

PANEL DISCUSSION

THE FUTURE OF CLOCK TECHNOLOGY FOR SPACE

Joe White, Moderator
U.S. Naval Research Laboratory

JOE WHITE: The topic this morning is about the future of clock technology for space. You have seen a lot this morning in the earlier papers about things that will happen hopefully in the future of GPS and Galileo. We saw some things yesterday about GLONASS. And we decided that it was worth a little more discussion with some of the principles in it, let people kind of argue with each other about which way things are going and what it is going to take to make it all work. We have an all-star panel here this morning: Ron Beard (U.S. Naval Research Laboratory), Martin Bloch (Frequency Electronics, Incorporated), Lt. Jason Bolger (GPS Joint Program Office, USAF); Mike Garvey (Symmetricom, formerly Frequency Time Systems and Datum), Professor Leschiutta (Istituto Elettrotecnico Nazionale, Italy), and finally Pascal Rochat (Temex Neuchâtel Time SA).

What I would like to talk about here today is the nature of the problem. I did a paper last year where we talked about what made space clocks different than ground clocks. And the last thing I mentioned in that paper was the fact that GPS is, in a way, its own worst enemy. GPS has fantastic clocks in the satellites; it does very well. And that is really the problem: it makes atomic clocks unnecessary in some applications. So the concern is, are we necessarily going to have atomic clocks when we need them for various space programs? The first thing that comes to mind is how many people actually need atomic clocks. And the list is fairly short.

Who are the users?

There aren't many space users of atomic clocks

GPS

MILSTAR

Galileo

Space experiments and demonstration satellites

This is the heart of the problem

Not many users

Valuable functions

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I have left off one important one, which I realized yesterday is more important and more current than I knew and that, of course, is GLONASS; but we have GPS, we have MILSTAR, and it is an EHF version that follows it. We have Galileo and then a number of space experiments and demonstration programs.

And that is really the heart of the problem. If you look, there aren't that many programs buying clocks, certainly not in the quantity that a vendor would sell clocks to a ground user. There just isn't really enough to support a continued production, particularly when you consider there is more than one vendor. So these few number of users, to have multiple vendors, gets to be a difficult problem.

So that is really kind of where we wind up. There are only so many people that can do this. They only have so many resources. If they are in business, they would like to use those resources as productively as they can. And if you have a customer like GPS, for instance, that launches a new block of satellites every 5, 6, 7 years, and buys a few clocks then and waits another 5 or 6 years to buy a few more, it is hard sometimes to justify keeping those resources available for that kind of time.

Another problem is that you just cannot keep building the same old design. The thing I bring up here is parts obsolescence. I think it was brought up earlier this morning by the ITT paper. What I bought 5 years ago for a space part to put in this clock, I probably cannot get now. At least for some of those parts, that is going to be true. So there is an issue there as well.

Effects

Not enough being bought to justify expenditure of corporate resources to develop products

Reliability and environmental requirements for space more taxing than for ground use devices

Design changes can be extensive

Sporadic buying makes it difficult to preserve development and production teams

Parts obsolescence makes it very hard to reuse old designs for new orders

New parts increasingly harder to get in space qualified form

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There have been a lot of people concerned about this problem. I have got a list here of some of the studies that have been done. Generally, they have all come to the same conclusion, that there is certainly a danger in the future of the space clocks that we need here in the United States, and perhaps other countries as well, that they won't be available at the time that they are needed.

It is not clear what has really come out of all these studies. In fact, there is a new one now; let me show you the most recent one. There is a National Research Council (NRC) study that was just completed. There are a lot of findings in it, and I have just taken a few of theirs relative to this, and put them in here. The first one says, "Accurate time and frequency have been and are, and will be, critical to the Navy and the DoD's war-fighting capability." Number two, there is very little incentive; we just talked about that. And finally, they recommended that the PTTI function be established as what is known as "the national Naval responsibility." Some of the recommendations that come out of that are putting more R & D money in it, keeping the basic research money at least stable where it is, and adding more money into the later development areas; and beyond that, trying to make sure that the things that are developed in these R & D programs actually wind up getting used, so there is a way of inserting them into the operational programs.

S&T Program Coordination Summary

Actions to Establish S&T Supporting Effort

DoD Reliance Joint Coordination of S&T Investment
Space Technology Panel Issues 1996 9798 & 99
Electronic Devices Panel - Special Technology Area
Review (STAR) 1995
NAVTP IPT Technology Issue 1997
USAF SAB GANS Study Technology Issue 1998
IDA Industrial Space Technology Base Study 1999-2000
National Space Clock Technology Coordination Meeting NRL
June 1999
DoD Space Technology Guide 5 May 2000

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National Research Council Study 2002

Findings

“Accurate time and frequency have been, are, and will be critical to the Navy’s (and indeed all of DOD’s) warfighting capability”
“There is little incentive for commercial firms to produce PTTI devices for defense systems”
“...PTTI should be established as a National Naval Responsibility”

Recommendations

Stabilize ONR 6.1 \$
Increase ONR 6.2/6.3 \$
Insertion plans to get 6.2/6.3 advances into operational systems

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What to do?

Choices are limited

Do nothing

Buy more and save them for future use

Use fewer space clocks to minimize the problem

Put a few vendors on a technology maintenance program

Government furnishes the clocks

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So the question is what to do. Again, it depends on where you are at in the program. For GPS, it is a mature system. We are in an evolutionary process; we go long times between blocks, so we have a problem with just keeping things running. If you are Galileo, you have a new system that is building up, so for the moment, your real problem is establishing the sources, getting the clocks you need available in the first place. Then once you get that done, you fall into the same problem.

GLONASS is somewhat similar in that they have been going for a while. They have built clocks; they have had a successful system. That system declined for a while, now they are resurrecting it, and they are going to have to worry where they get their clocks and how do they keep them available for the future. And Milstar has pretty much the same kind of problem.

So what are our choices? Well, I summarized some of them, there are probably a few more than this, but at least these are the things that are being discussed. One is we don't do anything. We could buy more and stockpile them away. We could find a way not to use so many of them. We could have some sort of a maintenance program that would keep our vendors in business and going. Or we could get the government to be the source of clocks. And I will take just a minute to briefly wander through each one of these things. This is George Bush's proposal, 1992.

Stay the Course

We have done amazing things with the current approach

Maybe the doom and gloom studies are wrong
What if they're right?

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What we have done so far has actually worked very well. GPS has been very successful. Milstar has done well. So maybe we don't need to do anything, maybe these studies that say we are going to have a problem are wrong. Maybe there really isn't a problem. The worry, of course, is that maybe they were right.

So if you decide you have to do something, one of the options that has been discussed is: let's stockpile things. It is a near-term solution. You can say okay, if I am running GPS or Milstar or Galileo, I know I am going to need this many clocks over the next years; I have got a clock; I have got a vendor; I will just have the vendor make an extra two dozen clocks, or however many clocks I think I am going to need. And I'll put them in the closet. And when I need them, I will pull one out and put it on. Obviously, you take the best clock you currently have, and you preserve that clock and you keep going.

There are some drawbacks. Shelf life is limited on clocks; particularly cesium clocks do not like to sit on the shelf all that long. The next one that worries me more than anything else is that there is no progress. If in GPS we had decided back in the mid-90s that the cesium clocks we had were excellent clocks, they would do everything we needed in the program for the next 20 years, and stockpiled 100 of those clocks, we would have never have seen the rubidium that flies in Block II-R today. So you have to worry that your system isn't going to do as well. This is always a problem when you talk about these systems because there is a specification to the system. And that is what it has to do. So if you want to put something in it, or make provision for something in it that is going to do better than that spec, sometimes that is a hard sell. And, of course, once you finally run out of this stockpile, I have no idea what you do after that because now you have no sources or anything.

Stockpile

Solves some problems

Provides near term solution to meet anticipated needs

Provides work for vendors for a while

Preserves best of current technology

But

Shelf life is limited

No progress

Even harder to recover when stockpile exhausted

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Another way to get at it is to try to find ways to use fewer space clocks. There have been a lot of things talked about in GPS; for instance, you could use in the satellites themselves, maybe fly a crystal oscillator, and not use atomic clocks at all. Other programs could use GPS as their clock; they can fly crystal oscillators and GPS receivers, and get the time they need wherever they need it. In GPS itself, you could fly a clock that is not as good, and update it more often. It ought to work as long as you don't lose your ability to update or something else goes wrong you did not plan on. But I think where you are going to wind up is that you have a system that won't work as well. It certainly is more labor-intensive if you have to do more frequent updates. And if you have got a space application that is higher in altitude than GPS, then you really cannot do it without a clock, because your GPS coverage just really isn't good enough to support that.

Another thing that we talked about is to somehow make this a smoother process to the vendor. Instead of ordering the clocks in large bunches every 5 or 6 years, order a few a year and try to spread it out that way. That keeps your production capability alive, and it keeps the engineers going after a fashion.

It gets to be a problem, though, because of the way GPS does their system. And it is true, I think, for most of these military systems. You tend to buy a system all at once; you go to a prime contractor and you say, build me a system. So the prime contractor goes out and does it. He really does not have the option of spreading that system out over several years; he has got to build the system when you tell him to, and deliver it when you tell him to. So there is a difficulty there.

Find Ways to use Fewer Space Atomic Clocks

Solve the problems by reducing need

Use GPS disciplined crystals for new applications

Reduce GPS needs by more frequent updates of poorer quality clocks

Fly ground clocks with shielding and put up with increased failure rates

Some problems will remain

Probably won't work as well

More labor intensive

Applications higher in altitude than GPS

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Continuing Orders to Vendors

Buy clocks or technology between block buys for satellites

Keeps production capability alive

Provide challenges to engineering staffs to make better clocks

Some old problems persist - new ones arise

Could be costly

Who pays?

How we get satellite prime contractors to use these sources?

How do we do it fairly?

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Also, if we do this continuing order of systems some way other through the prime, how do we do it fairly? You have got more than one vendor, maybe you only need one vendor or two vendors for the next block buy of satellites. How do you decide who gets it and how do you keep these things going fairly? Obviously, there are procurement rules, but the procurement and technology may not go together too plainly.

GFE Clocks

Direct Government management to keep things going

Prime contractors on government projects must use
government furnished clocks

Assures continued availability and progress

But

Could remove incentive for prime contractors

Could be viewed as an intrusion on private enterprise

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And finally, the other option that is being discussed these days is about whether we should look at the idea of government-furnished equipment; that is what “GFE” means. You can direct a government organization to buy clocks at a slower rate; see what developing needs occur; and then provide those to the prime contractor for the vehicle as they are needed. And that sounds pretty good.

But there are a few problems there. One of the reasons that when we do these large developments, we have a prime contractor instead of a whole mess of little ones with the government running them, as we want one person who you can point out and say, “You have got to make the system work.” So if now you say, well you have got to make this system work, but you don’t have control over it anymore, you are going to get this piece from here and that piece from there, you wind up with a situation where the contractors kind of do this when you have a problem. So that is a worry that you want to be concerned about.

And finally, one of the things you worry about here from the government side, or from the industry side, is that some people will consider this an intrusion of the government into things that most rightly are a part of private industry to do.

So that is the way I see the problem. And what I would like to do at this point is to turn it over to the panel, and let these folks have a cut at it.

Mike Garvey from Symmetricom has a few comments he would like to make, so we will let him go from here.

MIKE GARVEY (Symmetricom, Inc.): Thank you, Joe. Maybe just to give a little bit of perspective on this, the organization, now Symmetricom, previously Datum, and before that, Frequency and Time Systems, has been involved in the GPS program for 30 years. And a lot of the data that we saw earlier today, especially the cesium beam on-orbit data for GPS is clocks that were designed and produced in the 70s and 80s – I think it is pretty impressive what that old technology did or continues to do.

One of the facts of life of GPS clock production is that it is intermittent, it is inter-spaced, and it is really not feasible to accept that corporate I, R, & D funds are going to develop it. So that is kind of a backdrop to the whole discussion.

What Works Well



- Guided evolution from volume commercial product to low volume space clock design
- Active DoD sponsored development in the early phases of clock design

And I think another part of it – and Joe touched a little bit on this – the evolution of clock technology is very important. We would like to take advantage of that evolution, but at the same time balance the risks so that we don't launch something that is perhaps not fully qualified. So, based on my personal experience and experience of others within the organization, I would like to start with what works well. And I think what I see working very well is if you have a commitment, a necessity to build a small number of clocks where you want to be very sure of

their reliability and performance. That it is of great value to have a large-scale commercial production on which you not only gain experience, but have various experts involved, so that you can parallel-design if you like, one of which you make in ones, twos and maybe tens; and the other that you make in hundreds and maybe thousands.

Requirements for Clock Vendor Success



- ▶ Parallel Product Technology with volume production
 - Provides critical (technical) mass
 - Statistical experience of volume production
- ▶ Experience in space manufacturing

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The other thing that I have seen work well is active involvement by DoD, and specifically by the NRL, to sponsor development in the early stages so that it doesn't wind up being rushed at the last minute. NRL has the visibility into clock technology; it has the visibility into what kind of performance is going to be needed for what kind of navigational performance as well. So they are in a good position to be able to make the technical decisions there.

I have talked a little bit about the parallel production that provides the critical mass for the technology as well as the statistical experience. And maybe an obvious thing, too, is you need experience in space manufacturing; you need the engineering expertise that understands both the quality and the technical requirements of building hardware for space applications.

If we look from our perspective of what works not so well, we see a lack of continuity in the PTTI community from one GPS block to the next. They are sort of delta functions. They occur. We all get focused and do something, and then we have the requirement to go dormant for 5 or 6 or 8 years. And, of course, the technology doesn't do that; it moves on.

What Works Not So Well



- ▶ There is a lack of continuity in PTTI from one GPS block to another
- ▶ Exclusive clock/prime contractor relationships are not desirable (so make them avoidable)
- ▶ DoD lacks long term strategies with authority and funding to make them effective
 - Taxpayer is the looser

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I also see that exclusive clock and prime contractor relationships are not desirable. And maybe to be more specific about this, the two prime contractors that have been involved in the GPS program have evolved to two different clock architectures which do not even have the same output frequency. Now, there are a lot of reasons for this, but it sort of makes the clock vendors a bit schizophrenic. I mean, which clock are we going to build for GPS III – we don't even know at this point what the frequency is. So that might be something that we could clean up. And I think, also, notwithstanding the efforts by the NRL, there really isn't a long-term strategy within DoD with authority and the funding to make it effective. And from my perspective as a taxpayer, I feel that that is inefficient.

So, today's issues lack long-term perspective. There is a lot of discussion about the health and interest of the vendors; there is also a very serious issue of quartz resonator availability, or maybe even quartz material availability.

In terms of recommendations that I would make: continue active research inside DoD to understand the science. Ultimate-performance clocks here, I am talking about some of the work, for example, at the USNO on fountains where DoD has resident experts who understand clock technology and who can help make the intelligent decisions from programmatic perspectives.

Today's Issues



- ▶ Lack of a long term perspective in space clock production
- ▶ Clock vendor “health” and interest in space clocks
 - Lack of long term vision
- ▶ Precision quartz resonator availability

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Recommendations



- ▶ Continue active research programs inside DoD
 - Science understanding
 - Development of ultimate performance clocks
 - Technical support to funded R&D in industry
- ▶ Support and fund PTTI development in industry

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Recommendations (continued)



- Address the long term issues by giving DoD a more formal role in space clock development
 - DoD supplies clocks (thru a qualified vendor) to the satellite prime?
 - Satellite prime contractor must be “in the loop” technically

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And then, continue technical support to fund R & D within industry for clocks that could fly on GPS platforms. And, of course, that involves support and funding for that.

And I think the final recommendation I would make would be to try to address the long-term issues by some formal mandate, if you like, for someone to be responsible for the long-term continuity, including perhaps supplying the clocks to the primes with all the caveats that Joe mentioned.

That concludes my remarks.

WHITE: Thank you, Mike. Let's switch gears a bit and get a Galileo perspective. Professor Leschiutta, I believe you have some material you would like to present.

SIGFRIDO LESCHIUTTA (Politecnico di Torino and Istituto Elettrotecnico Nazionale “G. Ferraris,” Italy): Beforehand, let me thank your organization for inviting me here. Here is a list of the main topics of my presentation [slides not available]. But, I want to start by just pointing out the conclusions and the thesis. The thesis and conclusions are given in this slide. You can see that in Europe there is very brilliant research. There are a lot of activities, but absent or small industrial return. That tells the whole story, because in the past, just a unique section was the French government, which promoted the construction of a rubidium standard about 35 years ago. Until a few years ago, there was no public support for the industries making clocks.

So, brilliant research, a lot of people working, good services. Widespread activities also; for instance, in Europe there are about 26 laboratories in which there is knowledge concerning the time scale formation, timekeeping, and so on.

I will support my conclusion with a lot of information. Here you can see the papers presented at PTTI over some years. This year, 2002, we are here, roughly. About 60 papers or more, one-third (20) were prepared by European laboratories. So the presence is very consistent. Another 10 papers are presented each year at the Frequency Control Symposium, for a total of 30 papers. And the papers presented in Europe at the European Frequency and Time Forum are of the order about 20 to 25 – in some cases, over 30. This is 30 papers. So it is a very important thing. Please take note that these are just the figures concerning papers on cesium beams, fountains, optical frequency standards, rubidiums, and masers.

And another piece of information: regarding the activity in the year 1999 in the European laboratories, you can see that there were about more than 25 different devices under construction. Not all are working now, but of these 15 fountains, at least half are now operating. So, it's a very strong activity in all of Europe, but no results from our point of view. Most of the people present in this room were in the industrial effort about 25 years ago, but it quickly moved to California.

In this meeting, other information was given concerning the brilliant research of clocks in France. I am just presenting two. One is concerning the operation of a cold auto transportable clock, also for space application, and construction of a double fountain using rubidium and cesium. And that fountain should reach 10^{-15} accuracy. And this is an important piece now in construction.

Now, I think this is a good time to come to Galileo. The current Galileo baseline is comprised of 30 Middle Earth Orbit (MEO) satellites. Each MEO satellite will carry two passive hydrogen masers (one will be the master), and two rubidium clocks. One of those is on hot redundancy. The clocks will be monitored by a number of ways, ranging and integrity monitoring stations globally distributed, unmanned – this is interesting – and having just the one rubidium clock here. So this is the outline of the system, and in the total Galileo system this should leave about 160-170 atomic clocks to be provided before the end of 2006, because the implementation of the program is planned from the year 2006 to 2008.

In order to help the European industry to provide those clocks, ESA made the decision to support the development of clocks. I am asking for your consideration of three words: independence, technology, and multiplicity. Those three words are the guidelines: independence from other sources; technology diversity to test the different approaches; and also a multiplicity of sources available.

ESA sponsored the development of atomic clocks, some of which were presented yesterday and today in this room. This one was presented by Detoma yesterday. Some others were presented by Rochat *et al.* [Paper 17 not submitted to Proceedings] and in Paper 14 [Mattioni *et al.*].

Again, a concern in the policy of the European Space Agency: the first task is to weigh the suitable clocks in the right number for an additional deployment phase planned for the year 2006. But there also will be the future to think about.

The future will provide the means for the moment to advance research on new clocks for the future of the system. Those clocks for the future will be the following ones: for the present, the test bed will be rubidium and maser clocks. But the following alternatives will be tested: laser-pumped cesium clocks, coherent population trapping rubidium masers, and an improved rubidium

frequency standard. So those will be the lines for the future concerning the passive hydrogen masers. In Papers 14 and 17, some views were given by Rochat, so you also have the past history of those activities.

Not all the programs are closed; there are some programs that are still open. One is the use of two-way standard frequency and time for synchronizing the two precise timing stations and the laboratories keeping UTC. Experimental verification of the orbit determination and time synchronization accuracy at the level of 1 nanosecond. And that activity at the moment is performed by a laboratory/factory in Spain. There's a possibility of inserting an external time provider in order to ensure the link between the Galileo system time with TAI.

I prepared the black and white slides; the color ones were obtained by the ESA. Here you can see the program planned for the next year. Improve rubidium. The yellow one is for long-term projects. And hydrogen masers which are active on the ground, and some that are passive in space.

One could ask how much this will cost Europe for this effort. Here you can find some figures, also given in megadollars, concerning the present phases of this project. If you add these figures, you will reach, as you say in America, billions. Two or three billion dollars. That is indeed a very large figure, but it is not astonishingly high, taking in consideration that the French and Italian governments are spending at the moment double that figure in order to construct the tunnel for the high-speed train between Lyon and Turin. Thank you.

WHITE: I would like to follow up on that with Pascal.

PASCAL ROCHAT (Temex Neuchâtel Time SA, Switzerland): Joe White sent me principal questions related to the problem of space clocks. The first problem is that there are not many users, and there is no real market for that. There is sporadic buying, which makes it difficult to preserve development and production teams for the long term. The GNSS clocks are very complicated systems and need very experienced teams. Four is the capitalization of know-how and experience over decades. That is a key point, and it is very important and it is very important to achieve. The last point: who is willing to pay for that?

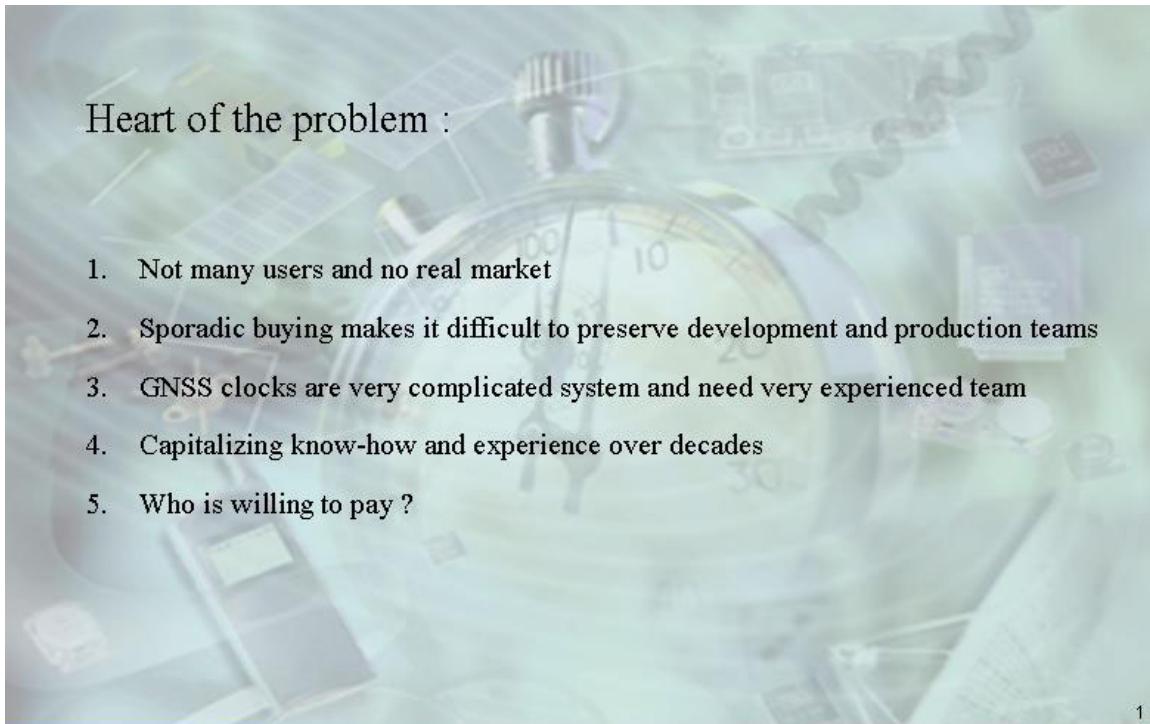
ESA addressed all these problems a few years ago, and on how it intends to solve these kinds of problems for the clocks. The first choice is technology diversity, because the first risk is to have only one technology to maintain the satellites. So the first priority for ESA was to focus on technology diversities, at least two.

The next is to have one, eventually two, companies working around one or two core technologies. For that, ESA needs to have some assurances concerning the future of the companies. A company could be bought by a competitor; it could merge. It is very, very difficult sometimes for a company to be quoted on a big gain, like in NASDAQ. So this is not going to work in assuring ESA of the long-term capabilities. ESA needs to find a member country that is willing to pay for these clocks and to maintain their capabilities.

The last point is that ESA wants to be sure to have companies involved in a space clock that have an industrial background in the same field. This is the best guarantee to maintain the expertise over the long term.

Next, how do we solve the problem of the Galileo clocks? We set up an industrial team. Temex Neuchâtel Time (TNT) is responsible at the moment for two core technologies; this means the

physics package. TNT is responsible for the physics package for the RAFS, and we have a long-term agreement with Austria and Germany, which are doing the flight electronics. This is not all core business, so we do not intend to grow doing some space electronics.



Heart of the problem :

1. Not many users and no real market
2. Sporadic buying makes it difficult to preserve development and production teams
3. GNSS clocks are very complicated system and need very experienced team
4. Capitalizing know-how and experience over decades
5. Who is willing to pay ?

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Future of Clock Technology for Space

PTTI 2002 Dec 3-5
Pascal Rochat / Temex Neuchatel Time SA / Switzerland

How ESA intends to solve the problem:

- Technology diversity (at least 2 technologies) to minimize risks.
- One (or 2) company(ies) working around the 2 core technologies
- Insurances concerning the future of this company
- Long term support to maintain the capabilities
- ESA member country(ies) willing to pay for it
- This company(ies) shall have an industrial background business in the same field.

SSO : Swiss Space Office TNT: Temex Neuchatel Time SA

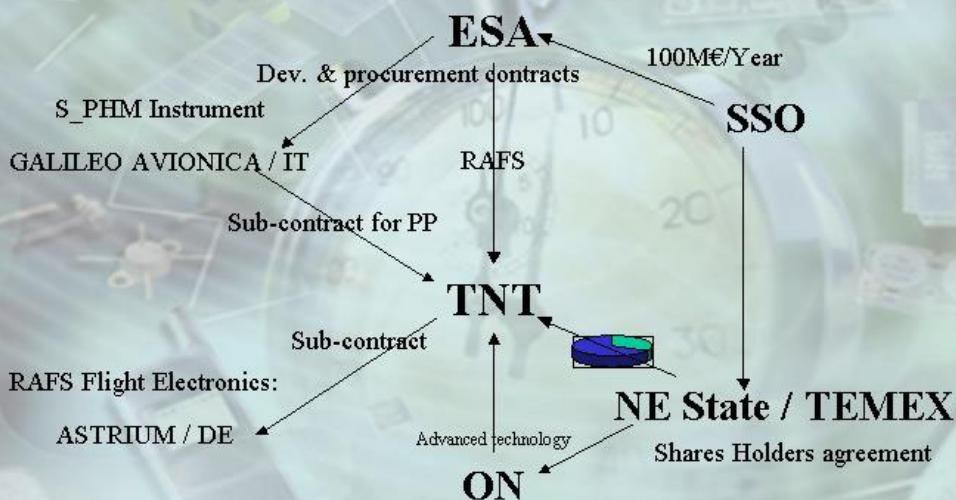
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Future of Clock Technology for Space

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Pascal Rochat / Temex Neuchatel Time SA / Switzerland

Galileo Clocks Industrial set-up:



ASTRIUM/ TNT long term agreement

GALILEO AVIONICA / TNT long term agreement

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Future of Clock Technology for Space

PTTI 2002 Dec 3-5

Pascal Rochat / Temex Neuchatel Time SA / Switzerland

Galileo Avionica is responsible for the instruments. Temex is also responsible for the physics package for the maser. This means these companies became quite important for the Galileo system.

So how we solved the problem and given all the insurances? Switzerland, the Swiss-based office here, is pushing 100 million Euro per year to the ESA organization, and Switzerland intends to pay into and to maintain these capabilities for a long term. How we can do that? Temex Neuchâtel Time is a joint venture between the state of Neuchâtel and Temex. And there is a special sharing of all the agreements behind that. And, Neuchâtel, which is active in the advancement of technology, belongs to the Neuchâtel state.

So there is advanced technology capabilities for the long term, some core technology, and some industrial prediction which guarantees expertise for the long term also, and the full support of the Swiss government for the clocks. So this ensemble will give long-term insurance to the Galileo program for clock procurements.

Thank you.

WHITE: Thank you. Let's switch back now to another program. Martin, I would like you, if you would, to discuss your experience with Milstar. I believe you also have some GLONASS information for us. And if you would like to discuss GPS, that's fine too.

MARTIN BLOCH (Frequency Electronics, Inc.): I want to start with the remarks that Ron Beard gave in his paper. He emphasized four times minimum investment. And I find this to be very disturbing. And by the way, I must compliment the Europeans on having made a much smarter approach to clocks for the present and the future, although it takes time for clocks like this to season and to be space-worthy.

The success of programs like GPS, Milstar, advanced EHF, and many of some of the classified programs were based on about 40 years of heavy investment in the development of frequency and time control products through multiple sources: at least five or six quartz companies; five or six atomic centers of doing research; and we are seeing the payback. And we have seen some problems in going from well-established clocks that look good on paper on the ground until they become performance clocks in space.

I think one of the greatest concerns of mine is that I look at the clock makers and we don't have a new generation of young scientists (maybe Europe is different, but this is at least in America) who I see will be there for us over the next decade. I made the same remark when I was asked to make a presentation for the National Research Council. It takes 5 to 10 years to make a clock maker. I find it very difficult to commit young people at FEI because space clocks are very unpredictable in their quantity and their cycle of time.

And I foresee this as a major problem that our government has to take under their wings and solve, and hopefully, not by establishing facilities in government, but by supporting a much larger clock program in the United States.

We are talking about minimum investment and affordability. Taking GPS, GLONASS, Galileo, Milstar, and the advanced EHF that you are talking about, programs that will cost approximately \$50 billion. They are all based on the ultimate results on how good the clock does. It sounds ridiculous that there is not enough money being put in on a continuous basis to support that, and it is a fraction of this money. But what also concerns me is that we spent many, many millions of

dollars trying to solve problems that occur in hardware that are being built because of the deficiencies of the clocks. And I can tell you about life reliability, frequency jumps, Allan deviations which vary – sometimes detected on the ground, sometimes not – stability, the effects of environment of clocks, which I feel has been totally ignored in space, when we are looking for more and more precise timing. We have to take in consideration effects that happen in space that are quite different than on the ground, such as vibration, the shocks due to station-keeping, the effect that Jim Camparo has indicated, that you do have solar events that upset the time. And it is true that it did not upset the timing for a communication satellite, but it sure would screw up any navigation during that period to the accuracy that we want to obtain.

So I feel that the community has to do a better job in getting recognized. We are supplying a critical part, and there has to be a continuous investment, not an intermittent investment, in order not only to build clocks, but to have the ability of a large family of scientists who improve the present status of the clock. I think that support of building newer and better-performance clocks is great, and we will always find the use if we have better performance. But the solving of the problems of the present clocks has to also be addressed. You cannot ignore the simple quartz clock; that is the basis for all the atomic clocks (or most of the atomic clocks), to the most sophisticated fountain or ion storage devices.

I would like to relate specifically FEI's involvement in GPS. We supplied quartz oscillators for the GPS program; we built some atomic standards for the early GPS; and we monitored the progress on the rest of the technologies. We also got involved early in building the quartz and rubidium clocks for Milstar and the advanced EHF that is under development right now.

Now, I just want to tell you the span. Milstar development of the clock started in 1984. The clocks were finished by 1990. They were not launched until 1995 to 2002. I think the last one is going to go very shortly in 2002. You can see the gap on this point. There was almost a 10-year gap before the next program rears its head, and this is the advanced EHF, which is the next-generation Milstar.

We need clocks, and what happens in those 10 years? Scientists lose interest, or lose jobs and disappear. Components disappear, as we all have noticed at this point. What is more is the art of building a space clock reliably, and this cannot be done, in my opinion, on an interim type of basis, where you do it over a 5- to 10-year span. There has to be a continuous process. How to accomplish that, Ron, I haven't got the solution. I only can highlight the problem.

But I think the item which is important to have a reliable future source of clocks supplied is to get a young generation of clock makers interested, experienced, and funded in order to do their work. It just frightens me that most of the real senior designers of clock technology are in their fifties to their seventies. And very, very few young people are attracted to the field, and part of it is because there is just not good stability in this area.

I think we have a job to do by ourselves, and mostly it is to sell this concept to the community that uses it. The clock development is a very, very small fraction of the total that is spent on those programs. And how to convince them that it should be done early in a stage on a continuous basis, rather to spend millions of dollars correcting the problems later on in the process, is something that maybe the Navy is the focal point to really start a program. I know in the early stages there were three major efforts on this. There was a lot of money spent by the Army in quartz development. There was a lot of money spent by the Air Force in rubidium. And a lot of money was spent by NRL and the Navy on cesium, rubidium, and quartz. Those have disappeared, at least in the United States, where the only funding is on an emergency basis when

the program comes up. And you cannot build reliable, predictable clocks on an emergency, intermittent basis.

WHITE: I would like to switch now and take a look at the U.S. government side of things. We have with us Lt. Bolger from the GPS Joint Program Office.

So, Jason, if you would like to make some comments?

LT. JASON BOLGER (U.S. Air Force): I am somewhat new to this problem. I sort of stepped into the program about a couple months ago. And this interesting problem was posed to me. There has sort of been a common theme across the board here, and I would like to simplify it and shed a little light on it. And maybe provide a couple options, not a solution because it still is really up in the air right now.

We have a unique clock here. It is a space-qualified atomic clock that requires an extreme accuracy, 10^{-14} , 10^{-15} within 1 day. That is known, we definitely need that and our requirement is increasing. This clock needs to survive launch; it needs to survive the radiation and the atmosphere of space. We are the only ones who are going to buy it. The Air Force right now is the only one who is going to buy such an accurate clock that is space-qualified.

Unless we have some other constellation satellites that need this requirement, we are the only ones that are going to buy it. With that, we have an unstable buy-time and unstable funding. Between each our blocks are Block II-R, between our Block II-R and II-F, we have a real short period of time. But we advance-purchased our II-F clocks. But between our II-F clocks and our GPS III clocks, we have a considerable amount of time. We are not going to buy clocks if they are not going to use them. What are we going to do with them? We are going to store them, put them in a shed. We have a real problem there because if we don't buy clocks, then our vendors will disperse their engineering team and our technical support. And for GPS III, we are going to be left with a severe problem.

With that is unstable funding. We are only going to fund for the current block, and in-between then we are not going to have any funding for clocks. And, by the way, when you do make these clocks, you are going to make little to no profit. And that is a big problem. So how do we attract people to build these clocks? That is also a big problem.

And we need to advance this technology. Our requirements are increasing from block to block, and we need better and better accuracy on our clocks. But to ask the GPS JPO, which is an operational office, to take its operational dollars, which they are thinking about today, and think 20 years out in its future of how we need a more advanced clock – that is very difficult because you come into a prioritization problem there.

As the gentleman hinted over here, our space community is getting older and most of our experienced personnel are not going to be around in about 10 years. So we are also going to have a problem there.

Possible solutions to fix this problem: as Joe White hinted earlier in the discussion, we could stockpile; we could go the GFE route; we could try to do an international route, a venture with the Europeans and Galileo. Stockpiling – if we buy a large amount of the current clocks that we have, there is not going to be any advancements in the technology to our GPS III block. So it is probably not going to meet our requirements for GPS III, but we will have clocks.

GFE: we run into the problem of transitioning the technology from the current vendors into a government organization. And are we going to have a decrease in performance and accuracy? That is going to take a lot of money, the transition. Where do we get that from? If we decide to purchase some clocks from international organizations, we have run into the problem of diminishing our industry here in the U.S. for clocks.

There is definitely a common theme here. If you need a clock, only the Air Force buys at unstable times, and there is little to no profit.

WHITE: Finally, to get around to the initial presentations, Ron Beard represents the NRL. We have done work in clock development for GPS for close to 30 years now. So from the lab side ...

RON BEARD (U.S. Naval Research Laboratories): Thank you, Joe. I think it is curious that the technology area that deals with the most stability, and is one of the more accurate sciences, if not the most accurate science, is unstable. There is something wrong with that. This is obviously a very difficult and complex problem dealing with everything from government procurement regulations to competitive industry, and profit, and it is a horrible problem.

Since we have been involved in GPS, and many of us since before it was GPS, we have evolved into the position of trying to support the program which, in my way of thinking, when it began back in the early 70s, was one of the first really truly joint service programs that I had been involved with. People that were on the GPS team were really more dedicated to the program than to services, as you would expect. Everybody appreciates the service rivalries within the government. But, in the early days of GPS, and I think it continues to a degree to this day, we were in the Navy; we were funded by the Navy; but it was one of the most unusual Navy programs that I was ever involved with, because our orders were to go do what the Air Force says, since they were the executive agent. And that was a rather different thing.

But our mission was to foster, develop in industry the capability of producing these clocks and handing that capability over to the Program Office. As a result, we were, I won't say liberally, but adequately (I hope I can describe it that way), funded to do that. And we supported the development of several sources in industry with the idea that we did a lot of the technology. What technology we did, we transferred to industry such as they could produce it in quantity for the program. And in early stages, that worked really well.

However, once it went operational, the whole geopolitical program changed. What we have been advocating and trying to sum up on a lot of these things is that a continuing technology program supporting an operational program is particularly needed in the area of a highly technical product like this.

I think there were some parallels in other fields, traveling-wave tubes spring to mind immediately, those sorts of things that you really need in a long-term continuing program to risk the technology that is not necessarily directly tied to the operation of the system. Because, under the division of acquisition and development that has been established in this country, it needs some independence, but it also needs to be tightly coupled. To establish something like that is very difficult, obviously.

If such a program were available and were constructed, involving young people would be much easier, because there is a program and there are things to do. It is hard to interest young people in programs where it is very difficult to do anything and changes from year to year. It is very difficult to maintain interest in that.

So, speaking as a government person, what we are trying to do is to help support this idea, remove some of the uncertainty in the market, and establish a continuing program so there is incentive to compete, contribute, and support this area. A lot of the technical things that have been mentioned really need to be explored. The resources to do that is the issue, and I probably did overstate too much this morning minimal investment, as I keep getting pounded with that all the time. Reasonable investment is what needs to be done. And that doesn't necessarily need to be a Manhattan Project. And considering the impact of GPS, these clocks do not belong in the battery equipment bay, which I have seen them at in the early stages of this program. They should be in the prime center and recognized as the thing that makes the system work. So there needs to be some investment in that. When GPS went operational, all the R & D, S & T investment dropped to zero.

We don't need it, we'll just buy a GPS receiver and do it with that. Well, that's great, but what if GPS isn't there? I won't belabor, but I think that sort of summarizes that what we have been trying to establish is that this technology needs to be advanced and preserved.

Thank you.

WHITE: Let's open up the panel for discussion.

BLOCH: Just to put some numerics on this, we spend about \$200 billion a year on government programs in electronics. This 0.02% would support a continuous program of improving clocks, generating a new generation of scientists that can go to the next generation; and what is most important is to really have multiple sources. I know the Europeans have focused a program, but again, from a United States point of view, it is one source for rubidium, it is one source for hydrogen maser, and it is one source for another type of technology. And sometimes that leads to danger and really inbreeding problems on this.

With respect to stockpiling, that is really not practical for many reasons: Not only for the advancement of technology, but we have to experience a lesson learned in the space industry. In the past 15 years, we have had occasions where programs slip by 10 years and clocks were in storage. And there were horror stories of what happens that would normally really not been a problem.

One that comes to mind is the diffusion of silver in feed-through capacitors. That is a simple kind of component, and it takes 10 years, and it continues if it is active or not. And all of a sudden, 10 years later, you find out that you have shorts that you never expected. Materials change with time.

So there are risks associated in taking clocks, in addition to not advancing the technology, because by the time you really need them, you haven't got a clock, or you have a lot of defective clocks. Refurbishing clocks, or refurbishing clocks in a satellite, has always been enormously expensive in this area. So I believe there has to be a continuous manufacturing process of clocks and the development.

Mike Garvey mentioned industry that makes products for commercial as a good base. That is definitely, in my opinion, true. That the industry that is making rubidium, cesium, or other clocks in large quantities for other commercial uses, is a good basis. But it is only a start, because there is quite a leap from making a good commercial clock to making a clock that exists for an extended period of time in space, for some known and some still-mysterious problems that we

don't know. I think if we take a look at the data presented yesterday – I have seen ground clocks, cesiums that have typically a 10- to 15-year life without any problems. We haven't experienced that in space. There is a gap of 2 or 3 to 1.

We have seen data on rubidium clocks that have 10 to 20 years' life on the ground. The rubidium clocks in space do not experience anything there. So there is some rudimentary research that has to be done to make the conductivity between what we see on the ground and what is happening in space in this area.

So it boils down, Ron, to what you have said. There has to be a national program, with or without European partnership, to establish multiple sources. And I know that some of the money is going to get wasted. But research is part of the process; you don't have results all the time. But if you put in a sufficient amount of funds, you solve the problem. So your task is to convince the government to spend \$50 million a year on clock development.

BEARD: There are a number of anecdotes that occurred to me while you were talking, Marty. On the stockpiling idea, and I have generally dismissed the idea of stockpiling because I think it really only works in the case of bricks and that sort of thing: In the early days of navigation satellites, some of you may have been told by your great-grandfathers, when Transit was being established, they did an estimate on the lifetime of a Transit satellite in orbit from the first few that were launched. And I think the calculation was like 14 months. Consequently, they went out on contract for 25 spacecraft, two of which were launched – well, maybe four. The remaining 10 plus sat in storage at their contractor facility for 20 to 25 years, well stockpiled. But as you may remember, Transit was a low-altitude Doppler satellite system; they really outlived their usefulness. But they were stockpiled and ready, in the can, at the contractor facility. Also, I think the issue is that the government really needs to try to adopt some kind of program to do this.

And I think this is in a developmental area that really needs to be established. And with today's environment, under minimal investment and high-tech philosophy, it is difficult to do. Because many of these acquisition and technology rules are made from generic things that it is in industry and it is just a matter of when you want it. Because industry supports everything, but in this case it doesn't.

GARVEY: Often in these sorts of things you come at it with a lot of ideas. Unless you sort of arrive at an approach, it is difficult to say that conclusions can be drawn. From my perspective, maybe a solution might be one of, to use the old phrase, "continuous improvement." We are in a model now where a group of clocks is built, and they sit around they are launched. And, of course, everyone holds their breath when the first new design is launched. And, in some cases, it is okay, and in some cases, it needs to be tweaked a bit. We've seen examples of that.

So maybe a model might be that, at the prime level anyway, part of the specification becomes a slot for new technology. And before we launch a bunch of clocks, we have a spot for an experimental clock. And that experimental clock successfully launched and performing on one satellite then becomes the basis for more clocks on more satellites. And we continue to evolve the process.

And for this to work, it means that somebody has got to be at the helm. And when the prime contractor changes, there has to be continuity. We cannot be faced with changing clock frequencies or maybe even changing the mounting-hole patterns. And I have advocated that there should be some responsibility within DoD, and maybe it is the Department of the Navy, for that long-term continuity.

But I think the primes would be the first to say, and I certainly agree with it, that they cannot be left out of the design picture. They are responsible for the satellite, they have financial incentives on the satellite working, and the business of the incentives will become unmanageable if they don't have some guarantee that the clocks are going to do what they need to do.

So I would sort of see it as a three-element process: the continuous improvement, part of it; the long-term responsibility within DoD to manage that; and some definition of intimate prime contractor involvement, so that they get the kind of clocks that they need, so that the business part of the satellite can work.

Maybe just as a final comment, I think I speak for all the industries here that if DoD is going in with the assumption that the clockmakers are not going to make money on making clocks, then they won't make clocks. I would love to do it from the technology perspective, but my bosses count beans. And if there aren't any beans to count, then we won't make clocks for GPS. That is the reality of life.

Now, I don't think any of us in industry would advocate that we need to take advantage of the situation and make unfair profits. But it is quite reasonable to sit down and define what "reasonable profits" are. It is done every day.

WHITE: I have noticed the contracting people and the contractors always disagree in what that amount is. There is a lot of negotiation of the issue.

GARVEY: Well, they ultimately come to some number. And like all negotiations, you wind up somewhere in the middle. But it won't work if it is zero.

BLOCH: Mike, there is a hidden profit in doing the development. And I am responsible, I am the boss that makes the decision, at least at FEI, and the clock development does not have to be, *per se*, profitable. It has to be continuous because the profit is in throw-off technology for the application; and we cannot forget it.

I also forgot to mention that for the first time in the history of PTTI, we had the GLONASS people here, and they have presented a plan and another resource of clock developments which, in this new spirit of world cooperation, they might be included the equation. And we can see how we can have a multiple, cohesive program of having clocks available. Our experience has taught us over and over again that the best clocks that are designed on paper and tested on the ground will have surprises. And in order to minimize those surprises, we have to – Mike made a very good point – we have to fly advanced technologies early enough to take what Ron emphasized, we have to get legacy of clocks before we can commit them to this.

So there is a reason for a continuous program of multiple sources, of multiple clocks in order to ensure that JPO, like GPS, has a job and has a mission. Because without clocks, you don't have a mission.

GARVEY: Clarification: I think there is a difference between making money in the R & D phase and making money in the production phase. And I would certainly agree with you that a lot of the funded development has technological spinoffs. But I think when you go into production, the opportunity to learn new technology is diminished, and the profit scenario there becomes different. And maybe that is just a distinction that we have.

BLOCH: Well, if you can call production 60 clocks over 10 years.

GARVEY: Okay, I will grant you that.

WHITE: Are there any questions for the panel from the audience?

JIM CAMPARO (The Aerospace Corporation): One thing, it seems to me my experience has been that system designers outside of the timekeeping community don't seem to recognize the need for atomic clocks. They view atomic clocks as very specialized high technology, a mature technology now, given the success of GPS, that doesn't require funding to make more advanced clocks.

And I would like to hear some comment on how to go about educating system designers about the need for atomic clocks in space. Because with my examination of space radiation, it seems clear to me that with tightening requirements on time, longer mission lifetimes, you have to consider operating through solar maximum. And I don't think you are just going to cut it with a crystal oscillator, unless you talked about some kind of GPS receiver that can correct the frequency on a time scale of minutes.

BLOCH: Jim, I think we have been in the Milstar program with system designers involved. And, unfortunately, people in the system design do not have awareness of the criticality of time and clocks and their effects until it is too late in the program. So I don't know the solution, but the education of the requirement of time has to really come from a higher authority than the subcontractor at the time where he is pressured on schedule and pressured on money. And there has to be some overview. There was at one time. The Naval Observatory, many, many years ago, had an overview of programs and said that if you have a timing on the system, we are going to make you aware of the criticality and function in this area. And I think there has to be some government organization to take that initiative.

JOHN PETZINGER (ITT Industries): All the discussion has been about clocks, and it seems to me – why don't we look at improving the age of upload by a factor of 10 or even 100 or 1000, rather than improving the clocks by a factor of 10 or 100 or 1000?

WHITE: I think that certainly an option, that is one that GPS has been discussing a lot, particularly for GPS III. I will speak to that first, and the panel may have some comments. My biggest concern has always been: suppose you are unable to do the updates. If you use, for instance, a crystal oscillator, which is usually the example that comes up, it actually may be more stable than some of these atomic clocks for periods of an hour or two. But, after that, it falls off very rapidly. So that is the concern I have. Any comments about that?

BLOCH: Well, it's also as Jim has pointed out, you have the events happening in space, and they happen very quickly. And you do not have time to really update because the whole concept of updating takes minutes or hours, and some of the events happen much faster. So you need a good clock, in my opinion, flying, in addition.

PETZINGER: I wasn't talking about not using atomic clocks.

WHITE: Just not making them not much better is what concerns you?

PETZINGER: Yes, maybe we should look at vastly improving, every 5 minutes every satellite gets corrected or something like that. I am just throwing this out to cause controversy.

GARVEY: We may be beyond it at this point, but in the early days of GPS, there was always the doomsday scenario of needing to run 6 to 8 months with nothing coming up from the ground. And that is a key military strategy, which I think has to come out of JPO and others. I mean, we're certainly not going to defend that here.

DEMETRIOS MATSAKIS (U.S. Naval Observatory): When you have limited resources, one response could be to cooperate. It is a little difficult with government contracts and competitive structure, but I wonder if there are things that could be done to foster cooperation, as opposed to competition among the few people that can make clocks.

BEARD: I can respond to that. It was mentioned earlier, the idea of GFE. That usually strikes fear into the hearts of acquisition authorities. GFE doesn't necessarily have to be a bad thing. GFE could be a government program involving both primes and manufacturers in a cooperative program, not just to develop something in isolation and give it to them, which is what gave GFE a bad name in some instances. There have been many instances in which GFE actually is a very good thing. Such a program doesn't necessarily have to be bad. So a cooperative program with a government-furnished piece of equipment that is to the prime spec, tested and accepted by them, is quite different than handing them a black box and saying "Here, use it."

BLOCH: There is a lot of cooperation, directly and indirectly, between the clockmakers, and this is one example. I mean, you have lots of technical papers being discussed, and willingly or unwillingly, we disclosed a great deal of our concepts, design, and techniques. But the basic idea is that how to implement it in hard, operational hardware on a continuous basis and to have the personnel that continue doing it from generation to generation, if you want to say it.

MATSAKIS: I just point out that there is a lot of cooperation. I have been highly amused by the fact that several people have told me that they have been ordered not to talk to me as part of the USNO, because they are involved in bidding, and they don't want any funny interactions taking place.

WHITE: Well, I think that is probably true. There are certainly competitive aspects there.

GARVEY: I think a key aspect of all of that has to be the perception of fairness around the table. The way things work these days in industry is if you work harder and if you are smarter, you succeed. If you fly up the flag of "we are all going to cooperate here," and one party works harder and is smarter, they deserve the reward. I mean, that is real life. And if you take that incentive away, it becomes very difficult to keep the people at the table. I don't have a good answer for it, but I am simply saying don't forget the incentive of working night and weekends to be better. That is human nature.

HENRY FLIEGEL (The Aerospace Corporation): I heartily agree with what the last speaker said, and we all must remember that the incentives are not only dollars over the table. The biggest incentive the companies have received in developing clocks in the past has been good publicity. Take, for example, Hewlett-Packard in the good old days. Not many people used their atomic clocks, but many people learned of the expertise that Hewlett-Packard had in that area and many others, just by the good publicity that they got. I think that is probably the greatest asset that a private maker of clocks can win into today's corporate world. And, of course, it is our business to make sure that that atmosphere continues, that we don't lose the opportunity for good publicity for those who turn out good products.

KEN JOHNSTON (U.S. Naval Observatory): I have one comment in that. One of the things that drives DoD is the establishment of requirements. And one of the problems that we have right now is that we look at how the time is that we get from GPS, and we have the clocks on GPS systems. We don't really have a requirement that really stresses as going beyond what we presently have there. And there is a reluctance among the DoD community for someone to come up and say they do have requirements. Because the person who says he does have requirements for better time, and he has to pay for it. So we do have a big conundrum here within DoD, in that we need to establish requirements for better time, but it is impossible, almost, to get anybody to raise their hand to pay the bill.

WHITE: If there are no more questions, I would like to thank our panel, first of all, for attending and presenting this. Thank you all for attending.