AF/NGA GPS MONITOR STATION HIGH-PERFORMANCE CESIUM FREQUENCY STANDARD STABILITY 2007/2008: FROM NGA KALMAN FILTER CLOCK ESTIMATES

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Abstract

The National Geospatial-Intelligence Agency (NGA) and the United States Air Force (USAF/AF) operate a worldwide network of GPS monitoring stations. The NGA and USAF monitor stations utilize high-performance cesium frequency standards (CFS) and geodetic quality GPS receivers. Products derived from the NGA Monitor Station Network (MSN) include the postprocessed GPS satellite ephemerides, and GPS broadcast ephemeris and clock parameters.

The NGA monitor stations are unmanned and operate in non-laboratory environments. As such, the NGA stations must be monitored frequently to ensure data integrity. The Monitor Station Network Control Center in St. Louis monitors all NGA stations on a 24/7 basis. The USAF operates their stations in a similar manner, with the USAF GPS Operational Control Segment (OCS) at Schriever AFB incorporating data from ten NGA monitor stations in their Kalman filter process.

This paper summarizes USAF and NGA MSN clock stability for 2007 and 2008, using the Kalman filter clock estimate data computed daily at NGA St. Louis. The clock stability of six USAF and ten NGA monitor stations is presented. Also presented are site-specific observations, along with an overview of station configuration and planned upgrades. Results show that the USAF/NGA station clock estimates generally meet or exceed specifications for high-performance cesiums, providing accurate, stable, and reliable clocks in support of the GPS program.

INTRODUCTION

The National Geospatial-Intelligence Agency (NGA) operates a globally distributed network of 13 unmanned GPS monitor stations. The NGA Monitor Station Network Control Center (MSNCC) collects, processes, and distributes GPS observations, environmental data, and station health information from the NGA monitor stations. The MSNCC provides 24/7 data integrity monitoring. The 11 production NGA monitor stations are located at Adelaide, Australia; Buenos Aires, Argentina; Hermitage, England; Manama, Bahrain; Quito, Ecuador; Washington, D.C., USA; Fairbanks, Alaska, USA; Wellington, New Zealand; Pretoria, South Africa; Osan, South Korea; and Papeete, Tahiti. NGA monitor stations in St. Louis, Missouri, USA and Austin, Texas, USA are used for development and training. The United States Air Force (USAF/AF) operates six GPS monitor stations. The six USAF monitor stations are located at Ascension Island; Diego Garcia; Kwajalein Atoll; Hawaii, USA; Cape Canaveral, Florida, USA; and the USAF Master Control Station (MCS) at Schriever AFB, Colorado, USA.

Figure 1. NGA and USAF stations.

Ten of the 11 production NGA stations (Tahiti is excluded) began contributing to the USAF GPS Operational Control Segment (OCS) as part of the Legacy Accuracy Improvement Initiative (L-AII). Today, NGA stations continue contributing to the GPS OCS under the Architectural Evolution Program (AEP). Adding the ten NGA stations along with the six USAF stations to the OCS Kalman process has improved the satellite-monitoring capabilities from 93.9% single-station coverage to 100% dual coverage and 97.9% triple-station monitoring coverage at a 10° elevation mask **[1]**.

The NGA and USAF GPS data are used by the OCS to compute the broadcast GPS ephemeris and clock parameters. The NGA GPS observations, in conjunction with observations provided by the USAF GPS OCS and two International GNSS Service (IGS) stations, are used to compute the postprocessed NGA precise ephemerides.

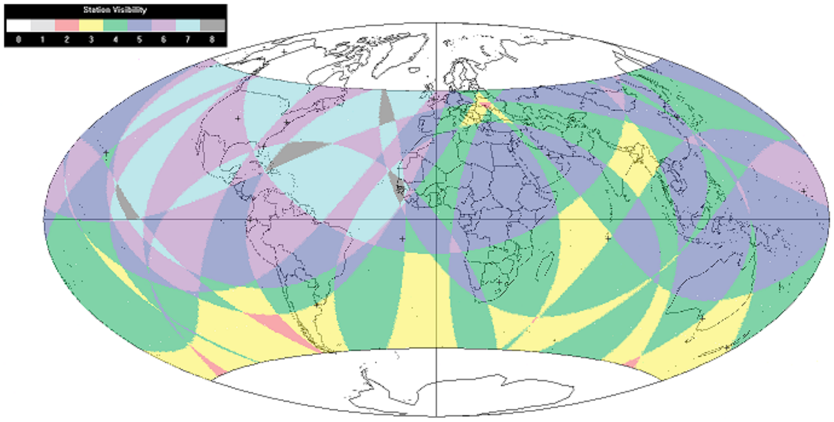


Figure 2. Satellite monitoring coverage from six OCS stations and ten NGA stations **[1]**.

MONITOR STATION OVERVIEW

The deployment of equipment and personnel to the NGA monitor stations can be a complex task. NGA personnel, along with a technical contractor from Applied Research Laboratories: the University of Texas (ARL:UT), travel to each NGA monitor station location each year to foster diplomatic relations with the host organizations. Personnel also perform yearly maintenance and upgrades to the station, and conduct training with the local point(s)-of-contact.

MONITOR STATION HARDWARE

Each NGA monitor station incorporates a suite of electronics that includes two geodetic-quality Ashtech Z(Y)-12 GPS receivers, and two Symmetricom 5071A cesium frequency standards (CFSs). The exception is the Washington, D.C., station at the United States Naval Observatory (USNO). Clock stability is calculated using the collected GPS observations, providing insight into potential environmental or electronic problems at the monitor stations. All station electronics, including the CFSs, are rack-mounted in 19-inch equipment racks, and generally monitor stations are situated in non-laboratory environments.

The CFSs contain a 6-gram (g) or 9g high-performance cesium-beam tube (CBT). The 6g cesium-beam tubes are replaced with 9g tubes when the 6g tubes reach end-of-life. Each CFS provides a 5-MHz frequency reference to a GPS receiver. The USAF monitor stations are similar in construction to the NGA stations. USAF stations employ geodetic-quality ITT Corporation (formerly Allen Osborne Associates) GPS receivers and 5071A CFSs, each with a high-performance CBT.

Figure 3. NGA monitor station.

MASTER CLOCKS

The NGA monitor station at USNO is tied to the USNO hydrogen maser Master Clock (MC). The USNO hydrogen maser Master Clock is nominally driven by 20+ hydrogen masers and 50+ CFSs.

The USAF station at Schriever Air Force Base near Colorado Springs is tied to the USNO Hydrogen Maser Alternate Master Clock (AMC) collocated at Schriever AFB. As of September 2008, the AMC is nominally driven by three hydrogen masers and 12 5071A CFSs **[2]**. The AMC maintains time which is traceable to the USNO Master Clock to within several nanoseconds.

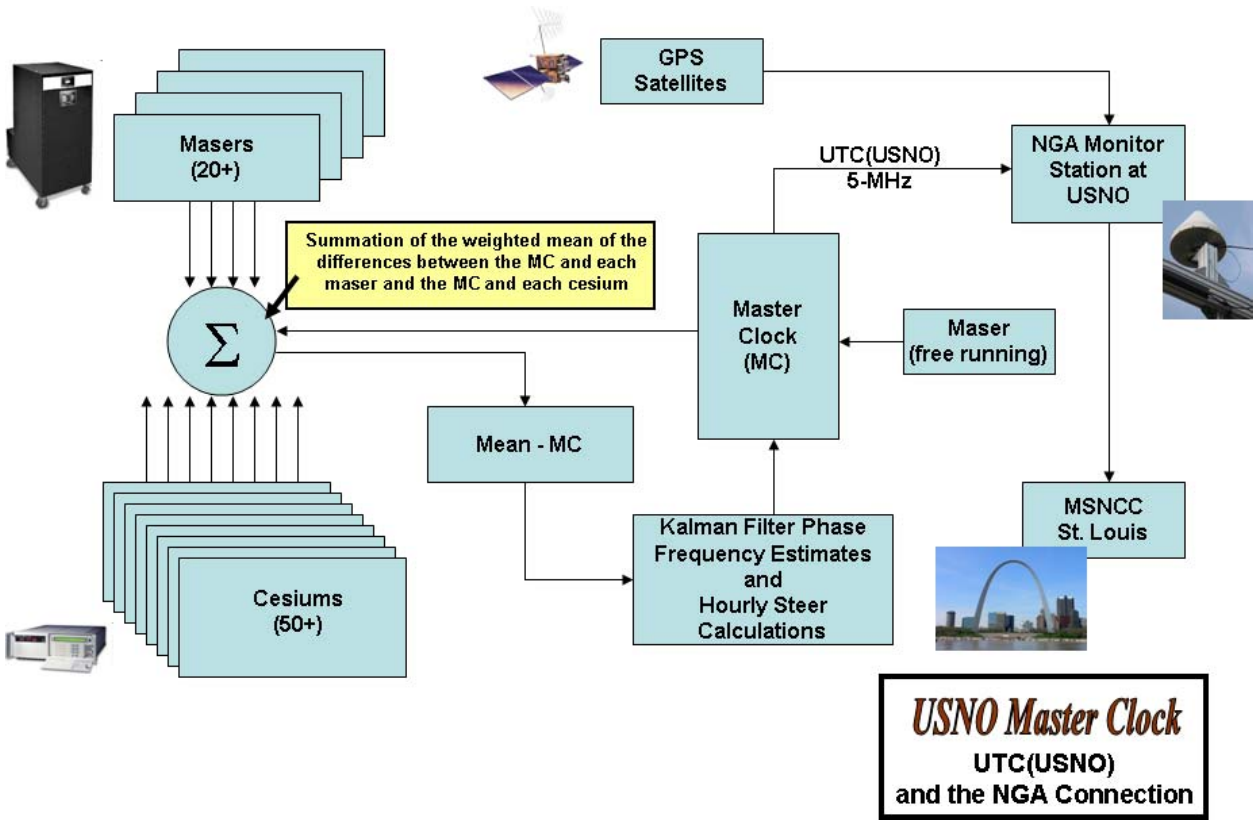


Figure 4. USNO Master Clock **[3]**.

DATA PROCESSING

NGA clock analysis is a multi-step process. First, 900-second (15-minute) smoothed GPS data are input to the Naval Surface Warfare Center (NSWC)/NGA Kalman filter process from the aforementioned stations. The NGA Kalman filter produces both satellite and station clock offsets, which are then adjusted to GPS time. After a phase-to-frequency conversion, outlier removal, and drift removal, clock stability analysis is completed using the overlapping Allan deviation.

SMOOTHING ALGORITHM

A smoothing algorithm provides GPS pseudorange and carrier-phase estimates every 900 seconds at the NGA stations. The USAF stations have a similar smoother algorithm to that used by NGA. The NGA smoothing algorithm "uses the carrier-phase measurements to smooth the pseudorange data to reduce the measurement noise, and it provides smoothed pseudorange and sampled carrier-phase values at GPS transmit times which are common to NGA and OCS stations" **[4]**.

The receiver clock correction at the NGA stations is bound by the Ashtech GPS receiver to be less than 1 ms. The Ashtech GPS receiver clock is further constrained by the phase-locking of the receiver to the CFS. This minimizes clock resets, or epochs in which the clock bias changes in meters by $0.001c$, where c is the speed of light.

ADJUSTED CLOCK ESTIMATES

NGA evaluates the characteristics of the atomic frequency standards at each monitor station with respect to a fixed master clock – typically the MC at USNO, but occasionally the AMC at Schriever AFB. NGA produces daily clock estimates using the Multisatellite Filter/Smoother (MSF/S) programs within OMNIS (Orbit Mensuration and Navigation Improvement Software). A complete description of the MSF/S processing is beyond the scope of this paper, but at a high level the MSF/S includes the *Editing and Clock Automation Tool* which identifies clock events, a *Filter* program, consisting of a linear Kalman filter providing clock estimates, and a *Smoother*, consisting of data smoothing algorithms **[5]**. Since the magnitude of the monitor station clock resets are known, they can be detected and accounted for in the Kalman process.

The USAF/NGA clock offsets are adjusted to be consistent with GPS time through a sliding window technique. GPS time is defined by the GPS Composite Clock, which is an implicit ensemble of monitor station and satellite vehicle frequency standards **[6]**. Station and satellite clock differences between OCS offsets and NGA offsets are formed at 900-second time steps within a window centered on the time of interest. The time span is normally the middle day of a 3-day fit. The middle day provides the lowest variances and, hence, the best clock estimates. The average difference for each satellite and each station is then formed over the entire window. The average of all average station, or satellite, differences is then added to all USAF/NGA station, or satellite, offsets. This computation yields the final clock estimates used for the NGA precise ephemerides and this study.

FREQUENCY STABILITY CALCULATION

Analysis uses OMNIS clock estimate data. The 900-second phase data are scaled (multiplied) by 10^{-6}, as USAF/NGA phase data are stored in microseconds. The phase offset is converted to frequency offset, plotted to identify and remove any 5-σ outliers remaining in the data, and linear drift is removed. Stability analysis metrics are computed using Clock Tools **[7]** and Stable32 stability analysis software **[8]**.

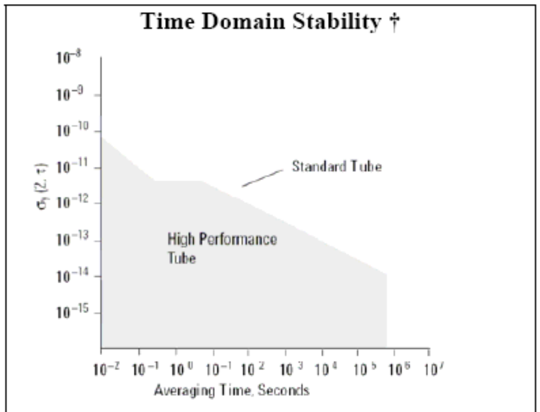
All USAF/NGA frequency standards are CFSs, with the exception of MC and AMC. The fully overlapped Allan deviation is the IEEE Std. 1139-1999 standard for frequency and phase instabilities in the time domain **[9]** and appropriate for use with low-drift CFSs **[10]**. Additionally, the overlapping Allan deviation provides improved confidence in stability estimation over the Allan deviation.

The monitor station GPS receivers, cabling, and other components can have a notable impact on clock estimates. The temperature coefficient of the Ashtech GPS receiver is on the order of ns/°C, but is receiver dependent. The Ashtech GPS receiver temperature coefficient is orders of magnitude greater than the CFS temperature coefficient of ps/°C or less **[11]**. Monitor station clock estimates generally follow the CFS trend, but are affected by other sources that are uncompensated for herein. A CFS may be functioning within specifications despite appearing otherwise in the analysis presented. NGA uses stability plots to guide maintenance activities and notifies the USAF when stabilities appear out of nominal bounds for their stations.

FREQUENCY STABILITY ANALYSIS

Data analysis spans January 2007 through September 2008, or GPS weeks 1408 to 1499. Discrete points noted are the stabilities at 1-hour, half-day, and 1-day averaging times. One-day and shorter averaging times correspond with the windowing used to generate OMNIS clock estimates. Stability plots are also examined for any discrepancies in the magnitude or shape of the stability curves. Clock estimates are generated using data from the selected (i.e., operational) GPS receiver at each station.

The 5071A time-domain stability specifications as defined by the 5071A manual are as follows.



Averaging Time (Seconds)	σ_y (2, τ)†	
	Standard Cesium Beam Tube	High-Perf. Cesium Beam Tube (Option 001)
10^{-2}	$\leq 7.5 \times 10^{-11}$	$\leq 7.5 \times 10^{-11}$
10^{-1}	$\leq 1.2 \times 10^{-11}$	$\leq 1.2 \times 10^{-11}$
10^{0}	$\leq 1.2 \times 10^{-11}$	$\leq 5.0 \times 10^{-12}$
10^{1}	$\leq 8.5 \times 10^{-12}$	$\leq 3.5 \times 10^{-12}$
10^{2}	$\leq 2.7 \times 10^{-12}$	$\leq 8.5 \times 10^{-13}$
10^{3}	$\leq 8.5 \times 10^{-13}$	$\leq 2.7 \times 10^{-13}$
10^{4}	$\leq 2.7 \times 10^{-13}$	$\leq 8.5 \times 10^{-14}$
10^{5}	$\leq 8.5 \times 10^{-14}$	$\leq 2.7 \times 10^{-14}$
5 days	$\leq 5.0 \times 10^{-14}$	$\leq 1.0 \times 10^{-14}$

Figure 5. 5071A frequency stability **[12]**.

At averaging times of 1 day or less, NGA stations generally meet CFS stability specifications throughout the 2007 and 2008 time period. Time-domain stability specifications for the CFS are plotted in red. The NGA stations in England and South Korea show frequency stability degradation in calendar year 2008 when compared to calendar year 2007. At select averaging times of 1 day or less, the Alaska, Australia, England, and South Korea stations all have stabilities that are greater than CFS specifications, as shown in Figures 6 and 7. The Australia, Argentina, and Bahrain stations all received new CFSs in 2008 and all meet specifications post-swap. These CFSs had either reached or were close to reaching end-of-life.

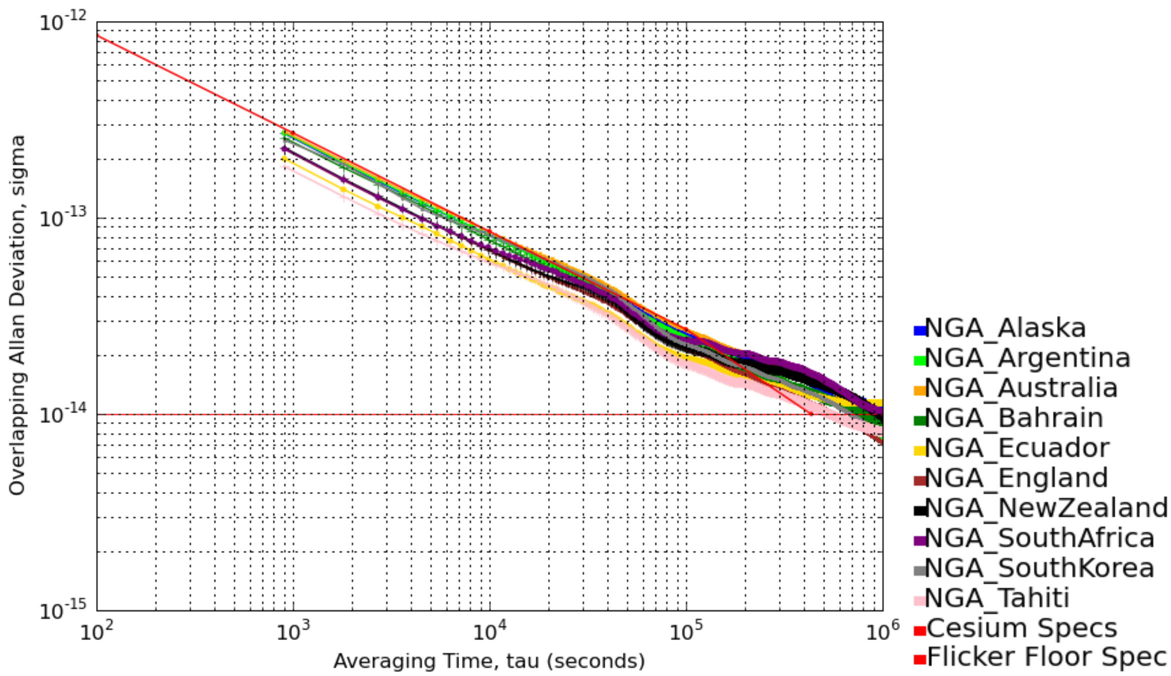


Figure 6. NGA monitor station frequency stability 2007.

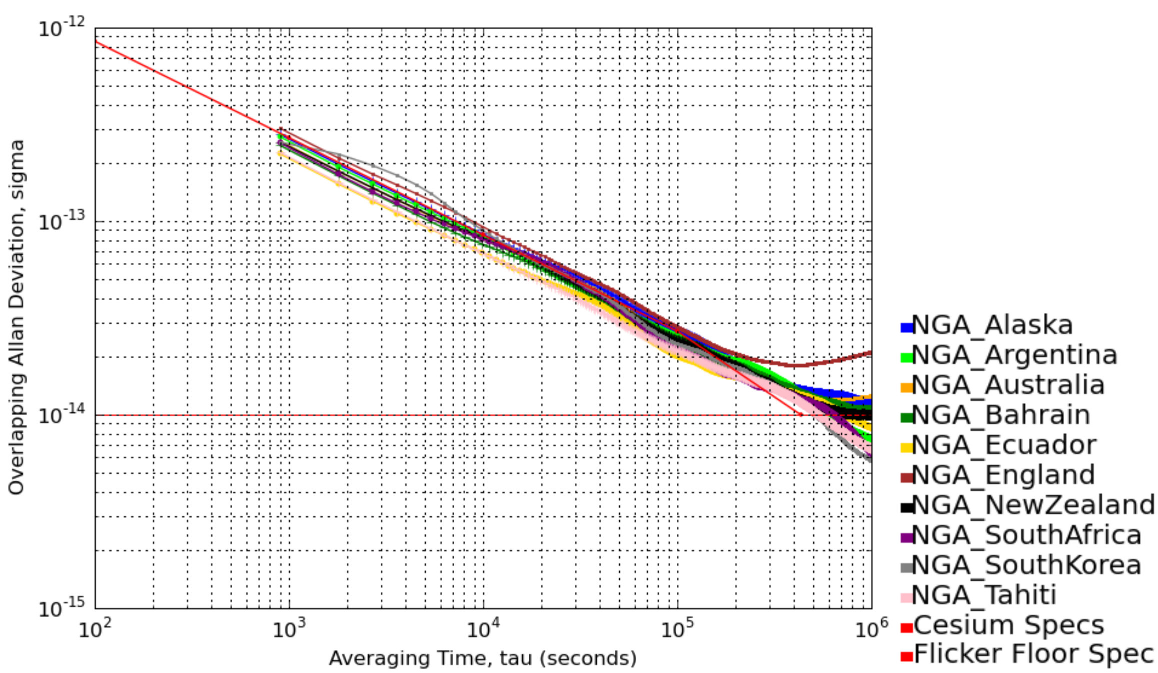


Figure 7. NGA monitor station frequency stability 2008.

The NGA monitor station in England has degraded frequency stability in 2008 when compared to 2007. On 29 April 2008, a CBT swap occurred in England, as the in-use CBT had a high-probability of reaching end-of-life within the next year. The electron multiplier voltage (EMV) for the CBT was approaching the maximum EMV of 2553V and the 6g CBT was over 6 years old **[13]**. Normal procedure dictates the shipment of a tested 5071A CFS (chassis and CBT) to the station for replacement. An unknown problem with the replacement 5071A CFS led to a field swap of the CBT from the replacement chassis to the original on-site chassis. Normal 5071A diagnostics were not possible in the field post-CBT-swap, and, for an unknown reason, degradation of the CFS is ongoing. Subsequent examination determined that the A2 CBT controller assembly in the replacement 5071A chassis unseated in transit.

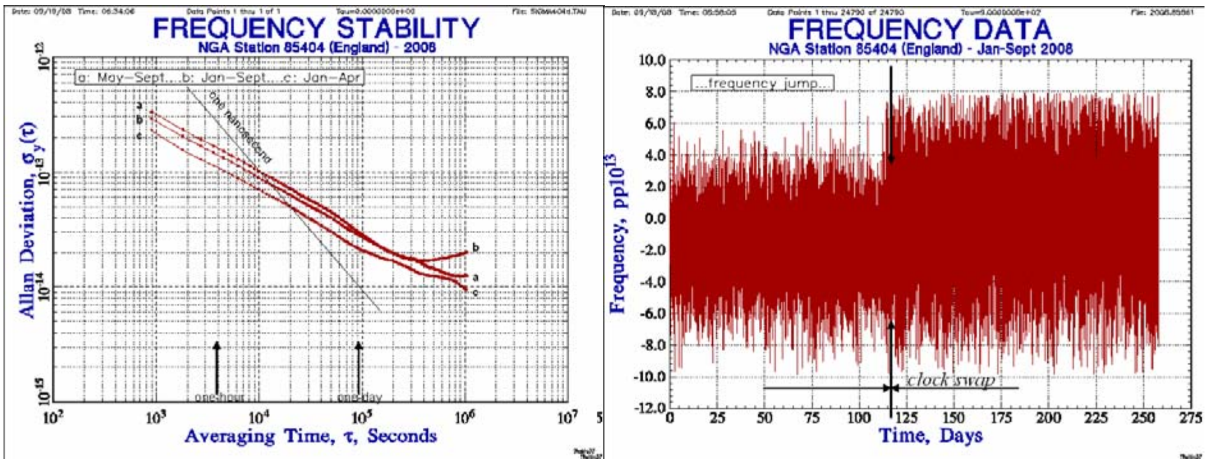


Figure 8. NGA England monitor station frequency stability 2008.

The South Korea monitor station also has degraded frequency stability in 2008 when compared to 2007. For GPS week 1475, 13-19 April 2008, the South Korea monitor station frequency stability is not within CFS time-domain stability specifications. The South Korea monitor station frequency stability for week 1475 does not follow the trend characteristic of the CFS. During GPS week 1475, regular temperature variations were present at the South Korea monitor station. These temperature variations have a significant impact on Kalman filter clock estimates.

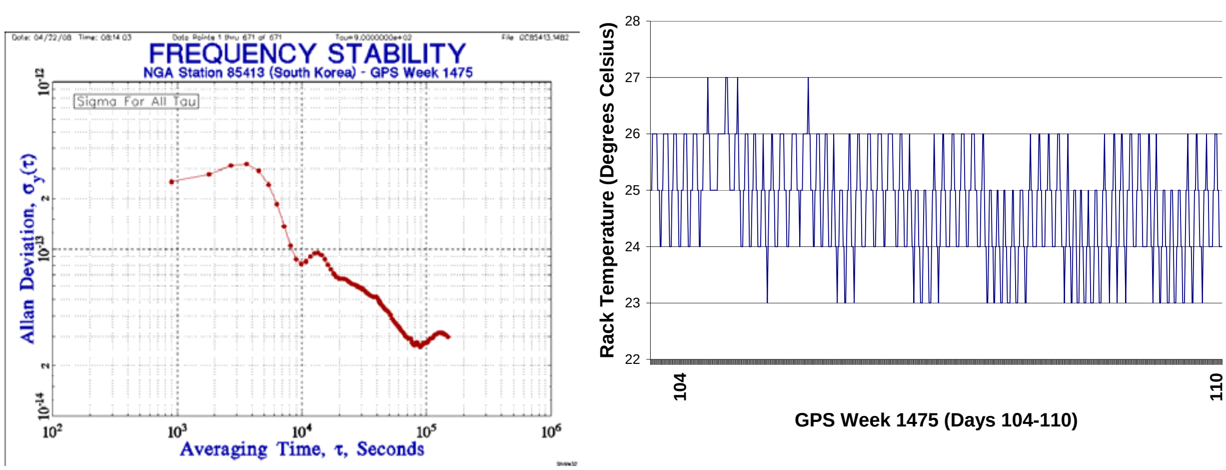


Figure 9. NGA South Korea monitor station frequency stability GPS week 1475.
a) monitor station frequency stability, b) monitor station temperature variations.

The thermostat in South Korea was adjusted after week 1475 in an attempt to minimize the temperature variations, but temperature-induced frequency degradation remains. Temperature variations are regularly examined at each station. Thermostat hysteresis and oversized air conditioners and/or heaters are two primary sources of temperature variations across the Monitor Station Network (MSN). The Alaska station also has elevated stabilities caused by temperature fluctuations.

At averaging times of 1 day or less, USAF stations generally meet CFS stability specifications for the 2007 and 2008 time period. Time-domain stability specifications for the CFS are plotted in red. At select averaging times of 1 day or less, the Ascension Island station stability is greater than CFS specifications, as shown in Figures 10 and 11. The USNO station is held as the master clock for the majority of the analysis period. As expected, the Colorado Springs station has superior frequency stability. There are not enough data points with the AMC as master to run a similar analysis on the USNO station. The AMC at Colorado Springs is plotted below in light green.

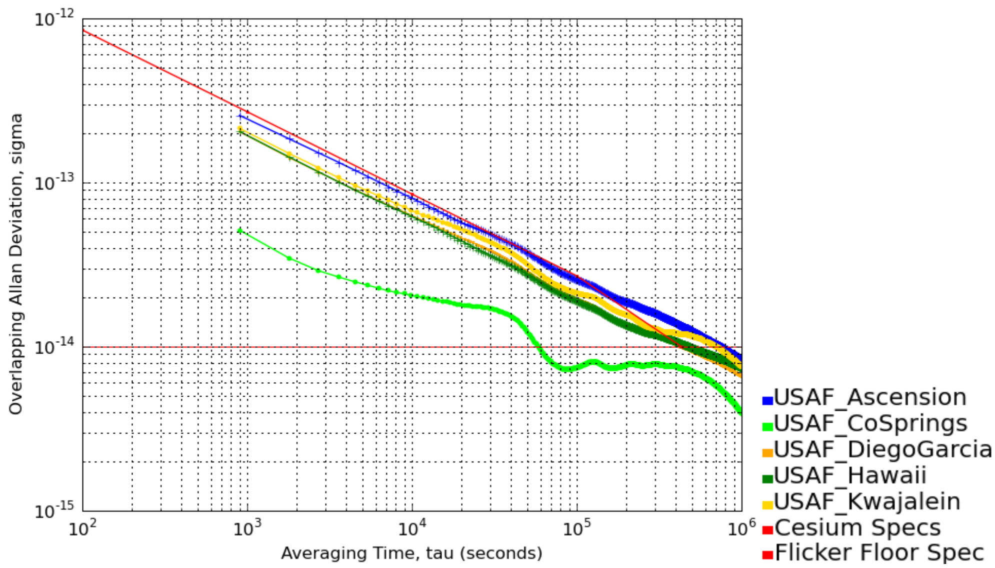


Figure 10. USAF monitor station frequency stability 2007.

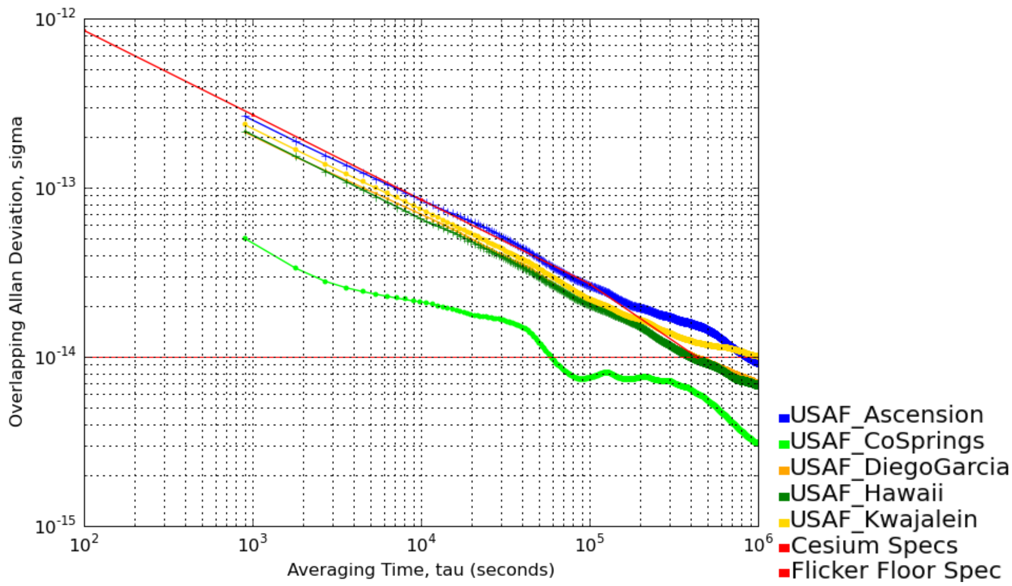


Figure 11. USAF monitor station frequency stability 2008.

As seen in Figure 12, station frequency stabilities at 1-hour, half-day, and 1-day times are generally below 0.5 ns, 2.0 ns, and 2.5 ns, respectively. The England station before the April 2008 CBT swap is denoted England1, and after the April 2008 CBT swap is denoted England2.

All NGA stations are scheduled to be serviced on the next maintenance trip in 2009 (barring any need for unscheduled maintenance). Special attention will be devoted to the Alaska, England, and South Korea stations. The Colorado Springs station is tied to the AMC and has the best stabilities in the network after the MC at USNO. The USNO station is typically the master clock and is not analyzed herein.

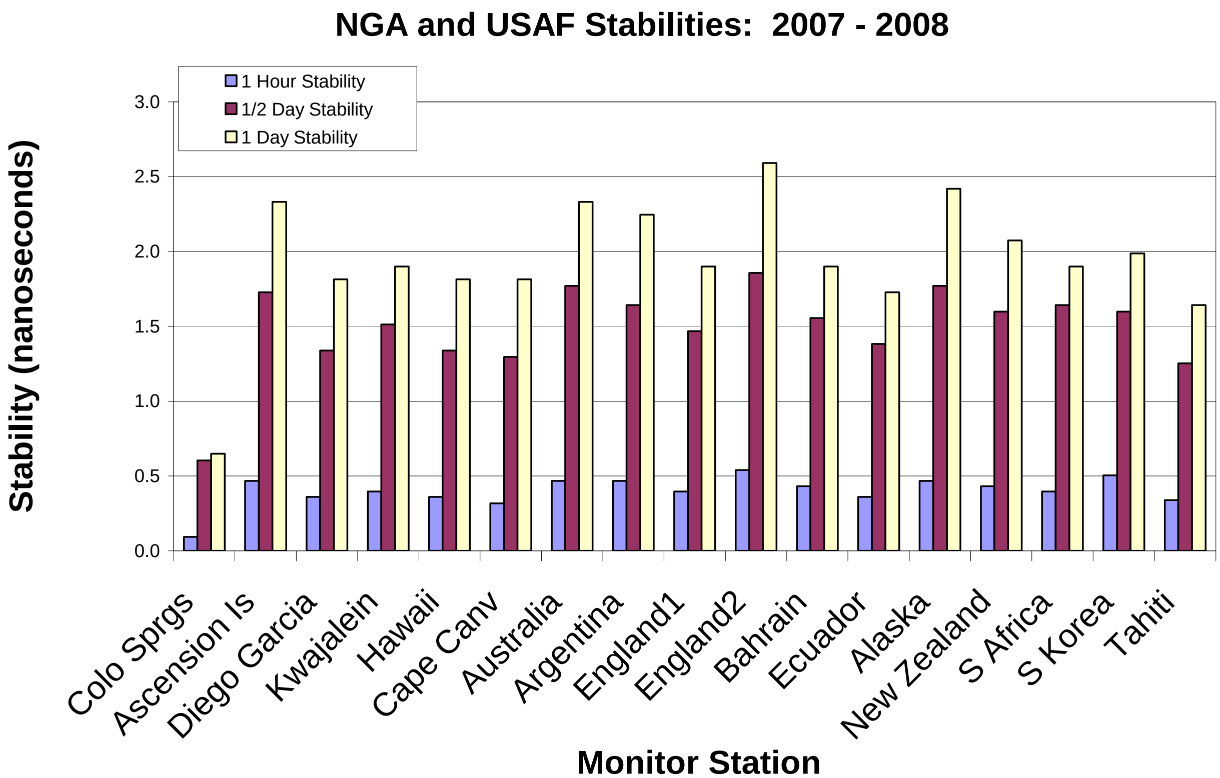


Figure 12. Monitor station clock stability 2007-2008.

CONCLUSION

To ensure data integrity, NGA monitors all 11 production NGA stations on a 24/7 basis. Yearly trips, sometimes sooner, are taken for both maintenance and administrative purposes. Extensive analysis of the GPS observation data is a daily procedure at NGA, giving NGA and the USAF OCS high confidence in their respective clock and ephemeris generation. NGA and OCS monitor station stability plots are generated using NGA Kalman filter clock estimates. This analysis helps identify possible problems and ensure monitor station quality. Results show that the NGA and USAF monitor stations generally meet industry standards for high-performance CFSs. The NGA GPS program has some of the finest and most reliable monitor station clocks to support current and future GPS navigation systems.

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