28TH ANNUAL PRECISE TIME AND TIME INTERVAL (PTTI) APPLICATIONS AND PLANNING MEETING

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U.S. Naval Observatory

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TABLE OF CONTENTS

SESSION II

NEW PRODUCTS FOR THE TIMING COMMUNITY

Dr. Joseph D. White, Chairman
U.S. Naval Research Laboratory

Presentations were made by representatives of Absolute Time Corporation; Allen Osborne Associates, Inc.; Datum, Inc.; Sigma Tau Standards Corporation; Telecom Solutions; 3S Navigation; TRAK Systems; and TrueTime, Inc.

SESSION III

TELECOMMUNICATIONS APPLICATIONS

Dr. Samuel R. Stein, Chairman
Timing Solutions Corporation

POSTER SESSION

Mr. Jeffrey S. Ingold, Chairman
Allied Signal Technical Services Corporation
(papers have been reassigned to Sessions VI, VII, IX, and XI)

SESSION IV

MILITARY APPLICATIONS

Commander Mark M. Atkisson, USN, Chairman
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SESSION V

OPERATIONAL PTTI

Mr. R. Michael Garvey, Chairman
Frequency and Time Systems, Inc.

SESSION VI

THEORETICAL ASPECTS OF TIMING

Mr. Martin B. Bloch, Chairman
Frequency Electronics, Inc.

SESSION VII

ATOMIC FREQUENCY STANDARD PERFORMANCE

Dr. Andreas Bauch, Chairman
Physikalisch-Technische Bundesanstalt

SESSION VIII

CONFERENCE/WORKING GROUP UPDATES

SESSION IX

TIME TRANSFER TECHNIQUES

Dr. Marc A Weiss, Chairman
National Institute of Standards and Technology

SESSION X

TIMING SYSTEMS PERFORMANCE

Mrs. Angela D. McKinley, Chairman
U.S. Naval Observatory

SESSION XI

CLOCKS IN SPACE
(originally part of the Poster Session)

PTTI OPENING ADDRESS

Admiral Paul Tobin
Oceanographer of the Navy
Washington, DC 20392, USA

CAPTAIN KENT FOSTER (USNO): Good morning, ladies and gentlemen. Again, welcome to the 28th Annual PTTI Meeting. This is only my second time at one of these meetings, but I'm sure that there are at least a few of you out there today that have been present at all or most of the prior 27 sessions. I must say that your commitment, your dedication, and your expertise are most commendable.

Before going any further into this meeting, I would like to identify, and then let us all acknowledge, the hard work of some folks who have arranged these facilities and services that we will be enjoying here for the next few days, and for the overall organization of the entire sessions. First of all, from NASA JPL, Dr. Richard Sydnor and Mr. Paul Kuhnle; from AlliedSignal, Mr. Clark Wardrip and Mr. Jeff Ingold. I'm told that are a couple uncompensated folks of a purely volunteer spirit who have spent much time this year, as in the previous years, working the registration desk. They are Betty Wardrip and Aline Kuhnle, who I assume are in some capacity associated with Clark and with Paul.

From the Hyatt Regency side of the team, the very accommodating efforts of Helene Williams and Jean Messick are very much appreciated. And from the Naval Observatory, Ms. Francine Vannicola, the Technical Program Chairperson for the PTTI Executive Committee; Dr. Lee Breakiron; and of course our all-around brochure and graphics mechanic, Nikki Jardine, have been very busy planning for the success of this meeting. Lastly, even though she said she has retired "not just from the Observatory," she is still doing her thing as the overall ramrod of style, class, and smoothness that characterize these annual PTTI sessions – at least the last 14, I'm told – Mrs. Sheila Faulkner. If you would please join me in expressing some appreciation for the hard work of all these folks.

[Applause]

As a sponsor for the PTTI meeting, I feel somewhat at liberty at making minor adjustments to the program as it's printed here in your brochure. And I am going to deviate from that tradition this morning by not presenting the PTTI opening address. Thank you, I was afraid that would draw a standing ovation from the crowd. I am even more pleased, however, that Admiral Paul Tobin, the Oceanographer of the Navy, has accepted my invitation to present the opening address. Besides being my boss, Admiral Tobin is the Resource Sponsor for the Naval Observatory's operation mission as well as for all operational meteorology, oceanography, and mapping, charting, and geodesy programs carried out by the Navy.

As a resource sponsor, he and his staff provide the Observatory with the mother's milk of sustained operations: money and people. However, Admiral Tobin's most prestigious credentials for speaking to us today are not his present duties or the fact that he happens to be my boss.

They are, rather, his career experience and success as a surface warfare officer. As such, he has been in many situations in which reliable precise time capabilities were critical to his operational responsibilities involving navigation, communications, and putting weapons on target. He has commanded two surface combatants, a guided missile destroyer, and a guided missile cruiser, as well as a battle group staff in the Western Pacific.

While not at sea, Admiral Tobin has held many key staff leadership positions ashore, including Director of Naval Communications and Information Systems and Director of Navy Information Resources Management. He holds a Master of Science Degree from the Naval Post Graduate School in Computer Systems Management, and he is a distinguished graduate of the Industrial College of the Armed Forces where, quite a few years ago, I had the pleasure to first meet the Admiral as a classmate.

Ladies and gentlemen, if you would please welcome Admiral Paul Tobin.

[Applause]

ADMIRAL PAUL TOBIN: Good morning. I'm delighted that my schedule allowed me to spend a little time with you today to tell you how much I support your work, and how important I think it is, and how important it is to the United States Navy. I'm delighted to see this large turnout. I didn't realize that the PTTI conference really had this large a turnout from industry, other government agencies, and, of course, from the Navy as well. So I'm delighted to be here today and I'd like to give you a little view into how I feel about what you're doing and the future of your work certainly in relation to the Navy.

About a year ago, I didn't know what PTTI meant. I was vaguely aware that the Navy had some association with the Master Clock up at the Observatory, and that was about it. A few things have happened since then that have heightened my awareness. First of all, when I left my last job at the Chief of Naval Education and Training down in Pensacola, Florida, the staff gave me a wonderful going away gift; it was a Garmon GPS hand-held navigation instrument.

I'm a boater, and I've been boating for years – that's what most surface warfare officers do when they take their ships away them, we buy a boat and continue to go to sea in one form or another. But I got this little device and I walked around my back yard trying to get it to work, and it was seeking out stations; and after about 8 or 9 minutes, it shut itself off; that was a feature to save the batteries – it actually consumes quite a bit of battery power. And I was very frustrated because I couldn't get it to work.

So finally I went back, as a last resort, and read the manual. And it indicated that you had to tell this device roughly where you were and you could fire it up and see where it thought roughly where you were. I did that, and at the initial starting point it thought I was somewhere in the Indian Ocean; and I was in Pensacola, Florida. So I was giving it a hard challenge. So I roughly put in the latitude and longitude of Pensacola and then about 3 minutes later it acquired all the stations and I began to see the magic of GPS.

That kind of made me ask: How does this thing work? Well, I found out that the key to GPS, as you all know, is very precise time; the more precise, the more accurate it is. But, I've become a great GPS believer. Having had commands before the advent of GPS, where I've been stuck around the Equator with bad weather, not being able to get sun lines, no Omega, no Loran, literally D-R-ing with a $500 million warship out in the ocean trying to find a little island called "Diego Garcia," I now appreciate the significance of having these instrument that really make navigation a much simpler job – and also make it a lot safer. We're working now with digital nautical charts where we can actually have a small representation of a ship on a digital nautical chart, and rather than wait 3 minutes for the navigator to take his lines of variance, make the fix and report it to the commanding officer, the commanding officer or the counting officer can see the position of the ship in a matter of 2 or 3 seconds, every 2 or 3 seconds. And it's going to certainly simplify the navigation process and help us avoid some of the accidents that unfortunately we still have.

The second thing that heightened my awareness is that I received a new job. Quite unexpectedly, I was called and asked if I would like to be the Oceanographer of the Navy. I immediately said yes because I knew it was something that I would want to do and I knew that it would give me an opportunity to learn a great deal. During the last 9 months, I have learned a great deal, thanks to Ken Johnston and Kent and all his folks; I've learned a great deal about astronomy, or astrometry, as it's correctly called; and I've also learned a great deal about oceanography and meteorology and know how come complex a subject it is; and I've also learned what an important part precise time plays in all of these domains.

Navigation, we have talked a little bit about that. Extremely important for navigation to know where you are in your own ship, to also know where you are from the standpoint of the initial launch point of a weapon system. Also, we are now incorporating GPS systems into long-range gun projectiles, and that's really saying something when you think about the electronics in a gun system has to withstand initial setback of around 2 to 3 thousand g's when it's fired; so not only does it have to be small and light, it has to be resilient to these tremendous physical forces. But the chips are now available, the capability to do that. And we're also incorporating GPS in our long-range cruise missile programs.

Precise time is also an important part of our crypto-systems, synchronizing systems – it's fundamental to that. It's also fundamental to most of our communications systems where time multiplexing is a very important part of what we do; and without precise time, it just wouldn't happen.

I'm not going to talk too much about technology this morning because there are really too many experts here in the audience for me to even risk getting into that area. But it does remind me of a story of an individual who was involved in the great Johnstown flood in Pennsylvania, a very serious event in our history. Unfortunately, he was overcome by the flood, but not before he had performed a number of heroic feats and gone through many experiences.

So when he got to Heaven, he spent a lot of time going around telling everybody about his experiences with the Johnstown flood. And I can kind of relate to that because I was in the Philippines during the eruption of Mount Pinatubo; and we were about 5 miles too close; and I learned a lot about volcanoes and I learned a lot about the frailty of human life. And my wife told me I talk too much about it and in every opportunity when people asked me about it, I would go into a long discussion. So finally she said, "How about knocking off the Mount Pinatubo stories?"

Well, this fellow up in Heaven was getting on everybody's nerves with these stories about the Johnstown flood, and he just wouldn't stop. But he went to St. Peter, and he wasn't getting a large enough audience; and he said, "I'd like to talk to the town council and make a presentation on the Johnstown flood." St. Peter said, "Really don't think we're ready for that, and we don't want you to do that." He said, "No, I really would like to do that." And St. Peter said, "Well, I think I have to warn you that Noah's going to be there."

Well, I feel like there are a lot of Noahs here in the audience, so I'm not going to get very technical this morning. But I do want to talk to you about a revolution in oceanography. Believe it or not, knowing where we are has really opened the door to a whole new world in oceanography. There are lots of twin peaks that are out there that are charted that are now suddenly being realized are not twin peaks at all, there was only one peak. And we found out that we really didn't know exactly where we were, and in terms of all of our hydrographic surveys, all the work we had done over the past 200 years, there is an awful lot of catching up to do, an awful lot of refinement. And now we truly have a capability to know exactly where we are; and we have the tools to do precise surveys of the ocean bottom, and it's opened up a whole new world.

I've been amazed at how inaccessible oceanography is. There is just an explosion of interest in meteorology – and astronomy, for that matter, tremendous interest. If you go to the Nature Company or any of the big book stores, you'll see books and books on that, not to mention personal computers where half the stores are tied up with that. But when it comes to oceanography, there is very little. And usually it's because it's so inaccessible; it's hard to see what's on the ocean bottom and hard to get a feel for it. I think now with GPS and precise navigation, that's all changing. We're beginning to paint very accurate pictures of the ocean bottom, have a much better appreciation of what's down there; it has great implications for us in the Navy for submarine navigation; it has implications in mine warfare. It's very important for us to know the difference between a high-explosive mine and a refrigerator. Those are the kinds of distinctions we're having to make on the ocean bottom, but we have the tools now that can tell the difference between a car and a refrigerator. And also, we can create databases that actually go into areas and chart all the stuff that's on the bottom, and then we can go back and do computer surveys and figure out what has changed over a period of time. So if some new large physical object has entered into that particular area, that certainly would be the basis of a more detailed search for mine hunters. It's very important technology that we're spending a lot of time on now and we're very interested in.

As I mentioned before, GPS plays a big role in our weapon systems and will play a greater role – that little problem I had in my backyard in Pensacola acquiring was a stumbling block now; but now we have new GPS systems that can acquire very rapidly or can be preprogrammed with station data before they're fired. So they literally can acquire correct positions in a matter of seconds rather than in the 4 to 5 minutes that I'm used to.

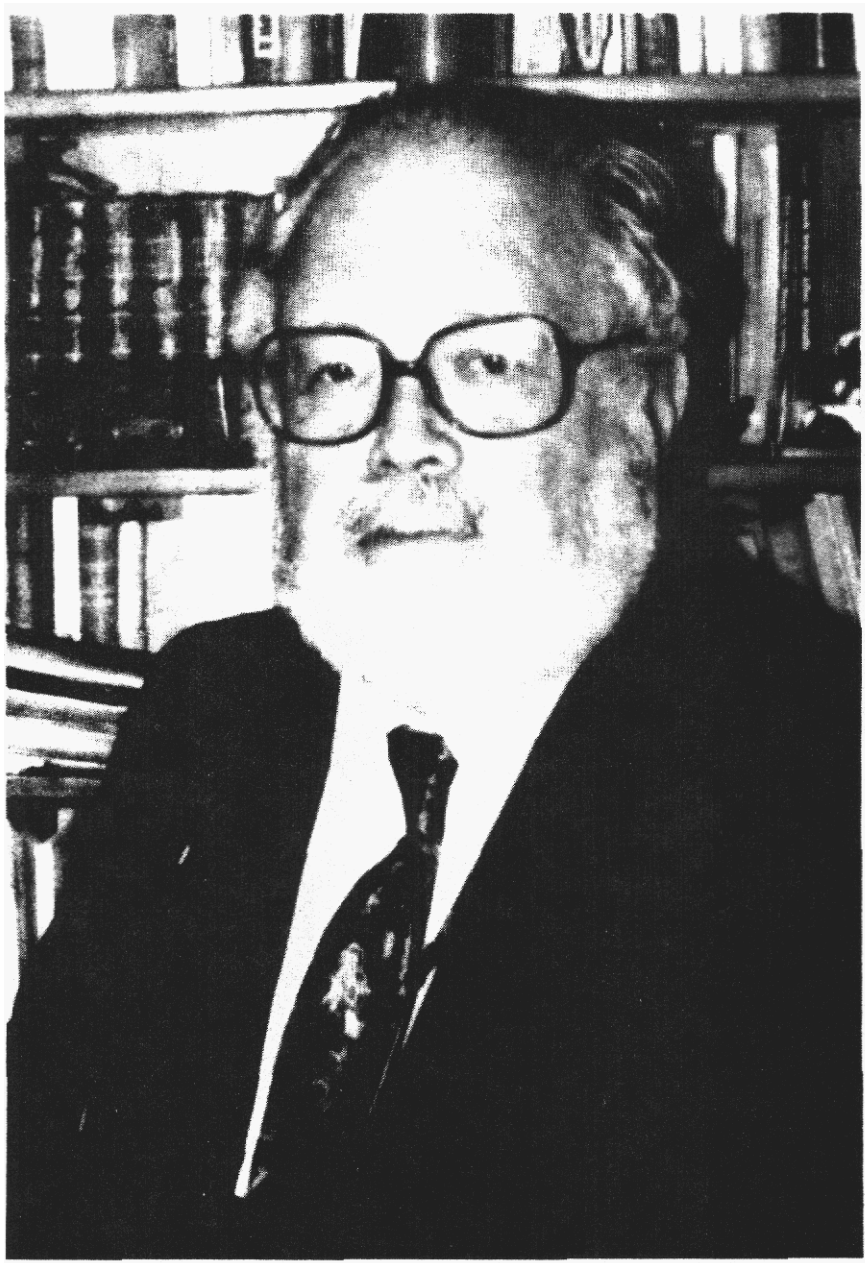
So truly, the ability to accurately predict time and time interval is a national asset. The work that you're doing, I think, is a national asset. And anybody who doesn't appreciate it should just get on the Internet like I did yesterday – I thought I'd start looking around on our Home Page and see what's available – to be able to go up and check out the performance of all the clocks and all 24 of the GPS satellites; that's kind of incredible that that kind of technology's available; and it's open to the general public and certainly is a national asset.

At one of my budget hearings earlier in the job, someone suggested that we start selling time. Of course, we jumped up and down and said, "You know, you're missing the point. That's one of the great things that we do, and we wouldn't want to do that." But there are actually people who are thinking that we ought to be selling precise time. I don't think the Navy is certainly intending to that, but that was one of the types of things that came up, because people put a lot of value on it; but it is a resource that we are glad to provide and we certainly value our role in doing that.

So, in short, it's not hard for me to understand how important your work is. I am very supportive. I know that you are thinking about new technologies, we are in the Navy; it's time probably to replace our hydrogen masers and cesium clocks with new technology. Dr. Johnston has talked to me about that a number of times. I'm a supporter of it; I'm going to support the effort, and certainly going to support continued research in this field. I thought precise time down to a microsecond was fine, but I soon learned that we're really talking about nanosecond accuracy, and we would like to do better than that. I thought 5-meter accuracy for GPS was fantastic; but now with differential GPS and what's called "kinematic GPS," we're talking about accuracies in a matter of centimeters. *Incredible* stuff, and it's all based on an accurate knowledge of time. And that's what you do, and certainly we appreciate the work that you're doing.

I hope you have a very productive conference. I'm going to be here this evening, and I hope I have an opportunity to meet and visit with you this evening. And I appreciate the opportunity to talk with you a short period this morning. Thank you very much.

[Applause]



Sigfrido M. Leschiutta

PTTI DISTINGUISHED SERVICE AWARD

Presented by
Dr. Len S. Cutler
Hewlett-Packard Co.

to

Dr. Sigfrido M. Leschiutta
Istituto Elletrotecnico Nazionale Galileo Ferraris
and Politecnico di Torino

It's a great honor and pleasure for me to help recognize at this time past achievements in the time and frequency arena. I'm very happy that I can do this for my friend Sigfrido Leschiutta, whom I've known for about 28 years. I'm sure everyone agress that he's very well qualified to receive this award, as evidenced by a long list of important accomplishments. Those who know Sigfrido well are always impressed with the number of projects with which he has been involved in a leading way and with his energy and enthusiasm.

He was with the LASSO project. He was chairman of the URSI Commission A on Electromagnetic Technology and vice chairman of the CCIR UIT Commission 7 on Time and Frequency and was also involved with the BIPM. He was chairman of the scientific council of the Italian space agency and member or chairman of several URSI working groups. He organized a number of international conferences, particularly on laser-ranging instrumentation and measurement of both G and g, and he organized two experiments on the Equivalence Principle of relativity using clocks. He helped set up a course on metrology and fundamental constants. And this is, of course, by no means a complete listing.

Sigfrido was the chief of the Time Section of the IEN, the national standards laboratory in Italy at Torino, and was active in atomic and piezoelectric frequency standards, as well as in the computation of the UTC(IEN) timescale. He set up dissemination services using TDN satellite comparisons. He has been president of the IEN for the last several years. He is a full professor of electronic measurements at the Politecnico di Torino and a joint professor of time and frequency metrology.

He has published more than 100 papers in various fields and written several books. He has a very broad range of interests and talents, as we all know. Dr. Gernot Winkler says, "Sigfrido is one of the most educated people I have ever met." Winkler talks about Sigfrido's collections of musical instruments and the books that he has written on harpsichords. He also mentions that Sigfrido is an excellent tour guide, particularly in Florence, Italy, where Gernot had the pleasure of being squired around by Sigfrido. Gernot Says, "I have very great regard for him as a wonderful human being full of esprit, patience, tolerance, and humor."

Prof. Andrea De Marchi mentions a number of things, both technical as well as personal. One time a number of people, including Sigfrido's wife, couldn't piece together the scarce information available well enough to be able to decide in which continent Sigfrido was, let alone where he was. He also talks about Sigfrido's interest in music and musical instruments of all kinds. Not only does he collect the instruments and write about them, but he also builds them. He collects antique radios and, a few years back, had about 40 of them stolen, but he still has plenty. He also collects mopeds and has a very large number of books. Andrea says, "He is a really remarkable man."

Dr. Franco Cordara has had a long association with Sigfrido and remembers many of the important technical contributions he made. He talks about the great enthusiasm that Sigfrido had for the annual USNO flying clock visits. He also mentions the joint program that Sigfrido was involved in in 1983 between IEN, the U.S. Naval Research Lab, and the Italian Navy to test out a synchronization system based on GPS. That's a long time ago. He tells of a joke letter that Sigfrido helped prepare to send from India to the IEN about the "discovery in an Indian research institute of a new clock based on the Adam's apple movement stimulated by the drinking of a particular kind of whiskey."

I remember first meeting Sigfrido in the late 1960s when he came to visit our lab in Beverly, Massachusetts. We were all very impressed with his knowledge of frequency and time technology and his great enthusiasm. His visit is deeply imprinted in my memory.

Clearly Sigfrido has made many valuable contributions to the time and frequency community as well to physics and electronics in general. He is indeed a very capable individual with great breadth and depth in his knowledge and his ability to apply it. He is also a fine human being.

With great pleasure we now give him his award and express our congratulations and appreciation for his outstanding contributions and service to our community. Sigfrido, will you please come up?

DR. SIGFRIDO LESCHIUTTA: Len Cutler was so kind as to give a list of some things I have done. I think the list is too wide. I don't think I have performed all the things you have said. But let me put the things in another way. The honor I am receiving is a big one, and I think it is my duty, since you are giving me this award, to say a few words about two groups of people that were instrumental in my activities. One group of people was here in the United States when I visited the U.S. Naval Observatory about 30 years ago. I met Dr. Winkler. From that visit I took the impression of how important it is, when a task is given, to be concentrated on and devoted to the task.

The second part of my stay was at the National Bureau of Standards, where I met Jim Barnes, another recipient of this award. And at NBS I learned the importance of the dignity of a national standards laboratory as the backbone of the research for the industry of the country. In that laboratory I met Dave Allan, who became a friend of many, many occasions. He was also with us for a period of about a month.

And finally, Len, my first visit to a factory in the United States was to you in Beverly about 30 years ago at the old BOMAC Factory. And of you and your group, I remember Bob Vessot and Jacques Vanier. From you and your coworkers I learned the importance that also a factory has to devote to fundamental research. And the 5060 was really a good accomplishment for science and technology.

This is the first group of people I have to thank. The second one are the people that are working with me in Torino. Some of them were named. I am relying continuously on the help of all my coworkers.

So thank you again, Len, and thanks again to this community.

IMPACT OF ATOMIC CLOCKS ON NAVIGATION, COMMUNICATION, AND SCIENCE

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Abstract

An analysis of the development of atomic clocks during the last decade shows that the applications, particularly where related to GPS, have grown at a rate much faster than the clock development itself. However, improved clock performances and reliability are expected to be determinant for future applications in navigation, communications, and science. This problem is illustrated considering five basic topics. The first is the relevance of space atomic clock, a subject certainly noncontroversial in the Time and Frequency (T&F) community. The second and third topics are more provocative and concern, respectively, the alternative to the use of space atomic clocks in satellite navigation systems and the associated important issue of the atomic clock lifetime. The fourth topic is an ideal program towards the realization of high performances and reliable space atomic clocks. Finally, the last topic is a review of the flight opportunities for atomic clocks around the year 2000.

1 RELEVANCE OF SPACE ATOMIC CLOCKS

It is not difficult to recognize the relevance of space atomic clocks in the framework of GPS. The GPS market is growing exponentially thanks to civil applications, which will account for 90% of the overall applications around the year 2000.[1] The economical importance of GPS is recognized worldwide and also in Europe[2], not without some concerns, GPS being a totally American system. Even if the T&F community as always been aware of the fact that the space atomic clocks are at the heart of GPS, this awareness was not common outside this community and only recently has touched the policy makers and managers, as illustrated in the following short review.

The Space Agency of Japan in September 96[3], referring to the development of a local contribution to GPS and to the four main technical obstacles identified, commented that "the onboard atomic clock is the technology giving the biggest headache." This comment contains two concepts: 1) the atomic clock technology is important, 2) the technology is difficult. The same agency in November 1996, while scaling down plans for an immediate local contribution to GPS, recommended that "Japan continue to develop related satellite navigation technology such as atomic timing standards."[4]

In Europe, the recent activity of the Observatory of Neuchâtel (ON), as external support laboratory of the European Space Agency (ESA) focusing essentially on the development of space atomic clocks, has contributed to the award of a first industrial contract for the development of a space rubidium clock in connection with the European Global Navigation Satellite System (GNSS-2) program.

In the USA, the NAPA report charting the future of GPS[5] proposes to "reduce satellite clocks errors through use of improved clocks" and also suggests the development of a suitable space hydrogen maser. From the industrial side, important and exciting plans have been made public for adding navigation payloads containing space atomic clocks aboard 12 ICO communication satellites.[6] In conclusion, the relevance of the space atomic clocks seems presently well recognized.

2 ALTERNATIVES TO THE USE OF SPACE ATOMIC CLOCKS

Alternatives to the use of space atomic clocks have been considered in the past and are still considered today. An ESA study in 1983 in connection with the navigation system NAVSAT, similar to GPS, proposed replacing the space atomic clocks by a continuous uploading of timing and navigation signals to transparent transponders on the satellites. The signals were generated by an ensemble of suitably synchronized ground stations (five stations and fifty antennas required without considering the redundancy problem).

Today, the European Geostationnary Navigation Overlay Service (EGNOS), presently under implementation, is realizing such a philosophy. The NAPA report[5] also suggests replacing, at least partially, the space atomic clocks with high-performance quartz oscillators. However, a study by the Observatory of Neuchâtel (ON) for ESA in 1993, based upon the assumption of a space atomic-clock lifetime of 7.5 years, showed clearly that, contrary to the conclusion of the previous NAVSAT report, the onboard atomic clocks could reduce the overall system complexity and cost and improve the system performance and reliability.

The same report showed also that the availability of more performers and more reliable clocks could reduce further the overall system cost and increase the number of applications, including possibly the precision landing of aircraft.

All the previous considerations are dominated by the assumption made about space atomic clock lifetimes; this is the real central issue of the problem.

3 SPACE ATOMIC CLOCK LIFETIME

The lifetime is defined as the time period during which the clocks perform according to the given specifications. The lifetimes of GPS clocks reported in the following are based on the very recent data furnished by Dr. R. Beard of Naval Research Lab, whose contribution is acknowledged.

Block II rubidium clocks:

No. of clocks: 11   Average lifetime: 1.1 years

Block II cesium clocks:

No. of clocks: 35   Average lifetime: 2.9 years

Current rubidium clocks:

No. of clocks: 4   Average lifetime: 1.04 years

Current cesium clocks:

No. of clocks: 21   Average lifetime: 3.14 years

The GLONASS cesium clocks' average lifetime, as given by Dr. Gevorkian of the Russian Institute of Radionavigation and Time (RIRT), whose contribution is also acknowledged, is approximately 1 year. With three cesium clocks onboard, a GLONASS satellite has by consequence an average lifetime of 3 years.

It is clear that using atomic clocks with a lifetime of the order of 1 year makes the overall system very costly. A logical question is then why the space clocks' lifetime is so much shorter than the lifetime of the ground clocks of the same type. It would be strange that a solution of this problem could not be found, within the capability of the present technology, in the near future.

4 PROGRAM TOWARD THE REALIZATION OF RELIABLE SPACE ATOMIC CLOCKS

The realization of reliable space clocks, ideally and historically, appears as the conclusion of a complex process involving five phases:

1) R&D accompanied by the prototyping of ground clocks
2) Production in small quantities of ground clocks
3) Production in large quantities of ground clocks
4) Prototyping of space clocks
5) Industrial production of space clocks.

This process should involve ideally the continuity of the personnel and the continuity in time through all the process. The phases 3 and 5 are typical industrial tasks. The other phases are suitable also for research institutes. Referring to the GPS rubidium and cesium clocks, all the phases of the process have been realized; however, the continuity of the personnel was not always preserved.

In Europe, with respect to the rubidium clock, the phase 5 (industrial production of space clock) has started recently. All the previous phases have been performed and the continuity of the personnel assured from the development work at ON to the production phase in a spin-off company.

With respect to the space hydrogen maser (SHM), the phase 4 is under completion, in the USA at the Smithsonian Astrophysical Observatory, and in Europe at the ON, without industrial involvement. However, the phase 3 of the SHM process is missing, being unrealistic for this device. Tables 1 to 5 illustrate in more detail the present or recent activity for each one of the five phases.

Commenting on the recent development of new microwave frequency standards presented in Table 1, we can surely predict that the future space clocks will be derived from the new developments described in this table. We can already anticipate today that more new clocks will be certainly be performing than the actual space clocks now. However, we cannot predict today their reliability, which depends strictly upon the evolution of the technology, particularly laser technology, during the next few years. As shown in Table 5, the most important effort is related to the laser-cooled clocks. A significant effort is also present in ion traps and laser-pumped devices. The reasons of the success of laser-cooling are outlined in Table 1.1. We think we are in the presence of a technical revolution of historical significance. The technique gives high line Q, high line homogeneity, and a relatively good S/N, which is expected to improve further with transverse cooling of the atomic beams. The microgravity clock, operating on a satellite in the absence of gravity, is expected to be the "ultimate" clock of the future.

Table 1.2 shows the particular contribution of the industry to the R&D.

Tables 2 to 5 illustrate the present international situation relating to the corresponding phases.

Table 5.1 is a summary of recommendations that we are trying to implement in the European programs.

5 FLIGHT OPPORTUNITIES IN THE YEAR 2000

Flight opportunities exist for demonstrating new technology and improved lifetime. Table 6 illustrates some of these opportunities.

6 CONCLUSION

In conclusion, the development of space atomic clocks is still an active process which has perhaps a bottleneck in the final phase of the process: the industrial production of reliable space clocks.

Some general reflections on how to solve this problem have been presented and flight opportunities for proving new concepts and clocks reliability have been reviewed.

In a period of shrinking budgets, a way for obtaining better results at lower cost can be through increased international cooperation. We hope that this will be the case, particularly in relation to technical and scientific experiments onboard of the International Space Station and in connection with the GPS II F Reserve Auxiliary Payload opportunities.

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TABLE 1: RESEARCH ON NEW ATOMIC CLOCKS: Phase 1

Institutes	Country	Status	Ref
Laser-Cooled Cs Clocks			
Fountains			
LPTF in collaboration with ENS, LHA	France	operational	[7]
CRL	Japan	work in progress	[8]
NRLM		" "	
PTB	Germany	" "	
NPL	England	" "	[9]
NIST	USA	" "	[10]
NRC	Canada	" "	[11]
IFTAR	Romania	" "	[12]
Beijing Univ.	P.R. China	" "	[13]
IEN	Italy	" "	
Continuous Beam			
ON	Switzerland	first clock signal obtained	[14]
LHA	France	work in progress	[15]
Other Microwave Standards			
Laser-Pumped Cs Beams			
NIST	USA	operational	[16]
LPTF	France	operational	[17]
Ion Traps			
JPL	USA	operational	[18]
PTB	Germany	work in progress	
Laser-Pumped Cs, Rb Gas Cells			
Several institutions	USA, Japan China, Europe	work in progress	[19]

TABLE 1.1: WHY LASER COOLING ?

The Magnetic Optical Trap (MOT)

MOT: appears as the historical conclusion of process dealing with a basic physics problem: the confinement of atoms for the interrogation: (buffer gas, bulb Teflon coating, Ramsay cavity with thermal beams)

MOT: allows cooling from gas phase:

Potentials:
- Relatively compact clock
- Relatively high density of atoms
- Low velocity beams (see below)

Inconvenient:
- Acceleration sensitivity

Velocity dependent effects:

	Fountain or continuous beam	Conventional Cs (including laser pumped) clocks
- Average velocity	~1M/s	100 ÷ 200 M/s
- Velocity distribution width	~cm/s	10 ÷ 100 M/s
- 2nd order Doppler effects reduced by 4 orders of magnitude		
- High line Q potential	10^{10}	$2 \times 10^{7} \div 10^{8}$
	(microgravity clock 10^{11})	
- High atomic signal potential	10^{5} - 10^{6} atoms/s	$10^{5} \div 10^{8}$ atoms/s
- High accuracy potential	3×10^{-15} REF [7]	$\leq 1 \times 10^{-14}$

TABLE 1.2: CLASSICAL MICROWAVE ATOMIC CLOCKS. NEW INDUSTRIAL DEVELOPMENT : Phase 1

	Manufacturer	Country	Main characteristics	Ref
Laser pumped gas cell Cs	Westinghouse	USA	miniaturized, low power, low cost	[20]
Laser pumped Cs beam	Tekelec Telecom	France	presented at this meeting	

TABLE 2: NEW INDUSTRIAL PRODUCTS : Phase 2

Hydrogen Maser	Various companies or institutions	RUSSIA, USA, Switzerland	Utilization in time keeping. ~50% of masers reported to BIPM show a low frequency drift $\leq 1 \times 10^{-16}$/day	[21]

TABLE 3: NEW INDUSTRIAL PRODUCTS : Phase 3

Cs beam	Hewlett-Packard High Performances	USA	low flicker floor: 6×10^{-15}	[21]
Rubidium gas Cell	Tekelec Neuchâtel Time	Switzerland	magnetron resonator 0.25 liter 0.47 kg 8 w drift $\leq 1 \times 10^{-11}$/month	

TABLE 4: SPACE ATOMIC CLOCKS DEVELOPMENTS : Phase 4

Device	Institute	Characteristics	Ref
Microgravity laser cooled, Cs clock: PHARAO	CNES - LPTF - LKB - LHA - LPMO France	ϕ = 30 cm L = 80 cm Length of interaction = 20 cm Stability goal $\sigma_y(\tau) = 3 \times 10^{-14} \tau^{-1/2}$ $1 \leq \tau \leq 10^5$ s.	[22]
Space Hydrogen Maser	SAO USA	Physics Package 70 kg Flicker floor < 1×10^{-15}	[23]
Radioastron SHM	ON Switzerland	35 kg Flicker floor $\leq 2 \times 10^{-15}$	[24]
Space Rubidium			
DWE / Cassini-Hugens	Dornier satellites system, Germany	1.8 kg 2,3 liters 12 watts 40 g	[25]
Radioastron S-RUSO	ON	1.2 kg 1.2 liter w = 8 w $\sigma_y(\tau) = 1 \times 10^{-11} \tau^{-1/2}$ $1 \leq \tau \leq 100$s drift 4×10^{-11}/month	[26]

TABLE 5: SPACE ATOMIC CLOCKS. NEW INDUSTRIAL PRODUCTS : Phase 5

GPS / GLONASS	Business as usual	
ESA GNSS-2 S-RUSO - GPS compatible	Tekelec Neuchâtel Time Switzerland	Specs ≤ 1 kg ≤ 0.6 liters ≤ 10 watts Flicker ≤ 5×10^{-14} Drift ≤ 1×10^{-13}/day

TABLE 5.1: IMPROVING THE SPACE ATOMIC CLOCKS RELIABILITY AND LIFETIME

Establishing a better connection between the space clock production and the industrial production of ground clocks.

- Use of same critical physics package hardware for space and ground clocks.
- Space electronics derived from the industrial electronics package for ground clocks.

Scientific study of the clock lifetime limitation factors.

- Identification of the problem areas.
- Study of the phenomena (normally related to the physics package).
- Solution of the problems (typical example: the GPS Rubidium lamp aging problem successfully solved).

Extensive long term ground testing prior to launch.

TABLE 6: OPPORTUNITIES FOR SPACE CLOCKS UTILIZATION IN THE YEARS 2000

		Ref
□	Radioastron S-VLBI mission 2 S-RUSO + 1 SHM	[27]
□	GPS II F — Flexibility Reserve Allocation: 154 kg 465 W thermal power 350 W DC power	
□	International Space Station	
-	EXACT (Experiment on Atomic Clocks and Timing)	[28]
-	ACES (Atomic Clock Ensemble in Space) Microgravity clocks, SHM, Ion Traps, Laser Time Transfer	[22]
□	NASA Research Announcement Proposals: Fundamental physics in μ-gravity: Laser cooling, atomic physics, gravitational and relativistic physics	

Questions and Answers

SAMUEL STEIN (TIMING SOLUTIONS CORP.): Which is really better, do you think, clocks in space or to do synchronization from the ground clock continuously?

GIOVANNI BUSCA: The answer is very simple. As far as the atomic clock is working, it's much better to have the atomic clock in space. Cheaper, more performance, more reliability. But it has to work, of course.

ROBERT DOUGLAS (NRC, CANADA) : I would just like to comment. It's dangerous to believe someone unreservedly has a vested interest in clocks in space. I have a vested interest in clocks on the ground and not in space, and I agree with Giovanni.

RICHARD GRIFFIN (TEXAS INSTRUMENTS) : On the short lifetime in space clocks, has there been any correlation worked out between space environment effects, particular proton belts, and the short lifetimes?

GIOVANNI BUSCA: I think this question should probably be answered by Ronald Beard. From what I know myself, it's just an impression, the lifetime limitation is associated more to electronic problems than anything else.

RONALD BEARD (NRL) : Thank you. It's a complicated answer to the lifetime issue that's an average lifetime of operation. As far as we can tell, and many people have looked at it, there is a radiation effect on them *per se*. It's a complicated interaction within the system. And, say, the average lifetime is so long, a number of them failed early, but quite a few of them have operated for a long period of time, except for the rubidiums, which seem to be consistently of short duration.