PRECISE TIME AND TIME INTERVAL (PTTI), AN OVERVIEW

Gernot M. R. Winkler
Naval Observatory

ABSTRACT

Present applications of precise time and frequency (T/F) technology can be grouped as follows:

1. Communications systems which require T/F for time division multiplexing and for using spread spectrum techniques.

2. Navigation systems which need T/F for position fixing using a timed signal.

3. Scientific-Metrological applications which use T/F as the most precisely reproducible standard of measurement.

4. Astronomical-Space applications which cover a variety of the most demanding applications such as pulsar research, Very Long Baseline Interferometry (VLBI) and laser/radar ranging. In particular, pulsar time-of-arrival measurements require submicrosecond precision over a period of one-half year referred to an extraterrestrial inertial system, and constitute the most stringent requirements for uniform timekeeping to date.

The standard T/F services which are available to satisfy such requirements are based on an international system of timekeeping coordinated by the Bureau International de l'Heure (BIH). The system utilizes the contributions from the major national services for standard frequency and time (USNO and NBS in the USA), and it is implemented through a variety of electonic systems (HF, T/F signals, VLF, Loran-C, etc.). The performance of these systems will be briefly reviewed. Several

of the user systems (such as VLBI) can, in turn, be used as contributors to the global effort of T/F distribution.

Moreover, PTTI is the one common interface of all time-ordered electronic systems. Time coordination (not necessarily synchronization) is the first necessary step for any wide scale integration and mutual back-up of such systems.

OVERVIEW

In this short overview we can only mention the major aspects of time and frequency (T/F) which will be discussed extensively in the papers of the Proceedings. The main concepts are as follows:

1. Time of Day → UT1 (Rotation of Earth)
2. Clock Time at Standard Meridian → UTC
3. Synchronization
4. Accurate Frequency
5. Relativity: Local (Proper) Time, Coordinate Time
6. Coordination: 1 ms → 10 μs progress during the last 10 years.

For economical as well as practical reasons, SYNCHRONIZATION will usually be accomplished via clock time (UTC). Very accurate frequency cannot entirely be handled without also considering time. Relativity aspects must be considered if precision of better than a few hundred nanoseconds is involved. Lastly, the various international time services are coordinated with the BIH to the order of 10 μs - 100 times better than required by pertinent CCIR recommendations.

T/F has become a very active field during the last 10 years, due largely to the availability of commercial atomic clocks. Information is exchanged at a number of regular conferences, including the following:

1. Annual Frequency Control Symposium*, Atlantic City (U.S. Army), May.
2. CPEM, next meeting June 1976, Boulder (NBS-URSI-IEEE, Conference Proceedings in IEEE Trans. IM).
3. PTTI Planning Meeting*, Washington, December (annually), NASA-DoD.
4. URSI Commission 1 (National Meetings).

5. URSI Commission 1 (General Assembly (3 years), next in Lima, August 1975).
6. IAU, Commission 31, General Assembly (3 years) next Grenoble, August 1976.
7. International Congress for Chronometry* (5 years), last September 1974.

*Proceedings available

In addition there are regular training seminars by various groups, e.g., the NBS T/F seminars.

Let us consider the uses of T/F:

1. UT1 (mean solar or sidereal time) which is related to angular orientation of the Earth is needed for navigation, space tracking and geodesy. Essentially this application group is concerned with the orientation of the Earth in space and its rotation around its axis.

2. Other major uses deal directly with clock time. These applications come from a variety of time-ordered electronic systems:

a. Communications Technology

1) Time division multiplexing - channel packing, many stations on one frequency.
2) Reducing spread spectrum acquisition window.

b. Electronic Navigation in TOA Mode (Absolute)

1) For improved geometry of position determination (RHO-RHO).
2) For improved coverage - mixed systems.
3) For integration with communication and identification systems.

c. Metrology

Time and frequency are by far the best controllable parameters and can be used for measurement of length, voltage, pressure, temperature, etc.

d. Astronomy - Space Technology. This last application has the most stringent requirements - fractions of a microsecond over 1/2 year related to an inertial system (with relativity corrections for the movement of the Earth in the solar system).

These requirements for precise time are being satisfied in a variety of ways; with time signals, publications and superpositioning of the timing capability on existing electronic systems.

We have available the following time information services:

1. BIH Announcements.
2. U.S. Naval Observatory publications, particularly Time Service Announcements Series 1 through 17, and Almanacs (Ephemerides) (See Appendix).
3. National Bureau of Standards Time & Frequency Bulletins.

These services refer to time as it is disseminated by the following systems:

1. HF Standard T/F Signals: (WWV, CHU, etc.).
2. Timed electronic navigation signals: Loran-C, OMEGA, Transit, and later Global Position System (GPS), etc.
3. Wideband Communication links: Two-way.
4. Portable clocks, Precise Time Reference Stations (PTRS).
5. Special systems, largely under R&D: TV, etc.

The HF signals provide a global capability (including a great number of coordinated foreign services) of 1 ms precision, if propagation and receiver delays (3-5 ms depending mainly on band width used) are taken into account. Item 3 is potentially the most accurate, but portable clocks remain our final "authority" to calibrate services.

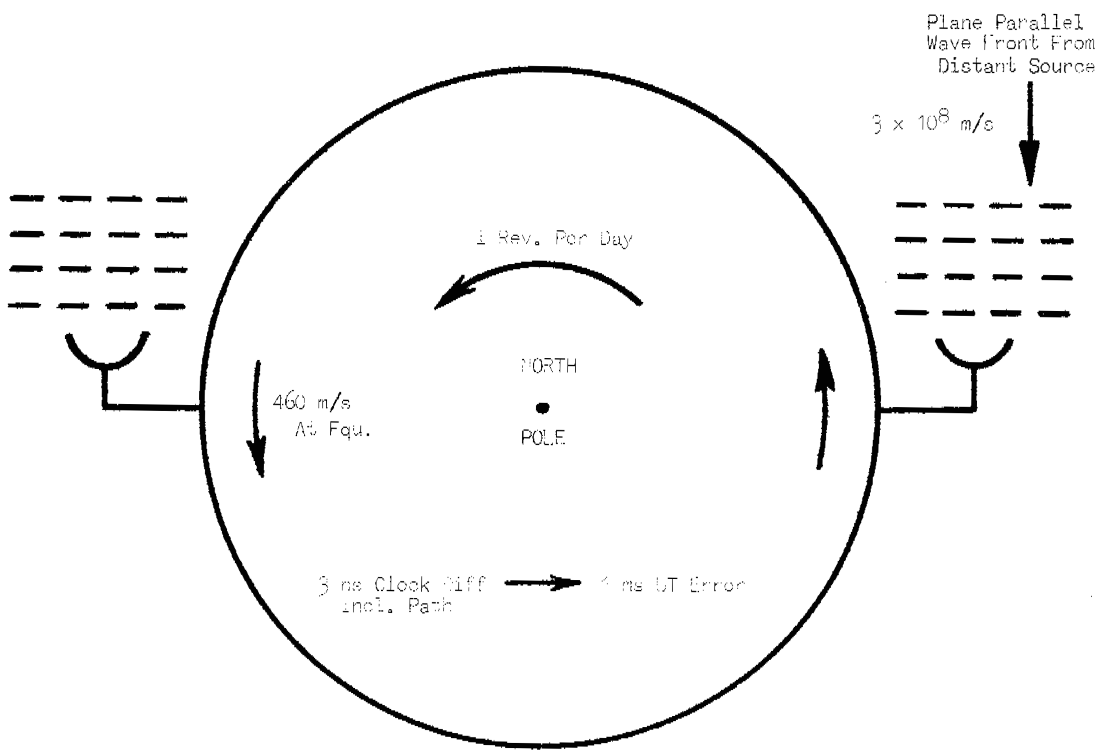
In greater detail, we could summarize the distribution capabilities as follows:

1. HF radio time signals:	1 ms global	
2. Portable clocks:	0.5 μs global	
3. VLF-OMEGA:	1-3 ms phase track (Relative)	
4. Loran-C/D	0.5 μs Northern Hemisphere	
5. Satellites:		
a. DSCS	0.1 μs "trunk line", global	2-way
b. TACSAT	0.5 μs "intermediate"	2-way
c. TRANSIT	10 μs global	Silent (one way)
d. GPS	0.1 μs global	Silent (one way)
6. Television:		
Local:	10 ns	
Long range:	1 μs	

7. Microwave, laser
   (local): 1 ns
8. Others: (R&D, VLBI, power lines, etc.)

As an example of users who can also help in global timekeeping, we can mention VLBI which, as the following sketch shows, provides both synchronization and UT (also the polar coordinates, x and y).

PRINCIPLE OF VLBI TIME DETERMINATION
UT1 VERSUS SYNCHRONIZATION
A USER AND CONTRIBUTOR



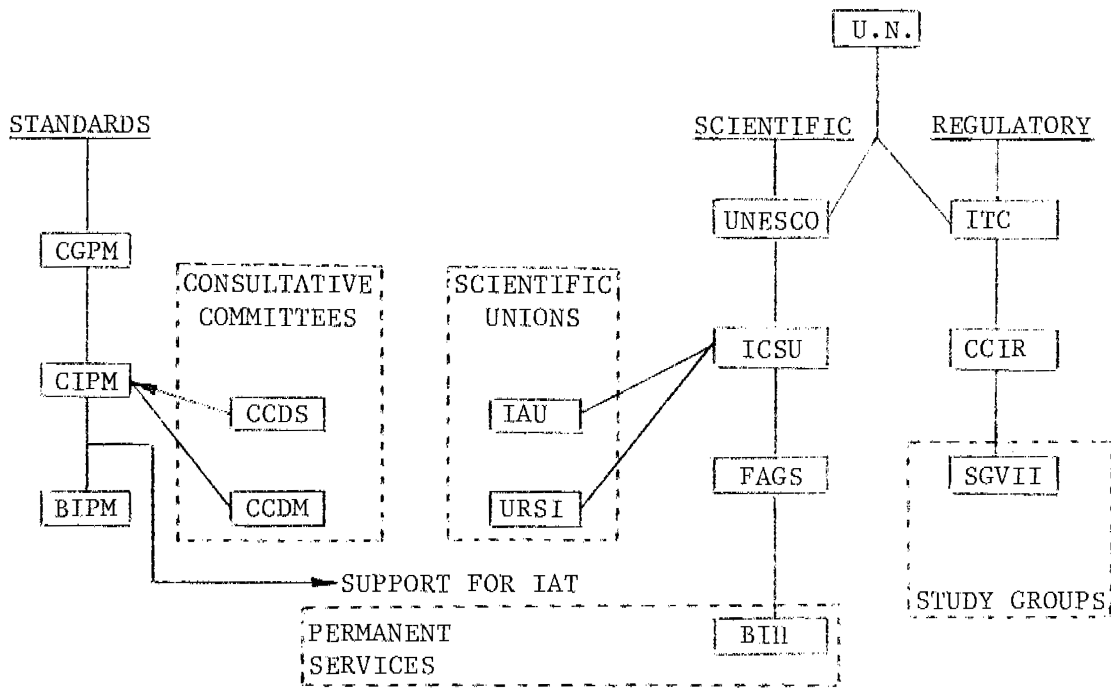
Redundant observations allow determination of time difference, base line, UT1 and polar coordinates.

Coordination of Services:

We have a system of international timekeeping in existence, coordinated by the BIH which is located at the Paris Observatory, and which is operated with some support from various international organizations.

The BIH operates under the auspices of the following organizations:

INTERNATIONAL ORGANIZATIONS INVOLVED WITH STANDARD FREQUENCY AND TIME



Abbreviations for PTTI

BIH	- Bureau International de l'Heure
BIPM	- International Bureau of Weights and Measures
CCDM	- Consultative Committee for the Definition of the Meter
CCDS	- Consultative Committee for the Definition of the Second
CGPM	- General Conference of Weights and Measures
CIPM	- International Committee for Weights and Measures
CCIR	- International Radio Consultative Committee
IAT	- International Atomic Time
FAGS	- Federation of Astronomical and Geophysical Services
IAU	- International Astronomical Union
ICSU	- International Council of Scientific Unions
ITU	- International Telecommunication Union
SGVII	- Study Group 7
U.N.	- United Nations

UNESCO - United Nations Education, Scientific and Cultural Organization
URSI - International Union of Radio Science

The national organizations (time services and/or standards laboratories) provide basic data to the BIH. The U.S. contributions from the U. S. Naval Observatory and the National Bureau of Standards are given in detail in NBS Technical Note 649, "The Standards of Time and Frequency in the USA".

In the United States, the division of responsibilities can be briefly summarized as follows:

T/F Responsibilities

NBS	USNO
National Standard of Frequency	National Standard of Time (Epoch, Date)
Standard Frequency (and time) Broadcast	Control of DoD T/F Transmissions
Fundamental Research in T/F as Related to Clock Time, Frequency Measurements	Applied Research in Time as Related to Clock Applications, Astronomy, Geophysics, and Navigation
Synchronization	Consultation and Management of PTTI Activities as Related to DoD
Consultation and Education	
PTRS for USNO	

The international clock time scales IAT and UTC are based on a number of individual clocks, presently operated by the following contributors:

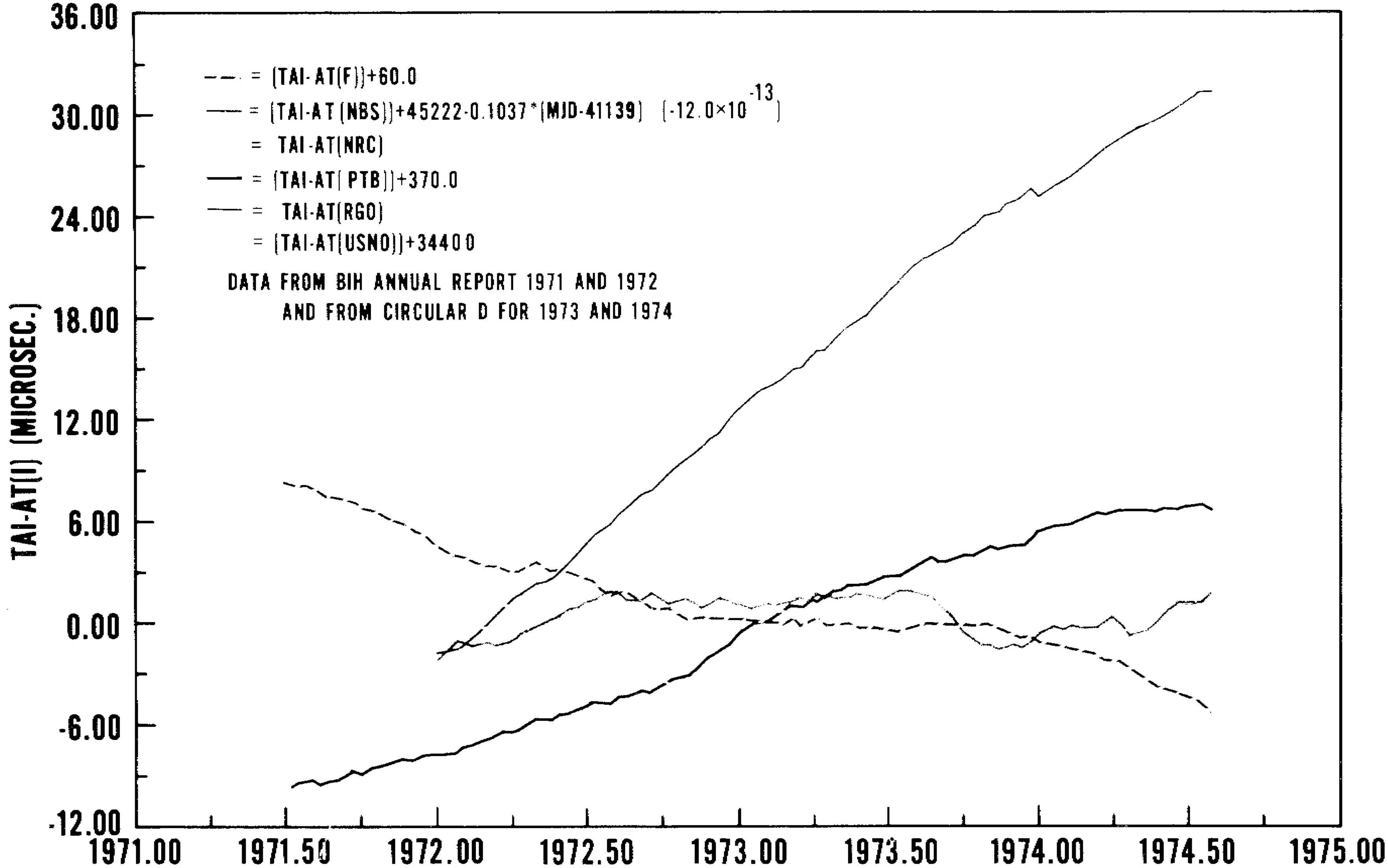
CONTRIBUTORS TO TAI (BIH)
(SOURCE BIH)

AGENCY	WEIGHT PER CLOCK	CLOCKS	TOTAL %	RANK
	%		%	
NPL	89	4	10	3
PTB	83	4	9	4
IEN	78	3	6.5	7
RGO	74	4	8.2	5
USNO	56	24	37	1
F	54	8	12	2
NBS	48	6	8.1	6
ON	44	4	5	8
NRC	37	3	3	9
ORB	26	1	0.7	10
TP	13	1	0.4	11
OMSF	3	2		
FOA	0	2		
PTCH	0	1		
VSL	0	1		

The table reflects the August 1974 situation. The Time Services in turn keep their coordinated scales for dissemination within about 10 μs of the BIH by making very small adjustments to their scales (10^{-13}). The clocks which contribute to the BIH are not adjusted.

The graph TAI - AT(i) depicts the performance of the internal scales of the major contributors as derived from BIH reports.

TAI-AT (I)


36.00
30.00
24.00
18.00
12.00
6.00
0.00
-6.00
-12.00
TAI-AT(I) (MICROSEC.)
1971.00
1971.50
1972.00
1972.50
1973.00
1973.50
1974.00
1974.50
1975.00
= (TAI-AT(F))+60.0
= (TAI-AT(NBS))+45222-0.1037*(MJD-41139) (-12.0×10^-13)
= TAI-AT(NRC)
= (TAI-AT(PTB))+370.0
= TAI-AT(RGO)
= (TAI-AT(USNO))+34400
DATA FROM BIH ANNUAL REPORT 1971 AND 1972
AND FROM CIRCULAR D FOR 1973 AND 1974

The results of the timing operations are published in bulletins which give actual clock differences. This is an example from Section 3 of the BIH Bulletin, Circular D92 dated 1974 July 4.

COORDINATED UNIVERSAL TIME

a. From Loran-C and Television pulses receptions

Date 1974		May 2	May 12	May 22
MJD		42 169	42 179	42 189
Laboratory i		UTC-UTC(i) (unit : 1 μs)		
DHI	(Hamburg)	- 1.3	- 1.2	- 0.6
FOA	(Stockholm)	+ 38.5	+ 39.5	+ 40.1
IEN	(Torino)	- 10.5	- 11.0	- 10.9
NBS	(Boulder)	- 2.2	- 1.8	- 1.5
NPL	(Teddington)	- 36.4	- 36.8	- 37.1
NRC	(Ottawa)	- 0.6	- 0.5	- 0.1
OMSF	(San Fernando)	- 0.2	- 0.2	- 0.3
ON	(Neuchâtel)	+ 20.5	+ 20.3	+ 20.2
OP	(Paris)	+ 1.7	+ 1.9	+ 2.0
ORB	(Bruxelles)	- 33.5	- 32.3	- 31.8
PTB	(Braunschweig)	+ 0.3	+ 0.2	0.0
RGO	(Herstmonceux)	- 2.1	- 2.3	- 2.6
TP	(Praha)	- 25.4	- 25.6	- 26.5
USNO	(Washington) (USNO MC)	+ 0.3	+ 0.4	+ 0.5
VSL	(Den Haag)	+ 21.2	+ 23.1	+ 25.0

b. From clock transportations (unit : 1 μs)

From "Daily Phase Values", Series 4, No. 382, USNO

San Fernando Naval Observatory, San Fernando, Spain:
1974 May 16 (MJD = 42 183.3), UTC(USNO MC) - UTC(OMSF) =
- 1.2 ± 0.1

CONCLUSION

PTTI technology offers capabilities which are desirable and useful in many modern electronic systems. With the availability of high performance atomic clocks (cesium beam, rubidium-gas cell and hydrogen-masers), the system designer can allow remote stations to operate with a high degree of independence (e.g. the VLBI receivers need no link, only initial synchronization).

As always, such extra benefits extract a premium price of additional complexity and training of operators. A standard timing interface (1 pulse per second, etc), with the large number of systems which are coordinated with UTC, allows some additional benefits and/or redundancy. One can therefore expect an expansion of the PTTI activities in the future.

APPENDIX

U.S. NAVAL OBSERVATORY
Time Service Publications

Series 1. LIST OF WORLDWIDE VLF AND HF TRANSMISSIONS suitable for Precise Time Measurements. Includes: Call sign, geographic location, frequencies, radiated power, etc. (Time Signal Transmissions)

Series 2. SCHEDULE OF U.S. NAVY TIME SIGNAL TRANSMISSIONS in VLF and HF bands. Includes: Times of broadcast, frequencies, etc.

Series 3. SCHEDULE OF U.S. NAVY VLF TRANSMISSIONS, including OMEGA System. Includes: Location, frequencies, power radiated, maintenance periods, type of transmission, etc.

Series 4. DAILY RELATIVE PHASE VALUES (Issued weekly). Includes: Observed phase and time differences between VLF, LF, Omega, Television, Portable Clock measurements, and Loran-C stations and the UTC(USNO Master Clock). Propagation disturbances are also given.

Series 5. DAILY TELETYPE MESSAGES (sent every working day). Includes: Daily relative phase and time differences between UTC(USNO MC) and VLF, LF, Omega, Loran-C stations. Propagation distrubances and notices of immediate concern for precision timekeeping.

Series 6. USNO A.1 – UT1 DATA. Preliminary daily values distributed monthly with final data issued as available.

Series 7. PRELIMINARY TIMES AND COORDINATES OF THE POLE (issued weekly). Includes: General time scale information; UT1 – UTC predicted 2 weeks in advance; time differences between A.1, UT1, UT2, UTC(BTH) and UTC(USNO); provisional coordinates of the pole; DUT1 value; and satellite information.

Series 8. TIME SERVICE ANNOUNCEMENTS pertaining to synchronization by television. Includes: times of coincidence (NULL) ephemeris tables.

Series 9. TIME SERVICE ANNOUNCEMENTS PERTAINING TO LORAN-C. Includes: Change in transmissions and repetition rates, times of coincidence (NULL) ephemeris tables, coordinates and emission delays, general information, etc.

Series 10. ASTRONOMICAL PROGRAMS (issued when available). Includes: Information pertaining to results, catalogs, papers, etc. of the Photographic Zenith Tube (PZT), Danjon Astrolabe, and Dual-Rate Moon Position Camera.

Series 11. TIME SERVICE BULLETINS. Includes: Time differences between coordinated stations and the UTC Time Scale; earth's seasonal and polar variations (as observed at Washington and Florida): Provisional coordinates of the pole; adopted UT2 – A.1, etc.

Series 12. Time Service Internal Mailing.

Series 13. Time Service Internal Mailing.

Series 14. TIME SERVICE GENERAL ANNOUNCEMENTS: Includes: General information pertaining to time determination, measurement, and dissemination.

Should be of interest to all Time Service Addressees.

Series 15. BUREAU INTERNATIONAL de l'HEURE (B.I.H.) Circular D; Heure Définitive et Coordonnées du Pôle a 0^h TU: Includes: Coordinates of the pole; UT2 – UTC, UT1 – UTC, and TA(AT) – UTC; UTC – Signal.

NOTE: USNO Time Service will distribute Circular D of the B.I.H. to U.S. addressees only.

Series 16. COMMUNICATION SATELLITE REPORTS; giving the differences UTC(USNO) – SATCOM Clock for each of the available SATCOM stations.

Series 17. TRANSIT SATELLITE REPORTS: Includes Satellite Clock – UTC(USNO) and the frequency offset for each of the operational satellites.

QUESTION AND ANSWER PERIOD

DR. REDER:

What was the semi-disaster?

DR. WINKLER:

The semi-disaster refers to some questions concerning the link across the North Atlantic on which the contributions to the BIH from the National Research Council, the National Bureau of Standards, and the U.S. Naval Observatory depend. There were also some operational difficulties which in the meantime, I think, have been straightened out. Most, but not all, of the questions have been clarified.

I think there has been an increased noise contribution to the various rate measurements as they are available to the BIH. But we are talking about fractions of microseconds and not more.

DR. GUINOT:

I wish to make some comments on what Dr. Winkler said. We have the impression that the link through Loran-C is the link of the American clocks to the BIH. I want to make clear that the European clocks and the American clocks have a completely symmetrical role in the BIH. The fact that the BIH is located in Europe does not influence at all the weights which are given to the clocks.

The Loran-C disturbance recently prevented us from making the necessary computations.

MR. LIEBERMAN:

Ted Lieberman, NAVELEX.

On your slide where you talk about the frequency standard precision and about the complexity, that may be far beyond what you need. Once again, I would like to emphasize or try your opinion on the life-cycle course that the Admiral talked about versus the initial complexity. How much does it take to keep something that is marginal for your needs to meet the requirements such as crystals, rubidium, et cetera.

DR. WINKLER:

I don't quite understand the question. You talk about what total effect it has, not only at the original purchase point, but also in maintaining that standard and all through its complete lifetime?

MR. LIEBERMAN:

Right.

DR. WINKLER:

I think it will have, of course, an even greater effect. An item like a precision cesium standard which has five times as many components as a rubidium standard, (simplified bare bones rubidium standard) can be expected to present, I wouldn't say five times as much maintenance effort, would certainly require much greater maintenance effort.

What I am asking for, what I am recommending, is that before a decision is made for any particular standard, one should not only consider the purchase price, but consider everything which comes after which is again at least as much in dollars and cents as the budget, maybe more. I think it is completely hopeless to establish true and completely independent, self-consistent field maintenance capabilities for cesium standards.

Anyone who is going to attempt that will pay very, very dearly. He will pay so dearly because it takes a good technician about, I would say, a year to become familiar with it. The effort in training, the effort in stockpiling of spare parts, I think is simply not worth such a method.

You also should consider that these clocks, even the lesser performers here, all have mean time between failures which certainly ought to be greater than 10,000 hours.

So you are dealing with standards where only rarely something can be expected to go wrong. Now how much training effort do you want to spend in field locations where people may be reassigned after six months? It is simply not a practical concept. And all of these aspects have to be considered.

Incidentally, in the literature, there have been several points where attempts have been made to put the benefits into some kind of a payoff matrix. For instance, in the special issue of the IEEE Proceedings, May, 1972, I believe, there are at least two locations where such matrices are discussed. And I have some reprints here of my own paper on path delays.

This can be only understood as a first try. I think such engineering decisions ought to be made much more sophisticated that what they are. Up to now, to say it quite bluntly and frankly to you, I think most of these decisions are made on the basis of glamor.

MR. MITCHELL:

Don Mitchell, Kwajalein Missile Range.

We have two cesiums and we do at the present time have a qualified techniciam who is capable of working on these and has a complete complement of spares. How would we go about getting our cesiums into the Naval Electronics Repair System?

DR. WINKLER:

I wouldn't recommend it: you have a special situation. You have been lucky enough to keep personnel on the job for a sufficient time to familiarize themselves with problems.

The point I am making is that you must allow specialization to a great degree and assure that the people, these specialists, are kept on location or at least in the same field of applications for a long time and then you can do what you do quite successfully. I think an alternative is that you do not field-maintain these standards at all and simply operate on the basis of redundancy. Equip every station with two, or if you can, three standards. If any one fails, send it back to a central depot.

That is the idea of having established the Naval Engineering Command Maintenance System where there is a central location where these cesiums can be diagnosed, readjusted, repaired to a certain degree.

But I tell you, that system sometimes works out like the following. We received from a distant station a cesium, and all that was wrong is that the alarm light doesn't go out, and you have to adjust the trigger circuit. Many repairs are of this kind of sophisiticati on.