

PROCEEDINGS
OF THE NINTH ANNUAL
PRECISE TIME AND TIME INTERVAL
(PTTI)
APPLICATIONS AND PLANNING MEETING

Held at NASA Goddard Space Flight Center
November 29 - December 1, 1977

Sponsored by
Naval Electronic Systems Command
NASA Goddard Space Flight Center
Naval Research Laboratory
Naval Observatory
Defense Communications Agency

Prepared by
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Subject: Human Periodic Phenomena

CALL TO SESSION

Dr. James A. Barnes
National Bureau of Standards, Boulder

WELCOME ADDRESS

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FOREWORD

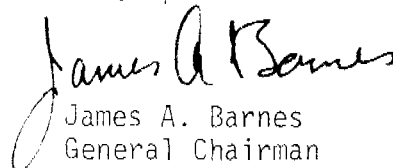
The Proceedings contain the papers presented at the Ninth Annual Precise Time and Time Interval (PTTI) Applications and Planning Meeting. The questions and answers following the presentations are also included after each paper.

This meeting provided an opportunity to exchange information on precise time and frequency technology. The attendees came from various U. S. Government agencies, private industry, and universities. A number of foreign countries were also represented.

The meeting was divided into six sessions:

- I. Topics of Special Interest
- II. Very Long Baseline Interferometry (VLBI)
- III. Time Transfer Techniques
- IV. Time Distribution
- V. Hydrogen Masers
- VI. Frequency Standards

On behalf of the Executive Committee, I want to thank all those who contributed to the success of this year's meeting. Special credit should go to the Technical Program Chairman and his committee, the Editorial Chairman and his committee, the Session Chairmen, Speakers and Authors.


James A. Barnes
General Chairman

CALL TO SESSION

Dr. James A. Barnes
National Bureau of Standards

DR. BARNES: Good morning. I am Jim Barnes with the Time and Frequency Division of the National Bureau of Standards. It is my pleasure to call to session the Ninth Annual Precise Time and Time Interval Applications and Planning Meeting.

The main purpose of my opening remarks this morning is to handle a few housekeeping details and then introduce the speakers for the Welcoming Address and the Opening Comments. But first, I want to take this opportunity to call your attention to the banquet Wednesday evening. The speaker is Professor Franz Halberg, who will speak on "Human Periodic Phenomenon," which is a time and time interval problem and somewhat akin to what we are doing here. If not quite as precise as we will be talking about for the next three days, it should be at least interesting. I would heartily recommend that you consider the banquet.

I also want to bring up my personal indebtedness to the members of the organizing committee who are listed in the program, and I want to take this opportunity to publicly thank each and every one of them. I would like to give some special thanks to a few members of the group: in particular, Clark Wendrip of NASA, who has handled the many, many details of putting the meeting together; and Lauren Rueger, who was the General Chairman last year, for his guidance and assistance in helping me understand what needed to be done. Also, of course, I must thank Henry Pliegel of JPL, who is this year's Program Chairman, for putting together an excellent program for the meeting.

Now to a couple of housekeeping details. As I am sure most of you remember, the questions, answers, and comments that follow each of the technical papers are recorded and transcribed into the published proceedings of the meeting. It is important that you use a microphone so these comments get on tape and that you state your name and affiliation so they can be attributed to the right person. In this way, we can get the proper documentation and the proceedings will go much easier.

At this time, I would like to call on the representatives of the agencies who sponsor the PTII meetings, and to start with, Dr. Robert S. Cooper, Director of NASA Goddard Space Flight Center, will present the Welcoming Address.

WELCOME ADDRESS

Dr. Robert S. Cooper
Director, Goddard Space Flight Center

Thank you Dr. Barnes and good morning ladies and gentlemen. It was my pleasure last year to welcome you to the PTTI Meeting hosted by the Naval Research Laboratory as a representative of one of the Sponsors. I am very pleased to welcome you here this morning to Goddard as the host. This is the fourth (4) time that Goddard has had the pleasure of hosting this annual meeting. As everyone has probably become aware of by now it has become traditional for Goddard and NRL to alternately host these important meetings.

Last year I talked briefly about some of our programs in the PTTI and related areas. We have made progress over the past year which is worthy to note.

To bring you up to date on our hydrogen maser frequency standard activity, the four (4) Goddard built (NASA Prototype) NP type masers continue to be the backbone of our frequency standard field work. These four (4) masers have impressive field operable records. They have accumulated a total of thirty-three (33) years of field operation and have traveled over one hundred and twenty thousand (120,000) miles to thirty-five (35) separate installations in support of various VLBI programs in the geodetic and astronomical work such as the ARIES, MJS (Mars-Jupiter-Saturn) and the Goddard VLBI validation program.

We hope that the second generation hydrogen masers that we are presently designing and constructing with support from the Applied Physics Lab will have an equally impressive record. These new masers which we call NASA Research or NR Hydrogen Masers have oscillated and are nearing final assembly and testing.

With the NR masers, we hope to achieve the performance of our latest experimental masers in a rugged package designed to simplify field set up and maintenance. These masers will have a microprocessor based electronics package which among other things will monitor its own performance and perform self-diagnosis.

Work on our variable volume hydrogen masers and a new mercury ion frequency standard is continuing. As you have heard us mention in the past, we hope to achieve 10^{-14} frequency accuracy with these devices. I might mention that because of some recent measurements we made with our Concertina Maser and a new capillary bulb collimator developed at Williams College under a NASA grant, we think we can develop field operable hydrogen masers with a line of 6.5

times ten to the ninth. This maser is presently being designed and promises to yield parts in 10^{16} frequency stability.

Our new Frequency Standard Test Facility will at last be complete early in 1978. We have long awaited the completion of this separate isolated building. This new facility, in addition to housing hydrogen masers of various designs and configurations for our R&D programs, will contain an automatic data acquisition system capable of intercomparing up to 16 frequency standards with picosecond resolution. The facility will basically be used to study the long term stability, environmental performance and accuracy of hydrogen masers under controlled conditions.

As I mentioned we use hydrogen masers in support of VLBI work. Goddard, with collaborators at MIT, Haystack Observatory and colleagues at JPL, pioneered in applying hydrogen maser techniques to VLBI measurements in the geodetic and astronomical work. Hydrogen masers of various designs are currently at use in tracking stations, and radio astronomy stations in Massachusetts, California, West Virginia and Sweden, to study polar motion, the structure and kinematics of quasars and to develop VLBI techniques for subdecimeter accuracies necessary to measure continental drift.

The VLBI activity at Goddard in FY-78 will include the completion of the development of the wideband, centimeter accuracy Mark-III VLBI system. Breadboard Mark-III system tests were successfully completed in September and the implementation of the final system is underway. This Mark-III system will be used in the planned operational polar motion/UT.1 network of the National Geodetic Survey.

Starting next month, Goddard and JPL will jointly construct an interim intercomparison between the satellite laser ranging and the older Mark-I and Mark-II VLBI systems for measuring transcontinental baselines between Haystack Observatory, Massachusetts, Goldstone, California, and Owens Valley Radio Observatory, California. This is part of the NASA validation program to prove the capability of laser ranging and VLBI for measuring small crustal motions.

Since VLBI utilizes hydrogen masers and correlates the received signals from widely separated stations, VLBI has the potential of very accurate time synchronization between these stations. In March 1977 the GSFC/Haystack Observatory/MIT VLBI group and the U. S. Naval Observatory conducted a VLBI time synchronization experiment between stations at Haystack Observatory (Westford, Massachusetts) and the National Radio Astronomy Observatory (Greenbank, West Virginia). The synchronization was found to agree to within 25 nanoseconds with an independent synchronization by USNO traveling cesium clocks.

In addition to our frequency standard work and VLBI activity, Goddard also has requirements for very precise global clock synchronization, and we are continually looking to new techniques to meet our timing needs. As I reported last year, in cooperation with the Applied Physics Lab and the Naval Surface Weapons Center we were developing a time transfer receiver which would utilize the NRL developed Navigational Technology Satellites for world wide sub-microsecond clock synchronization. I am very happy to report that these time transfer receivers are being implemented into our eight (8) transportable laser tracking vans. One of the NTS time transfer receivers is on display at the rear of the auditorium. I would like to congratulate Roger Easton's group at NRL and others for the successful launch of NTS-2 this past summer. I know that the paper scheduled for presentation on the preliminary results of the NTS-2 satellite should be very interesting.

During the early to mid 1980's there will be two U.S. satellite systems that can be used for sub-microsecond clock synchronization. These two systems are the DOD Global Positioning System (GPS) and our own NASA Tracking Data Relay Satellite Systems (TDRSS). I see from the program that papers will also be presented on the use of these two systems for tens of nanoseconds global timing.

Among our guests today from the other PTTI sponsoring agencies are Rear Admiral Earl B. Fowler, Jr., Commander of the Naval Electronic Systems Command, Captain Joseph C. Smith, Superintendent of the Naval Observatory, Dr. Gart Westerhout, Scientific Director of the Naval Observatory and Dr. Alan Berman, Director of Research of the Naval Research Laboratory.

I would also like to welcome and acknowledge the attendance of the many foreign nationals. Your presence here makes the PTTI Meetings that much more meaningful. Goddard looks forward to continued cooperation with each of you and this includes our friends here at home.

I think that it is significant to note that of the 34 papers scheduled for presentation, ten (10) will be presented by authors from other countries. This world wide participation is evidence of the importance that the PTTI community and you the attendees place on these annual meetings. I encourage you to continue your efforts.

I look forward to participating in the Sessions as my schedule permits and I hope to get a chance to talk with many of you during the sessions. I thank you for coming and hope that you have a rewarding three days here at Goddard.

Thank you.

OPENING COMMENTS

RAdm. Harl B. Fowler, Jr.
Commander, Naval Electronic Systems Command

RADM. FOWLER: Thank you very much, Dr. Barnes, and good morning, ladies and gentlemen. It is my pleasure to be here at Goddard Space Flight Center this morning as one of the co-sponsors of this meeting. I welcome each of you and especially our distinguished foreign visitors. The Naval Observatory, the Naval Research Laboratory, the Naval Electronic Systems Command, the Defense Communications Agency and the National Aeronautics and Space Administration, Goddard Space Flight Center, are co-sponsoring this event which bring together many of the national and international agencies with responsibilities and interests in PTTI.

It is quite appropriate that three Navy organizations participate in this co-sponsorship. It was the increasing speed of ships as sail gave way to steam and their need for improved timing to improve navigation that placed the United States Navy in an early leading international position in PTTI.

Our illustrious Naval Observatory has from early time been the timekeeper of the world, and much later our very renowned Naval Research Laboratory began to play a key scientific and engineering role as the use of PTTI became important to communication and then later to almost all electronic systems.

The Naval Electronic Systems Command is a late arrival on the PTTI scene, but we now have a key role also. It among other things contains the Navy project management for the newest navigation system, the Global Positioning System which Dr. Cooper mentioned, so now PTTI has come full circle.

We need your best PTTI efforts to improve navigation once again. Just as our forefathers saw sail give way to steam, we modern naval officers are seeing the most exciting and revolutionary changes in our ships and airplanes, spacecraft, weapons, and command systems. Your best PTTI efforts are needed now in more ways and in more places for more uses than ever before. For the scientists here I challenge you to put forth your best ideas, and for my colleagues the

engineers here we must do substantially more to make communicators and navigators, the data processing specialists, and so on, the designers of these systems, understand better the fundamental place for PTII in their design concepts.

Since the last time I addressed this meeting, the Naval Electronic Systems Command has grown and matured in its assignment as the Navy manager for PTII. We have developed a master plan, which has provided the Navy's PTII program with a new system concept and program direction which will meet the current and future PTII requirements of the Navy and also be in accordance with the Naval Observatory's plan for the Department of Defense PTII program.

The new concept for a PTII system will provide the communication and navigation systems on Navy ships and aircraft and stations with PTII information from the Naval Observatory to the required accuracy on a continuous worldwide near real time basis via two major subsystems. These are a primary worldwide PTII dissemination subsystem and a standardized local distribution subsystem.

Today the technology is satisfying the current Navy PTII requirements. However, it appears that we must continue to improve on that technology in order to meet the needs of tomorrow. This does not negate the need I outlined the last time I addressed this planning meeting to encourage maximum usage of existing capabilities, to minimize the proliferation of PTII equipment and systems. This need to improve technology and to maximize the use of existing systems emphasizes the need for exchange of ideas and the dissemination of information, which these meetings provide.

I encourage each of you to take full advantage of this forum to increase your knowledge and understanding of the problems, techniques, and capabilities. The work you are doing is so very, very important.

I am certain that our NASA hosts will provide once again an enjoyable and informative meeting, and I certainly thank each of you for your participation. And I wish you the very best for this session. Thank you very much.

OPENING COMMENTS

Captain Joseph C. Smith
Superintendent, U. S. Naval Observatory

CAPT. SMITH: Dr. Barnes, Ladies and Gentlemen. It is indeed a pleasure to have the opportunity to address the 9th Annual PTTL Planning Meeting. I thought it would be appropriate today to give a status report of where we have been this past year and where we intend to go this next year in PTTL and timing matters. I have found this past year at the United States Naval Observatory most enjoyable and stimulating working in this important field. During this past year we have made advances in at least 10 separate timing matters:

1. The West Coast Loran-C chain has been synchronized and is now directly traceable to the U. S. Naval Observatory Master Clock.
2. The U. S. Naval Observatory Master Clock is now automatically updated by computer to provisional U. S. Naval Observatory mean time. This additionally includes a new computer system which was put into operation in Richmond, Florida.
3. Our publications have expanded in order to better service the many users of PTTL worldwide. There are over 1200 different organizations and individuals on our mailing list for various Time Service Announcements of which 300 are foreign. Series 4, 7, and 17, which are published weekly, go to about 800 different subscribers. Times of coincidence tables for the new Loran-C chain are sent out to over 400 subscribers. The new experimental series precise time transfer report is sent out to over 200 subscribers. It contains results of satellite and television timing transfers, portable clock trips, and Loran-C monitoring. The experimental series 6 publication is now sent to over 100 subscribers. This series contains time and latitude observations at Washington and Richmond and other data.
4. In the astronomical area, we are now determining UTC using new and different PZT's. The 65-centimeter PZT number 7 has become operational in Washington, and the 20-centimeter PZT number 6 has become operational in Richmond, Florida, along with a microdensitometer to measure plates there.
5. We have expanded our telephone service to include daily TV, Loran-C, and VLF phase values. The telephone series 4 is now available on both commercial and autovon numbers.
6. In the area of satellite usage for time transfer, the U. S. Naval Observatory has worked with the Transit Satellite Office on the commercial development of a transit time recovery receiver, which will

allow worldwide 25-microsecond time synchronization traceable to the U. S. Naval Observatory Master Clock. Additionally, the Naval Observatory was the prime mover in obtaining the funds necessary to build the first GPS timing receiver.

7. In the area of TV, our time work has expanded to now include Channel 11, KTTV, in Los Angeles. This station is used for distribution of absolute time traceable to the U. S. Naval Observatory Master Clock.

8. Our portable clock trips this year have visited 5 continents. They have gone from north of the Arctic Circle to south of the Tropic of Capricorn. They have traveled halfway around the world, east and west, visiting some 70 installations worldwide.

9. We have not neglected international cooperation and assistance in monitoring various timing systems. We are currently working with 10 different countries at 11 different sites on timing matters worldwide.

10. In the area of VLBI time transfers, we have had the opportunity to work closely with NRL and NRAO in setting up time transfer experiments. These experiments, conducted with Haystack and Algonquin Park as well as Green Bank, West Virginia, have proven most useful in setting the course for future VLBI work.

During the coming year, we intend to continue these areas as well as push forward in 10 other areas of concern.

1. We will be working on the synchronization of the Canadian West Coast and Alaska Loran-C chains.

2. We will develop an algorithm to compute UTC (USNO) in real time.

3. We are constructing an additional clock vault which will house the special clock boxes developed by the University of Maryland, and we plan to continue the applied research using the University of Maryland team working in close conjunction with our scientists.

4. The series 16 publications will be expanded from 4 to 6 pages in order to contain more Precise Time Reference Stations (PTRS).

5. Construction of PZT number 8 has started and will be part of our overall astronomical instrumentation system to better observe time.

6. We will begin observations with NRAO utilizing their 35-kilometer interferometer.

7. The GPS time transfer unit will continue to be developed and the first operational test will take place at the Naval Observatory upon

receipt of the unit.

8. The Washington local distribution of time utilizing TV will be further improved with a goal of 1 nanosecond precision.

9. We shall continue VLBI experimentation in conjunction with the Max-Planck-Institute (West Germany) and the NRL Maryland Point facility for time transfer.

10. We shall continue work with the Department of Defense on time details in order to strengthen the timing capabilities and procedures so necessary for the DoD to meet the future challenges of improved and rapidly-increasing technology requiring precise time.

It is our sincere desire at the U. S. Naval Observatory to continue to support the important role of timing in DoD and in the Navy. Obviously, these efforts carry over both nationally and internationally. It has indeed been a pleasure for me to have had the opportunity to meet many of you during this past year, and I look forward to meeting many more of you during the coming one. Please do not hesitate to call us on timing matters at any time. We are happy to be a part of this most important undertaking. I am sure this meeting will once more point out new avenues to explore and new challenges to conquer. We of the Naval Observatory wish you well in this important collective endeavor.

WELCOME ADDRESS

Dr. Alan Berman, Director of Research
Naval Research Laboratory

On behalf of the Naval Research Laboratory, I would like to welcome you to the Ninth Annual Precise Time and Time Interval Application and Planning Meeting. It is a pleasure for NRL to act as one of the Co-hosts and Sponsors of this meeting. As Director of Research of NRL, it has been my privilege to welcome five or six previous meetings in this series. I have noted that the PTTI meeting has grown in prestige each year. From rather small beginnings, attendance has expanded remarkably and each year has seen more and more foreign attendance.

In the course of writing welcoming addresses over a period of years, I have run out of anecdotal information to use as filler material. Therefore, I think it is appropriate that I look somewhat seriously at the progress which has been made by the PTTI community over the span of the last nine meetings.

I am impressed with the progress that has been made in the availability of frequency sources since the first meeting. While rubidium and cesium sources were generally available nine years ago, they have been made extremely compact, highly reliable, radiation hardened, and space qualified. Indeed at this moment, there are cesium sources in space in the NTS-2 satellite. Ten years ago a hydrogen maser was a large ungainly installation that required a team of PhD's to act as baby sitters. There are some who claim that this is still the situation. Actually, I think considerable progress has been made and we are developing hydrogen masers which will be space qualified, physically compact, and relatively light. For those of you who get a chance to visit Roger Easton over at NRL, I think he can show you some space qualified hardware that has been functioning for several years and is yielding excellent performance.

Above and beyond the development of hardware in the last nine or ten years, I am impressed by the broad recognition that has come about of the importance of precise time and time interval. The application of precise time and time sources to navigation is well understood and is based on the pioneering work of your community. The US will launch the GPS series of satellites. These birds will allow unprecedented navigational accuracy with all the attendant benefits to the military and civilian components of our society that you know well. The application of PTTI technology in the area of communications has allowed better and faster synchronization of communication links and the use of more sophisticated cryptological techniques. Geodesy, geophysics, long base line radio astronomy, and interferometry have certainly blossomed in the last ten years. Ultimately, all of the advances in these fields stemmed from the general availability of precise time sources and from our improved ability to transfer time. A possible breakthrough for society is the application of the long base line interferometry for detection of strains in the earth's crust. It is possible that this will provide earthquake warnings with great savings of life and possibly property. Missile and satellite tracking systems, meteorology generally, and a wide variety of maser application are subjects that are the substance of this meeting and areas where your community can generally be quite proud.

We at NRL are proud of the part we have played in the time and frequency field since we first opened our doors in 1923. We have been keenly interested in most of the developments in the field from that day to this. It is quite evident that the requirements of frequency stability and time precision will continue to increase in the future as they have in the past. It is therefore, with great pleasure that I join the other hosts in welcoming you to this conference.