PANEL DISCUSSION ON GNSS INTEROPERABILITY

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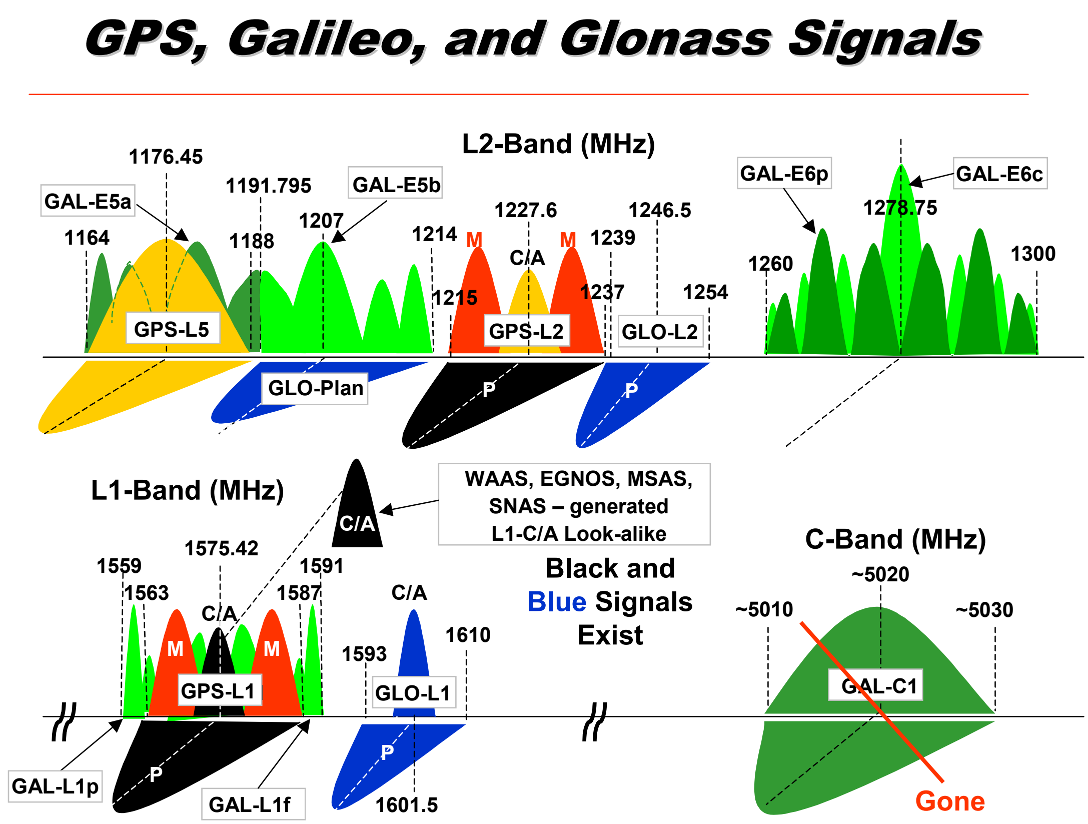
DETOMA: Good afternoon. Basically, the issues that you will find on GNSS interoperability are: signal spectrum and signal structure; reference frames, space, and time; and other issues that will come up during the discussion.

So first of all, I would like to introduce the panel. On the panel we have Wlodek Lewandowski from BIPM; Jens Hammesfahr from DLR, Germany; Dr. Nicholas Koshelyaevsky from the Institute of Metrology for Time and Space, Russia; Dennis McCarthy from the USNO; Ron Beard from NRL; Dr. Powell from the Aerospace Corporation; Dr. Hegarty from the MITRE Corporation; Hugo Fruehauf from FEI-Zyfer Corporation; Bill Klepczynski from the Department of State; and myself.

To start the discussion, I have asked all the panelists, as an introduction, just to introduce their ideas on interoperability. We will start with Hugo and proceed in sequence.

FRUEHAUF: Good afternoon, ladies and gentlemen. What we have right now in the GPS/ GALILEO/GLONASS area are the blue and black signals. I thought we would start with a chart that would put everyone on the same frame of what is happening here in the future.



You have the L1 band, C/A, and P. You have a GLONASS FDMA system, which is in the blue, with their equivalents C/A and P. Then we have what I call the L1-C/A look-alike, which comes from the WAAS, EGNOS, and MSAS systems. As you know, this is a transmission of the differential corrections to the user with the L1-C/A look-alike signal.

And then on the L-2, you have the American, of course, P-code and the Russian GLONASS P.

What is coming up in the future is a clear acquisition signal L2, and of course you realize that that is in order to give an instantaneous ionospheric resolution in the clear, because the user in the future can then do a code comparison between L1 C/A and L2 C/A to accomplish the same thing that was, as of now, only accomplished by the military P-code that compares P to P. This is to support the civil aviation community.

Then an L5 will be added, also to support the civil aviation, for integrity and an additional capability for WAAS and all of its tentacles. Then the infamous M-code will be put in between the same spectrum, of course, but on both sides of the C/A signal, both on L1 and L2. Then the Galileo signal is in green, first Galileo E5 will be superimposed on the GPS L5. And separate, as you know, of course, is that you do the coding structures with spectral densities on the edges, plus you use different modulation techniques in order to get the maximum amount of isolation between signals operating the same bandwidth.

And then the Galileo E5b, another signal just on the other side of the GPS L2, which will be Galileo E6, again structured in such a way that interference between the signals is minimized.

Then over the L1 GPS signal, you will have again a structured E1 and E2, again separated properly with code structures and modulation techniques. And the C-band frequency which was planned has recently been cancelled. So this area is gone mainly, probably because of the cost involved. It is very difficult to make a receiver now that is C-band and make it as cheap as the receivers that can be made in the bands that we spoke of.

So in general, then, it is quite a challenge and an opportunity for the commercial sector to be able to pick up all the commercial signals that will be integrated in the receiver, not only WAAS, EGNOS, MSAS, which are the differential correction issues, but also these additional signals. So the future's commercial receiver will be robust. And, of course, the military has the additional challenge of its existing SAASM technology to be updated to M-code and all of these other signals. And, of course, a receiver will then have a huge capability to sort out lots of signals and it is going to be the software man's game to make the best receiver on the planet.

DETOMA: Thank you very much, Hugo. Now the next speaker will be Ron Beard from NRL.

BEARD: Thank you, Ed. When Ed asked me to be on this panel about interoperability, I thought back about the various forms of interoperability I have been engaged in. I think I started working on interoperability between systems back in the 1980s at some point, because there are many dimensions to interoperability; and instead of putting them all on one slide, I thought it might be better to simply introduced the concept than really go through a slide. I think Hugo did a nice presentation on the signal's interfaces between these various systems. But there are also the interfaces of the reference systems and the usability of these within the different systems from different user groups that cause additional problems.

But the first form of interoperability that I became engaged with was looking at military timing signals in a NATO context. This is where you are thinking of a French airplane landing on German airfield serviced by English servicemen with U.S. equipment. There you are talking about a multiplicity of interfaces that have to fit together and how the timing would be used to synchronize a variety of these military systems in that context and then a larger context becomes even more complex.

A lot of those interfaces are still not really standardized or worked out as to how not just satellite systems fit together, but how the systems actually talk together through the various interfaces. I think the U.S. is just as culpable, guilty as anyone as to defining standardized timing interfaces and procedures for using these different systems to a common time. Also, the common time is another problem as to what realization of time you are using in these different systems.

That brings me to one of my latest adventures in interoperability, which is looking at the future of the

UTC timescale that I am involved in with the ITU-R. The question before the ITU-R is the usability of the UTC timescales, in particular the fact that it is discontinuous and has leap seconds. In the working group I am involved with, we have been working for about the past 4 or 5 years trying to determine the usability, the limits of performance, the impact of continuous or discontinuous, how that affects all these different communities. It gets very involved and can get quite emotional in some cases, because of the idea of having a discontinuous reference common time for the variety of systems that do not want to have discontinuous systems, are required to be continuous, such as telecommunications, data streams, and it becomes an enormous problem. This is a form of interoperability that affects the basic level of all these systems, the common reference frame that they use. What time do you get out of the system from Galileo Time or GLONASS Time or GPS Time, how do these all combine into an accurate common reference system that everyone can use? I think that is still a good issue in interoperability.

So hopefully we can get some suggestions in our discussion of that here today. Thank you.

DETOMA: Thank you very much, Ron. The next speaker is Dr. Bill Klepczynzski from the State Department.

KLEPCZYNSKI: I thought I was going to be the next to the last speaker, and I thought would say what I was going to say, so Ron started to say what I was going to say and I think Wlodek will eventually talk about more of what I am going to say, so hopefully I will be very short.

But when it comes to interoperability, there are on the market already combined GPS/GLONASS receivers. They have been around for a long time. And it is possible, from the timing point of view, to do a solution for the offset, to get different systems onto this same time by the individual receiver.

However, one of the shortcomings of doing it in this fashion is that you need to observe a lot more satellites than you would for your normal position fix, because now you are also solving for the time offset between the various systems. And it is possible to do that.

Another way to achieve timing interoperability is to have timing centers calculating and observing the offset and then transmitting, say, via the navigation message, what the offset is between the different navigation systems. There are some shortcomings with regard to that, and especially how does one coordinate the centers themselves? And it is not going to be a small minor thing; there is going to be some effort involved. And "some effort involved" means there must be some type of funding for doing it in this way and this fashion.

There is another way one can synchronize timing inoperability between all the systems: that they all adopt the same system time. And that to me is the ideal solution; however, one of the biggest shortcomings there is a political situation as to which time and how one goes about it.

If one tries to go for the ideal solution of trying to put all systems on the same time, there are some things which one has to keep in mind. First of all, the amount of effort that is necessary. And I refer to how one goes about doing this. It is not going to be a trivial exercise to do this, to get things done.

One has to also keep in mind, the way of reality to the current situation, that GPS Time is around now; people are using it and, as Ron alluded to, many systems are already synchronizing their telecommunication systems to GPS Time. So if we adopt some other type of standard or some other system, one has to take into consideration the effects on current users around.

GLONASS will probably use as their time basis TAI, but I think Wlodek Lewandowski will be saying something about that when he talks about it, perhaps. But, in some respects, TAI is really more of a working timescale within the BIPM and it is really not a real timescale out in the real world, where people are using it as such.

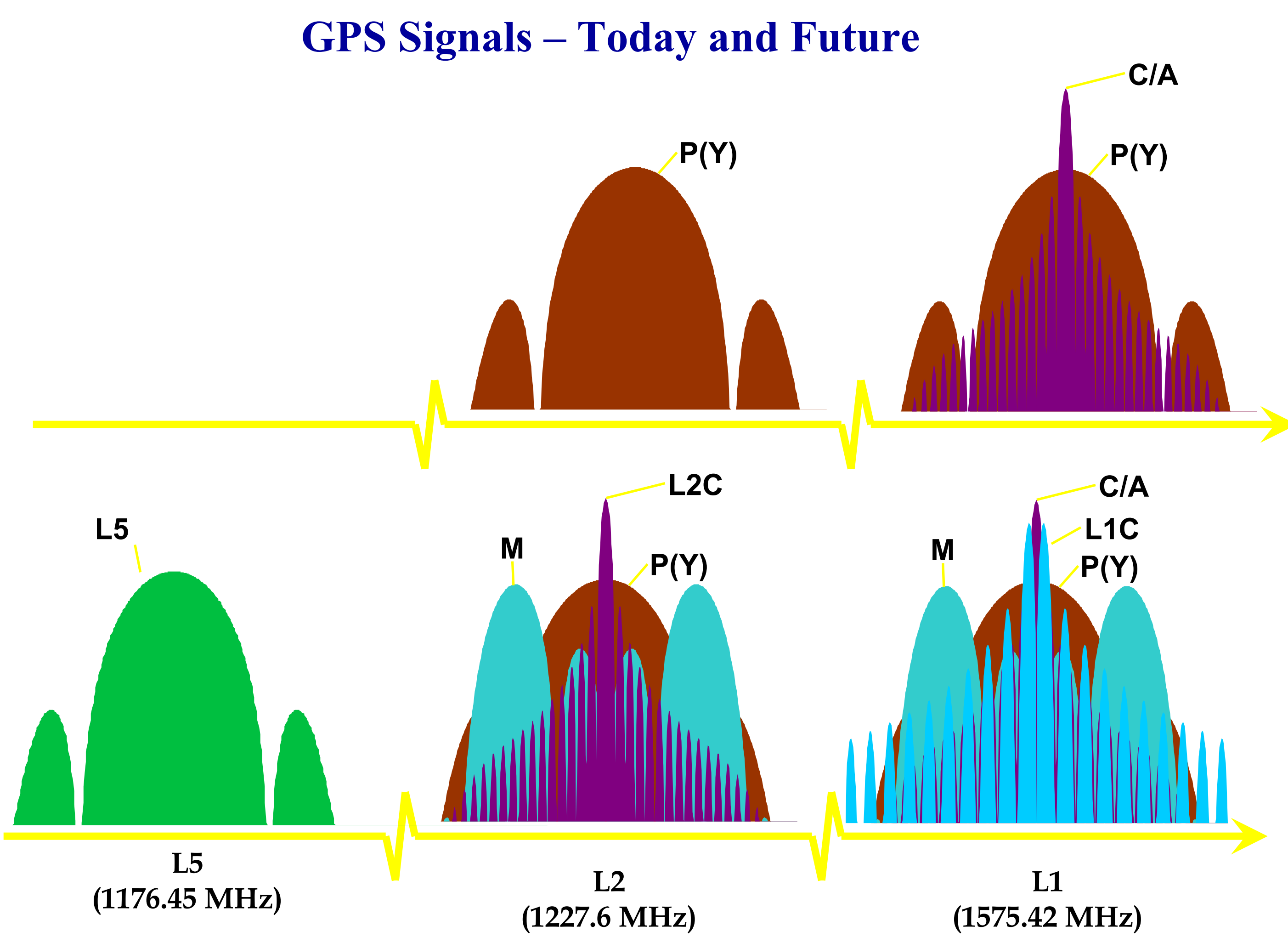
Ron also referred to the UTC problem of trying to get a timescale without leap seconds, because that makes the navigation systems work much better, as well as telecommunication systems.

So if one wants to try to get a timing interoperability between the various systems, some type of compromise will be needed, and that compromise, I am sure, will take several years of discussions between all the various players to come to some conclusion. And, hopefully, we might keep a number of people employed for a number of years if that goes on that way.

Thank you.

DETOMA: Thank you, Bill. The next speaker is Dr. Chris Hegarty from MITRE Corporation.

HEGARTY: Good afternoon again. The first chart I have here has been ably covered by Hugo. I will just try to hit some salient points that he did not cover the first go-round.



The top row here is just showing the GPS signals that we enjoy at present. As Hugo noted, right now dual-frequency use is confined to military users and those pesky civilians that have figured out how to track the Y-code without really knowing what it is. And, of course, that [semi-codeless] technology is quite widespread right now. But we will all benefit, starting hopefully next spring, when the first II-RM satellite goes up and we get a second civil signal; the II-RM satellite actually has the capability to either send on L2 the C/A code identical to what is on L1, but the baseline is actually a new improved signal structure – and the acronym of the day is "L2C," which stands for "L2 Civilian," which has a lot of advanced features compared to C/A code, including longer PRN code. Actually, it has an extremely long one as one component. It also has, as do all the new civilian and military components, a dataless component which allows more robust tracking. From a user perspective, this will hopefully mean you can track signals in foliage and other conditions when you couldn't otherwise.

On the II-RMs also will come these new military signals on L1 and L2. Starting with the first IIF satellite, which will hopefully go up in calendar year 2006, we expect to see a whole new frequency with a signal cleverly called "L5," same name as the carrier, which has two components, as Hugo showed. On L5, a quadrature channel actually is modulated by a PRN code, only without data, enabling this same kind of robust tracking benefit.

And, in the future, sometime perhaps in the Block III timeframe, one of the components of the US-EU agreement that was signed back in June of this year established a baseline signal structure that GPS would adopt, as well as the Galileo open service, which is here called L1C. This is a binary offset carrier 1, 1 signal. It roughly looks, in the RF spectrum, like two copies of the C/A code, plus or minus 1 MHz from the carrier.

GPS SIGNALS – GNSS INTEROPERABILITY CHALLENGES AND OPPORTUNITIES

•Ensuring Radio Frequency (RF) compatibility

- **June 2004 US-EU agreement for GPS-Galileo + follow-on working groups**
- **Ongoing bilateral discussions between United States and other nations/organizations for QZSS, GLONASS, SBAS, etc.**

•Enhancing interoperability

- **Incorporation of system time offset messages in navigation data for new civil/military signals**
  - **Are there other inter-system messages that would be useful?**
- **Increasing commonality in messages, signal structures, services**
  - **Is dissimilarity, in some cases, more beneficial?**

•Spectrum protection

Just a few bullets to hopefully stimulate discussion on interoperability. As Edoardo pointed out, one of the main tenets as in the Hippocratic Oath, "Thou shall do no harm," or however it is phrased. But this was, of course, very important to not just the U.S., but everyone worldwide, as new civil and military GPS signals and Galileo come online, want to ensure that people continue to enjoy all capabilities that they are enjoying today from GPS. And, of course, the Europeans are investing billions in Galileo, and they would like to make sure that they are not going to be interfered with by GPS.

So attached to that US-EU agreement in June 2004, by reference, was actually quite a lengthy document describing the methodology that should be used to ensure that the two systems are RF-compatible. And similar documents are being used by the U.S. now in bilateral discussions with Japan for QZSS, as in other bilateral discussions.

As far as interoperability goes, we have heard a lot today about the need to provide time offsets between Galileo system time and GPS time. That is certainly important; I guess, to stimulate discussions one question would be, "is there any other inter-system messages that might be useful?" This would be a good thing to think about now, because the signal specifications for the new GPS signals anyway are quite far along. Back in October, a document ICD-GPS-200D was approved by the GPS Joint Program Office, which is the new baseline document, not only for the new L2 civil signal, but also for the L1-L2 P (Y) Code and L1-C/A code. And this document describes all the messages that will be used for L2C.

Another document was considered in October, but not quite passed. It will probably be adopted very shortly as ICD-GPS-705, which defines all the gory details of the L5 signal, including the messages. These satellites are going up in the next 2 years, so if we do not have these messages defined or thought of, they certainly can be added later with the flexible messaging structure that we have. But it will be beneficial to be able to define them now so that early user equipment can perhaps benefit from them earlier.

One other thing to think about, as we talk a lot about commonality between new systems and messages, signal structure, and services, I just pose a question for the audience, which is "Is dissimilarity, in some cases, more beneficial?" For instance, is it actually better to have new GNSS signals on different frequencies to help mitigate against interference (which you may not expect to always be on the same frequency)?

And then, lastly, a cheap plug for spectrum protection, just to keep everyone focused to some degree on the challenges that we all face together, both in GPS, Galileo, and other new systems that are on the horizon in guarding the RNSS spectrum that is needed to support these.

Thank you.

DETOMA: Thank you, Chris. The next speaker is Dr. Hammesfahr from DLR.

HAMMESFAHR: I want to address two different issues for the interoperability of the Galileo and GPS systems. One of these issues is timing. There will be different reference timescales for Galileo and GPS. So there will be an offset between the GPS system time and the Galileo system time. This offset is abbreviated as GGTO. We made a simulation about its determination and influence on the positioning accuracy for users of combined GPS/Galileo equipment.

There were several assumptions for these simulations, so what is shown below is the average case and the worst case for horizontal positioning error and for vertical positioning error. The first row is for Galileo only. For the Galileo vertical positioning error, the simulated performance is to be approximately 4 meters on the average, and approximately 6 meters in the worst case. If we combine Galileo with the GPS system, and the user is to determine the difference in the timescales by himself, then the user has to have at least five satellites in visibility. This is the five-parameter solution. And as you see, there is some kind of improvement for the average and also for the worst-case positioning error.

DLR

GGTO Impact on User Positioning Accuracy

GGTO: GPS-to-Galileo Time Offset	average		worst case	
	horizontal position error (95%)	**vertical position error (95%)**	**horizontal position error (95%)**	**vertical position error (95%)**
Galileo only	2.1 m	3.7 m	3.3 m	6.6 m
GPS + Galileo 5-parameter solution	1.6 m	2.8 m	2.8 m	5.4 m
GPS + Galileo 4-parameter solution GGTO error *0 ns*	1.5 m	2.7 m	2.8 m	5.3 m
GPS + Galileo 4-parameter solution GGTO error *5 ns*	1.6 m	2.8 m	2.8 m	5.5 m
GPS + Galileo 4-parameter solution GGTO error *16 ns*	1.7 m	3.3 m	4.1 m	10.5 m

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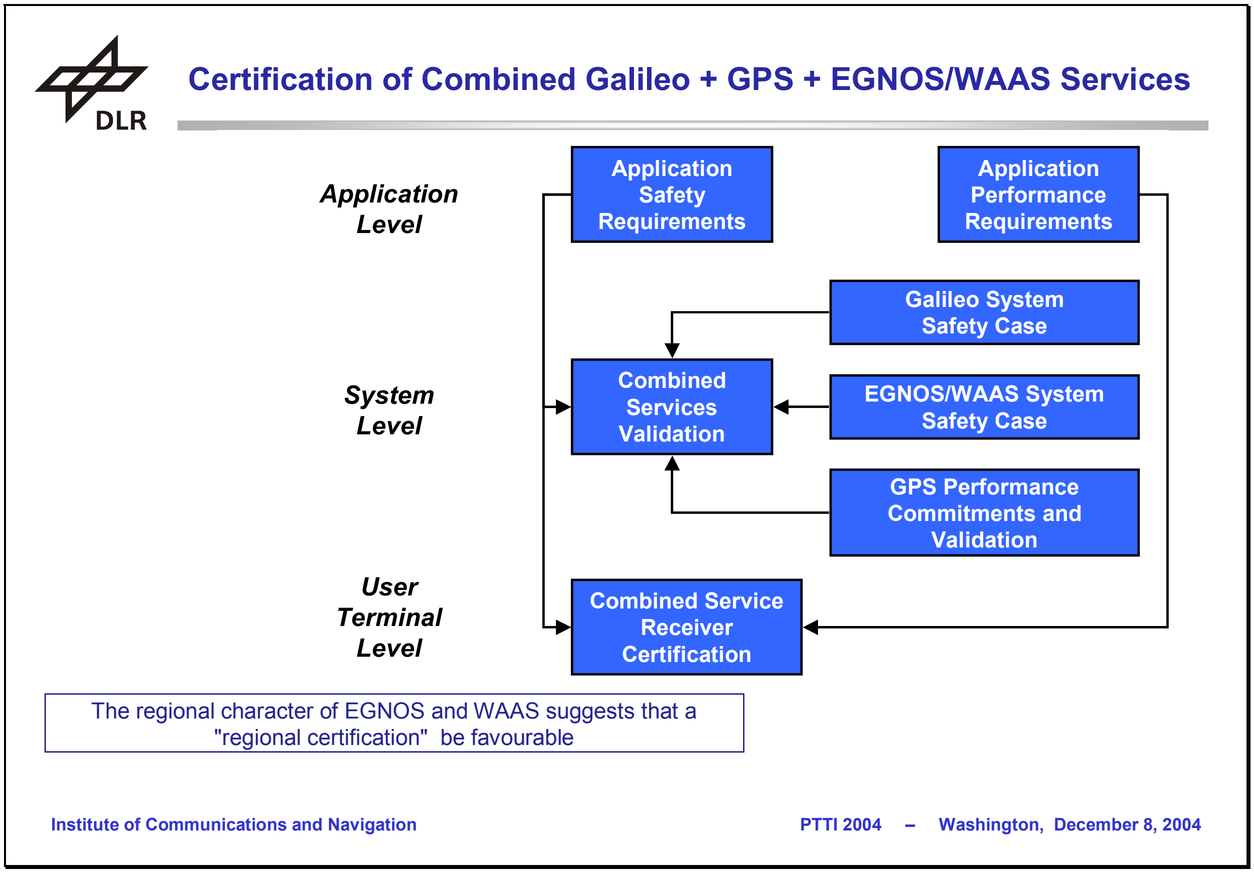
On the other hand, the operators of GPS and Galileo could determine the offset between the Galileo system time and GPS system time, and broadcast it to users who then correct their measurements with it (four parameter solution). If the broadcast GGTO values were fault-free, there would be a slight improvement with respect to the user-only solution. However, if we consider an error in the determination of GGTO of, say, 5 nanoseconds (95%) – that is the requirement in Galileo now – a slight degradation will occur for the average case; and also for the worst case, but it is very slight.

If we do not correct for GGTO at all, the total error may be as large as 60 nanoseconds. Then we come up with a deteriorated solution with respect to the solution the user would receive if he determines GGTO himself. And the worst case is even more deteriorated than the average case. A similar situation will occur if the uncertainty of the broadcast GGTO value increases.

So resulting from these simulations, we think we have to be careful about determining on the system level the offset between Galileo Time and GPS Time if we are not sure that the residual errors will be small enough.

The second issue I want to address is certification. Let's relate it to safety-critical applications. For example, civil aviation. For these applications, there are authorities requiring certification of the navigation services. And the certification procedure for Galileo as it is being planned now. This is not yet fixed, and will be done in two stages. So there will be certification on the system level. Related to the Galileo system, there are plans to have a Safety Case, that is, to provide visibility to the users about the development and operation of the system.



Related to the augmentation systems like WAAS, EGNOS, MSAS, and so on, there are also plans to have a Safety Case. However, if you want to combine these services, then with the GPS, we also need some commitments from the GPS system. So we need a kind of Safety Case or a kind of a validation file to be sure that this system is operated to specific standards.

The system-level certification is done for a generic environment and a generic receiver. However, the system combination occurs on the user level. Users receive signals from different systems in an application-specific environment and with an application-specific receiver. Then there shall be an additional certification related to individual applications. So this user certification has to take into account the safety requirements and also the requirements for the performance of individual applications. For example, for civil aviation, there are different phases of flight and there will be different sets of requirements.

So concerning safety-critical applications, we have to consider those different levels of certification in order to have these systems interoperable.

DETOMA: Thank you very much, Jens. The next speaker is Dr. Koshelyaevsky from VNIIFTRI, Russia.

KOSHELYAEVSKY: Let me briefly introduce myself. My position in GLONASS is limited. I am from the National Service for Time and Frequency. So I am responsible only for the time aspects of this problem.

As special fulfillment of the requirements of this system interoperability, we expect to generate the national timescale UTC (RU), which will be starting 30 December of this year. And we expect that we may steer to UTC within about 20 nanoseconds. So it will ensure possible timeframe for GLONASS.

Regarding GLONASS updates, I will be able to give you some information coming from Russia. The new generation of GLONASS satellites will have a much longer life. It is expected that it will be about 7 years and in the next generation, even more. Then it is expected that, up to 2008, the constellation will be about 18 to 24 satellites.

GLONASS people are strongly interested in our secondary time laboratories, which are widespread over the whole territory of Russia from Moscow to the Far Eastern region. And they would like to use it in a controlled segment of GLONASS as a source of precise ephemeris and timing information.
To my understanding, the GLONASS interoperability may be based on well-known CCTF recommendations, which require as close as possible time synchronization of system times. In other words, when you transform geodetic system to another, there will be no trouble transforming this system.

I will further apprise you and the International timing community to GLONASS when I come back after discussing this problem with my colleagues.

Thank you.

DETOMA: Thank you very much. The next speaker is Wlodek Lewandowski from BIPM.

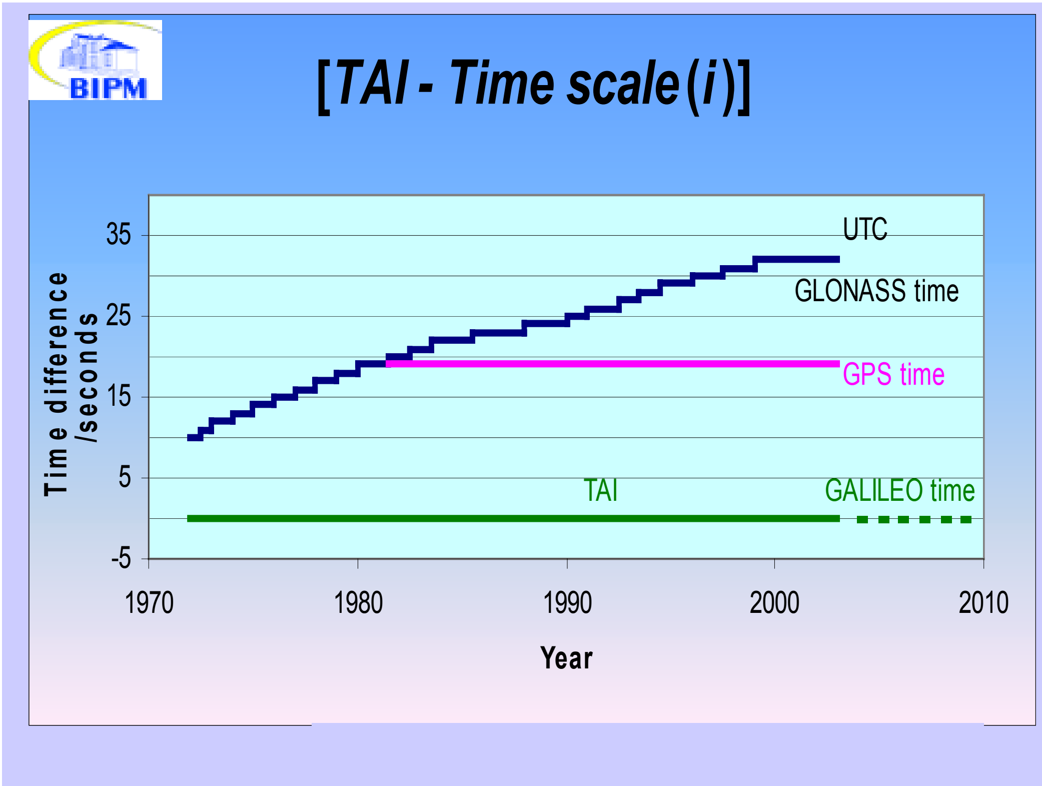
LEWANDOWSKI: Good afternoon. I would like to turn to the subject of reference timescales for the various GNSS systems that are in place now, or that we will have in the near future, and will speak about differences of the order of seconds, not nanoseconds.

In general, the GNSS systems are referred to the official international timescale UTC. However, there is some confusion about the use of different terms and timescales. I show below a plot which illustrates how UTC has evolved from the beginning of the 1970s, when this system was introduced. These steps are leap seconds. Currently, we have a 32 s difference between TAI and UTC. There have not been any leap seconds in the last few years.

GPS was introduced in 1981, and GPS time was set – I don't remember the date – to be zero with respect to UTC. It seemed logical for GPS be referenced to the official reference timescale. But since then, in agreement with the definition of this reference timescale for GPS, which is a continuous timescale, GPS has not applied any leap seconds. UTC, on the other hand, has leap seconds here.

Now, let's turn to another GNSS: GLONASS, which is not yet operational. GLONASS is also using UTC for its reference time, but it is applying leap seconds. This poses a technical problem; in the past, the GLONASS constellation encountered major problems during the introduction of leap seconds. In fact, it was probably this problem that triggered the discussion about the future of leap seconds.

Since GLONASS improved the introduction of leap seconds, have been no major problems on the GLONASS constellation. GLONASS, we must say, is the closest to following international recommendation, because it is following, for its reference timescale, the international reference timescale UTC.



What about the new system Galileo? Galileo has chosen to use TAI as a reference. At first look, this seems very logical, because TAI does not have leap seconds. Having seen the problems experienced by GLONASS, Galileo operators do not want to worry about the introduction of leap seconds. The issue is that if Galileo is officially referring to TAI and is saying that it is Galileo time, Galileo will be broadcasting TAI. But there are strong regulations for broadcasting time signals, and TAI is not the recommended timescale for broadcasting.

Also, from the BIPM point of view, TAI is a scientific frequency reference for the final product, which is UTC. It is true that it does not have leap seconds, but that does not mean that it is automatically a timescale for users. There are some strong currents of opinion to use it as an alternate timescale, but we do not have an official recommendation for that. And this would lead to a situation where we have two official timescales: UTC and TAI. But, in my opinion, having two official timescales, differing by tenths of seconds, may lead to problems, both now and in the future. So I would like to ask your opinion about this issue, which I think is a very serious one and an important part of the discussion about the future of leap seconds.

DETOMA: Thank you very much. Our next speaker is Dennis McCarthy from the U.S. Naval Observatory.

McCARTHY: I have taken a slightly different approach with respect to the rest of the speakers. This slide outlines some things which I think need to be considered, or have been considered.

Things to Consider

- **Time**
  - **Being discussed**
- **Terrestrial Reference Frame**
  - **WGS 84 = ITRF at the few centimeter level**

First of all, we have heard just about everyone on this panel speak about time being the issue. And no doubt that time is an issue, and it is now the time, I believe, to try to resolve that issue. Making no decision on the possibility of a navigational time scale different from UTC is, in fact, making a decision. Software is being written as we speak for navigational systems of the future, and right now we constantly hear about the issues of making any changes in the legacy issues. If we go back and reconfigure software, that has already been in the books for the last 30 years, it is a huge expense. We are doing that right now to the future generations. So generations from now will be thanking us for the fact that we did or did not make a decision at this point regarding a timescale. And at the rate that we are progressing, I guess, they will not be thanking us a lot.

So this decision needs to be made, and made rather soon as to what we are going to do, and if we are going to keep these leap seconds or if we are going to adopt some kind of navigational timescale that is common to all navigational systems.

So we have heard about time, and we have heard about the terrestrial reference frame as issues for interoperability. I think that we are all pretty much convinced now that the WGS 84 is essentially the ITRF and that we can dismiss the concern about the terrestrial reference frame at the few-centimeter level and go on.

- **But …**
  - **Terrestrial to Inertial Transformation?**
  - **Gravity Field?**
  - **Earth Orientation?**
  - **Models?**
    - **Tides**
    - **Troposphere**
    - **Ionosphere**

But there are other things that have yet to be considered, I submit, for concerns in navigational system interoperability. These are things that I show there as the terrestrial-to-inertial transformations. The International Astronomical Union in the year 2000 passed some recommendations regarding the future paradigm to be used to transform between the international celestial and the international terrestrial reference frames.

These call for essentially a total revamping of the way that things have been done in this area. I am sure that the GPS folks will not want to change from the system that has been built in for the last 30 years; however, I suspect that those designing new systems will want to take advantage of the most recent IAU recommendations. It is not that there is a lot of difference between them, but there are significant differences. These things need to be at least discussed, and the differences between them established. The gravity fields, the Earth orientation; how do we handle Earth orientation parameters? We know how we do it in the GPS system; they are built into this system to force the relationship between the terrestrial and the celestial system. Is that going to be done the same way in other navigational systems?

Are we going to use the same models for tides? What models to use for tides? What models are we going to use for the troposphere? What models are we going to use for the ionosphere? And this reference-frame issue is truly a four-dimensional issue. We also have to worry about the relativistic issues, and how one handles the relativistic concerns in analyses of orbits. We have clocks flying at altitude; we have got clocks flying on the surface of the earth. How do we relate those and put those into a common-time system?

And these things, while small in comparison to seconds, as we have heard about, are nevertheless going to be there and need to be discussed at this point. Again, failure to make decisions regarding these standards and these conventions is, in fact, making a decision.

DETOMA: Thank you very much, Dr. McCarthy. Our next speaker is Dr. Powell from the Aerospace Corporation.

POWELL: Hi, I am new to the world of interoperability, but my most recent experience is with the GPS JPO in the field of user equipment. So a couple of the issues that I would raise from a user-equipment perspective, or an applications perspective, are as follows. One has to do with the spacecraft applications of GPS, in particular, high altitudes of geosynchronous spacecraft. And I am interested in how the Galileo signals will or will not contribute to that, and how high-altitude spacecraft navigation will work in a combined GPS/Galileo era.

The other issue, I guess, going forward as far as clocks is the industrial base and how the industrial base for clock manufacturers, both for spaceborne and terrestrial clocks, will develop during a GPS/Galileo era.

And also, finally, how will integrity work for combined GPS/Galileo systems. I would also be interested in that.

That is all I have.

DETOMA: I thank all the speakers, and I think we have many questions and issues on the table. And possibly more when you start asking questions. I would ask if anyone would start the discussion by asking the first question.

MARC WEISS (National Institute of Standards and Technology): I have noticed that the way the GPS time minus the Galileo is going to be estimated is by measurement at the Galileo station. I have also noticed the importance of it getting it right. And I am wondering that why not do, say, Two-Way between Shriever Air Force Base, where GPS Time is known, and the source of Galileo Time, where the Master Clock is, and actually measure directly instead of through the satellite system?

HAMMESFAHR: I fully agree with you. However, the prerequisite for this procedure should that there will be direct access to GPS Master Clock or Master Time and to Galileo Master Clock/Master Time.

And then to have a direct link between these two facilities and to determine the difference in the timing scales.

So, presently, we are not sure if this direct access will be guaranteed. But if so, I think this would be the best means, yes.

BEARD: I think part of the problem is with GPS, and I am certainly not the foremost expert on this; it is their use of the Composite Clock and how will time will permit realization when comparing them. I think that is a fundamental issue.

If I could make a slight addition to the leap second question, if you don't mind. Part of the issue of the leap second question that seems to be reoccurring is that most of the projections by people looking at current geophysics is that the necessity for leap seconds will be increasing. So there could be the possibility of having multiple leap seconds a year.

So it is not only adding the leap second and introducing that, but having the multiplicity of leap seconds further complicates the issue.

Something else to think about.

DEMETRIOS MATSAKIS (U.S. Naval Observatory): Just wanted to clear up a technical issue, and you sort of said that, Ron. Time is not known at Shriever Air Force Base; the time for GPS is set right here in Washington, D.C., at the Naval Observatory. That is a time reference. The Composite Clock discussion could be taken somewhere else; this is not the time to get into it. That algorithm is a whole complicated subject; I would not say that anything was wrong with it. Whatever it does, it all gets washed away when it gets reference to the USNO here.

So, in fact, there are discussions about Two-Way; they involve taking time from the USNO in Washington, D.C., to the Galileo reference.

KLEPCZYNSKI: In regard to that, there still is the question, as Ron mentioned and as Demetrios alluded to, GPS time is really an algorithm output. And even though we measure the offset, say, at USNO, there is still always a delay between the time that the offset is known and when it gets uploaded to the satellite; so this would have to be taken into the loop also, to try to enclose and tighten the difference between the projected offset between, say, GPS and Galileo time.

MATSAKIS: That offset is about 1 nanosecond right now, and I showed a plot of it in my talk. And it is the standard plot I give in all my summary things.

Maybe it is not important – and I should have said this during the scientific sessions – the GGTO talk had a spec of 5 nanoseconds for the difference, and it was considered that that was hard to do. In my opinion, several items in that error budget were higher than they had to be, and it might be easier to achieve their 5-nanosecond spec, if that is what they want. It is good that they are conservative, though, and that means that they will really do it right.

BEARD: Certainly the Naval Observatory's time reference is the time reference for GPS. However, the practical operating time for GPS is determined by the Composite Clock. And I would think it would be more accurate if you were to reference a clock that is included in the composite clock and look at that difference as compared to the difference with the reference of the Galileo system, rather than one which is not included in the Composite Clock.

HAMMESFAHR: One remark. I think what the user wants to know is to know the offset of each individual satellite clock with reference to some reference system time. So if you could imagine one monitoring system monitoring all GPS satellites, monitoring all Galileo satellites, maybe monitoring all GLONASS satellites at the same time, using one orbit computation, including determination of individual satellite clock times, and then, to provide the information for each individual satellite clock, I think this would be the most adequate information the system could provide to the users.

BEARD: I think that is the value of the way the Composite Clock is implemented, in that it determines the offset for each individual satellite clock. And that is brought on to a common synchronized time. I think that is the value of the way the composite clock is implemented and it determines the offset from the three-clock satellite for each individual one.

HAMMESFAHR: Yes, but what we need is a GPS/Galileo Composite Clock, not a GPS Composite and a Galileo Composite Clock.

DETOMA: The problem is that right now we are facing a situation in which each system will maintain its independence, even though they are interoperable. Certainly, if you put all the solutions in one single, bigger system, you get an enormous advantage. But possibly this is not really the case right now.

MATSAKIS: In fact, I think you are right. And that is why there is a whole growth of real-time systems that give all the numbers like that, all the corrections that users, if they want to spend money, can buy from the real-time systems.

So it is happening, with or without the top people doing it, by these other groups.

BEARD: I think the closest to it right now currently is the IGS. It is already doing that.

KLEPCZYNSKI: Just some comments. Just to keep in mind and in perspective of what we are trying to discuss – because Jens referred to this in regard to what the user really needs. The user out in the field that is navigating would like to have a mixture of satellites to choose from to get his position fixed, whether it be Galileo or GPS or GLONASS, because that is what gives you a more robust navigational fix.

So the goal that has to be kept in mind is how you can make it easier for the user of this receiver to navigate into a multiple fix of satellites to avoid urban blockage and cities and by using different satellites. And that is the main ultimate goal that we are looking for.

BOB NELSON (Satellite Engineering Research Corporation): I would just like to offer a couple of comments to elaborate on some of the remarks that some the speakers have made and then pose a general type of question.

With respect to the leap second issue, Wlodek showed the trend of UTC since it was initiated in 1972. The fact is that we are currently in a kind of decade fluctuation in that we have not had leap seconds for several years. But that trend is going to continue; in fact, the trend has continued for literally millions of years. There is evidence through coral fossils and other types of evidence that show that the length of the day is increasing at a steady rate – which is extended over geological history.

The fact that we have not had a leap second for a few years implies that we will have multiple leap seconds in the very near future, if necessary, to keep the definition of UTC as it is now. Not simply because the length of the day is increasing, but simply to make up for the leap seconds we haven't had in the last few years.

So I would predict with the next 10 years, if UTC is not redefined, the IERS will mandate that we have maybe three or possibly four leap seconds in a single year, maybe. Or at least several over several years. So this is a very real issue in the near future, not in the long term.

Another thing that Dennis elaborated on, and also I commented it on before, is a need for a model. Amongst the speakers, I am hearing a need for statistical time comparisons among clocks on satellites and GPS Time and Galileo Time. But, really, we need to consider the distinction between proper time and coordinate time. And they are different for the two systems. Not only is there a secular difference, but there is a variable difference from satellite to satellite. And I would like to emphasize again the need to consider that variable difference. We do not have a Newtonian-like time; we have a relativistic time in the frame of reference of the rotating earth.

But the point that I would like to emphasize and pose a question to is, I believe we are in a unique point in the history of time, a confluence of events: the need to consider the possibility of redefining UTC, and the existence of many components of the GNSS, GPS, Galileo, GLONASS, and other possible systems in the future.

It will be desirable, I think many people agree, to converge toward a common timescale in the future, which poses many problems, and Bill hinted on some of them. So the question I would like to ask is: Are there any people on the panel or in the audience who would care to suggest how this goal of converging toward a common international scale of time, used by both the civilian community and by the GNSS, can be possibly attained?

FRUEHAUF: As a GPS applications kind of person, I view the timescale differences between GPS and Galileo to be the least of the problems that will be encountered. In other words, any properly designed GPS receiver should be able to make a timescale adjustment based on the geodetic model used for that satellite system. For example, for GPS satellites, it should make the PVT calculations using the GPS geodetic baseline. For Galileo satellites in view of the same receiver, it should calculate PVT on the basis of the Galileo geodetics and then provides a final PVT solution based on all the satellites in view properly corrected and voted.

BEARD: I believe the answer is simple. The common international time today is UTC as is recommended by the ITU-R. That is the common timescale used for telecommunications purposes and is coordinated internationally by the BIPM.

McCARTHY: Yes, I just have a few comments to make on the formation of a common timescale.

I think it is clear that Universal Time is considered to be the common timescale internationally. It is the reason the International Telecommunications Union Resolution was implemented in the definition and is why the International Telecommunications Union is reconsidering it.

However, I think it is necessary to distinguish between a navigational timescale and a timescale. The navigational timescale is part and parcel to the navigation solution of these navigational systems. And that situation is reflected in the fact that both Galileo and GPS provide their own system time, a navigational timescale for use in navigation, as well as a timescale for use in timing applications. And I think it is also clear that the proposed Galileo and GPS, that one of the products will in fact be the time, not it is built as a navigational system does – we found out that GPS Time is probably more an important product than the actual navigation solutions. There are more users of the time than there are the navigation. So we have to consider that.

In building a common timescale that reunites the navigational timescale, the timescale for time and frequency purposes, the issues are not difficult technically. It is clear that we have timescales that could mesh that could serve the purpose. Coordinated Universal Time can probably serve that purpose.

The issues are political and emotional, and not technical. So that this is why Bob's suggestion that the common timescale is called for, I think, is quite appropriate. But the tough part is cracking the politics and the turf of the various systems.

HEGARTY: I just had a thought earlier that I wanted to make sure I did not forget.

Earlier, my colleague was talking about the alternate method for determining the time offset between GPS and Galileo, which is actually to let the user equipment compute that as part of the navigation solution. The drawback, as was indicated, was the cost of an additional measurement.

I would just like to point out that if you have a sequence of measurements, given the fact that this bias is not expected to change very rapidly, nor are the receiver internal biases, there is certainly a practical solution; when you have five satellites in view, you fix it, and perhaps even average over the whole time; you have those extra measurements available. And if you are in an urban canyon situation, you can freeze it for quite some time. As I understand, your specification of 28 nanoseconds, whatever it was, over 10 days, I think that would work quite well.

LEWANDOWSKI: It is true that GPS Time, GLONASS Time, and Galileo Time are internal timescales for each of these systems. They play a technical role as reference time in the process of navigation solution. So in a theoretical world, they can be completely different from international timing; the only requirement would be their stability.

However, in the real world, what is happening with GPS time? Because of the lack of leap seconds in GPS Time, there are several communities, who instead of using UTC, also broadcast by GPS, are using GPS Time as the reference for their applications.

So we are now aware of this problem of leap seconds. Because leap seconds pose a problem, there are users who forget that GPS Time is meant to be an internal timescale of GPS, and adopt it as the reference timescale for their own applications. This is a problem.

Now with the imminent arrival of Galileo, and its consideration to use TAI, they are choosing a symbolic timescale. In my opinion, this is misleading, because this fairly technical reference timescale becomes something much more, because it is referring to International Atomic Time.

This leads to confusion, because many users of them are not aware of all the issues of leap seconds and how UTC is manufactured and so on. Particularly if they know that this timescale is referring to International Atomic Time, it is not immediately clear that this is different from legal time worldwide.

So the situation is that because of leap seconds and the problems they are causing, along with a number of other issues, people start to use internal timescales of navigation systems instead of the official reference timescale UTC.

The timing metrology community contributing to UTC is the first guilty party, because, instead of UTC, they chose GPS Time as a reference time for common view. I don't know when or why this choice was made. But all GPS receivers, professional receivers for timing, refer to GPS Time. Although it is possible to switch them to choose UTC for common view, GPS Time was chosen as reference. So this is the point: internal reference timescales of navigation systems are used, and very widely. We should not neglect this phenomenon.

DETOMA: Thank you. Any other comment on this same subject?

FRUEHAUF: As an applications kind of person, I'm thinking of the timescale to be the least problem. In other words, any GPS receiver can be set to GPS Time or UTC. To me, every time I receive a GO code and I find out what the satellite is, I could add or subtract whatever leap seconds you want in order to get the timescale I want to work on. It could even be user-defined. In my opinion, the bigger problem is the actual clock offsets. In GPS, of course, going with crosslinks will go a long way towards real-time updates of satellites and I guess that posed a question to the Galileo community; they have no plans for crosslinks. To me, this is where I would worry. I'm not worried about the fact that one is using TAI and the other is using UTC. I can easily do that with software once I have received the satellite GO code.

DETOMA: Thank you. Any other questions from the audience? If not, I would like to raise a question myself.

One of the things that we were discussing with Galileo is the possibility to broadcast via Galileo the integrity of GPS, since basically Galileo will act as an augmentation system for GPS, at least for integrity in this case. How do you feel about this possibility?

HEGARTY: I was just over to Zurich last week at a Euro-K meeting where there were some Galileo folks there. When this topic came, I believe the answer was that they do have a data rate limitation even using 125 bytes per second on both the L1 signal as well as on E5b, and they don't plan, as far as I know, to broadcast GPS corrections because they …

DETOMA: No, I am not talking about corrections.

HEGARTY: … they do not plan to provide integrity data because of that limitation as well as some certification issues that they do not have the insight to the reliability, robustness, and other things of the GPS satellite to do so.

DETOMA: Any other questions?

MATSAKIS: I would like to follow on Chris's comment that maybe we do not have to worry about interoperability, because we can measure the GGTO at one time.

I know that when E911 comes out, I am going to buy a cell phone for my daughter, and I am not going to care how much it costs, and she often has it turned off, so there can be situations where she just whips it on in a building, and we are going to want every satellite there and know the offsets too. Do you agree that are certain scenarios where that works?

HEGARTY: Well, I guess, thinking through that particular scenario, so if it does come on – and there is a broadcast one, but it is not as accurate as measuring it yourself, so when she dials E911, she is within 4 meters instead of 2. It does not seem like a severe limitation where you do take advantage of that fifth measurement when it is available. The ideal way would actually be able to use a Kalman filter where you look at the covariance, and when you see the covariance of your estimate that you have averaged, as long as you have five satellites visible, start to deteriorate when you are down to four; when that exceeds the achievable variance of the broadcast parameter, you switch from one to the other and that sort of thing.

MATSAKIS: There is no time for a Kalman filter. There is an emergency situation; you turn it on, you want it to go.

HEGARTY: Yes, in that situation – but, my personal preference would be to use it both ways, to actually provide it for people that care not to do extra work. But smart receiver vendors, whether you want them to or not, I am sure are going to estimate it if they do a better job than the broadcast parameter. And I frankly think you can in most situations.

BEARD: I think she is in trouble if she is in a building.

DETOMA: Any other questions? If not, I will close the session here. Thank you.