. In Figure 20 is shown the frequency-stability profile for the Colorado Springs monitor station using both code-phase and CDP measurements. Here is seen not only the greatest improvement, but an improvement that appears to continue beyond the maximum sample time of 8 days for which the stability was estimated. In Figures 21 and 22 are shown the frequency-stability profiles for the Block II/IIA timing signals using the code-phase and CDP measurements. The stability of all timing signals show an improvement using the CDP measurements, but the improvement is greater for those originating with rubidium clocks. In Figures 23 and 24 are shown the frequency-stability profiles for the Block IIR timing signals using the code-phase and CDP measurements. The timing signals originating with the Block IIR rubidium clocks show the greatest improvement.

CONCLUSIONS

The HP5061 time references at the USAF monitor stations are being replaced with the more stable HP5071. This has already been done at the Kwajalein Island and at the Hawaii monitor stations. The improvement in the stability profiles of the two monitor stations after replacement of the clocks was dramatic and persisted for all sample periods evaluated. On 14 March, NGA put into production low-noise carrier-derived pseudorange (CDP) measurements in addition to the code-phase pseudorange measurements previously used in analyses of clock performance by NRL. For the Block IIA CAFS, the improvement in stability using the CDP measurements is minor and disappears after about 3 hours. For the Block IIA RAFS, the improvement is significant at short sample times, but again it disappears after about 4 hours. For one of the best Block IIR RAFS, the improvement is significant and is sustained out to about 3 days, indicating that measurement noise in the code-phase measurements was masking the performance of the timing signal originating with these low-noise clocks. For the monitor station clocks, the more stable HP5071 shows slightly better improvement in the short-term stability, with both the HP5061 and the HP5071 showing improvement that disappears after 16 hours. The Colorado Springs monitor station, which had the largest measurement noise using the code-phase measurements, is the quietest of all the monitor station clocks using the CDP measurements. Furthermore, the frequency stability of the Colorado Springs monitor station clock showed the greatest improvement, which persisted for all sample times evaluated.

REFERENCES

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[4] W. G. Reid, 1997, *"Continuous Observation of Navstar Clock Offset from the DoD Master Clock Using Linked Common View-Time Transfer,"* in Proceedings of the 28th Annual Precise Time and Time Interval (PTTI) Applications and Planning Meeting, 3-5 December 1996, Reston, Virginia, USA (U.S. Naval Observatory, Washington, D.C.), pp. 397-408.

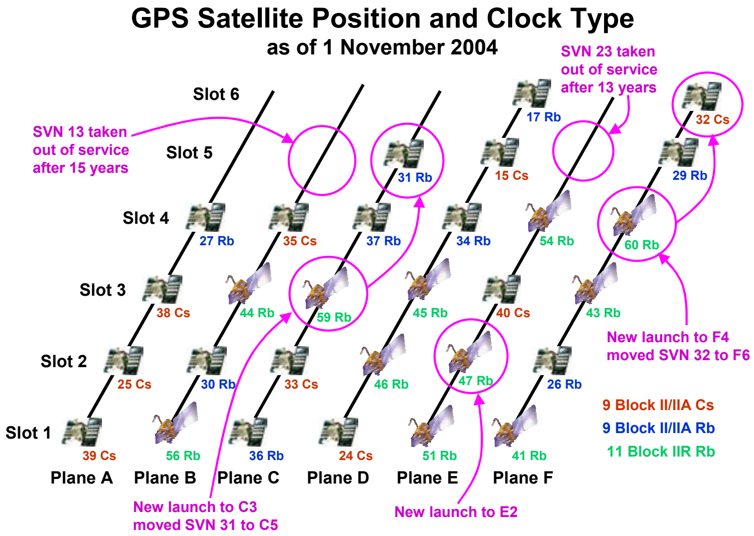
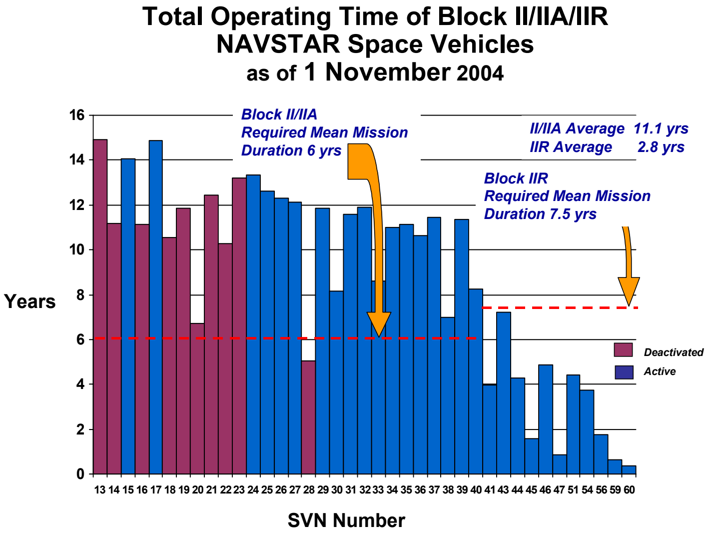


Figure 1



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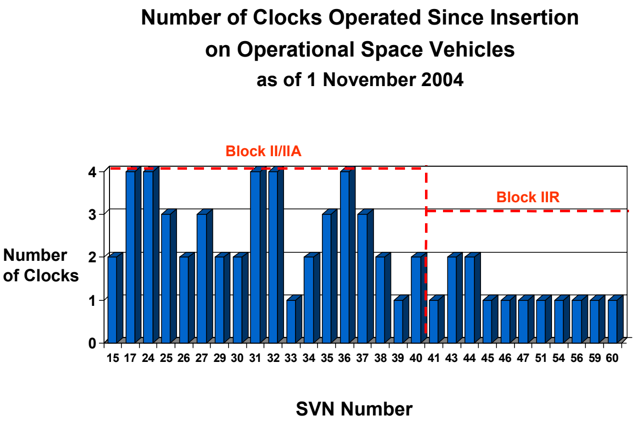

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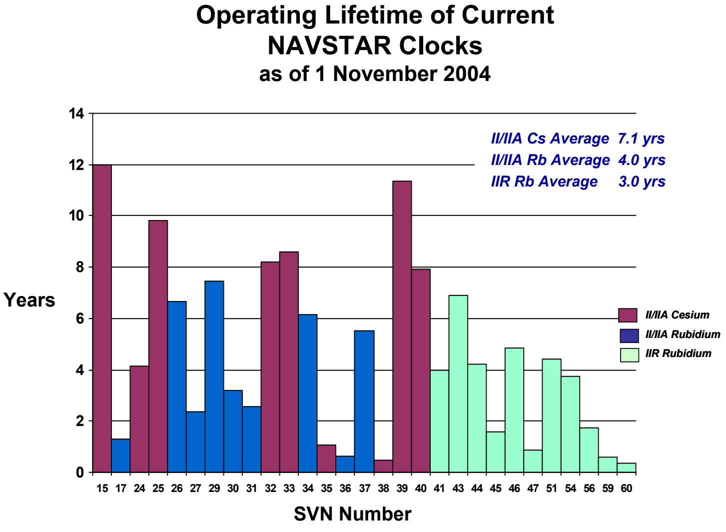

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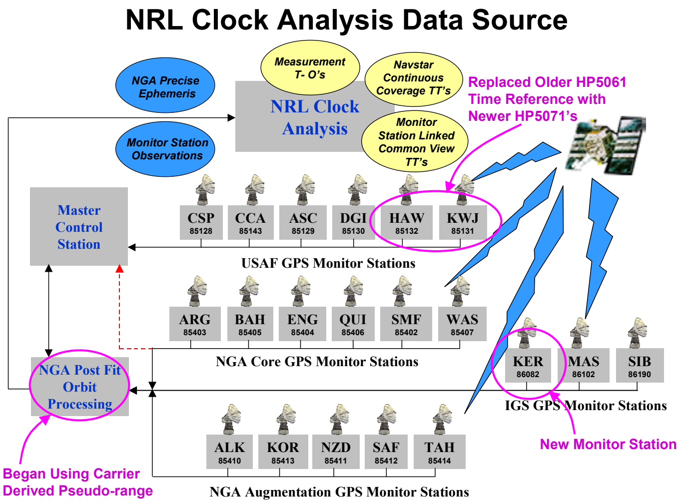

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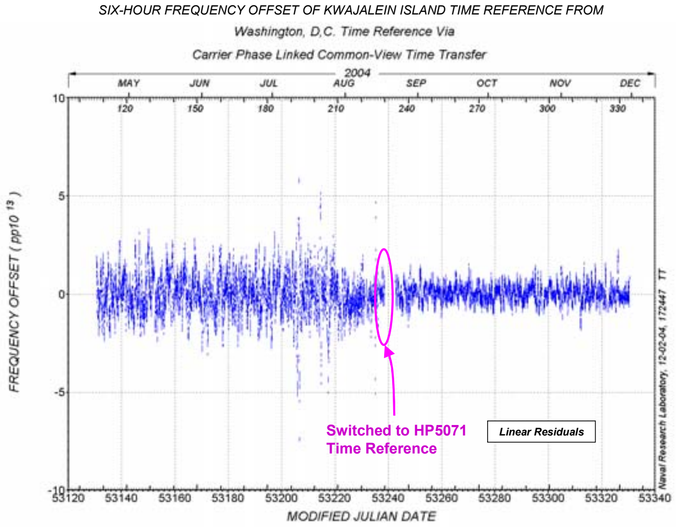

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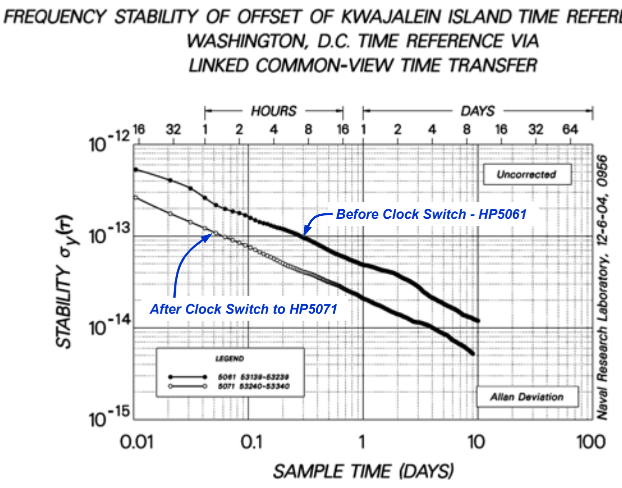

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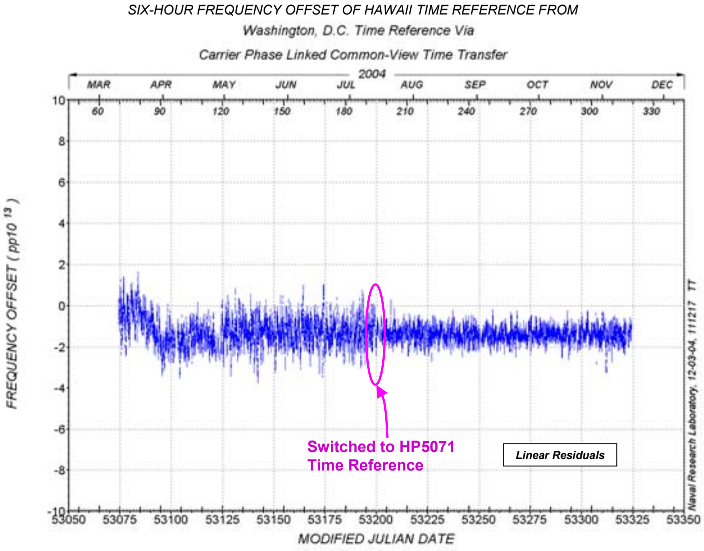

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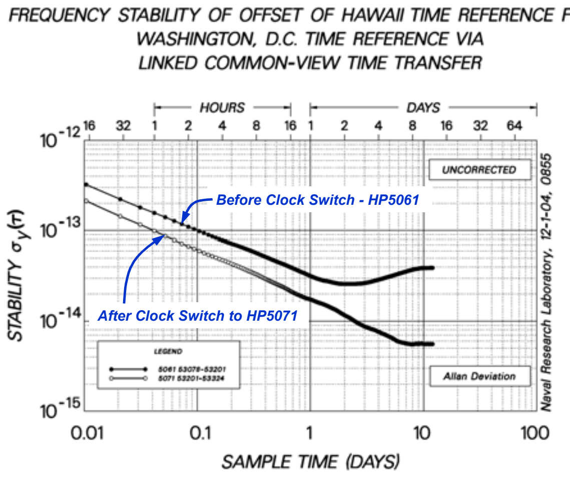

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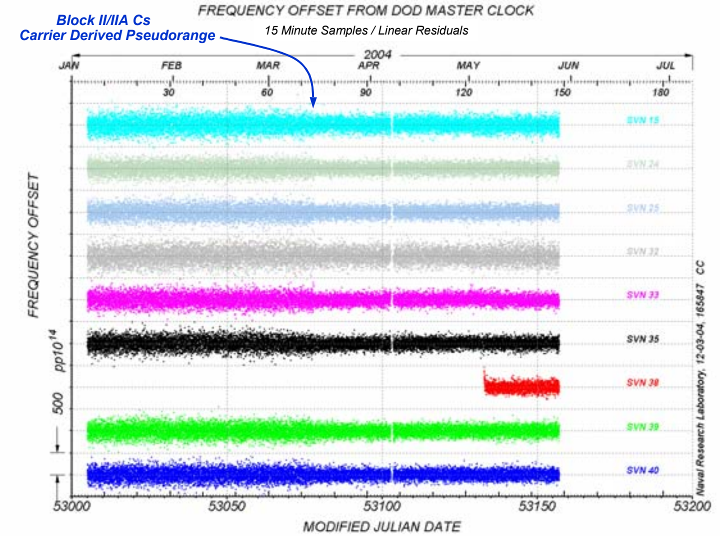

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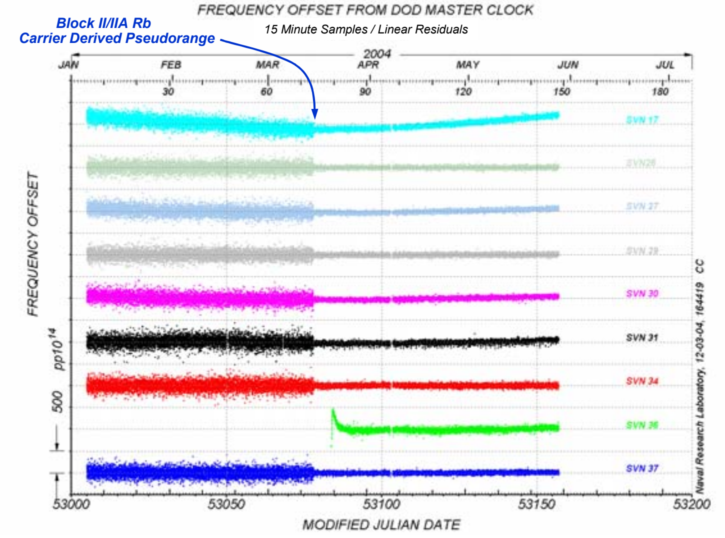

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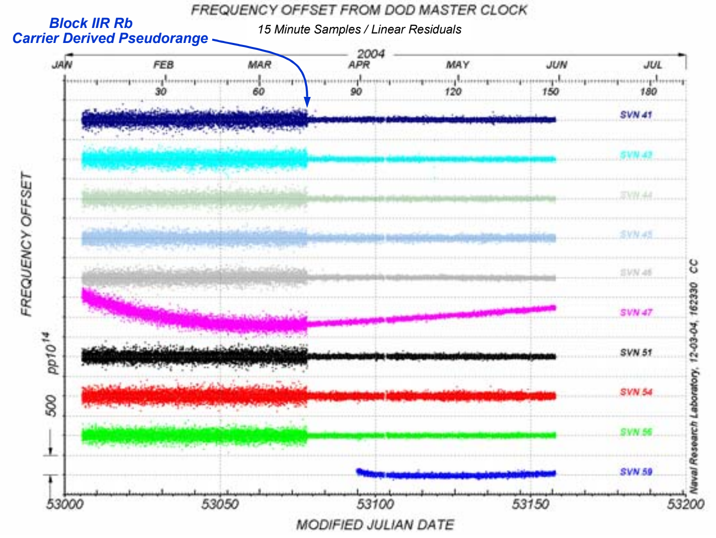

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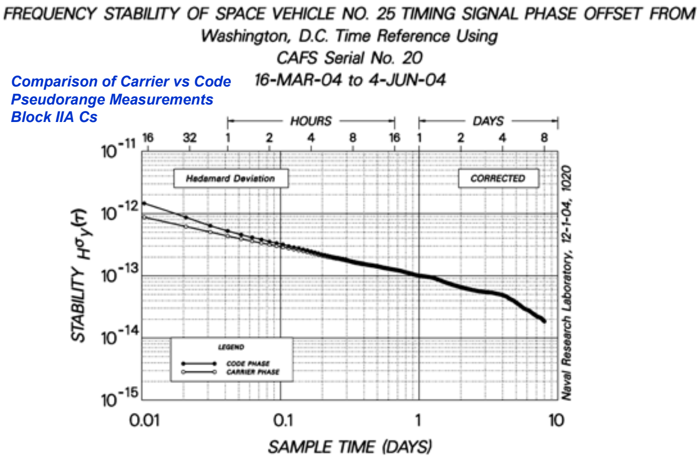

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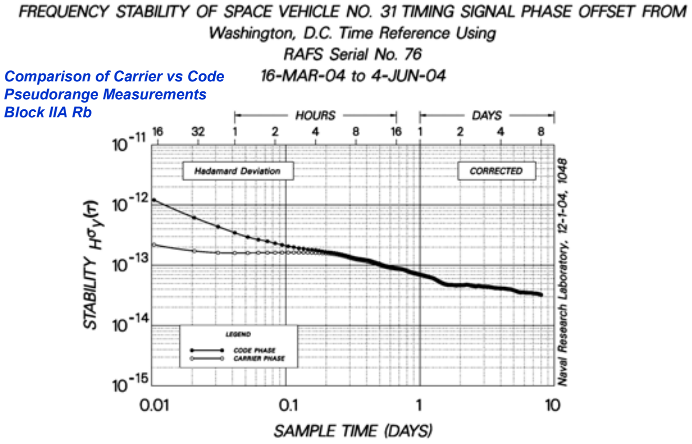

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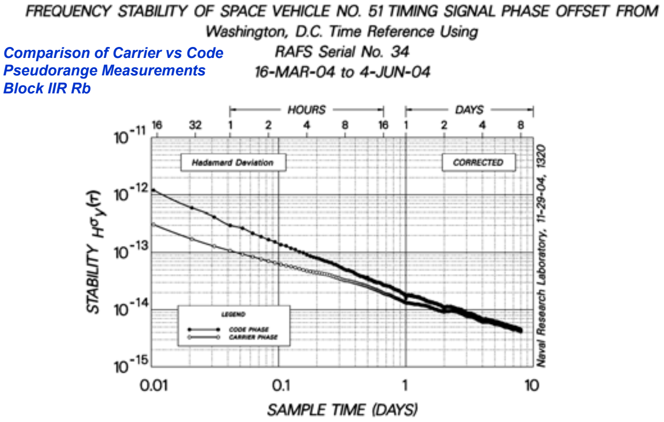

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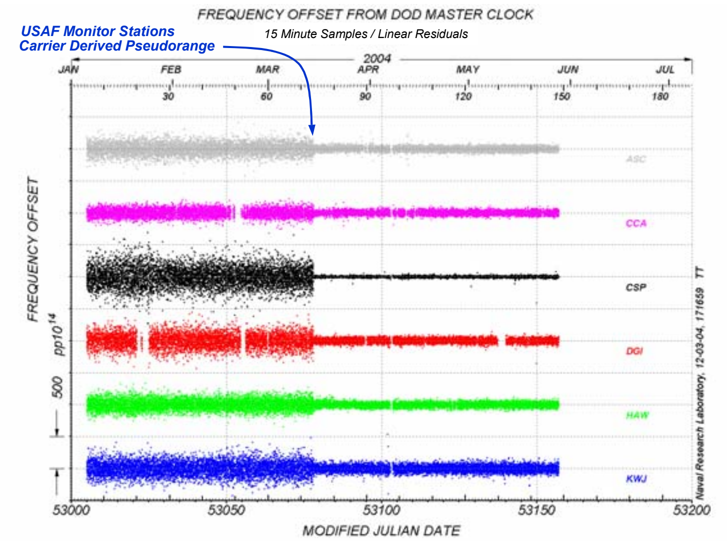

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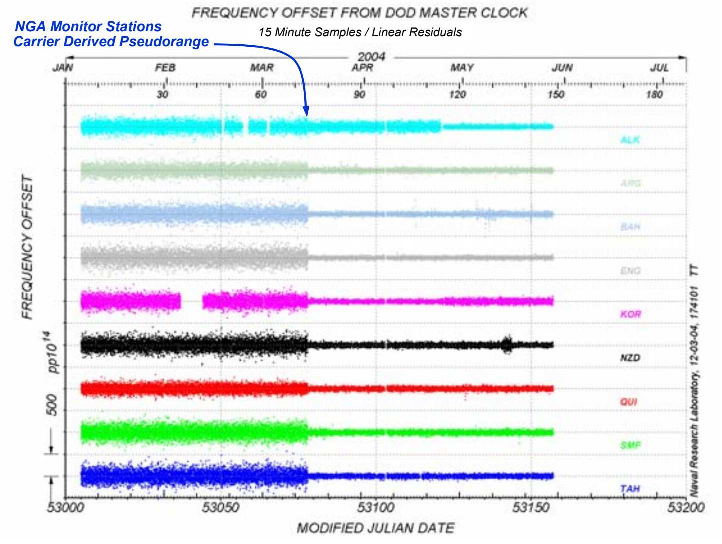

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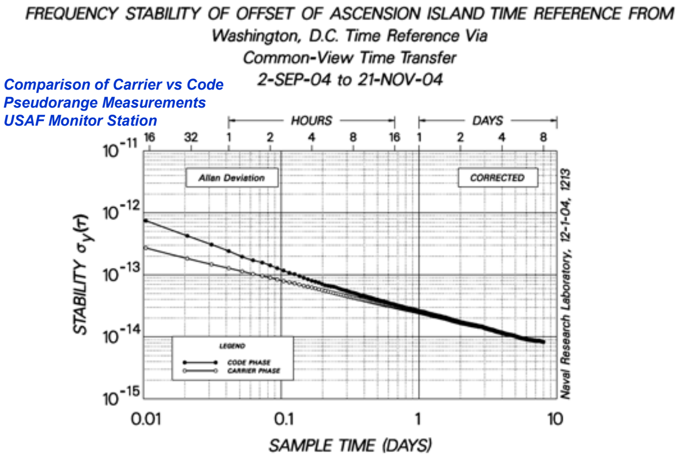

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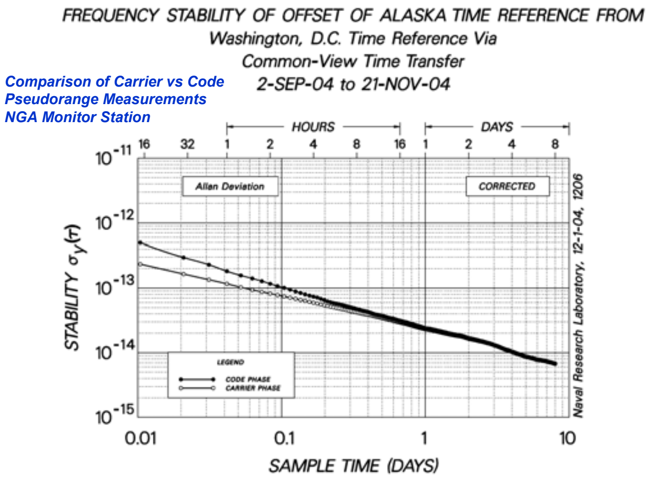

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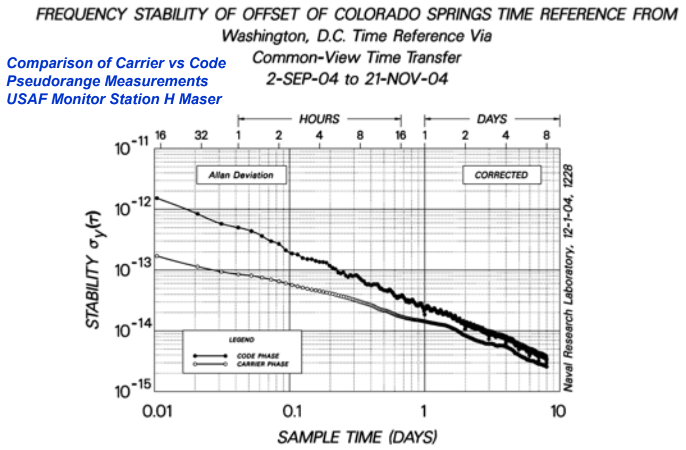

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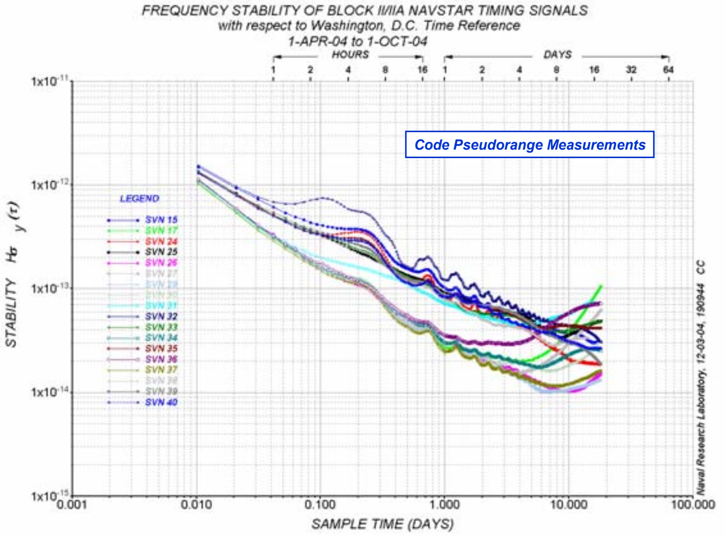

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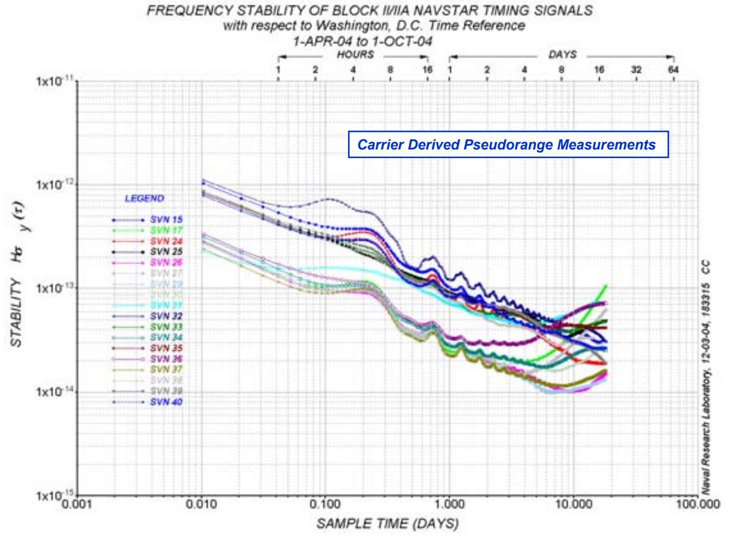

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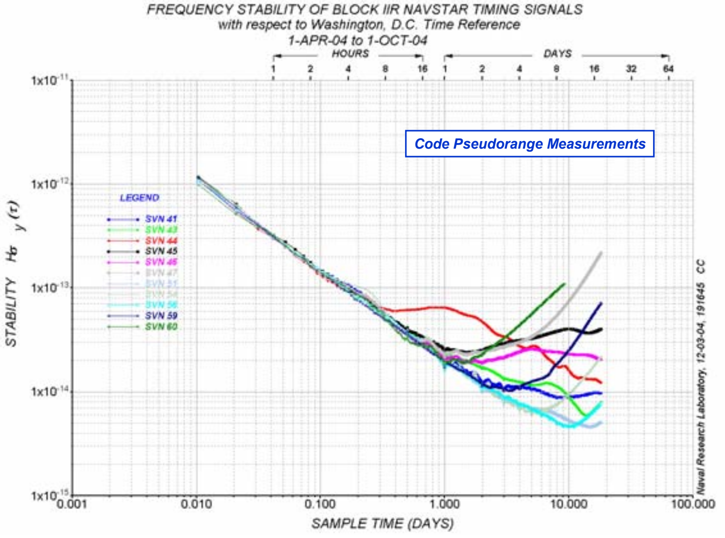

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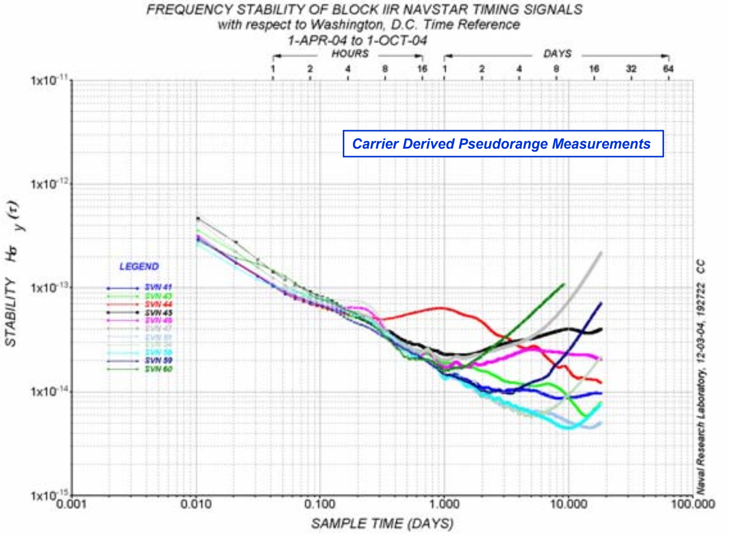

Figure 24

QUESTIONS AND ANSWERS

JIM CAMPARO (The Aerospace Corporation): It looked in some of that data as if there were oscillations in the Allan deviation. Could you comment?

J. OAKS: The little bumps, I think, are due to the periodics that possibly come out of the multi-path that is on a time period. The satellite comes up, you get a certain multi-path with a certain geometry and it is repeatable. And so that shows up as periodics – the aliasing of the periodics bump all the way down in the stability profile.

MICHAEL GARVEY (Symmetricom): Maybe just a reminder to those who don't study clocks as frequently and as often as many of us. And, also, maybe to emphasize the precision of language. These new methods of measuring the clocks really have not changed the performance of the clocks.

OAKS: You mean as far as the user goes? No. It is allowing us to do a better evaluation of how good the clocks are; that is your point.

GARVEY: Right. The separation between cesium and rubidium has always been there. It has been concealed by what some would call the phase noise of the code measurement of the clock performance. And, additionally, in the IIR clocks, the good performance of the rubidium is, to some extent, masked by the TKS noise as well.

So it is not a very simple analysis. There is a lot going on there that has to be taken into account.