OBSERVATIONS ON THE RELIABILITY OF RUBIDIUM FREQUENCY STANDARDS ON BLOCK II/IIA GPS SATELLITES

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Abstract

Currently, the Block II/IIA Global Positioning System (GPS) satellites are equipped with two rubidium frequency standards. These frequency standards were originally intended to serve as the back-ups to two cesium frequency standards. As the constellation ages, the Master Control Station is forced to initialize an increasing number of rubidium frequency standards. Unfortunately, the operational use of these frequency standards has not lived up to initial expectations.

Although the performance of these rubidium frequency standards has met and even exceeded GPS requirements, their reliability has not. The number of unscheduled outage times and the short operational lifetimes of the rubidium frequency standards compare poorly to the track record of the cesium frequency standards.

Only a small number of rubidium frequency standards have actually been made operational. Of these, a large percentage have exhibited poor reliability. If this trend continues, it is unlikely that the rubidium frequency standards will help contribute to the navigation payload meeting program specification.

INTRODUCTION

The GPS program was designed with atomic frequency standards at the heart of the navigation payload. The choice of available frequency standards limited the number of options available to the program designers. Although different atomic frequency standards were available on the commercial market, only rubidium standards could meet Air Force space qualifiction and be set into production quickly enough to meet the planned launch date of the first Block I satellites[2].

The first few satellites of the GPS Block I program provided the test bed for space rated rubidium frequency standards. Changes in the composition of the glass in the rubidium lamp and the amount of rubidium contained within the lamp enabled Rockwell and the Air Force to improve the design of the rubidium frequency standard. By the first Block II launch in 1989, the GPS rubidium frequency standard was in its eleventh and final production model.

Cesium frequency standards were subjected to a much slower production schedule. Delays in production and space qualification prevented the introduction of the production model cesium

frequency standard into the GPS payload until 1983, when it was included in the launch of SVN 8. A single cesium frequency standard was also included in each of the subsequent Block I nav payloads, each of which also included three rubidium standards. Not until the introduction of the Block II satellite in 1989 did the nav payload include two rubidium and two cesium clocks.

Rubidium frequency standards had several features that made them the obvious choice for precise time generation. They were small, lightweight, and their history suggested that they would be more reliable than the newly available cesium frequency standards. Despite these advantages, they also had certain drawbacks. They were very temperature sensitive and required occasional control segment intervention to maintain the proper frequency and phase offset. Perhaps most importantly, their relatively poor long–term stability prevented accurate extended navigation capability.

This extended navigation capability is essential to ensure continued GPS coverage in the event that the control segment is damaged or destroyed. Although not a consideration during the research and development phase of Block I, extended navigation was an important consideration in the Block II design. For this reason, the cesium frequency standard was advanced as the primary source of precise timing. The rubidium standard was included as insurance because its performance had been more thoroughly evaluated during the Block I phase.

This is the irony of the situation. The cesium frequency standard was included for its superior long-term stability, deemed necessary in an effective wartime asset. In the event of a catastrophic failure of the control segment, the extended navigation feature would require the long–term stability of a cesium standard. Fortunately, the GPS constellation has never required extended navigation and hopefully never will. Therefore, long–term stability is of lesser importance to routine daily operations. In fact, stability at periods longer than one day are, for the most part, invisible to the user due to control segment intervention.

The rubidium standard was included as a backup due to its reliable service in the Block I program. Although its stability was deemed inferior, past performance indicated that it should be included in order for the nav payload to meet reliability requirements. The cesium standards did not have enough history to accurately determine their reliability coefficient[2].

The experience of the personnel of the 2 SOPS and the GPS Master Control Station has contradicted these expectations. The typical stability of rubidium clocks is not inferior to that of typical cesium standards as measured under current operational procedures. In fact, the one–day stability of rubidium clocks is usually better than that of the cesium frequency standards. The reliability issue is also reversed. The previously unproven cesium standards have actually experienced longer lifetimes than the rubidium frequency standards.

This paper will attempt to show some concrete examples of the reliability and stability of the two types of frequency standards. A side–by–side comparison will show that rubidium atomic clocks, when viewed from the perspective of the Master Control Station, do not provide the level and consistency of operation demanded by the GPS community. In fact, they are frequently a source of error and frustration for the operators of the GPS program.

STABILITY

The stability of an atomic frequency standard is critical for its use as a timing source in the GPS navigation payload. The 2 SOPS operational definition of stability differs slightly from the definition used in the original program specifications. Both of these differ from the definition used by some independent analysis agencies.

The U.S. Naval Research Laboratory (NRL) periodically provides 2 SOPS with reports which summarize the performance of the on–board frequency standards. NRL uses data from a keyed receiver which can properly account for Selective Availability. The accumulated phase offset of each operational clock is measured daily by USNO. These data, gathered over a period of several months, allows NRL to generate reports detailing GPS clock performance. These reports provide insight into several different clock characteristics, including stability, frequency offset, phase offset and linear frequency drift.

NRL's stability plots show frequency stability as a function in the time domain: $\sigma_y(\tau)$ (Allan Deviation). NRL applies a constant "aging" correction to the raw data in order to remove a linear drift. This approach is warranted for evaluating rubidium frequency standards since the MCS also calculates a frequency drift value and adjusts the broadcast clock values to reflect this change in frequency. The difference between the two frequency drift values lies in the methodology used to measure the frequency drift. NRL applies a flat aging rate to the entire time span of collected data. The MCS updates the frequency drift value every 15 minutes and thus estimates aging more dynamically. Fortunately, the MCS–derived value of frequency drift changes very little over the lifetime of a rubidium clock (once it has fully warmed up).

The frequency drift values for cesium GPS clocks are negligible when viewed over the span of one day. Because of this, the MCS does not calculate a frequency drift value for cesium clocks. Hence, the correction applied at NRL is not reflected in the navigation signal.

The GPS stability specifications for rubidium (5×10^{-13} at one day) and cesium (2×10^{-13} at one day) clocks do not assume that an aging correction is applied[3, 4]. Therefore, although the $\sigma_y(\tau)$ plots (with aging correction included) from NRL are useful to the MCS as a measuring stick for GPS performance, they do not indicate adherence to the GPS program specifications.

To compare NRL collected data with the $\sigma_y(\tau)$ plot provided in the program spec, the following approach was taken to remove the aging correction from NRL's data. This method assumes that any frequency drift values are completely uncorrelated with other noise types. If this assumption is made, the instability due to aging is added to the corrected stability via the root sum squared (RSS) method[5]:

$$\sigma_y(\tau) \quad = \quad \text{Allan Deviation} \tag{1}$$

$$\sigma_{yNRL}(\tau) \quad = \quad \text{NRL's } \sigma_y(\tau) \text{ (Corrected for Drift Rate)} \tag{2}$$

$$A \quad = \quad \text{Aging Value (Calculated by NRL)} \tag{3}$$

$$\sigma_{yD}(\tau) \quad = \quad \text{Allan Deviation due to Aging} \tag{4}$$

$$\sigma_{yU}(\tau) \quad = \quad \text{Uncorrected Allan Deviation} \tag{5}$$

$$\sigma_{yD}^2(\tau) = 1/2(A\tau)^2 \tag{6}$$

$$\sigma_{yU}^2(\tau) = \sigma_{yD}^2(\tau) + \sigma_{yNRL}^2(\tau) \tag{7}$$

$$\sigma_{yU}(\tau) = [\sigma_{yD}^2(\tau) + \sigma_{yNRL}^2(\tau)]^{1/2} \tag{8}$$

This method allows us to compare stability data collected independently by NRL with the stability requirements outlined in the program specifications. The results of this comparison are shown in Table 1.

A comparison of data points corrected for aging to those not corrected found that NRL's aging correction for cesium clocks was minimal for τ equal to one day. The stability component due to aging was, however, significant at one day for the rubidium clocks. The magnitude of these aging coefficients suggest that the looser, non–corrected specification was appropriate. In order for a rubidium standard to conform to the tighter cesium specification, an aging correction would have to be included.

Two important considerations must be taken into account when looking at the one-day stability of GPS clocks. The first is that relatively few Block II/IIA rubidium frequency standards have been powered on. This skews the results of the analysis, as the rubidium clocks represent a smaller pool of data. Statistically, a greater percentage of the total number of cesium standards have been powered on. With more than half of all available cesium standards included in this survey, the occasional poor performer does not carry as much weight.

The second consideration is the lack of confidence in the measurement process for a newly enabled frequency standard. "Infant mortality" forced the authors to exclude data gathered from two clocks that were never set healthy. One of SVN 32's rubidium frequency standards never settled down to the point where it could be declared fully operational. Its abnormal behavior eventually resulted in a situation where the clock was powered down and the stand–by was powered up. Because this rubidium clock behaved so poorly and was never declared operational, it was excluded from the average. The same is true with an improperly modeled cesium standard on SVN 22. Although the cesium clock itself has since been excluded from blame, poor modeling of the orbital states by the MCS Kalman filter led to inaccurate phase measurements. This, in turn, led to incorrect modeling of the frequency standard stability. For this reason, this cesium frequency standard was excluded from the stability average.

The most obvious result of this analysis is that, with the aging coefficient accounted for, the average one–day stability of a rubidium frequency standard is no worse than the that of a cesium clock. Although the sample size is not large enough to provide a definitive answer, it appears that the corrected one–day stability of the rubidium standards surpasses that of the cesium frequency standards.

Even with the aging coefficient included, the rubidium clocks more than meet their stability specification of 5 parts in 10^{13}[3]. In fact, if aging is accounted for, the rubidium clocks meet the much stricter cesium spec of 2 parts in 10^{13}[4]. The cesium clocks also perform within specification. According to NRL, rarely does a GPS frequency standard's one–day stability exceed 2 parts in 10^{13}[1].

How does this result compare with the experience of the operators in the MCS? We measure frequency standard stability by the ability of the MCS to model and predict the phase, frequency, and frequency drift parameters. When a clock shows poor stability, the uploaded predictions diverge from reality. When this occurs, the operators are forced to update the navigation message in the satellite more frequently than once per day in order to prevent an accumulation of ranging errors. Good short–term stability leads to an improved ranging signal and eliminates the need for additional navigation uploads.

A one–day stability greater than approximately 2 parts in 10^{13} (corrected for aging) corresponds to an increased demand on the MCS to provide updated navigation uploads. If the stability is better than this, the normal upload frequency of once per day is sufficient. If the frequency of the clock is much less stable than this, the MCS Kalman filter will not be able to accurately predict the clock's behavior. At this point, no amount of navigation uploads will maintain the ranging error within tolerances. When this extreme instability occurs, the usual course of action is to power down the clock and select a redundant frequency standard.

Tracking frequency standard stability according to daily ranging errors is only approximate. Daily and long-term analysis of all clock parameters as well as independent analysis by NRL and the Defense Mapping Agency (DMA) allows the MCS to maintain confidence in the performance of our frequency standards.

RELIABILITY

Because the GPS frequency standards are physically inaccessible, reliability is very important for maintaining system integrity. Each GPS satellite contains four frequency standards (two cesium and two rubidium). In order to meet the required mission lifetime of 7.5 years, each of the four clocks should be expected to operate within stability specifications for approximately two years. Based on the lifespans of frequency standards that have been disabled, rubidium clocks fall short of this goal. The rubidium clocks which have been powered down averaged only 13 months of operation each. By comparison, cesium clocks have averaged 25 months of operation before being powered down. These figures are detailed in Table 2.

It is important to qualify these numbers with respect to clock lifetime. The numbers given above represent the average age of the cesium and rubidium clocks when they were powered down. The MCS will power down a frequency standard when it does not perform adequately; however, this may occur before every spark of life is extinguished. Because extensive control segment maintenance may provide limited use of a poorly performing frequency standard, the MCS may try to revive a previously used frequency standard before declaring the payload non–operational and disposing of the satellite. Therefore, these lifespans may not represent the total operational use of the clock. Instead, they are a good representation of the time during which the clock has performed to an acceptable level.

In order to gain a more representative sampling of frequency standards, it may be helpful to analyze the lifetimes of the currently operating cesium and rubidium clocks. The average life of the operating cesium standards is 44 months. The average life of the operating rubidium standards is 10 months. If every active clock were to fail in December 1995, the average

lifespan of expired frequency standards would improve. When the data from the active clocks are included in the total lifetime averages, the cesium lifespan increases from 25 to 37 months and the average rubidium lifespan is relatively unchanged (13 to 12 months).

The longevity figures for operational clocks must be taken in context. The MCS has only recently begun powering up rubidium clocks in relatively greater numbers. This recent change in operations is responsible for the low average lifespan of operational rubidium clocks. The cesium clocks more accurately represent the performance of the Block II/IIA program. Their greater longevity may be attributed to the reliance upon cesium standards in the early days of the Block II/IIA program. If rubidium standards had been powered up in greater numbers following the first few launches, it is possible that the MCS would now be operating rubidium frequency standards as old as the oldest cesium clocks.

The performance of GPS frequency standards as a whole is satisfactory. Active cesium frequency standards approach an average lifetime of four years. The GPS constellation may need this type of performance from the cesium clocks as the lifespan of the rubidium clocks lags behind. Based solely upon data from disabled clocks, the rubidium frequency standards do not show the type of longevity necessary to maintain a navigation payload lifetime of 7.5 years. As the constellation matures, more performance data will be available for analysis. These data may show that the initial sampling of rubidium standards does not accurately represent the entire collection as a whole. If this initial sampling of data does accurately represent all rubidium clocks, the GPS constellation will have to rely heavily on the performance of cesium standards to complete each satellite's 7.5 year mission.

MCS OPERATIONS

The MCS continuously monitors the 24 orbiting satellites via the L–band downlink. L–BAND MONITOR examines each six second bundle of data for inconsistencies. If the ranging signal begins to creep out of tolerance, an alarm triggers alerting the operations crew to the presence of an anomaly. Once an active contact is opened between the satellite and a ground antenna, the MCS operators can begin analyzing S–band telemetry. Often this telemetry pinpoints the cause of the ranging errors; other times it is not as helpful. In either case, once a satellite begins transmitting an unstable navigation signal, it is set unhealthy until the problem is resolved.

If further analysis indicates that the problem lies with the frequency standard, it may be necessary to swap to a redundant clock. When this is the case, the MCS operators often have the option of choosing between a rubidium and a cesium standard. There are several different factors that determine the choice of frequency standard.

Because of better short-term stability, the MCS benefits from the inclusion of rubidium clocks in the paper ensemble, called the GPS Composite Clock. An effective mixture of cesium and rubidium standards can only be maintained by selectively powering up the appropriate clock.

The MCS is still relatively unfamiliar with the maintenance of rubidium clocks. By slowly increasing our knowledge of the operating characteristics of these frequency standards, we can prevent the sudden and unexpected use of rubidium clocks in the waning days of the Block II/IIA constellation. By mixing the operation of rubidium and cesium clocks now, we can

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ensure the availability of both rubidium and cesium clocks at a later date.

Despite the advantages of rubidium clocks, their suspect reliability has made the operators at the MCS reluctant to power them up. During the first several months of operation, rubidium standards are prone to sudden and unpredictable phase jumps as well as a rapidly changing frequency drift rate. The MCS operators can quickly and easily fix these, but confidence in the constellation as a whole is reduced.

Outage time is also a major factor. Rubidium clocks require a longer initial warm up period than cesium clocks. Due to the rapidly changing frequency drift term (A2), the MCS can not accurately model or predict the future states of a new rubidium clock. Because of this, initializing a new rubidium clock necessitates an average outage of 7.7 days, while a cesium clock only stays unhealthy an average of 4.3 days. If the operational situation necessitates a minimal outage time, a cesium clock will probably be chosen over a rubidium clock.

The age of the satellite as well as the condition of the various support systems may indicate a limited available lifetime for a particular satellite. For those satellites with a limited expected lifetime, the choice of a cesium clock will reduce the amount of required maintenance. There are two main reasons why rubidium clocks need more control segment intervention. The large frequency drift requires occasional "Frequency Biasing" in which the MCS alters the output frequency of the timing signal. Also, since rubidium clocks require an external heat source, the entire payload operates at a higher temperature. This requires more frequent "Ion Pump Maintenance" for any stand-by or suspect cesium clocks. Since both of these procedures require several hours of down time, avoiding them entirely is an operational advantage.

CONCLUSION

The MCS has gained experience in the operation of cesium and rubidium frequency standards. This experience has shown a few trends. Rubidium clocks tend to be better performers with respect to short-term (one-day) stability. Since every satellite in the GPS constellation is provided with a fresh navigation upload every day, this improved stability is revealed by a more accurate ranging signal.

In order to meet program specifications, the GPS signal must not only be accurate, it must also be dependable. This dependability is directly related to the reliability of the on-board atomic clocks. Analysis of a limited number of GPS frequency standards shows that the expected lifetime of rubidium standards lags behind that of cesium clocks. Luckily, the overall lifetime of GPS clocks appears to be sufficient to fulfill the intended mission.

The combination of frequency stability and reliability makes the decision difficult when the time comes to power up a new clock. The importance of GPS timing stability and the need for an appropriate mixture of frequency standards in the constellation make the inclusion of rubidium clocks a necessity. Although only a case by case review of the appropriate factors will determine the new type of operational clock, the improved reliability and decreased maintenance time makes the cesium standard a more attractive option.

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ACKNOWLEDGEMENTS

REFERENCES

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[2] Personal interview, Dr. Brad Parkinson, 28 September 1995.

[3] MC474-0030 *Rubidium Frequency Standard Performance, Design Development and Test Requirements*, 5 May 1988.

[4] MC474-0031 *Cesium Frequency Standard Performance, Design Development and Test Requirements*, 2 October 1987.

[5] *2 SOPS Mission Support Study Guide 3-16: Timing Stability.*

Table 1 1 Day Stability				
Frequency Standard	Number of Data Points	$\sigma_y(\tau)$ τ = one day (corrected for aging)	$\sigma_y(\tau)$ τ = one day (NOT corrected for aging)	Specification (NOT corrected for aging)
Rubidium (active)	4	0.94 $(\times 10^{-13})$	2.23 $(\times 10^{-13})$	5.0 $(\times 10^{-13})$
Rubidium (dead)	4	2.35 $(\times 10^{-13})$	3.84 $(\times 10^{-13})$	5.0 $(\times 10^{-13})$
Rubidium (all)	8	1.79 $(\times 10^{-13})$	3.14 $(\times 10^{-13})$	5.0 $(\times 10^{-13})$
Cesium (active)	18	1.34 $(\times 10^{-13})$	1.36 $(\times 10^{-13})$	2.0 $(\times 10^{-13})$
Cesium (dead)	10	1.37 $(\times 10^{-13})$	1.37 $(\times 10^{-13})$	2.0 $(\times 10^{-13})$
Cesium (all)	28	1.36 $(\times 10^{-13})$	1.37 $(\times 10^{-13})$	2.0 $(\times 10^{-13})$

Table 2 Average Operational Lifetime		
Frequency Standard	Number of Data Points	Life in Months
Rubidium (active)	5	10.2
Rubidium (dead)	6	12.7
Rubidium (all)	11	12.2
Cesium (active)	19	43.7
Cesium (dead)	12	24.9
Cesium (all)	31	36.6

Questions and Answers

KEN MARTIN (BONNEVILLE POWER ADMINISTRATION): I'm trying to figure out — it looked like when you have standby time and "on" time that, I take it, it's operating on one oscillator; and then the other ones are just completely turned off for a couple of years; and they turn those on, and turn the other ones off; and each one wears out in a couple of years or a year. Is that - - - ?

1st LT. GARY L. DIETER (USAF): I'm a little bit confused when you say "standby" time and "on" time. Could you please - - - ?

KEN MARTIN (BONNEVILLE POWER ADMINISTRATION): I'm not sure. It looks to me like all the clocks will wear out in maybe a couple or three years, and that must not be the case. So - - -

1st LT. GARY L. DIETER (USAF): Right, three years is definitely not a cutoff time for clocks to stop dying. Some of them can last a lot longer than that.

KEN MARTIN (BONNEVILLE POWER ADMINISTRATION): So what you're saying is that you use a cesium clock for like 33 months and then it dies; and then you turn a different one on?

1st LT. GARY L. DIETER (USAF): Yes, there are four clocks on each satellite. Obviously, we use a clock as long as it can operate within stability specifications. Once either it has a hard death or it starts to operate outside of specs and is causing problems, we will swap a redundant clock on a satellite. So, we'll pick from one of the three remaining clocks.

KEN MARTIN (BONNEVILLE POWER ADMINISTRATION): So the clocks that are not being used are actually turned off? And that's not shelf life, that's standby life while it's heated up?

1st LT. GARY L. DIETER (USAF): Right, yes. The clocks that aren't being used for the signal are turned off.

UNKNOWN: Do you have any insight into possible reasons for the poor reliability of rubidium in GPS?

1st LT. GARY L. DIETER (USAF): That's a good question. I'm sure there's much speculation on that topic. I personally cannot give a good official reason for why this is.

One thing, as I said before, it's important to keep in mind the numbers — we're not looking at a great number of data points for rubidiums. So, as I said, hopefully this isn't a trend; hopefully, this is some bad beginning luck. I'm not sure why we're having bad luck now; I'm not sure anyone knows for sure what the problem is, if there is a problem. It may just be, like I said, some initial bad luck. Sorry I can't answer your question better.

ALBERT KIRK (JPL): I notice on your cesium lifetime that the disabled clock had a shorter lifetime than the other clocks. Can you explain what "disabled" really means in this context?

1st LT. GARY L. DIETER (USAF): In this context it means — for instance, say we turn on a cesium clock first on a satellite. As soon as it starts to perform poorly, or if it dies, we'll

turn it off and turn another one on. And that disabled number is the average lifetime for the clocks that we've already turned off.

ALBERT KIRK (JPL): But then the clocks, if they have a lifetime of 40, then that means they're disabled after 40. So they're all disabled eventually, right?

1st LT. GARY L. DIETER (USAF): That's if they were to die today. If all the cesium clocks that are on right now were to die today, their average lifetime would be 44 months.