DEVELOPMENT AND EVALUATION OF GPS SPACE CLOCKS FOR GPS III AND BEYOND

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Abstract

The current GPS has exceeded its globally averaged position and timing accuracy of 16 m (50 % spherical error) and 100 ns (1 σ) as stated in the 1990 GPS System Operation Requirements Document (SORD). The 1999 GPS Operational Requirements Documents (ORD) set a new goal for the GPS III and beyond. The 1999 ORD specifies the ranging accuracy 1.5 m threshold and 0.5 m objective. The 95% time transfer accuracy threshold and objective are 20 ns and 10 ns, respectively. This paper will evaluate how the current clocks and the clocks being developed can support the ORD threshold and objective. The paper will include the following topics: (1) atomic clocks on the GPS Block II space vehicles, (2) estimated accuracy of the IIF Rb clock by Perkin Elmer and digital Cs clock by Datum-Beverly and assessment of their performance against the ORD threshold range requirements, (3) description of the new space clocks being developed jointly by the GPS JPO, Aerospace, and NRL, and evaluation of their predicted performance to see if they can support the ORD objective of 0.5 m (rms), and (4) Prediction of the GPS signal-in-space accuracy, including all the space and control segments errors, using IIF Rb and Cs clocks. The predictions are based on replacing the NIMA estimated GPS II/IIA/IIR clock data, contained in the actual tracking data of the GPS monitor stations and the NIMA tracking stations, by simulated IIF Rb and Cs clock data. A Kalman filter similar to that of the OCS then processes the resulting tracking data and the estimated results are compared with NIMA estimates treated as truth. Evaluations of the various options to see whether the ORD objective can be achieved based on the predicted signal-in-space accuracy are included.

1. ATOMIC CLOCKS ON THE GPS BLOCK II SPACE VEHICLES

Atomic Frequency Standards (AFSs) or clocks in the GPS satellites are essential in providing GPS users accurate position velocity and time determinations. Two rubidium (Rb) clocks and two cesium (Cs) clocks were used in the GPS Block II/IIA satellites. Rockwell produced the Rb clocks using Efratom physics packages, and the Cs clocks were provided by three different companies. Frequency and Time Systems (FTS) supplied the majority of the Cs clocks. Second source units were provided for flight validation by Kernco, which provided three units, and by FEI, which furnished two units. These clocks are the first ones produced in any quantity for space operation, and have experienced lower-than-expected life, even though no GPS II/IIA satellite has been lost due to clock failure. Designed in the late 70's and early 80's, these now out-of-date units are no longer produced by any of those companies [1].

Two Rb clocks and one Cs clock were originally planned for each satellite in the GPS Block IIR program. The selected Rb clocks resulted from second source development performed at EG&G during Block II/IIA procurement. However, after several years of unsuccessful attempts by the IIR Cs clock contractor to space-qualify a production unit, a three-Rb-clock-configuration was selected for the IIR program to maintain schedule. Testing of the first two GPS Block IIR satellites on-orbit and results from a dedicated Rb clock life-test ongoing at the Naval Research Laboratory (NRL) indicate that the Rb clock is performing nicely (much better than specification), and indications of mission success are excellent.

A clock configuration consisting of three Cs clocks and one Rb clock has been chosen for the GPS Block IIF spacecraft. The electronics packages of all spaceborne clocks so far have used analog technology, but Datum-Beverly (formerly FTS) will produce the IIF Cs clock using a digital electronics approach based on their commercial digital clock design. The development of the digital Cs clock was initiated by the GPS Joint Program Office and NRL to produce prototypes demonstrating the application of digital electronics technology to space-qualified atomic clocks. The GPS Block IIF contractor, Boeing North America (BNA), took over this project midway, including funding, after being convinced that the new digital Cs clock will meet their IIF requirements. This is a success story in the transfer of commercial technology to space applications being supported by continuing R&D for GPS. The history of atomic clock deployment on board GPS satellites is summarized in Table 1.

GPS Program	RAFS	CAFS
Block II/IIA	two (Rockwell)	two (FTS, Kernco, FEI)
Block IIR	three (EG&G)	none
Block IIF	one (Perkin Elmer)	three (Datum-Beverly)

Table 1. Clocks on GPS Satellites

2. GPS BLOCK IIF CLOCK ACCURACY ASSESSMENT

The IIF current baseline is to operate satellites in the cross-link navigation update mode such that with each upload to one satellite, corrections for the rest of constellation are also uploaded. These corrections are then relayed to the corresponding satellite through the cross-links. The Block IIF contractor, Boeing, offers a minimum update rate of once every 3 hours.

User Range Error (*URE*) is defined as the rms value of the total Space/Control segment or signal-in-space (SIS) range error components. User Equipment Error (UEE) is defined as the rms value of the total User segment range error components. User Equivalent Range Error (UERE) is the total statistical system ranging error (rms), defined as the root-sum-square (rss) of URE and UEE:

$$UERE = (URE^2 + UEE^2)^{1/2} \tag{1}$$

The 1990 GPS System Operation Requirements Document (SORD) specifies the position and timing accuracy requirements as:

Position: 16 m (50% spherical error), globally averaged.
Transfer of UTC: 100 ns (one standard deviation), globally averaged.

The derived UERE is 7 m, URE is 6 m, and UEE is 3.6 m.

The URE requirement for the IIF system operating in the cross-link navigation update mode as documented in the *GPS IIF System Specification, SS-YSY-600,* is:

> URE <3 m (rms) at less than 3 hours Age of Data (AOD), with a goal of URE ≤1 m (rms).

The 1999 GPS Operational Requirements Document (ORD) specifies the ranging and timing accuracy as:

> UERE threshold (≤1.5 m (rms) [URE threshold (≤1.25 m (rms) and UEE threshold ≤0.8 m (rms)]
> UERE objective (≤0.5 m (rms)
> Time transfer threshold (≤20 nsec (95%) [Time transfer to a surveyed site]
> Time transfer objective (≤10 nsec (95%)

In general the ranging accuracy requirement seems more stringent that the time transfer requirement; however, the timing accuracy included the UTC to GPS uncertainty.

The goal of the GPS JPO is to reduce ranging and timing errors as much as possible by exploring all possible means to do so.

SIS URE includes clock random errors, clock errors due to orbital temperature variations (about ±3°C with a period of 12 hours), and magnetic field effects due to three electro-magnets in the attitude determination and control system, L-band signals group delay differentials, ephemeris errors, and other small errors. It is assumed here that the URE budget is allocated equally to the above-mentioned four major independent error sources, so that the goal is to limit the GPS clock random error contribution to less than 1/2 of URE. The rms IIF range error contributions from random clock noise can be estimated using the clocks' measured Allan deviations from several engineering and production units , and are shown in Figure 1. The estimated range error contribution of the IIF Rb clock is about six times smaller than that of IIF Cs clock. Examination of the precision of the IIF clocks to verify whether they can support the various 1/2*URE requirements mentioned above with 3-hour updates yields the results provided in Table 2. For the ORD objective, 1/2*UERE instead of 1/2*URE is used, since the current UEE of 0.8 m is larger than UERE of 0.5 m, and thus the URE cannot be computed.

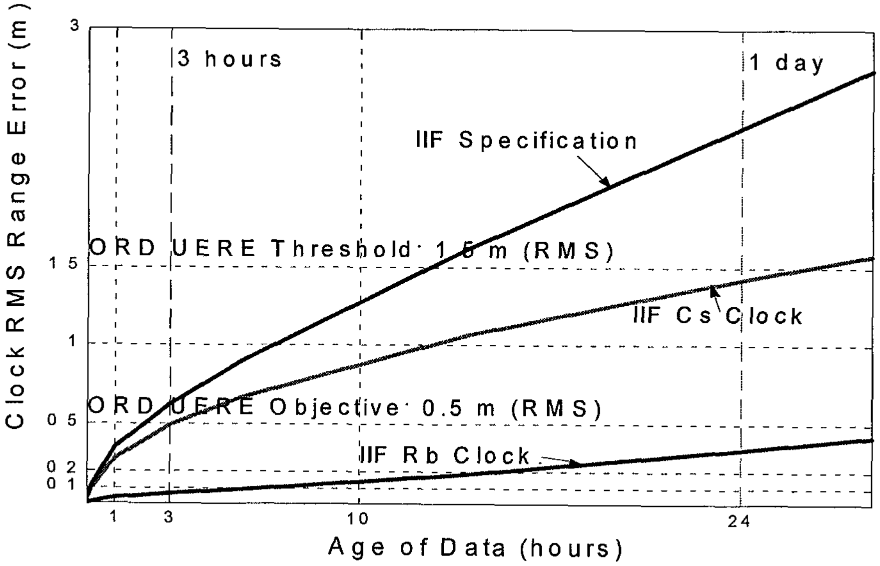

Figure 1. Estimated IIF Clocks Range Error

Clock Type	Estimated Clock Range Error	1990 SORD	GPS IIF AOD ≤ 3hrs	1999 ORD Threshold	1999 ORD Objective
	m (rms) at AOD of 3 hours	½*URE ≤ 3 m	½*URE ≤ 1.5 m	½*URE ≤ 0.75 m	½*UERE ≤ 0.25 m
IIF Cs	0.49	yes	yes	yes	no
IIF Rb	0.06	yes	yes	yes	yes

Table 2. Support of IIF Clocks with 3-hour Updates to Meet URE/UERE Requirements

It can be observed from Table 2 that:

1. Both IIF Cs and Rb clocks can support IIF system requirements,
2. The IIF Cs clock with 3-hour updates can support the 1999 ORD Threshold requirement, but it will not support the 1999 ORD Objective, and
3. The IIF Rb clock with 3-hour updates can support both the 1999 ORD Threshold and Objective requirements.

Other characteristics of the IIF Cs and Rb clocks are provided in Table 3 for information.

	IIF Rb Clock	IIF Cs Clock
Weight	14 (lb)	27 (lb)
Envelope	7.5X6X12.1 (in^3)	7.5X6X16.5 (in^3)
Temperature controller	Built-in	None
Power	< 39 watts	< 25 watts
Temperature coefficient	5E-14 Δf/f/°C	1E-13 Δf/f/°C
Design Life	15 years	10 years

Table 3. GPS Block IIF Clock Comparison

The IIF Rb clock provides advantages over the IIF Cs clock except power. To preserve the legacy of better-performing Rb clocks from Block IIR, Boeing is being tasked under a special study to consider a minimum of two Rb clocks for each IIF space vehicle.

3. NEW CLOCK TECHNOLOGY ROADMAP PROGRAM

The GPS program has a dual clock technology requirement as documented in Section 3.2.7.2 of the System Requirements Document for GPS Block IIF system (SRD-GPS-IIF). This requirement was set to mitigate the risk that one of the clock types cannot be space-qualified. This requirement saved the GPS Block IIR program when the Cs clock, the preferred choice from the Block II/IIA experience, failed in multiple attempts to pass space qualification tests. Another advantage of this requirement is performance improvement through competing technologies.

Since the IIF Cs clock cannot support the 1999 ORD range error objective, a new clock technology program is needed to sustain the GPS system for future applications. The GPS JPO, Aerospace, and the Naval Research Laboratory (NRL) jointly developed the new clock technology roadmap program [1, 2] which was endorsed by atomic clock experts from a number of US Government organizations and FFRDCs in a GPS Spacecraft Clock Coordination Meeting held at NRL on 17 June 1999. The proposed effort includes:

1. Evolving the current design of the Block IIF Rb clock, which relies on an analog technology electronics package, to reduce clock variability and environmental sensitivity,
2. Developing space-qualifiable new technology clocks based on proven ground clock technologies,
3. Building flight demonstration models (FDMs) for qualification tests,
4. Conducting ground tests of the FDMs to monitor their characteristics and performance in a simulated space environment for space flight selection,
5. Developing and building an on-board clock comparison subsystem to evaluate the on-orbit performance of the FDM selected for space flight,
6. Providing funding to Boeing for integration of the on-board clock comparison subsystem with the SV and performance evaluation, and
7. Making available the spaceworthy new technology clocks for future GPS applications.

The new technology clocks being developed are [1-3]:

3.1 Advanced Digital Rb Clock, by Perkin Elmer (formerly EG&G) and NRL

This project will take space-qualified Rb clock technology, as implemented in the GPS Blocks IIR and IIF programs, to the limit of what present state of art allows. It will do so by: (a) modifying slightly the physics package to incorporate technical advances either already implemented in tactical Rb clock or suggested by the experience accumulated while manufacturing the Blocks IIR and IIF clocks, (b) modifying radically the clock electronics package to incorporate a state-of-art 6.8 GHz signal source, direct digital signal synthesis, digital servo loop, and microprocessor monitoring and control of all critical clock parameters.

The resulting clock is expected to have a stability performance about twice as good as that of the Block IIF clock. It will be more producible by incorporating automated setup, checkout, test, and calibration processes. It will have a smaller aging coefficient and lower environmental sensitivities (particularly thermal) than the current Rb clock. This project presents a low technical risk.

3.2 Optically Pumped Cs Beam Clock, by Datum-Beverly (formerly FTS) [4-6]

This task will introduce optical methods, instead of conventional magnetic methods, for state preparation and signal detection in the Cs clock. This concept has been demonstrated in the current US time and frequency standard, NIST-7, at the Time and Frequency Division of the National Institute of Standards and Technology (NIST), in Boulder, CO. It allows more efficient use of the Cs atoms emitted by the Cs oven, thereby potentially prolonging the useful life of the Cs beam tube, while at the same time increasing the flux of detected atoms, and thus improving the short-term stability of the clock. This clock is expected to have frequency stability comparable to that of the analog Block IIF Rb clock. The technical risk presented by this project is moderate, because of the challenge of identifying a source of laser diodes with appropriate stability, availability, and radiation hardness.

3.3 Space Linear Ion Trap System (LITS), by the Jet Propulsion Laboratory (JPL) [2, 3]

JPL will design and build a small, light, and space-qualifiable version of the linear mercury ion trap clocks developed for the NASA's Deep Space Network. JPL has built several operational ground units that display very good frequency stability. A significant difference between the way trapped mercury ion clocks and Cs or Rb clocks operate is that in the latter, microwave interrogate the Cs or Rb atoms continuously, while in the former, interrogation of the mercury atoms takes place in a low duty-cycle discontinuous fashion. Because of this a better quality local oscillator than that for Cs or Rb clocks has to be used. JPL plans to use the best available

BVA-cut quartz crystal oscillator, and interrogate the physics package approximately every 3 seconds. The expected stability of the LITS is about 10 times better than that of the advanced digital Rb clock. The technical risk involved with this redesign is moderate, with no evidence of fundamental problems.

The estimated new clock contributions to range error are provided in Figure 2. With 3-hour cross-link updates, all three new clocks can support the 1999 ORD range objective of 0.5 m (rms). With 24-hour updates, both the Advanced Digital Rb Clock and the Linear Ion Trap Clock can also support the 1999 ORD objective, while the Optically Pumped Cs Clock can support the 1999 ORD range objective only marginally.

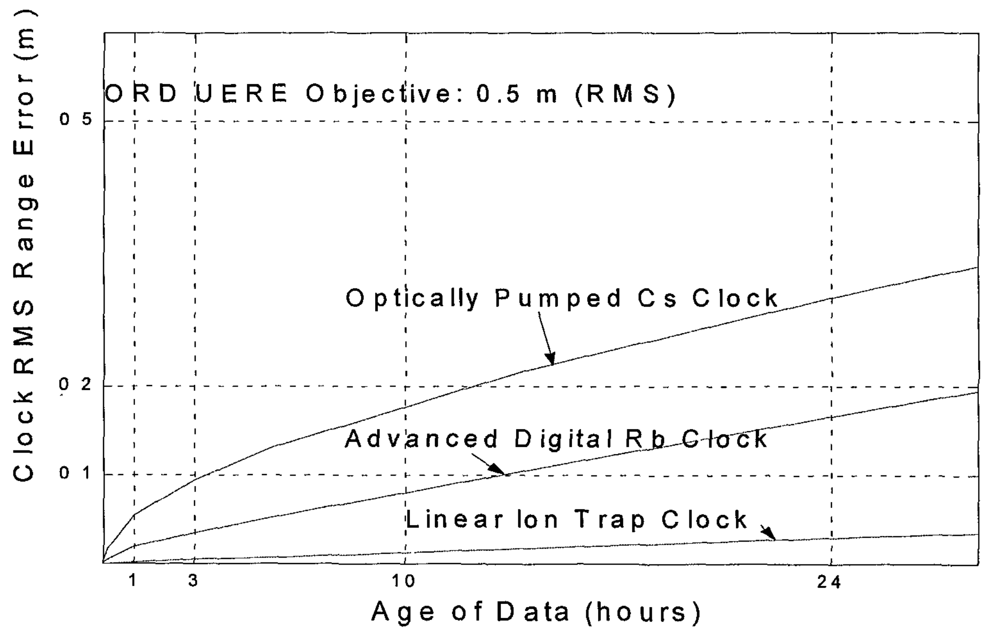

Figure 2. New Technology Clock Estimated Range Error Contributions

Educated guesses about the characteristics of the new clock technologies discussed above are provided in Table 4 below [3].

Clock Type	Technical risk	Estimated range error @ 3 hr (cm)	Estimated range error @ 24 hr (cm)	Weight (lb)	Dimensions (in)	Power (w)
Advanced Rb clock	Low	3.5	16	14	7.6x6x12	35
Optically Pumped Cs clock	Moderate	9.5	30	29	7.5x6x18	25
Linear Ion Trap clock	Moderate	0.5	2.9	25	16x10x8	25

Table 4. Expected Characteristics of New Technology Clocks

The current new clock technology roadmap schedule indicates that the flight demonstration models (FDMs) of the Digital Rb Clock and the Optically Pumped Cs Clock will be ready for on-orbit test on a Block IIF space vehicle in late 2004, and, if successful, will be ready for future GPS application in 2007. The FDM of the JPL LITS will be ready for on-orbit test in 2006 and could be available for future GPS application in 2009.

Other clock technologies being monitored/considered for GPS applications are:

1. Small space hydrogen masers
2. Laser-cooled Cs clocks
3. Double-bulb Rb masers.

4. PROJECTED GPS SIGNAL-IN-SPACE (SIS) RANGE ACCURACY

NIMA routinely postprocesses GPS tracking data received from the GPS monitor stations and NIMA tracking stations to provide the best estimates of ephemeris, clock offset, and other states of every GPS satellites in the constellation. These NIMA estimates of satellite ephemeris and clock offset at 15-minute intervals have commonly been regarded as truth in the GPS community. Aerospace has developed a procedure to replace the NIMA estimated GPS II/IIA/IIR clock data, contained in the actual tracking data provided and used by NIMA, by simulated IIF Rb clock and Cs clock data. A Kalman filter similar to that of the GPS Operational Control Segment (OCS) then processes the resulting tracking data. The Aerospace filter estimates ephemeris and clock offset for each satellite and propagates these estimates forward in time. The propagated ephemeris and clock predictions for every satellite in the constellation are compared with the NIMA truth data to compute the globally average SIS URE for the near earth GPS user using the formula [8] as provided below:

$$SIS - URE = (Variance(R - C) + 0.0192 * [Variance(IT) + Variance(CT)])^{1/2} \qquad (2)$$

where R, IT, CT, C = radial, in-track, and cross-track ephemeris errors and clock errors.

The projected GPS SIS URE accuracy data with IIF Rb and Cs clocks, II/IIA Cs clock, and a perfect clock, using 2-week GPS tracking data in October 98, as a function of age of data is shown in Figure 3. The projected SIS URE for the IIF constellation with mixed Cs and Rb clocks is expected to be somewhere between the IIF Cs and IIF Rb curves. These results were obtained without changing the filter or its tuning parameters.

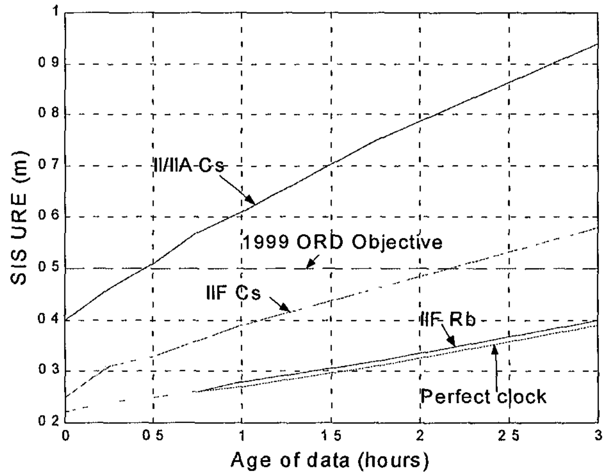

Figure 3. Projected GPS SIS URE

By comparing curves with IIR Rb and the perfect clock, it is evident that ephemeris and other errors dominate GPS SIS URE if the GPS Block IIF Rb or better clock is used. With IIF Rb or better clock, it offers an opportunity to reduce further the projected GPS SIS range accuracy by:

1. Retuning the Kalman filter
2. Improving multi-path mitigation and atmospheric modeling at the monitor stations
3. Identifying and estimating the errors not being modeled currently
4. Improving ephemeris estimation and prediction accuracy
5. Others.

Once the SIS URE range accuracy is improved by addressing the issues suggested above, it might become evident that the SIS URE can be further reduced with a much better clock. This shows that development of better clocks is a necessary first step to further improve the SIS URE.

5. COMMENTS ON THE PROJECTED GPS SIS URE

The IIF current baseline is to operate satellites in the cross-link navigation update mode with a minimum update rate of once every 3 hours. It is seen from Figure 3 that the SIS URE for the IIF with Cs and Rb clocks and with age of data of 3 hours are 0.58 m and 0.40 m respectively. To achieve the ORD range threshold of 1.5 m, the UEE allocation can be 1.38 m and 1.45 m for IIF with Cs and Rb clocks respectively. These UEE budgets can be met with today's user equipment technology, so the ORD range accuracy threshold can be achieved with today's technology.

In the 1999 ORD a benchmark user with user equipment error (UEE) of 0.8 m (rms) is assumed to specify the GPS range rms accuracy threshold of 1.5 m. Since UEE of 0.8 m is already greater than the ORD range accuracy objective of 0.5 m, it is obvious that further user equipment development and improvement are needed in order to meet the ORD range accuracy objective.

When the GPS Block IIF cross-link system works properly without interference and degradation, it is conceivable that the constellation can be refreshed every OCS Kalman cycle, i.e., every 15 minutes. Assuming that more advanced GPS receivers become available in the future, the projected signal-in-space accuracy as a function of age of broadcast data, as provided in Figure 3, can be used to see whether the ORD objective can be achieved. Based on the projected SIS URE as shown in Figure 3, the allocation of the UEE to achieve the ORD range accuracy objective of 0.5 m is plotted in Figure 4.

It is evident that from Figure 4 that:

1. GPS with IIF Rb clocks can support ORD range objective with 3-hour cross-link updates if UEE is 0.3 m or less,
2. GPS with IIF Rb clocks can support ORD range objective with 15-minute cross-link updates if UEE is 0.43 m or less,
3. GPS with IIF Cs clocks can support ORD range objective with 15-minute cross-link updates if UEE is 0.39 m or less,
4. GPS with IIF Cs clocks can support ORD range objective with 1.1-hour cross-link updates if UEE is 0.30 m or less, and
5. GPS with IIF Cs clocks cannot support ORD range objective if the cross-link update is 2.2-hour or longer.

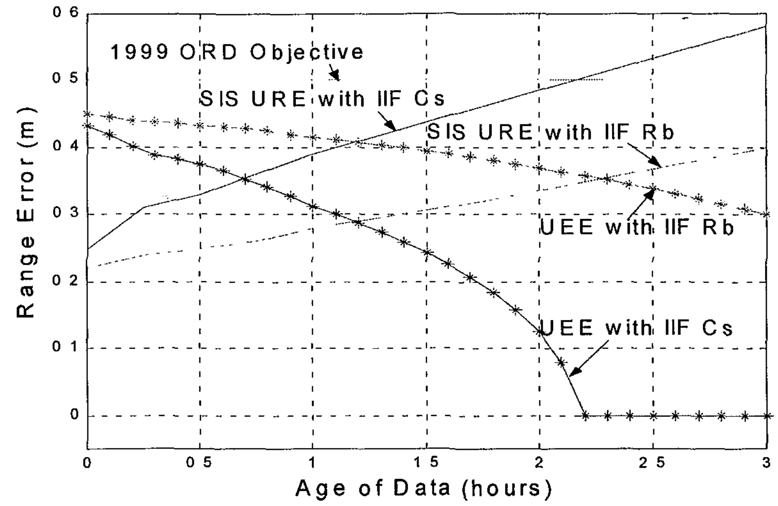

Figure 4. User Equipment Error (UEE) Allocation

6. CONCLUSIONS

1. Development of new space clocks is well underway. Digital Rb clock and Optically Pumped Cs clock could be ready for future GPS application in 2007, and JPL LITS could be ready in 2009.

2. The projected SIS URE based on the IIF Rb clock shows that development of advance clocks is the first step in improving GPS user range accuracy.

3. Improvement of current IIF cross-link system and development of more advanced GPS receivers are needed to meet the ORD range objective of 0.5 m and beyond.

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Questions and Answers

MICHAEL GARVEY (Datum): Andy, you had one of your slides which talked about contributors to URE that were not clock-related. I wondered if you had put them in order of priority, and maybe if you could go back to that slide and comment what the really big ones are.

ANDY WU: Oh, I see that. What we should do?

GARVEY: Yes, that is the one. Are those in order of priority and maybe could you put—?

WU: I think so, yes. We can do this, and this is not easy. We cannot do that, I guess, monitor cesiums, the receiver guy has to do that, and just send it down.

THOMAS CLARK (NASA Goddard Space Flight Center): I am surprised, and perhaps others are, that for the IIF satellites the rubidium is showing a factor of two to three or so better than the cesiums. I' a little curious why. Is it that the performance has been tuned for short-versus-long term?

WU: That is just on the test results.

CLARK: Okay, so this is the actual implementation of the hardware?

WU: Yes, it is.

CLARK: I was wondering if there was some new breakthrough in rubidium physics that accounted for this rather than–

WU: I guess the rubidium for the 2-hour today was showing something like this. So it is no surprise to us that they did that. It is better than the cesium today. Most rubidiums are, surprisingly enough. Also, in the 2-hour rubidiums, there is a mechanism for them to get rid of the frequency drift and the frequency offset. So in 2 hours a rubidiums look just like a cesium. The drift is small; it has been removed now.

DENNIS McCARTHY (USNO): I am wondering, on some of these things that you showed us, the sources of error. Some of these issues have already been addressed to some extent by the International GPS Service in which they produced, characteristically, now operationally, orbits and even clocks that are much better than you typically see from anything available operationally from the operational GPS. Is there any effort at all in what you are describing here to make use of that capability that is provided by the IGS?

WU: Yes, we are aware of them. Most of that would be incorporated by the OCS, but slowly. It is not high priority right now; there is something else to worry about.

McCARTHY: When you say slowly, how slowly?

WU: Three or four years, unfortunately. It takes a long time. They have other problems to worry about.