

AF/NGA GPS MONITOR STATION HIGH-PERFORMANCE CESIUM FREQUENCY STANDARD STABILITY 2005/2006: FROM NGA KALMAN FILTER CLOCK ESTIMATES

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Abstract

Both the National Geospatial-Intelligence Agency (NGA) and the United States Air Force (USAF/AF) operate a worldwide network of GPS monitoring stations that utilizes high-performance cesium frequency standards (CFSs) and geodetic quality GPS receivers. The USAF stations are somewhat equatorial, whereas the NGA stations are primarily in both the Northern and Southern Hemispheres. The NGA Monitor Station Network (MSN) has been in operation since 1983 and the operation in St. Louis currently monitors all the NGA stations on a 24/7 basis. The USAF operates their stations in a similar manner. The NGA monitor station CFSs are located in non-laboratory environments and in some instances, are logistically challenging. With the onset of the Department of Defense GPS Accuracy Improvement Initiative (Aii), the NGA monitor station cesiums, along with the associative electronics, must be monitored more frequently for quality control. Aii involves the USAF Operational Control Segment (OCS), at Schriever AFB, to incorporate at first a subset (six) of the NGA monitor stations in real-time processing to improve the quality of the broadcast ephemeris and clock parameters. Two more NGA monitor stations were added in the early fall 2006. The remaining three are scheduled to be added during the fall/winter 2006 timeframe. The addition of the NGA stations will expand the network coverage to allow all GPS satellites to be monitored without any gaps.

This paper is a summary of the stability of the USAF and NGA MSN cesiums, along with other upgrades during the year 2005 and fiscal year 2006, using the Kalman Filter clock estimate data computed daily at the NGA facility in St. Louis. The quality of the CFSs shown and summarized in this report are from six AF and eleven NGA monitor stations, of which eight NGA stations have been added to the OCS estimation process under Aii. Results show that the AF/NGA configuration of CFS has maintained the industry standards for high performance cesiums. This gives the AF/NGA GPS program some of the most reliable monitor station clock data to support current and future GPS navigation systems.

INTRODUCTION

Today, the National Geospatial-Intelligence Agency (NGA) operates a globally distributed network of 13 automated GPS monitor stations, while the United States Air Force (USAF/AF) operates six GPS monitor

stations. The primary mission of the NGA Monitor Station Network Control Center (MSNCC) is to collect observations from the GPS constellation. These observations, in conjunction with observations provided by the USAF GPS Operational Control Segment (OCS) and three International GNSS Service (IGS) stations (Figure 1), are used to compute the NGA precise ephemeris and clock information for all the GPS satellites. Currently, the 11 NGA monitor stations are located in: Adelaide, Australia; Buenos Aires, Argentina; Hermitage, England; Manama, Bahrain; Quito, Ecuador; Washington, D.C.; Fairbanks, Alaska; Wellington, New Zealand; Pretoria, South Africa; Osan, South Korea; and Papeete, Tahiti. The additional two stations, currently used for testing, evaluation, and training, are located in St. Louis, Missouri and Austin, Texas. These stations do not usually contribute to the precise ephemeris production. The six USAF monitor stations are located in: Schriever AFB, Colorado (Master Control Station – MCS); Ascension Island; Diego Garcia; Kwajalein Atoll; Hawaii; and Cape Canaveral, Florida. All NGA monitor stations, with the exception of the United States Naval Observatory (USNO), are outside of the continental United States. The first six NGA stations, listed above, were added to the Department of Defense (DoD) Accuracy Improvement Initiative (Aii) in the fall of 2005 [1]. Recently, the stations at Wellington and Pretoria were added to Aii. Adding the eight NGA stations along with the six AF/OCS stations to the Aii process has improved the satellite-monitoring capabilities to 100% dual coverage. The OCS MCS, at Schriever AFB, which processes the ranging measurements in a Kalman filter every 15 minutes, will incorporate the GPS satellite tracking data, to be supplied by the NGA monitor stations. The addition of the NGA data will be used to improve the quality of the broadcast ephemeris and clock parameters [1,2]. The three remaining NGA monitor stations are scheduled for a 24-hour communications upgrade before the winter of 2006 and should be added to the Aii process as they come online. Adding all 11 NGA stations has shown to improve satellite-monitoring capabilities from 97% single-station coverage to continuous 100%, triple-station monitoring of all satellites [2,3]. This will help eliminate non-coverage of satellites during station down-times due to maintenance or other problems that might occur.

Each NGA monitor station, with the exception of USNO, incorporates a suite of electronics that includes two geodetic-quality GPS receivers (Ashtech Z(Y)-12) and two Symmetricom (formerly HP/Agilent) 5071A cesium frequency standards (CFSs). The USAF stations are similar with the exception that their GPS receivers are ITT Industries (formerly Allen Osborne Associates – AOA). The NGA monitor station at the USNO is tied to the USNO DoD hydrogen maser Master Clock. 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. The AMC, being a “precise time reference station,” maintains time and rate which is traceable to the USNO DoD Master Clock. The AMC maintains their version of Coordinated Universal Time (UTC) to UTC (USNO), or the USNO DoD Master Clock, to within a few nanoseconds. The CFS used at each station contains a high-performance cesium-beam tube [4]. Each CFS provides a 5-megahertz (5 Mhz) frequency reference to a GPS receiver. All station electronics including the CFS are rack-mounted in standard equipment racks and located in general office space. The deployment of equipment and personnel to the NGA monitor stations can be a complex task. NGA personnel, along with a technical contractor, travel to each location each year to foster diplomatic relations with the host organizations. They perform yearly maintenance and upgrades to the station, conduct training, and evaluate operational details for optimal performance.

The data used to determine frequency stability of the AF/NGA CFSs is produced through a Kalman filter process. NGA produces both satellite and station clock offsets which are then adjusted to GPS time. This paper studies and evaluates the AF/NGA station clock stability to support the Aii program.

KALMAN FILTER (ADJUSTED) CLOCK ESTIMATES

NGA produces daily Kalman Filter clock estimates, currently using a suite of programs called OMNIS (Orbit Mensuration and Navigation Improvement Software). From [5], “OMNIS is a system of programs designed to determine the orbits of several classes of satellites. Two different solution techniques are used: the method of batch least squares and the Kalman filtering/smoothing method. The batch least squares, referred to in this document as the Batch Processor, and is used to determine the orbits of the Transit and low altitude satellites. Kalman filtering/smoothing is used to determine the orbits of the Global Positioning System (GPS) satellites and/or certain host vehicle satellites and is referred to in this document as the GPS/Sequential (SEQ) Processor. The GPS/SEQ Processor can estimate parameters and covariances of many satellites at a time using data from numerous stations and/or satellite-to-satellite (SST) data. Additionally, GPS/SEQ Processor can be used to solve for station coordinate solutions. The Batch Processor is designed to solve for the parameters of one satellite using ground station data.”

The clock estimates are derived via the OMNIS Kalman Filter/Satellite Adjust program. This program is used to adjust the NGA clock offsets to be consistent with GPS time. The GPS time system is one that is maintained by the OCS as part of their support to the GPS constellation, which in turn produces the OCS clock estimates. The NGA clock offsets are derived relative to a “master station,” which is held fixed in the clock estimation process. The master station for NGA is usually the USNO clock ensemble, or occasionally, the AMC ensemble at Schriever AFB. Both sites maintain an ensemble of hydrogen masers, which provides very stable frequency standards. Once the NGA clock estimates are adjusted to the OCS clock estimates, the resulting adjusted clock file is referred as the GPS satellite/station clock file. These are the final clock estimates, which is used for the final precise ephemeris provided by NGA and used for this study.

The AF/NGA clock offsets are adjusted to be consistent with GPS time through a sliding window technique. Satellite/Station clock differences between NGA offsets and OCS offsets are formed at 900-second (15-minute) time steps within a window centered on the time of interest. The time span is normally the middle day of a 3-day fit. For each satellite/station at each 900-second, clock differences are formed. The average difference for each satellite/station is then formed over the entire window. The average of these values is then added to all AF/NGA satellite/station offsets. This adjustment of the offsets makes them consistent with GPS time.

FREQUENCY STABILITY ANALYSIS

The analysis of the NGA Kalman filter clock estimate data, using Stable32, Stability Analysis Software [6], is quite simple. The data-sampling rate is, as mentioned above, 900 seconds (15 minutes). The data read in is the phase offset. It is then scaled (multiplier) to E-06, i.e., AF/NGA phase data are stored in microseconds. The phase offset is then converted to frequency offset. Now, by plotting the frequency data, outliers or any other oddity can be seen. In most cases, it is easier to visually examine frequency data vs. phase data. A linear frequency drift is then removed and residuals can be plotted. Then, an appropriate stability analysis statistic is performed. Since all AF/NGA frequency standards are cesiums, with the exception of the two master stations mentioned above, the Allan deviation is performed; moreover, the Overlapping Allan deviation is preferred. This is just due to the increased number of degrees of freedom and the improved confidence in the estimation [7]. Additional editing and/or analysis, if necessary, can be performed at this time. The final analysis consists of the relationship of frequency uncertainty to time (or phase) uncertainty.

Analysis of the frequency stability gives an indication on how well the frequency standards are performing. It also gives an idea of the types of noise that are generally inherent within the clocks and other environmental issues that could be introduced into the remaining electronic system. This includes temperature, pressure, and humidity extremes that could occur at each site. Two of the NGA stations have had special maintenance trips beyond the normal yearly maintenance trip for handling of environmental issues. Bahrain and South Korea are two stations that have required additional attention. Points of contacts (POC) at each station have also remained diligent.

This study looks at the Allan variance of the AF/NGA monitor station data primarily to get an idea how the AF/NGA CFSs are performing. This is used to help for any NGA maintenance related situations. Since the USAF maintains their monitor stations, NGA only notifies them when something appears to be “out of order.” The Hadamard/Allan variance data is used by the Air Force (MCS/OCS) to help in the fine-tuning of their Kalman filter [8,9]. Numerous signal-in-space studies have shown to improve navigation performance by the tuning of GPS clock estimates [10]. These also include current to future GPS programs [11]. The Naval Research Laboratory in the Washington DC performs more extensive work determining the GPS space vehicle clock offsets using NGA data [12]. This group uses data, both station and satellite, to aid in helping the MCS/OCS in the fine-tuning of the Air Force Kalman filter.

FREQUENCY STABILITY ANALYSIS FIGURES

The data used for the next few figures span the year 2005, which covers GPS weeks 1304 through 1355. The primary interest on these plot is the data at 1-hour, ½-day, and 1-day times.

Figure 2 shows the stability, from the NGA Kalman filter clock estimates, of five of the six USAF monitor station clocks. NGA uses 15-minute smoothed data received from the AF in the Kalman filter to produce clock offsets that is derived relative to the Master Clock at the USNO. Note the line labeled “Colo Sprgs.” This is the AMC hydrogen maser with respect to the USNO master hydrogen maser.

Figure 3 shows the frequency change and stability of the sixth AF monitor station clocks at Diego Garcia. About one-third the way through 2005, the station was upgraded from the CFS 5061A to the newer CFS 5071A. A few months later, the second newer CFS 5071A was used in the clock estimate process. Note the improved “tightening” of the frequency and the improvement of the stability.

Figure 4 shows the stability of the first five NGA clocks and the one USNO master hydrogen maser introduced in the Aii process in the fall of 2005. The second plot shows the stability of the remaining five follow-on NGA clocks.

Australia through Ecuador (85402 through 85406) show the standard white frequency modulation (WFM) noise/characteristics found in the passive-resonator frequency standards, such as cesiums. The station at the USNO (85407) shows the WFM at the 1-hour stability, then proceeds through flicker floor FM and then into random walk FM at the 1-day stability. This characteristic is found in active hydrogen masers [13]. Alaska through Tahiti (85410 through 85414) also show the standard white frequency modulation (WFM) noise/characteristics found in the passive cesium frequency standards.

Figure 5 shows the frequency to time stability of all the AF and NGA stations for the year 2005. Again, note the stability improvement of the AF station at Diego Garcia (85130a, b, and c). Table 1 shows the frequency uncertainty to phase (time) uncertainty statistics of the AF/NGA monitor stations for the 2005 time frame. Although not shown, the frequency range for the first five (cesium) NGA stations is

predominately pp 10^{13} . The frequency range for the USNO and AMC master stations (85407/85128) is pp 10^{14} to pp 10^{15} (not shown).

The data used for the next few figures span the fiscal year 2006, which covers GPS weeks 1343 through 1394. The fiscal year is from 1 October 2005 through 30 September 2006. Again, the primary interest on these plot is the data at 1-hour, ½-day, and 1-day times.

Figure 6 shows the one AF monitor station at Kwajalein and one NGA monitor station at Ecuador for the fiscal year 2006. So there is a 3-month overlap of data. The remaining AF and NGA station are not shown, but are available, due to no significant happenings. At the beginning of the year 2006, the AF swapped clocks at Kwajalein. Note the stability differences between Figure 2 and Figure 6. They are very similar. The NGA monitor station at Ecuador had a clock swap mid-June 2006. Note the improvement in both the frequency and stability plots.

Figure 7 is similar is similar to Figure 5, but for the fiscal year 2006. This figure corresponds to Table 2, which is similar to Table 1, which again shows the frequency to time stability of all the AF and NGA stations for the fiscal year 2006.

OTHER IMPROVEMENTS (NOT CLOCK-RELATED)

Figure 8 shows the range data received from the AF monitor station at Schriever AFB for the partial year 2006. Up to the end of May 2006, minus about 2 weeks in mid-February, this station was considered the noisiest when it comes to receiving range data. When the station was first put into work, the antenna was covered by a larger than normal dome along with a “plate” to collect moisture within the dome. Numerous tests were conducted, and the noise was believed to be a multi-path problem. On 23 May 2006, the new antenna was formally put into the works and the multi-path problem appears to have subsided.

Finally, Figure 9 show the dual antenna at the NGA monitor station in Alaska. Currently, NGA has older receivers and the dual antennas are to be used for phase measurement cycle-slip detection/correction testing [14]. It is hoped that, when NGA replaces the older receivers with the newer (SAASM) ITT receivers, cycle-slip problems will be reduced.

CONCLUSION

To ensure the highest possible degree of accuracy, stability, and reliability, NGA monitors all 11 stations on a 24/7 operation. Yearly trips, sometimes sooner, are taken for both maintenance and administrative purposes. Within the next year to 2 years, each monitor station will be upgraded with dual AOA (now ITT) receivers, newer cabling, new antennas, and upgrades to the cesium frequency standards. Also, five of the monitor stations will be upgraded to get dedicated 24-hour communications. These five stations are also to be added to the Aii process at a later date (Fiscal Year 2006).

Extensive analysis of the GPS observation data is a daily procedure at NGA. This enables NGA to maintain the best possible orbit and clock precise ephemeris. Along with satellite clock evaluation, analysis of the AF/NGA station CFS is also ongoing. Weekly NGA station CFS stability, along with monitoring the OCS station clock stability, via the daily NGA Kalman filter process, is performed. This weekly analysis has helped with identifying possible problems and to help determine NGA monitor station quality. Results show that the NGA configuration of CFS has maintained the industry standards

for high performance cesiums. For further detail, see **15**, Chapter 6, Specifications. This gives the NGA GPS program some of the finest and most reliable monitor station clock data to support current and future GPS navigation systems.

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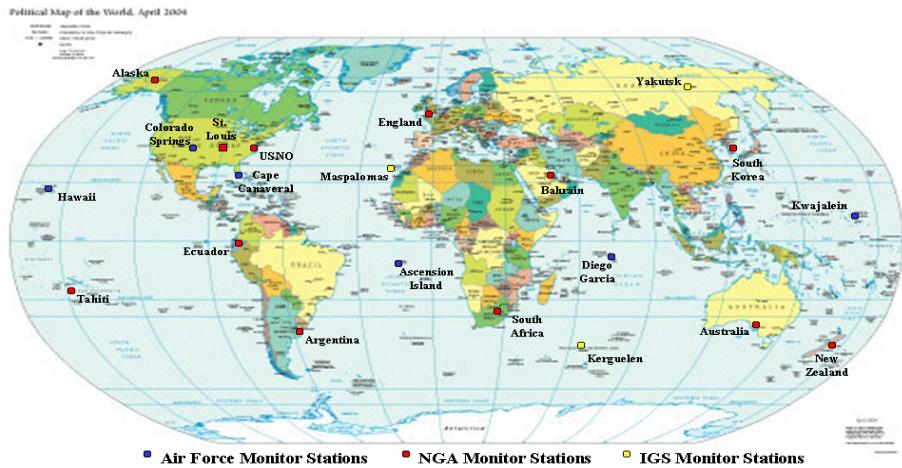


Figure 1. The location of the USAF, NGA, and IGS monitor stations used for the processes in St. Louis.

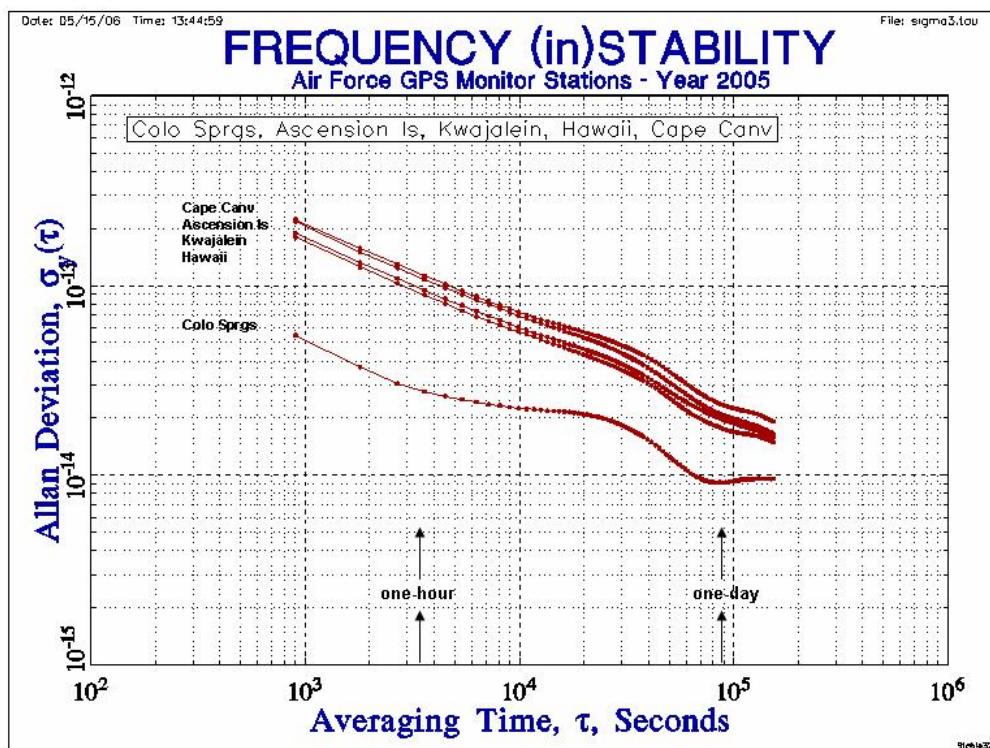


Figure 2. Frequency stability plots of the “clocks” at five of the six AF monitor stations. The AF station at Colorado Springs (Schriever AFB) is tied to the USNO/AMC. The remainder of the AF stations each has two cesium frequency standards.

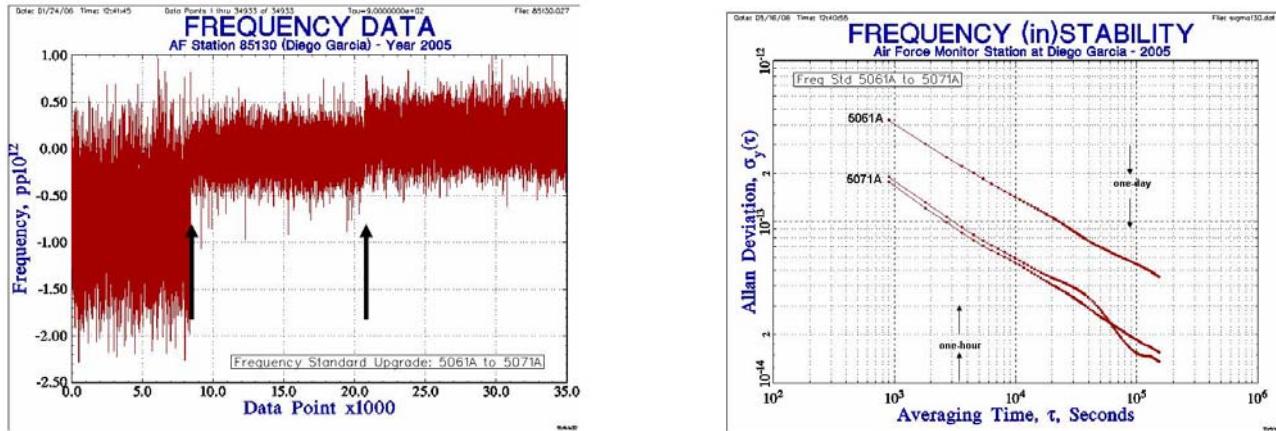


Figure 3. The AF station at Diego Garcia was upgraded from a CFS 5061A to a CFS 5071A about one quarter the way through 2005. The first arrow (left), on the frequency data plot, shows the large improvement in the frequency data noise. The second arrow (right), on the frequency data plot shows a small jump in the frequency. This corresponds to a start-up of the second CFS 5071A. The stability plot shows the improvement.

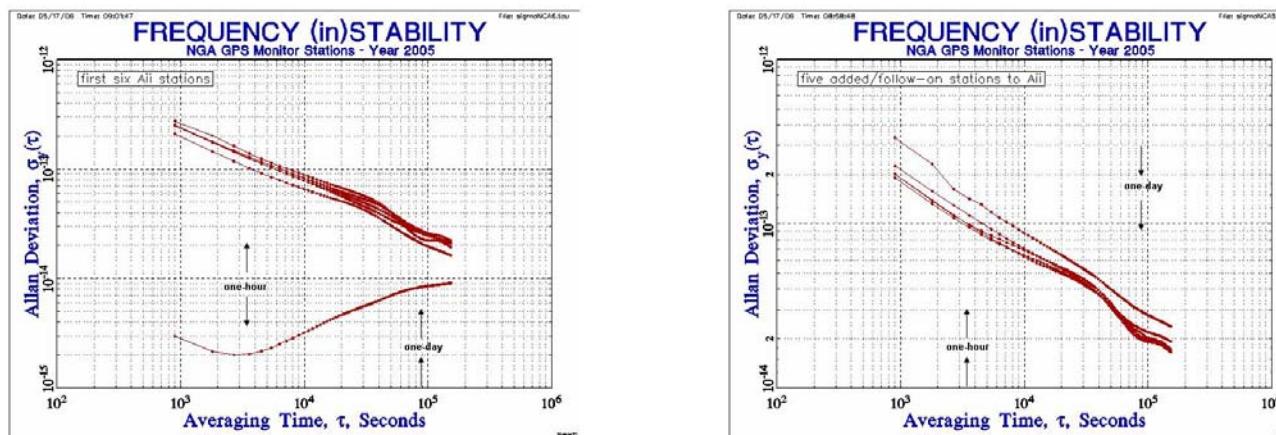


Figure 4. Frequency stability plot (left) of the CFS at the first five (Aii) NGA monitor stations and the hydrogen maser ensemble at the USNO. All show the white frequency modulation (WFM) standard of CFS. The USNO plot shows the random-walk FM standard of masers. Frequency stability plot (right) of the CFS of the added/follow-on NGA monitor stations. The monitor station at South Korea has the largest values due to environmental problems and power loss at various times throughout the year. Maintenance at this station has been ongoing.

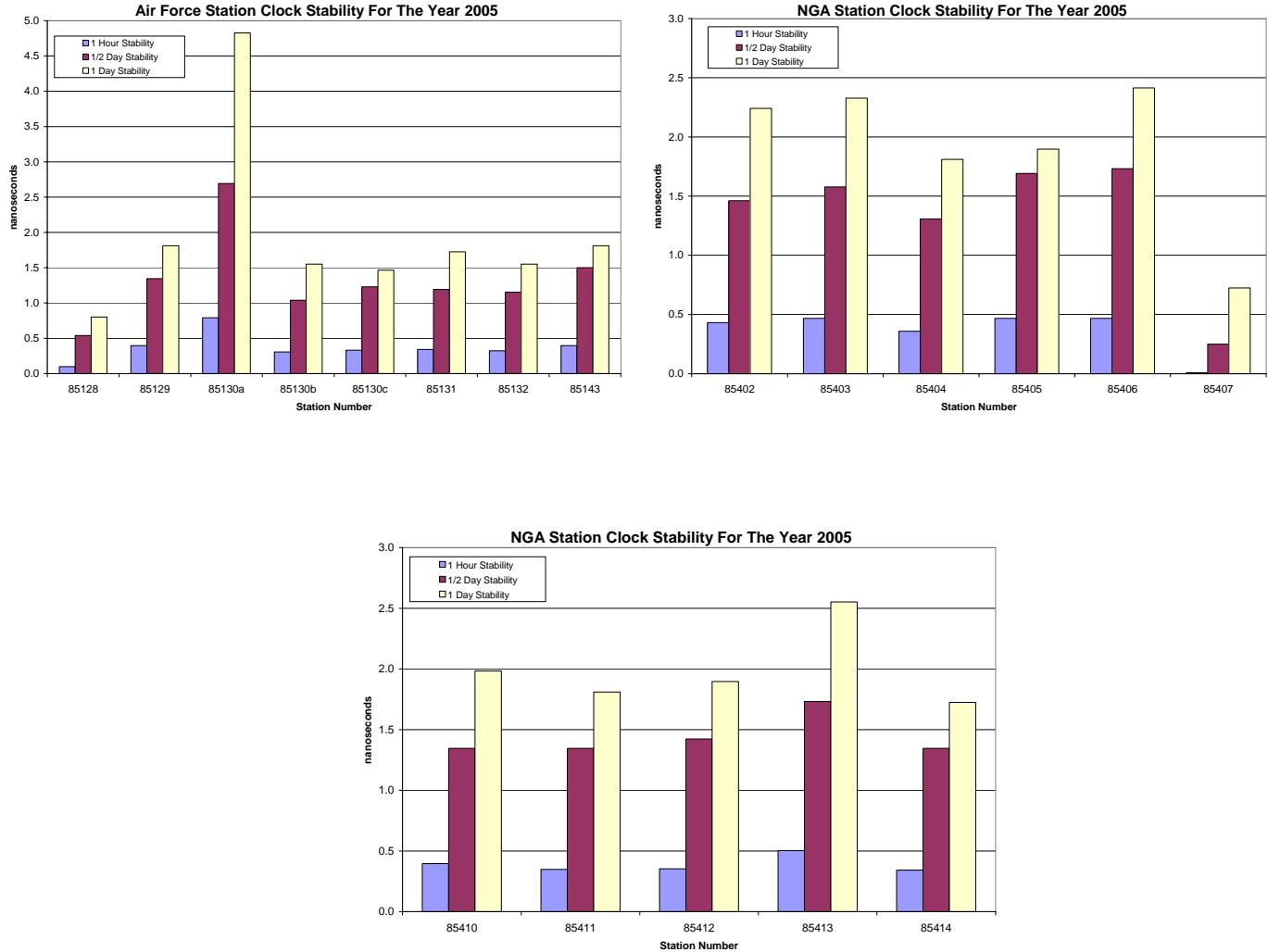


Figure 5. Station clock (frequency to time) stability of the AF and NGA monitor stations for the year 2005. The top chart shows the stability of the AF monitor computed by the NGA Kalman filter process. This chart shows the improvement at the Diego Garcia (85130) station with the upgrade to the new 5071A CFS. The second chart shows the NGA monitor stations that were included in the Aii process in the early fall of 2005. Stations at Colorado Springs (85128) and at the USNO (85407) statistics are much better due to being hydrogen masers. The $\frac{1}{2}$ -day stability statistics are used by NGA for quality control and are approximates. The bottom chart shows the stations to be included in future Aii plans. The station 85413 (South Korea) has the highest values due to the numerous maintenance problems. Stations 85411 (New Zealand) and 85412 (South Africa) were recently added to the Aii process. Note text for the explanation.

Table 1. The AF/NGA monitor station statistics, from the Overlapping Allan deviation, covering the time period of the Year 2005. The relationship of frequency uncertainty to time uncertainty. Diego Garcia (85130) is broken down into three groups: 85130a relates to the older 5061A CFS, 85130b relates to the first new 5071A CFS, and 85130c relates to the second new 5071A CFS.

The Numbers* for 2005

| Frequency Uncertainty | Measurement Period | Time Uncertainty |
|----------------------------|--------------------|------------------|
| $\pm 2.78 \times 10^{-13}$ | 1-hour | ± 1 ns |
| $\pm 2.32 \times 10^{-14}$ | ½-day | ± 1 ns |
| $\pm 1.16 \times 10^{-14}$ | 1-day | ± 1 ns |

*Courtesy of NIST [16]

| Station # | NGA Station | Measurement Time (nanoseconds) | | |
|-----------|----------------|-----------------------------------|----------|-------|
| | | 1-hour | 1/2-day* | 1-day |
| 85402 | Australia | 0.432 | 1.462 | 2.241 |
| 85403 | Argentina | 0.468 | 1.577 | 2.328 |
| 85404 | England | 0.360 | 1.308 | 1.810 |
| 85405 | Bahrain | 0.468 | 1.692 | 1.897 |
| 85406 | Ecuador | 0.468 | 1.731 | 2.414 |
| 85407 | USNO | 0.007 | 0.250 | 0.724 |
| 85410 | Alaska | 0.396 | 1.346 | 1.983 |
| 85411 | N. Zealand | 0.349 | 1.346 | 1.810 |
| 85412 | S. Africa | 0.353 | 1.423 | 1.897 |
| 85413 | S. Korea | 0.504 | 1.731 | 2.552 |
| 85414 | Tahiti | 0.342 | 1.346 | 1.724 |

| Station # | AF Station | Measurement Time (nanoseconds) | | |
|-----------|---------------|-----------------------------------|----------|-------|
| | | 1-hour | 1/2-day* | 1-day |
| 85128 | Colo Sprgs | 0.097 | 0.538 | 0.802 |
| 85129 | Ascension Is | 0.396 | 1.346 | 1.810 |
| 85130a | Diego Garcia | 0.791 | 2.692 | 4.828 |
| 85130b | " | 0.306 | 1.038 | 1.552 |
| 85130c | " | 0.331 | 1.231 | 1.466 |
| 85131 | Kwajalein | 0.342 | 1.192 | 1.724 |
| 85132 | Hawaii | 0.324 | 1.154 | 1.552 |
| 85143 | Cape Canv | 0.396 | 1.500 | 1.810 |

* ½-day values are approximate and are used at NGA to note possible environmental issues at a monitor station.

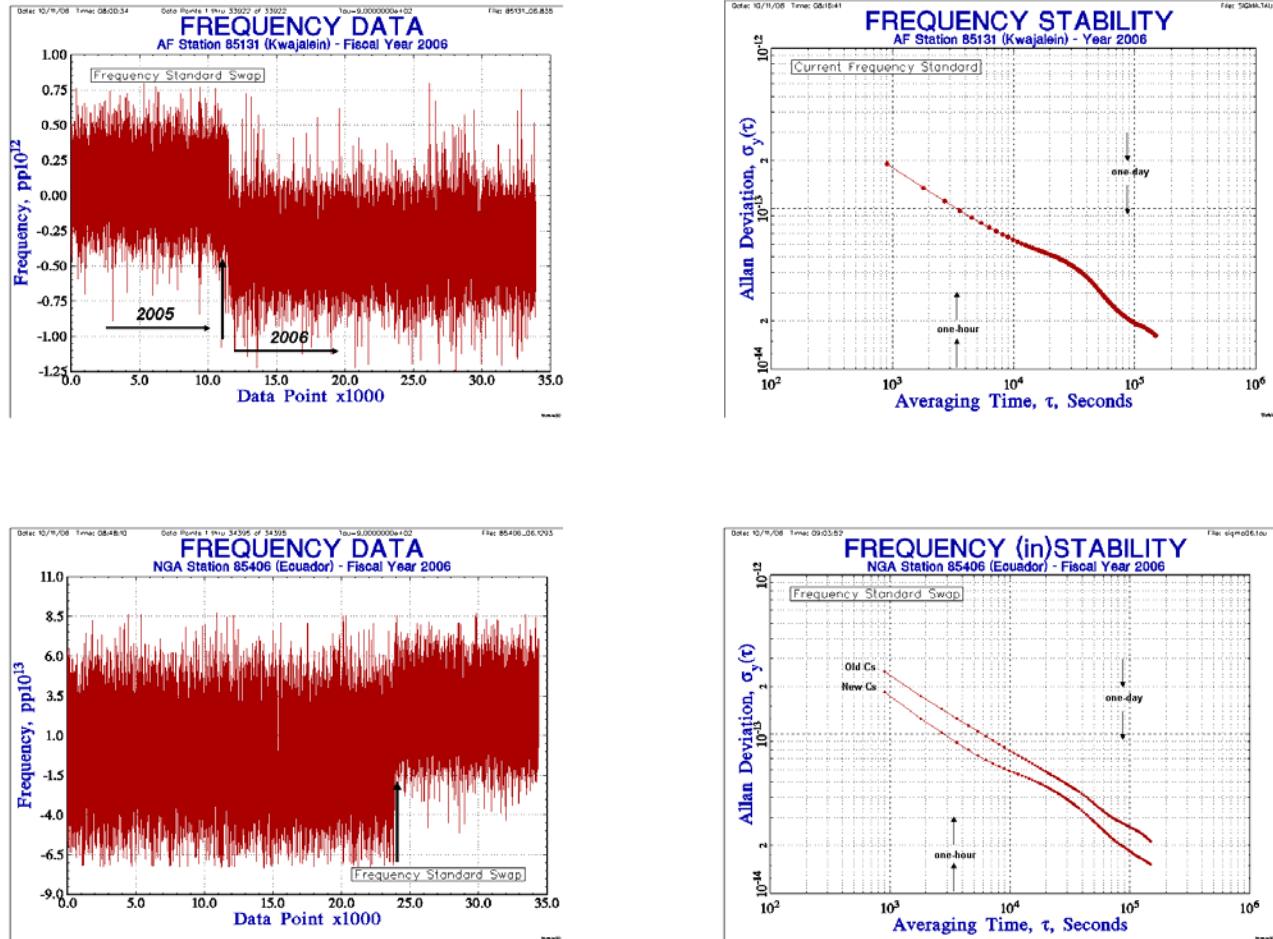


Figure 6. The AF station at Kwajalein changed frequency standard at the beginning of the year 2006. The stability plot is very similar to the stability in Figure 2. The NGA station at Ecuador upgraded the cesium beam tube of an older 5071A frequency standard in mid-June 2006. Note the improved frequency and stability of the old versus the new cesium standards.

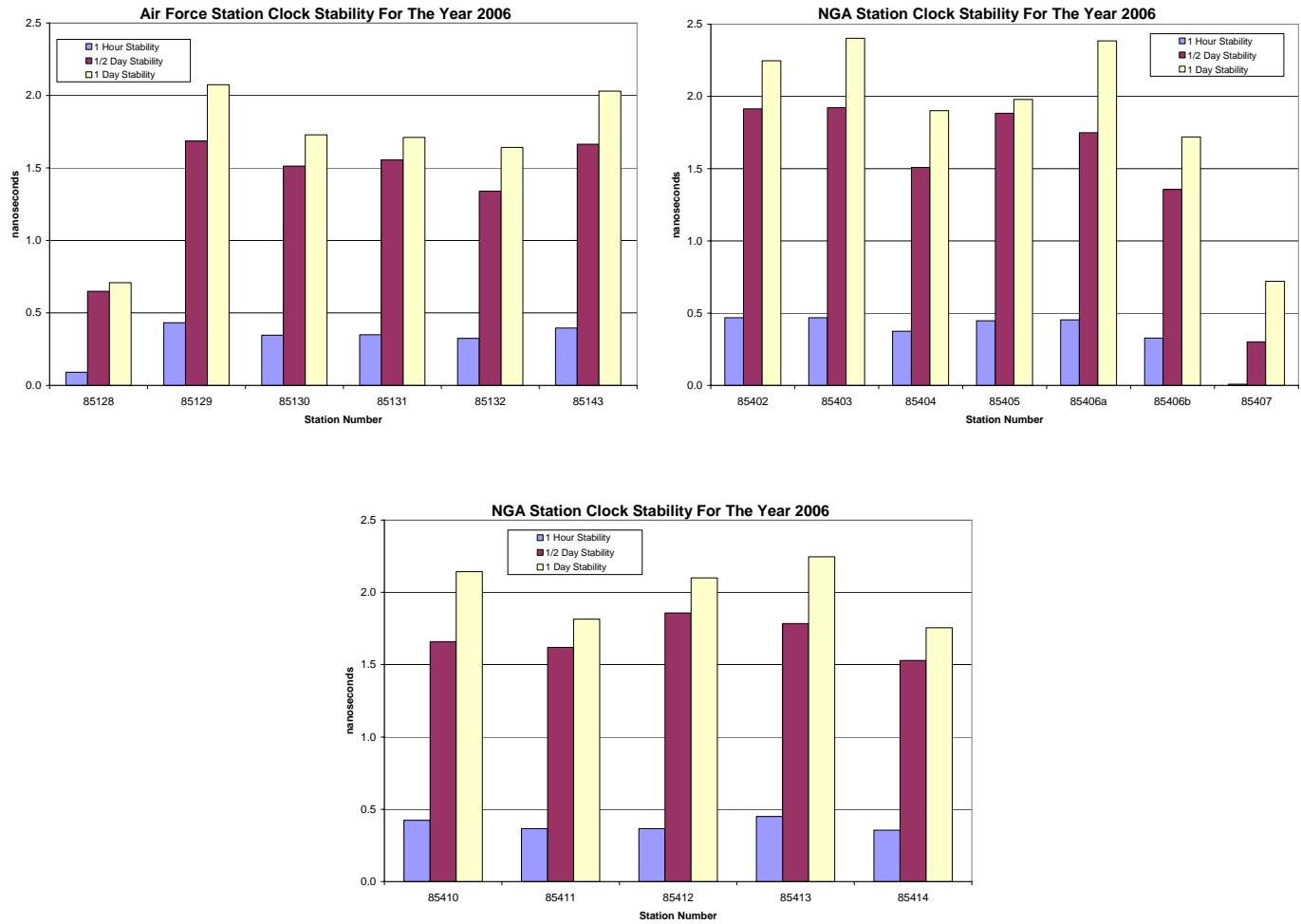


Figure 7. Station clock (frequency to time) stability of the AF and NGA monitor stations for the fiscal year 2006. The top chart shows the stability of the AF monitor computed by the NGA Kalman filter process. The second chart shows the NGA monitor stations that were included in the Aii process in the early fall of 2005. This chart shows the improvement at the Ecuador (85406) station with replacement of the CFS. Stations at Colorado Springs (85128) and at the USNO (85407) have statistics that are much better due to being hydrogen masers. The $\frac{1}{2}$ -day stability statistics are used by NGA for quality control and are approximates. The bottom chart shows the stations to be included in future Aii plans. The station 85413 (South Korea) has the highest values due to the numerous maintenance problems. Stations 85411 (New Zealand) and 85412 (South Africa) were recently added to the Aii process. Note text for the explanation.

Table 2. The AF/NGA monitor station statistics, from the Overlapping Allan deviation, covering the time period of the Fiscal Year 2006 (10/01/05-09/30/06). The relationship of frequency uncertainty to time uncertainty. Ecuador (85406) is broken down into two groups due to a clock swap in mid-June 2006. Diego Garcia (85130) is labeled with a ‘c’ from Table 2.

The Numbers* for 2006 (Fiscal)

| Frequency Uncertainty | Measurement Period | Time Uncertainty |
|----------------------------|--------------------|------------------|
| $\pm 2.78 \times 10^{-13}$ | 1-hour | ± 1 ns |
| $\pm 2.32 \times 10^{-14}$ | $\frac{1}{2}$ -day | ± 1 ns |
| $\pm 1.16 \times 10^{-14}$ | 1-day | ± 1 ns |

*Courtesy of NIST [16]

| Station # | NGA Station | Measurement Time (nanoseconds) | | |
|-----------|--------------|--------------------------------|----------|-------|
| | | 1-hour | 1/2-day* | 1-day |
| 85402 | Australia | 0.467 | 1.909 | 2.241 |
| 85403 | Argentina | 0.464 | 1.918 | 2.397 |
| 85404 | England | 0.374 | 1.504 | 1.897 |
| 85405 | Bahrain | 0.446 | 1.879 | 1.974 |
| 85406a | Ecuador | 0.453 | 1.746 | 2.379 |
| 86406b | “ | 0.329 | 1.353 | 1.716 |
| 85407 | USNO | 0.008 | 0.300 | 0.719 |
| 85410 | Alaska | 0.424 | 1.655 | 2.138 |
| 85411 | N. Zealand | 0.367 | 1.616 | 1.810 |
| 85412 | S. Africa | 0.367 | 1.853 | 2.095 |
| 85413 | S. Korea | 0.450 | 1.780 | 2.241 |
| 85414 | Tahiti | 0.356 | 1.526 | 1.746 |
| Station # | AF Station | Measurement Time (nanoseconds) | | |
| | | 1-hour | 1/2-day* | 1-day |
| 85128 | Colo Sprgs | 0.090 | 0.642 | 0.703 |
| 85129 | Ascension Is | 0.424 | 1.675 | 2.103 |
| 85130c | Diego Garcia | 0.345 | 1.509 | 1.698 |
| 85131 | Kwajalein | 0.349 | 1.539 | 1.802 |
| 85132 | Hawaii | 0.335 | 1.345 | 1.629 |
| 85143 | Cape Canv | 0.396 | 1.659 | 2.026 |

* $\frac{1}{2}$ -day values are approximate and are used at NGA to note possible environmental issues at a monitor station.

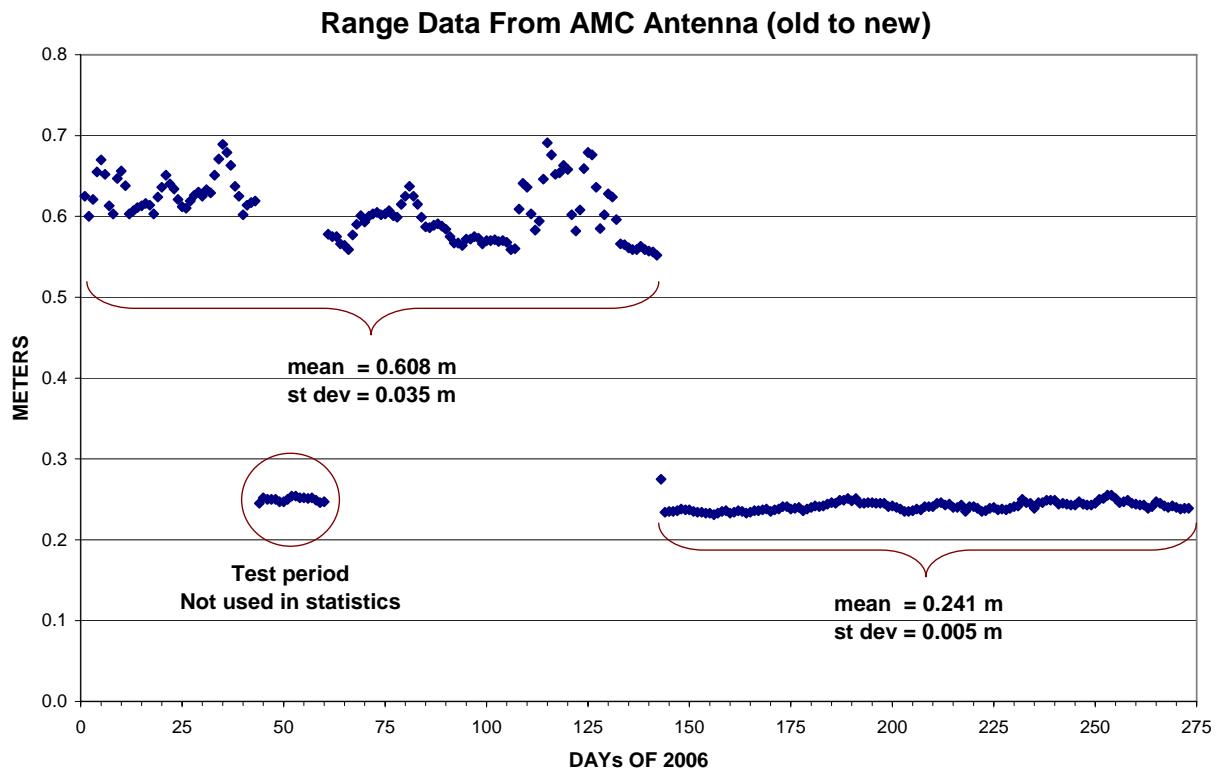


Figure 8. Range data received from the antennas at Schriever Air Force Base (AMC1). For days 001 to 142, note the higher mean value. This was due to multi-path problems (?) due to a large dome over the antenna. The new antenna, which replaced the old, does not have this problem. Note the improvement in the mean from day 143 onward. The test period from days 44 to 60 shows a similar improvement in the data. Also, note the lower standard deviation from the new antenna compared with the old antenna. There is currently no dome over the new antenna.



Figure 9. Dual antennas at the NGA monitor station in Alaska to be used for phase measurement cycle-slip detection/correction testing.