PROGRAM

THIRTY-SECOND ANNUAL
PRECISE TIME AND TIME INTERVAL (PTTI)
SYSTEMS AND APPLICATIONS MEETING

November 28-30, 2000

32 Years of Progress
1969-2000

Hyatt Regency Hotel
Reston, Virginia

The Schedule

Monday, November 27,2000

0800-1300	Pipe and Drape Set-Up for Exhibitors
0830-1600	Navtech Seminars Tutorials
1300-2000	Exhibitor Set-Up
1900-2100	Registration - PTTI Meeting*
1900-2100	Committee on GPS and GLONASS Time Transfer Standards

Tuesday, November 28,2000

0700-0800	Speakers' Breakfast
0700-1500	Speakers' Room Open
0700-0800	Attendees' Breakfast
0715-1600	Registration - Grand Ballroom Foyer
0800-1700	Technical Exhibits
0800-0900	Opening Session and Keynote Address
0900-1030	Session I
1030-1050	Intermission - Exhibits Area
1050-1150	Session II
1150-1320	Attendees' Lunch
1320-1440	Session III
1440-1500	Intermission - Exhibits Area
1500-1620	Session III (con't)
1620-1720	Session IV
1830-2030	Reception

Wednesday, November 29,2000

0700-0800	Speakers' Breakfast
0700-1600	Speakers' Room
0700-0800	Attendees' Breakfast
0800-1600	Registration
0800-1700	Technical Exhibits
0800-0920	Session V
0920-1020	Session VI
1020-1040	Intermission - Exhibits Area
1040-1140	Session VII
1140-1300	Attendees' Lunch
1300-1420	Session VIII
1420-1440	Intermission - Exhibits Area
1440-1640	Poster Session
1730-1830	Joint PTTI Executive Board and Advisory Board Meeting
1900-2030	Evening Speaker

Thursday, November 30, 2000

0700-0800	Speakers' Breakfast
0700-1200	Speakers' Room
0700-0800	Breakfast
0800-1000	Registration
0800-1000	Session IX
1000-1020	Intermission - Pre-Function Area
1020-1140	Session X
1140-1150	Closing Session
1150-1200	Close of Meeting

*Registration for the PTTI Meeting is available each day. Exhibits will be open Tuesday and Wednesday only.

PTTI 2000

THIRTY-SECOND ANNUAL
PRECISE TIME AND TIME INTERVAL (PTTI)
SYSTEMS AND APPLICATIONS MEETING

Sponsored by

U.S. Naval Observatory
U.S. Naval Research Laboratory
NASA Jet Propulsion Laboratory
U.S. Air Force Office of Scientific Research
Defense Information Systems Agency
U.S. Coast Guard Navigation Center
U.S. Army Research Office

November 28-30, 2000

Hyatt Regency Hotel
Reston, Virginia

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OBJECTIVES

The objectives of the PTTI Systems and Applications Meeting are to:

- Disseminate and coordinate PTTI information at the user level
- Review present and future PTTI requirements
- Inform Government and Industry engineers, technicians, and managers of precise time and frequency technology and its problems
- Provide an opportunity for an active exchange of new technology associated with PTTI

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This year, PTTI 2000 addresses:

- Advances in Frequency and Timing Systems
- Telecommunications, Utilities, Internet Protocol, and Network Timing
- GPS, GLONASS and Two-Way Satellite Time Transfer
- WAAS, EGNOS and MSAS GPS Augmentation Systems
- Time Scales
- Panel Discussion: Leap Second and Future Considerations
- Future Timing and Frequency Applications
- PTTI Vendor Presentations

WELCOME TO PTTI 2000

MEETING INFORMATION

Registration

Questions concerning registration should be directed to Ms. Nicolette Jardine at the PTTI Registration Desk.

The registration fee is $275.00

The full registration fee includes entry to all the sessions, the exhibit area, a copy of the Proceedings, the welcoming reception, breakfast and lunch on Tuesday and Wednesday, breakfast Thursday, and a special presentation on Wednesday evening. Guest tickets are $30.00 for the reception, $20.00 for breakfast and $25.00 for lunch.

The registration fee for students and full-time retirees is $50.00 and includes entry to the scientific sessions and the exhibit area only. It does not include a copy of the Proceedings, entry to breakfasts, lunches, the reception, or the Wednesday evening special presentation.

Please make checks payable to: **Treasurer, PTTI**. Attendees, including presenters and exhibitors, must register and receive a badge and badges must be worn for admission to all sessions and functions. Badges for registered attendees are not transferable.

Visitor badges <u>for the exhibit area only</u> may be obtained at the registration desk. The exhibit area is open to everyone.

PTTI 2000 proceedings will be provided on a CD in Adobe Acrobat (pdf) format. For those wishing to have a hardcopy version instead, a printed copy may be requested for an additional $35 at the time of registration.

PTTI 2000 Home Page

Access the PTTI 2000 Home Page from the World Wide Web at:
http://tycho.usno.navy.mil/ptti.html

Registration Desk Hours

The registration desk will be open during the following hours:

27 November, Monday	-	1900 - 2100
28 November, Tuesday	-	0715 - 1600
29 November, Wednesday	-	0800 - 1600
30 November, Thursday	-	0800 - 1000

Hotel Information

The Hyatt Regency Hotel at Reston Town Center
(PTTI 2000 Meeting Room Block)
1800 Presidents Street
Reston Town Center
Reston, Virginia 20190
703-709-1234
Fax 703-709-2291

DIRECTIONS TO HYATT REGENCY RESTON FROM:

Washington National Airport & Washington, DC —
Follow signs to 1-66 West. (Be alert to late afternoon HOV restrictions.) From 1-66 West, take Exit 67, Dulles Airport Toll Road and follow it west to Exit 12, Reston Parkway. Turn right and continue ¼ mile to second stop light. Hotel is on the left.

Baltimore/New York —
Follow 1-95 South to Washington DC beltway then exit right (west) onto 1-495. Follow 1-495 across the Potomac River into Virginia and exit right onto Rt. 267, Dulles Toll Road. At Reston, use Exit 12, Reston Parkway; turn right and proceed ¼ mile to second stoplight. Hotel is on the left.

Fredericksburg/Richmond —
Follow 1-95 North to Washington, DC beltway (at Springfield), then exit onto 1-495 (north). Follow 1-495 to Rt. 267, Dulles Toll Road. At Reston, use Exit 12, Reston Parkway; turn right and proceed ¼ mile to second stoplight. Hotel is on the left.

Dulles International Airport —
From airport take Dulles Access Road East toward Washington, DC. At Reston, take Exit 12, then left onto Reston Parkway and follow it north ¼ mile to third stoplight. The hotel is on the left.

Leesburg/Loudoun County —
Two choices: (A) Follow Rt. 7 East to Dranesville and turn right onto Reston Parkway (Rt. 602). Proceed south approximately 3 miles. Hotel will be on the right. (B) Take Dulles Greenway Toll Road East past Dulles International Airport to Exit 12, Reston Parkway. Turn left onto Reston Parkway and follow it north ¼ mile to third stoplight. Hotel is on the left.

I-81 Corridor (North) — Hagerstown, Winchester —
Follow 1-81 South to Winchester and exit onto Rt. 7 East. Follow Rt. 7 eastbound for approximately 50 miles to Dranesville and then turn right onto Reston Parkway (Rt. 602). Proceed south for approximately 3 miles. Hotel will be on the right.

I-81 Corridor (South) — Roanoke, Harrisonburg —
Follow 1-81 North to the Strasburg area then exit onto 1-66 East and go approximately 58 miles. After passing Rt. 28, look for and exit onto the Fairfax County Parkway and follow it north to the end. Exit right onto Sunset Hills Rd. East and proceed 1 mile to Reston Parkway. Turn left and hotel will be one block on the left.

Transportation

Rental Car

Avis has been chosen as the official rent-a-car company for **PTTI 2000**. To receive a reduced rate, call **1-800-331-1600** to book your reservation and give the Avis Meeting Sales Agent the Avis Worldwide Discount (AWD) number for PTTI 2000 - **J628452**. Special meeting rates are available one week before and one week after the meeting and include unlimited free mileage.

Airport Shuttle

Complimentary hotel shuttle service is available from Dulles airport.

Parking

Self and valet parking is available at the hotel. Parking for overnight guests and self parking is complimentary. Valet parking is $7.00 (day only) and $14.00 overnight and includes unlimited in and out privileges.

Messages

Messages may be left for PTTI attendees through the hotel's telephone number of 1-703-709-1234.

Exhibit Information

For exhibit information, please contact Don Mitchell, TrueTime, Inc.

List of Exhibitors for PTTI 2000

Allen Osborne Associates, Inc.
Brandywine Communications
Datum, Inc.
End Run Technologies
Femtosecond Systems, Inc.
GPS World
Lange Electronics
Oscilloquartz
Perkin Elmer
Quartzlock, U.K. Limited
Spectro Dynamics, Inc.
Stanford Research Systems
Syntonics LLC
Timing Solutions Corporation
TIMETECH GmbH
Trak Communications, Inc.
Trimble Navigation Limited
TrueTime, Inc.
U.S. Naval Observatory
Zyfer, Inc.

Speakers' Room

Please check the PTTI Registration Desk or the hotel's Function Board for the location of the Speakers' Room. Session chairs should alert their sessions' members to meet them in the Speakers' Room for the Speakers' Breakfast that is served each day. Beverages and speaker supplies are available during the day.

Presented Papers

Papers in camera-ready form must be submitted to Dr. Lee A. Breakiron, Editorial Chairman, by November 28, 2000, unless prior arrangements have been made with him. If prior arrangements have not been made, the paper will not be published in the Proceedings.

Proceedings

The proceedings will be mailed to the attendees in 2001. If you cannot attend, but wish to reserve a copy of the Proceedings, please return the Registration Card with a check for $275.00 made out to Treasurer, PTTI. Please note on the card that you are not attending. Your reserved copy will be then sent to you. If you wish extra copies, they will also be available at $100.00.

PTTI 2000 proceedings will be provided on a CD in Adobe Acrobat (pdf) format. For those wishing to have a hardcopy version instead, a printed copy may be requested for an additional $35 at the time of registration.

Temperature

The climate during late November and early December in the Washington, DC area could be cool. A light coat or raincoat is recommended.

Thirty-third Annual PTTI Meeting

The 33rd Annual PTTI Meeting will be held at the Hyatt Regency Hotel, Long Beach, California, November 27-29, 2001.

PTTI EXECUTIVE COMMITTEE

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

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Lieutenant David Fowler
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U.S. Naval Research Laboratory

MRS. BRENDA McHALE
Datum-Timing, Test & Measurement

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TrueTime, Inc.

DR. RICHARD L. SYDNOR
NASA Jet Propulsion Laboratory

RECIPIENTS
OF THE
DISTINGUISHED PTTI SERVICE AWARD

1994
DR. GERNOT M. R. WINKLER
U.S. Naval Observatory (Retired)

1995
DR. JAMES A. BARNES
National Institute of Standards and Technology (Retired)

1996
PROFESSOR SIGFRIDO M. LESCHIUTTA
Politecnico di Torino
and
Istituto Elettrotecnico Nazionale Galileo Ferraris

1997
PROFESSOR BERNARD RENE GUINOT
Honorary Astronomer
Paris Observatory

1998
DR. JACQUES VANIER
National Research Counsel (Retired)

1999
DR. LEONARD S. CUTLER
Agilent Laboratories

2000 ADVISORY BOARD MEMBERS

PTTI 2000 SESSION CHAIRS

SESSION I - Vendor Presentations
MR. ALECK HOLCOMB
TrueTime, Inc.

SESSION II - GPS Augmentation
DR. WILLIAM KLEPCZYNSKI
Innovative Solutions International

SESSION III - GPS and GLONASS Time Transfer
MS. LISA NELSON
National Institute of Standards and Technology

SESSION IV - Time Scales I
DR. DEMETRIOS MATSAKIS
U.S. Naval Observatory

SESSION V - Two-Way Satellite Time Transfer
DR. FRANÇOISE BAUMONT
Observatoire de la Côte d'Azur Grasse

SESSION VI - Leap Seconds
DR. DENNIS McCARTHY
U.S. Naval Observatory

SESSION VII - Time Scales II
DR. DEMETRIOS MATSAKIS
U.S. Naval Observatory

SESSION VIII - Advanced Frequency and Time Systems
DR. ROBERT TJOELKER
NASA Jet Propulsion Laboratory

SESSION IX - Future Applications
COMMANDER CHRIS GREGERSON
U.S. Naval Observatory

SESSION X - Telecommunications and Network Timing
MR. ED BUTTERLINE
Symmetricom

POSTER SESSION
DR. ANDY WU
The Aerospace Corporation

PTTI 2000

THIRTY-SECOND ANNUAL PRECISE TIME AND TIME INTERVAL (PTTI) SYSTEMS AND APPLICATIONS MEETING

TUESDAY, NOVEMBER 28, 2000

0800-0805 **OPENING**
Hugo Fruehauf, Zyfer, Inc.

0805-0815 **OPENING REMARKS**
Captain B. Jaramillo, U.S. Naval Observatory

0815-0830 **DISTINGUISHED PTTI SERVICE AWARD** Presented by: Joe White, U.S. Naval Research Laboratory

0830-0835 **CALL TO SESSION**
Paul Koppang, Datum-Timing, Test & Measurement

0835-0900 **KEYNOTE SPEAKER, IN THE BEGINNING OF GPS,**
Roger Easton, U.S. Naval Research Laboratory (retired)

SESSION I **PTTI VENDOR PRESENTATIONS,**
0900-1030 **Chairman: Aleck Holcomb, TrueTime, Inc.**

1030-1050 **INTERMISSION**

SESSION II **GPS AUGMENTATION**
Chairman: William Klepczynski, Innovative Solutions International

1150-1320 **ATTENDEES LUNCH (Provided)**

TUESDAY, NOVEMBER 28, 2000

WEDNESDAY, NOVEMBER 29, 2000

WEDNESDAY, NOVEMBER 29, 2000

WEDNESDAY, NOVEMBER 29, 2000

THURSDAY, NOVEMBER 30, 2000

Paper 1

CAPABILITIES OF THE WAAS AND EGNOS FOR TIME DISTRIBUTION AND TIME TRANSFER

W. Klepczynski
Innovative Solutions International
Vienna, VA

E. Powers
U.S. Naval Observatory
Washington, DC

P. Fenton
NovAtel
Calgary, Canada

M. Brunet
CNES
Centre National d'Etudes Spatiales
Toulouse, France

R. Douglas
National Research Council
Ottawa, Canada

ABSTRACT

While these Satellite Based Augmentation Systems (SBAS) to GPS are still under development and currently broadcast test transmissions, they can be used to obtain an indication of their capabilities for timekeeping purposes. The current situation parallels the development of GPS when it was used for global time transfer before it was used for global navigation.

Observations of the geostationary satellites (GEOs) used in the Wide Area Augmentation System (WAAS) and European Geostationary Navigation Overlay System (EGNOS) have been made with three different types of antennas attached to two NovAtel WAAS Narrow Band receivers at the U.S. Naval Observatory (USNO) in Washington, DC. The USNO Master Clock provided time and frequency for the receivers during this experiment. The antennas used in Washington were a geodetic omni-directional, a feed horn and a 1.8-m dish. Additional observations were made at the National Research Council in Ottawa using an omni-directional antenna and a 1.8-m dish.

When the Japanese developed Multi-Function Transportation Satellite [MTSAT] Augmentation System (MSAS) becomes fully operational along with the WAAS and EGNOS, the potential for having a real-time, global timing system exists. Preliminary analysis of the timing data indicates that a nanosecond operational capability in time distribution can be achieved and sub-nanosecond time synchronization over large distances can be realized.

Paper 2

WAAS, EGNOS, MSAS FOR TELECOM SYNCHRONIZATION

H. Fruehauf
Zyfer, Inc.
Anaheim, CA

ABSTRACT

The WAAS, EGNOS, and MSAS GPS Augmentation Systems bridge the gap between applications of GPS and the needs of civil aviation navigation. These U.S., European, and Asian systems consist of a network of differential GPS ground stations, using the Inmarsat-3 geo-synchronous satellite constellation as the means of relaying the differential corrections to the users. In the process of providing the navigation signals, GPS time is maintained through the Inmarsat downlinks. It is this functionality that provides for robust time retrieval for the synchronization needs of the telecommunications community.

This paper will discuss:

- The basic makeup and performance of the system
- How time and frequency can be extracted for the telecom terminals
- Added functionality and noise rejection capabilities using these signals
- How the system offers the first true backup to the GPS C/A signal

Paper 3

MODELISATION AND EXTRAPOLATION OF TIME DEVIATION OF USO AND ATOMIC CLOCKS IN GNSS-2 CONTEXT

J. Delporte, M. Brunet and T. Tournier
Centre National d'Etudes Spatiales
Toulouse, France

F. Vernotte
Observatoire de Besançon
Besançon, France

ABSTRACT

In Global Navigation Satellite Systems (GNSS), the on-board time has to be modeled and predicted in order to broadcast the time parameters to final users. As a consequence, the time prediction performance of the on-board clocks has to be characterized.

In order to estimate the time uncertainty of the on-board oscillator, a linear or parabolic fit is performed over the sequence of observed time difference and extrapolated during the prediction period. In 1998 the Centre National d'Etudes Spatiales (CNES) proposed specifications of orbit determination and time synchronization for GNSS-2. The needs of synchronization were specified as the maximum error of the time difference prediction from the extrapolated fit.

Using our work about the estimation of uncertainties in time error extrapolation, we have translated these time domain specifications into a noise level limit or an Allan deviation limit. Of course, these limits depend on the main type of noise for integration time of about one day and on the type of adjustment which is performed (linear for cesium clocks and quadratic for other oscillators).

A table summarizing these limits will be presented. These values will be compared to experimental results obtained with different types of oscillators (quartz, rubidium and cesium).

Paper 4

EVALUATING THE ACCURACY OF GPS CARRIER-PHASE FREQUENCY TRANSFER USING DATA FROM NIST AND PTB

L. Nelson and J. Levine
National Institute of Standards and Technology
Boulder, CO

ABSTRACT

In recent work, comparisons were made between the primary frequency standards at the National Institute of Standards and Technology (NIST) and the Physikalisch-Technische Bundesanstalt (PTB) using dual-frequency geodetic receivers that measure the phase of the GPS carrier relative to the local standard. In this work we report on studies of the effects of data gaps, station outages, data merging routines and atmospheric modeling on these comparisons. Initial results indicate that these effects currently make contributions to the error budget at parts in 10^{15}. We will report on the techniques we have developed for reducing the contributions of these effects, so as to lower the overall error budget of the comparison technique.

Paper 5

A TRANSATLANTIC GeTT TIME TRANSFER EXPERIMENT - LATEST RESULTS

R. Dach, T. Schildknecht and T. Springer
Astronomical Institute
University of Berne
Bern, Switzerland

G. Dudle and L. Prost
Swiss Federal Office of Metrology
Wabern, Switzerland

ABSTRACT

Two Geodetic Time Transfer terminals (GeTT) were installed at the Physikalisch-Technische Bundesanstalt (PTB), Braunschweig, Germany and at the U.S. Naval Observatory (USNO), Washington, DC. The receivers store GPS Carrier Phase (GPS CP) data as well as GPS Pseudorange (GPS PR) observations from both frequencies. This time and frequency transfer experiment over the Atlantic has now been running for more than two years. Comparisons of the results from our GPS based time series with other, independent, methods like Common View (CV) and Two-Way Satellite Time and Frequency Transfer (TWSTFT), allows one to study the long term stability of these techniques.

The analysis of GPS data gives differences between two clocks with a high sampling rate (300 seconds or even less). Therefore, GPS gives the possibility to compare two clocks nearly continuously over intercontinental distances.

High quality GPS products, e.g.; satellite orbits, are necessary to get good results for the clock estimation. We will compare the time transfer results using the final and the rapid products from the Center for Orbit Determination in Europe (CODE), one of the analysis centers of the International GPS Service (IGS). Using the rapid products the time transfer results are available at approximately 1800 UT the day after the observations. The final solution is usually available one week later.

Paper 6

EVALUATION AND PRELIMINARY RESULTS OF THE NEW USNO GPS PPS TIMING RECEIVER

M. Miranian, E. Powers, L. Schmidt and F. Vannicola
U.S. Naval Observatory
Washington, DC

ABSTRACT

The U.S. Naval Observatory (USNO) is tasked to provide the Global Positioning System (GPS) with a reliable and stable reference to UTC(USNO). This is accomplished using GPS Precise Positioning Service (PPS) timing receivers with a UTC(USNO) reference input. The USNO monitors GPS Time from all available healthy satellites. On a daily basis, the GPS Time correction with respect to UTC(USNO), and based on the entire constellation, is determined and provided to the GPS Master Control Station (MCS) 2nd Satellite Operations Squadron (2 SOPS) at Schriever AFB in Colorado.

The USNO's GPS PPS operations have been limited to a single channel receiver which only allows tracking of one satellite at a time. Since February 2000, the USNO has been evaluating a 12-channel GPS PPS timing receiver, based on the GPS Monitor Station receiver. The unit is capable of tracking P(Y)-code and removes the effects of Selective Availability.

This paper will describe the various tests conducted, the receiver's performance and expected improvements to the USNO GPS PPS operations.

Paper 7

ABSOLUTE AND RELATIVE CALIBRATION OF CARRIER PHASE GPS RECEIVERS

E. Powers
U.S. Naval Observatory
Washington, DC

ABSTRACT

We will report on a series of calibration experiments and hardware sensitivity studies conducted to better understand the ability of GPS Carrier Phase time transfer. These experiments were conducted at the U.S. Naval Observatory (USNO) and Naval Research Laboratory (NRL) using both broadcast and simulator generated GPS signals. We will also report on modifications made to a Turbo Rogue GPS receiver that will allow the receiver to be useful for true time transfer.

Paper 8

RESULTS FROM TIME TRANSFER EXPERIMENTS BASED ON GLONASS P-CODES MEASUREMENTS FROM RINEX FILES

F. Roosbeek, P. Defraigne and C. Bruyninx
Royal Observatory of Belgium
Brussels, Belgium

ABSTRACT

We have used GLONASS P-codes from different geodetic GPS/GLONASS receivers, involved in the International Glonass Experiment (IGEX) campaign, to perform frequency/time transfer between remote clocks. GLONASS time transfer is commonly based on the time receiver-computed clock differences between GLONASS system time and the local clock. This is the classical CGGTTS method (GPS/GLONASS Time Transfer Standard). We chose another approach and analyzed the raw P-code data, available in the RINEX files.

This allows one to work also with the data from geodetic receivers involved in the IGEX campaign. Because the frequency emitted by each GLONASS satellite is different, P-code data must be corrected for these frequency dependent receiver hardware delays. We propose an original approach to determine these differential receiver hardware delays. After this correction, time transfer (using the GLONASS P-code) is done with a rms of about 2 nanoseconds for a typical one day session between two receivers separated by a few hundred kilometers. This is better than the precision obtained with the GPS C/A codes, currently used for the realization of International Atomic Time (TAI), with the advantage that our method allows one to work with a higher number of data points (about 3000 per day) and allows control of every aspect of the correction terms from the raw data to the final product.

Paper 9

RECOVERING UTC(USNO,MC) WITH INCREASED ACCURACY USING A FIXED L1-CA CODE GPS RECEIVER

R. Giffard
Agilent Laboratories
Palo Alto, CA

ABSTRACT

The accuracy with which a L1, single-frequency, GPS receiver can recover the time-scale UTC(USNO,MC) is well-known to depend on many factors including the accuracy of the signal in space, propagation path effects, the quality of the GPS/UTC(USNO,MC) correction, and the behavior of the receiver itself. Overall performance is now dominated by a number of short and medium term noise sources that have hitherto been obscured by Selective Availability (SA). We report the development of a technique for periodically estimating the local ionospheric delay from observations of the GPS code and carrier phase observables made with a multi-channel, L1, receiver module. An algorithm has been developed that uses information from several satellites to model the delay in real-time. The data is then used to correct each raw satellite pseudorange, improving the overall accuracy of the receiver's real-time estimate of GPS time or UTC(USNO,MC). This technique should enable simple GPS Disciplined Oscillators (GPSDOs) to approach the time accuracy usually given by a Precise Positioning Service (PPS) receiver. We will report measurements of the noise level obtained using the real-time estimated ionosphere corrections. This will be compared with that obtained using the built-in single-frequency model. The measurements are made with respect to a cesium standard ensemble related to UTC(USNO,MC) by common-view time-transfer.

Paper 10

PROGRESS ON A NEW GPS COMMON-VIEW RECEIVER

M. Weiss
National Institute of Standards and Technology
Boulder, CO

ABSTRACT

We are developing a new GPS common-view time transfer receiver to support both International Atomic Time (TAI) and comparison of frequency standards. Our goal is to realize a time-transfer accuracy of one ns or below, and time-transfer stabilities of 0.5 ns out to one year. Having obtained consistent stabilities at 100 ps or below with common-clock experiments out to one month with three laboratory prototype systems, we are now building a unit that can be moved among different timing labs. We show studies of three different time-interval counter cards considered for this project, revealing stabilities as a function of temperature and supplied voltage.

Paper 11

THE INFUSION OF MCS KALMAN FILTER DATA INTO GPS BLOCK II/IIA FREQUENCY STANDARD ANALYSIS TECHNIQUES

G. Dieter, G. Hatten and J. Taylor
Boeing Space and Communication Services
Schriever Air Force Base, CO

ABSTRACT

Recent advances have allowed Boeing GPS navigation payload analysts the ability to transfer, archive, and manipulate Master Control Station (MCS) Kalman filter data. Previously, access to this data was cumbersome and restricted to a limited timespan. The new data retrieval process has proven to be useful in many areas of GPS analysis, including frequency standard performance characterization. Both routine and anomolous frequency standard performance analysis techniques are enhanced by considering the characteristics and trends of key MCS filter variables.

This paper describes the methodology by which the MCS Kalman filter data is attained. It also examines situations in which MCS Kalman filter clock state estimates and navigation performance metrics have proven to be useful in analyzing frequency standard performance. Examples include routine examination of frequency standard stability using MCS phase offset estimates, analysis of MCS frequency offset estimates before and after a “clock q-bump”, and comparison of MCS clock state estimates versus those of other organizations, such as National Imagery and Mapping Agency (NIMA) and Naval Research Laboratory (NRL). Conclusions reveal that new, valuable insight is gained by considering MCS Kalman filter data when performing frequency standard analysis.

Paper 12

TIME LINKS FOR THE CONSTRUCTION OF TAI

J. Azoubib and W. Lewandowski
Bureau International des Poids et Mesures
Sèvres Cedex, France

ABSTRACT

The Global Positioning System (GPS) has served the principal needs of national timing laboratories for regular comparisons of remote atomic clocks for the last two decades. Single-channel GPS C/A-code common-view time transfer is, however, barely sufficient for comparison of today's atomic clocks within a few days, and certainly not sufficient for comparison of clocks currently being designed. For this reason the timing community is engaged in the development of new approaches to time and frequency comparisons, including techniques based on multi-channel GPS and GLONASS C/A-code measurements, GLONASS P-code measurements, GPS carrier-phase measurements, temperature-stabilized antennas, standardization of receiver software, and Two-Way Satellite Time and Frequency Transfer (TWSTFT) through tele-communication satellites. This paper describes how the above mentioned techniques can be used to meet TAI needs. Some of the techniques are already operational, and the others are expected to be introduced to meet the requirements of future higher accuracy clocks.

Paper 13

TOWARDS A METHOD FOR COMBINING A GROUP OF TIME TRANSFER LINKS TO FORM AN OPTIMAL COMPOSITE

J. Davis, S. Shemar, J. Clarke, P. Harris and M. Cox
National Physical Laboratory
Teddington, UK

ABSTRACT

During the past few years the National Physical Laboratory (NPL) has been actively involved in the development, evaluation, and inter-comparison of microwave satellite time and frequency transfer techniques. The main methods being used are Two Way Satellite Time and Frequency Transfer (TWSTFT), Geodetic GPS Time Transfer, and GPS and GLONASS Common-View Time Transfer. Regular time transfers are made between U.S. Naval Observatory (USNO) and NPL using all these techniques. Significant redundancy is present in the system as more than one set of receiving/transmitting hardware is used for some of the above techniques. In this paper, work aimed at developing a method for combining data from the individual UTC(USNO)–UTC(NPL) time transfer links to form a composite is described. Such a combination is of particular value for links such as UTC(USNO)–UTC(NPL) where time transfer noise dominates clock noise for averaging times up to several days.

Correlated clock noise is present in all the individual UTC(USNO)–UTC(NPL) links. In contrast, noise originating within the different time transfer systems is independent to a much greater extent although some correlation is still expected between the time transfer noise of separate links. The group of individual time transfer links are characterised at a given averaging time τ by forming $\sigma_y^2(\tau)$ and $\sigma_x^2(\tau)$ covariance matrices. These matrices enable information to be inferred concerning the sources of correlated noise. A method is discussed to weight the data from the individual time transfer links to produce a composite which is a more precise measure of UTC(USNO)–UTC(NPL) than is available from any individual link.

The data sets available from the individual time transfer methods have significantly different characteristics. For example the TWSTFT data sets consist of very precise measurements made in a Monday–Wednesday–Friday cycle. In contrast, the GPS and GLONASS common-view measurements consist of much less precise measurements made every 16 minutes. Strategies for combining these data sets are considered, as is the effect on the composite of the possible noise types of both the clocks and time transfer links. Ideas for treating missing data are examined as are possible treatments of the problem of losing/acquiring individual time transfer links.

Paper 14

A REVISED WAY OF FIXING AN UPPER LIMIT TO CLOCK WEIGHTS IN TAI COMPUTATION

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ABSTRACT

The free atomic time scale Échelle Atomique Libre (EAL), from which International Atomic Time (TAI) is derived by frequency steering, is obtained as a weighted average of a large number of free-running and independent atomic clocks spread world-wide, using the algorithm ALGOS which is optimized for long-term stability. Since January 1998, a new procedure for implementing an upper limit of clock weights has been used. The use of an absolute maximum weight p_{MAX}, was replaced by the choice of a relative maximum weight, ω_{MAX}. This new technique is more robust than the former one and it optimizes the stability of the time scale at the expense of a more complicated computation. The chosen value $\omega_{MAX} = 7.00 \times 10^{-3}$ corresponded to the value of the maximum relative weight assigned to clocks in the EAL computation, with $p_{MAX} = 2500$, in the 60 day interval November/December 1997. In this paper, we show that $\omega_{MAX} = 7.00 \times 10^{-3}$ is no longer appropriate. No efficient discrimination is made between the HP 5071A units: more than 80% of such clocks reach the maximum relative weight. The value of ω_{MAX} really needs to be updated from time to time in order to obtain an efficient discrimination between the HP 5071A units and to improve the stability of EAL. To avoid frequent redefinition of ω_{MAX}, we suggest here to make ω_{MAX} a function of the number, N, of clocks that participate in TAI. A relation such as $\omega_{MAX} = A/N$, where A is an empirical constant, could be used. Such a relation has been tested using ALGOS with values 3.0, 2.5 and 2.0 for A. The resulting computed time scales (over 2.5 years) using real data show that all the HP 5071A units are not equivalent. We also obtain an improved stability for the computed time scales, which is the underlying aim of this study.

Paper 15

RESULTS OF A CONTINUOUS TRANSATLANTIC TWO-WAY SATELLITE TIME TRANSFER TEST USING COMMERCIAL SATELLITE MODEMS

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ABSTRACT

A new method for collecting continuous two-way satellite time transfer data with commercial satellite modems has been developed. Communications modems employing time based communications technology are used to collect two-way data in the background of a bi-directional data channel. The two-way process uses a negligible portion of the channel bandwidth and is transparent to the data user. Proof-of-concept collections have shown sub-nanosecond performance for averaging times on the order of two to five minutes. A transatlantic experiment will be conducted in October 2000 using time based communications links over a one week period. Data from this test will be presented including the two-way results, temperature compensation, and supporting measurements using calibrated GPS and/or clock trips.

The paper begins with an introduction to the concept of time-based communications and the SATCOM implementation. Next, the experimental set-up is described including the details of the communications channel. Data is presented to show the quality of the measurement and level of agreement with other methods.

Paper 16

TWO-WAY FREQUENCY TRANSFER VIA SATELLITE USING CARRIER PHASE

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ABSTRACT

Two-Way Satellite Time and Frequency Transfer (TWSTFT) traditionally measures travel time of pseudo-noise coded signals transmitted via geo-synchronous satellites. Recently, a new method called Two-Way Carrier Phase for Frequency Transfer via Satellite has been introduced. It uses similar TWSTFT signal structures. Carrier phase measurements are performed in parallel to the normal two-way time transfer function.

This method adds high precision to traditional code-phase measurements, even if only low chip-rate signals are available. In contrast to TWSTFT links, where minimum mathematical effort is required, two-way carrier phase measurements have to consider three major unknowns: the on-board transponder's local oscillator frequency and the two relative velocities of the satellite with respect to the two ground stations involved. The satellite's movement causes additional Doppler-induced frequency shifts. The operational configuration aimed to resolve these unknowns is presented together with an outline of the algorithmic approach. It can be shown, that similar to TWSTFT, most link and satellite induced errors cancel.

Residual errors are described, which are caused by both mathematical simplifications and asymmetries of the propagation path. The methods applied for experimental verification are discussed together with a comparison of the theoretical errors with actually achieved frequency transfer accuracy.

An interesting application might be to determine the frequency stability of a satellite on-board clock without having to solve for the actual satellite orbit and without the need for dedicated on-board instrumentation.

Paper 17

TWSTFT NETWORK STATUS IN THE PACIFIC RIM REGION AND DEVELOPMENT OF A NEW TIME TRANSFER MODEM FOR TWSTFT

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ABSTRACT

Two Way Satellite Time and Frequency Transfer (TWSTFT) is one of the most precise and accurate time transfer techniques. Recently TWSTFT results among the European and North American time and frequency institutes have been applied to the International Atomic Time (TAI) calculation.

A TWSTFT network in the Pacific Rim region is also being developed rapidly. CRL and NRLM in Japan, NML in Australia, CSAO in China and TL in Taiwan have been making TWSTFT time transfer on a regular basis. Some other institutes, such as KRISS in South Korea and PSB in Singapore, are also planning to join this network within one year. We will present the latest situation of the TWSTFT network in this region at the meeting.

By performing TWSTFT time transfer it became obvious that several problems in TWSTFT should be solved for practical use and contribution to TAI using full performance of TWSTFT. They are:

(1) Difficulty of full automatic operation; due to transmission of signal to the satellite,
(2) Difficulty of performing time transfer exactly at the TAI calculation reference date and time,
(3) Expensive cost of the satellite links, and
(4) Accurate evaluation of internal delays and delay variations in earth stations.

We have been developing a new time transfer modem to solve or reduce most of these problems. It has three units of PRN code modulated for transmission and eight units of PRN code demodulated and time interval measurement for receiving. It realizes simultaneous time transfer among stations up to eight stations. We also will present the basic concept of this new time transfer modem under development at CRL.

Paper 18

REPORT ON THE 8TH MEETING OF THE BIPM WORKING GROUP ON TWO WAY SATELLITE TIME AND FREQUENCY TRANSFER

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ABSTRACT

The 8th Meeting of the BIPM Working Group on Two Way Satellite Time and Frequency Transfer (TWSTFT) took place on October 5-6, 2000. It was hosted by the Time and Frequency Division of the BIPM at Sèvres, France. This paper will report on highlights of the meeting as well as cover the latest developments in the area of Two Way Satellite Time Transfer (TWSTT).

Paper 19

RELATING TIME TO THE EARTH'S VARIABLE ROTATION

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ABSTRACT

With the beginning of the 21st Century, the timing community finds itself again facing a decades-old decision to synchronize atomic time with the Earth's rotation. Atomic time is the basis for most timing applications. However, time astronomically determined from the Earth's rotation is essential for navigation. The history of relating atomic time to the Earth's rotation is presented including our current synchronization method of leap seconds. Attempts to deal with astronomical time since from the time that it was realized that the Earth's rotational speed was variable, are reviewed.

Paper 20

A TOTAL ESTIMATOR OF THE HADAMARD FUNCTION USED FOR GPS OPERATIONS

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ABSTRACT

The objective of this paper is to describe a method, based on the Total Deviation Approach, whereby we obtain an improvement in the confidence of the estimation of a sample Hadamard deviation. The particular Hadamard deviation has a primary use in GPS and its master control operations. The resulting "Hadamard-Total" deviation described in this paper provides a significant improvement in confidence as indicated by a two to four times increase in Equivalent Degrees of Freedom (EDF) for the usual Hadamard deviation's applicable range of frequency-modulation (FM) power-law noises. The new Hadamard-Total deviation has a constant slight negative bias for each FM noise with respect to the usual Hadamard deviation.

This work is motivated by earlier work in developing an improved modified Allan deviation, known as mod-Total deviation. This is because the unique 3-sample function of the Hadamard deviation used in GPS operations is identical to the 3-sample function of the modified Allan deviation. This paper applies the steps in the mod-Total deviation to define a Hadamard-Total deviation. Additionally, we give simple formulae for computing EDF, investigate new refinements to the total approach, and provide an automatic way to remove the Hadamard-Total bias as well as estimate the confidence interval, both based on determining the characteristic noise type.

The Hadamard deviation is derived from a sample variance that is sensitive to the range of expected long-term GPS-oscillator FM noises, while it is insensitive to linear frequency drift. This avoids the complication of estimating and removing drift before applying the variance and consequently avoids suppression and underestimation of the characteristic FM noise level at large tau-values. Thus, the Hadamard-Total Deviation with its improved confidence intervals provides an efficient statistical tool to estimate the level of long-term underlying FM noise in the presence of drift.

The significance of this work is that the time needed to estimate the Hadamard deviation function is substantially reduced. Parameters of the Hadamard function are used to determine q coefficients in the GPS Kalman algorithm. We test the new Hadamard-Total estimator against the present Hadamard estimator using actual GPS clock data and a variety of real scenarios. As an example, to obtain a one-week estimate of the Hadamard deviation with, say, 40 days of measured data, the Total approach obtains a one-week estimate with the same or better confidence in only 20 days of measured data.

Paper 21

ON DEVELOPING AN INTEGRATED IGS FREQUENCY SCALE

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ABSTRACT

Currently, the International GPS Service (IGS) provides a set of clock products for both satellites and tracking receivers, tabulated at five-minute intervals. These products provide users with sufficient information to determine consistent coordinates and clock values for an isolated GPS receiver with an accuracy at roughly the five-cm level. However, because the underlying time scale for the IGS combined clocks is based on a linear alignment to broadcast GPS time separately for each day, the day-to-day stability of the IGS clocks is poor. The authors show the results of continued work toward developing an integrated IGS frequency scale to which the IGS clock products may be referenced.

Paper 22

PERFORMANCE AND CHARACTERIZATION OF U.S. NAVAL OBSERVATORY CLOCKS

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ABSTRACT

The U.S. Naval Observatory clock database extending over five years is analyzed to determine the frequency and drift characteristics of the individual clocks, and to compare cesium-beam frequency standards with hydrogen masers. Correlation-corrected N-cornered-hat analyses of frequency stability are performed, sigma-tau and Hadamard plots are derived, and the advantages and disadvantages of aggressive clock data editing are assessed.

Paper 23

THEORICAL AND EXPERIMENTAL STUDY OF LIGHT SHIFT IN CPT-BASED RB VAPOR CELL FREQUENCY STANDARD

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ABSTRACT

One of the important subjects in Coherent Population Trapping (CPT)-based vapor cell frequency standards is the light shift (ac Stark shift). We calculated the light shift using a numerical method and perturbation approximation. Experimentally, we measured light shift using a pair of phase-locked lasers as well as a frequency-modulated laser. There was good agreement between the theory and experimental values. Methods of controlling light shift in CPT-based frequency standards were proposed and implemented at Agilent Laboratories. The short term stability of our CPT-based rubidium frequency standard was measured as $2\text{x}10^{-12} / \sqrt{t}$, which was limited by the local oscillator phase noise. Measurement results to date will be presented.

Paper 24

PRELIMINARY RESULTS FROM THE USNO ATOMIC FOUNTAIN DEVELOPMENT PROJECT

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ABSTRACT

Atomic fountain clocks are emerging as an important new technology for the realization of extremely precise passive atomic standards. The U.S. Naval Observatory (USNO) has undertaken a project to develop atomic fountains for eventual incorporation into the USNO Master Clock.

We have recently demonstrated short term stability of 2×10^{-13} at one second with white frequency behavior into the mid 10^{-15}'s in our first R&D device. We will report on these and any improved results and hope to have frequency measurements relative to internal timescales at the USNO. We will also discuss plans for more heavily engineered operational devices and their incorporation into the USNO Master Clock.

Paper 25

STABILIZED REFERENCE FREQUENCY DISTRIBUTION FOR RADIO SCIENCE WITH THE CASSINI SPACECRAFT AND THE DEEP SPACE NETWORK

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ABSTRACT

The preliminary design and prototype development of the Stabilized Fiber Optic Distribution Assembly (SFODA) and the Compensated Sapphire Oscillator (CSO) was reported at the 1998 PTTI. These systems were developed to enable gravitational wave searches and atmospheric occultation experiments between the Cassini spacecraft and the NASA Deep Space Network (DSN). These experiments are conducted at Ka band (32 GHz) frequencies and demand the best possible short term and long term stability. A frequency standard located 16 km from the remote antenna acts as the source of the reference frequency. The SFODA is the conveyance device to deliver the reference signal to the remote antenna while the CSO provides the short term stability and low phase noise.

This paper will provide an overview and update of the end-to-end high performance frequency and timing subsystem. Focus will be given to the final SFODA design and test results using a 16 km optical fiber under controlled test conditions. The SFODA utilizes active feedback with a temperature compensating fiber optic reel to compensate for thermally induced phase variations over the 16 km fiber cable. A reference frequency signal at 1 GHz is transmitted over the fiber link to the remote antenna site where the stability of the source frequency standard is maintained. This signal is used to steer the CSO which provides the required ultra-stable reference signal for the Cassini Ka band users. Test data show a factor of 1000 improvement in long term stability when the active phase compensator is used thus enabling degradation free distribution from the highest performing atomic frequency standards.

This work was carried out at the Jet Propulsion Laboratory, California Institute of Technology, under a contract with the National Aeronautics and Space Administration.

Paper 26

A 100 GHZ LOW PHASE NOISE CLOCK BASED UPON SUPERCONDUCTING ELECTRONICS

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ABSTRACT

A clock that can be used to synchronize 100 GHz digital signal processing electronics while simultaneously providing the time base for high performance phase array antennas and/or high precision Doppler radar must have very little time jitter over time scales ranging from picoseconds to milliseconds. Equivalently, the 100 GHz clock must have very low phase noise from $\sim 10^2$ to $\sim 10^{12}$ Hz. In this paper we describe an approach to satisfying these requirements that is based upon superconducting electronics. An oscillator, based upon the ac Josephson effect and which has excellent intrinsic low-noise characteristics, is used in a Phase-Locked Loop (PLL) to further reduce phase noise or timing jitter. An extremely low-noise superconducting harmonic mixer, similar to those used in state-of-the-art radio astronomy, forms the basis of the PLL phase detector. In addition to overall clock design and measurements made so far, we will discuss related issues such as superconducting device speed and noise characteristics and methods of clock signal distribution that preserve low timing jitter.

Poster 1

THE TIME LINKS BETWEEN CSAO AND CRL — TWSTFT AND GPS COMMON VIEW

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ABSTRACT

The cooperation on TWSTFT between the National Time Service Center of China Shaanxi Astronomical Observatory, the Chinese Academy of Sciences (CSAO) and the Communication Research Laboratory, the Ministry of Post and Telecommunication (CRL) in Japan are going to play a very important role in the International TWSTFT Network.

The CSAO-CRL TWSTFT data has been accumulated for more than one year since the time link was established. The routine results are acquired twice a week and each time with 30 minute time comparison. Because of some trouble with the RF Transceiver and Low Noise Converter (LNC) at CSAO, the TWSTFT had to be suspended from September 1999 to June 2000.

A new step in the project has begun with a new satellite by changing from JSAT 3 to JSAT 1. The Japanese Satellite Company set the antenna for JSAT 1 at CSAO on July 18, 2000. The TWSTFT between CSAO and CRL starts again after a 10 month absence. We have collected excellent data.

The TTR-6 GPS receivers at both CSAO and CRL have timing data for at least four years for the time link in the TAI computation. The GPS common view data are now calculated at CSAO for obtaining UTC(CRL)-UTC(CSAO). The correct coordinates for the TTR-6 antenna at CSAO were introduced recently, which improves the precision of the time comparison.

To compare TWSTT results UTC (CRL)-UTC (CSAO) [by Mr. Hirotaka Yukawa, CRL] with GPS results of UTC(CRL)-UTC(CSAO), we used 55 groups of effective data in the period from January 1999 to August 1999. The profiles of TWSTFT results and GPS results coincide well. However, the larger fluctuations can be seen in the GPS time link. Improvements are expected with the installation of GPS/GLONASS receivers at CRL and CSAO.

Poster 2

DISCRIMINATING A GRAVITATIONAL WAVE BACKGROUND FROM INSTRUMENTAL NOISE IN THE LISA INTERFEROMETRIC DETECTOR

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ABSTRACT

The Laser Interferometer Space Antenna (LISA) is a proposed mission which will use coherent laser beams exchanged between three remote spacecraft, to detect and study low-frequency cosmic gravitational radiation. The multiple Doppler readouts available with LISA, which incorporate frequency standards for measuring phase differences between the received and transmitted laser beams, permit simultaneous formation of several observables. All are independent of lasers and frequency standards phase fluctuations, but have different couplings to gravitational waves and to the various LISA instrumental noises. Comparison of the conventional Michelson interferometer observable with the fully-symmetric Sagnac data-type allows unambiguous discrimination between a gravitational wave background and instrumental noise. The method presented here can be used to detect a confusion-limited gravitational wave background.

This work was carried out at the Jet Propulsion Laboratory, California Institute of Technology, under a contract with the National Aeronautics and Space Administration.

Poster 3

TIME AND FREQUENCY ACTIVITIES AT THE CSIR - NATIONAL METROLOGY LABORATORY

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ABSTRACT

The Council for Scientific and Industrial Research (CSIR) is empowered by the Measuring Units and National Measuring Standards Act, 1973 (Act 76 of 1973), as amended, to keep and maintain all national measuring standards for South Africa. It performs this duty through the CSIR - National Metrology Laboratory (CSIR-NML).

The Time and Frequency laboratory of the CSIR-NML is responsible for the maintenance and development of the standards in time and frequency. Specifically, the laboratory is responsible for the following standards: time, frequency, phase angle, pulse rise-time and pulse characterization and time interval. Fiber optic measurements also are the responsibility of this laboratory.

The national measuring standard for time in South Africa consists of two commercial cesium beam atomic clocks. Time transfer is performed using single and multi-channel GPS and GLONASS receivers. The CSIR-NML is the only contributor in Africa of time transfer data to the BIPM.

In addition to its standards activities, the Time and Frequency laboratory also offers time services in the form of a dial-in Telephone Time Service (TTS), as well as a Network Time Protocol service on the Internet. These services are provided free to any user in Southern Africa.

Recent developments at the CSIR-NML include the development and deployment of multi-channel GPS receivers, the deployment of a multi-channel dual frequency GPS / GLONASS receiver and the re-development of the Telephone Time Service.

This paper will discuss the various activities in time and frequency in detail and briefly touch on the other activities of the Time and Frequency laboratory.

Poster 4

THE DEVELOPMENT OF MULTI-CHANNEL GPS RECEIVERS AT THE CSIR - NATIONAL METROLOGY LABORATORY

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ABSTRACT

In 1998 the Time and Frequency laboratory of the Council for Scientific and Industrial Research - National Metrology Laboratory (CSIR-NML) had to decide on its replacement strategy for the Allan Osborne and Associates (AOA) TTR5 and TTR5A single channel Global Positioning System (GPS) timing receivers. These receivers would have stopped working at the GPS week rollover, which occurred on August 22, 1999 at zero hours Universal Coordinated Time (UTC). It was extremely important to replace these receivers, as they formed the primary traceability link for time in South Africa at that time.

Several options were available to the CSIR-NML. These included replacing the firmware of the AOA receivers, purchasing new timing receivers and designing and building receivers in-house. The replacement of the firmware of the AOA receivers was ruled out due to cost and the age of the receivers. The purchase of new timing receivers was ruled out due to cost. This meant that receivers had to be designed and built at the CSIR-NML. These receivers were put into operation in the week preceding the GPS week rollover.

Several excellent papers are available in the literature on this subject. The significance of this contribution is that the module used for this work is the Motorola UT+ Oncore, and not the Motorola VP Oncore. The software for the CSIR-NML receivers was written at the CSIR-NML under the Windows operating system, while the software for the receivers discussed in the literature was developed using the Linux operating system.

This paper will discuss the hardware used, the software developed and the results obtained using these receivers.

Poster 5

USNO ALTERNATE MASTER CLOCK (AMC) STEERING

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ABSTRACT

The primary mission of the U.S. Naval Observatory (USNO) Alternate Master Clock (AMC) facility, located at Schriever AFB, is to back up the critical functions of the USNO Time Service Department in Washington, D.C. The USNO AMC operates two master clocks, AMC#1 and AMC#2. Each one of these [Alternate] master clocks is ready to function as the nation's source for precise time, UTC(USNO), should the need arise.

This paper will summarize the current status of, and strategies used for, the steering of these Alternate Master Clocks. The various USNO AMC steering strategies utilize clock comparisons from Two-Way Satellite Time Transfer (TWSTT), GPS Common View (CV), and USNO AMC Timescale data. All current Alternate Master Clock steering strategies employ a combination of Kalman filtering and second-order control, first introduced into USNO operations in 1995.

The respective designs for these steering strategies are based on several factors, including goals for synchronization and stability, as well as the desire for robustness and simplicity of operation. This paper will analyze the performance of these respective designs.

Poster 6

ONE-WAY GPS TIME TRANSFER 2000

S. Hutsell
USNO Alternate Master Clock
Schriever AFB, CO

Captain M. Rivers and 1Lt T. Kelkenberg, USAF
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ABSTRACT

On May 1, 2000, the White House issued a Presidential directive for the Global Positioning System (GPS) to turn off Selective Availability (SA) on May 2, 2000. For nearly a decade, authorized user performance of one-way synchronization via GPS has improved every single year. This paper provides an annual assessment of how well the Global Positioning System can predict and disseminate UTC (USNO) to these specified users, based on data generated and processed by the United States Naval Observatory (USNO). The recent Presidential directive now permits civilian timing users to exploit nearly the same, impressive time transfer accuracy of GPS, these annual metrics now offer a fairly representative performance assessment for both military and civilian timing users.

Poster 7

DETECTION OF THE GRAVITATIONAL RED SHIFT OF CS FREQUENCY STANDARD IN CRL

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ABSTRACT

We have detected the gravitational red shift of a Cesium (Cs) frequency standard that has been transported from Communications Research Laboratory (CRL) Tokyo head quarter, at an altitude of 84 m, to the Ohtakadoya-yama LF standard time and frequency station, located about 250 km from CRL Tokyo head quarter and at an altitude of 794 m.

In the Ohtakadoya-yama Low Frequency (LF) station, two or three Cs clocks are used for the standard frequency reference for radio signal emission, and they are linked to UTC(CRL) by the GPS Common view time transfer method. By using this link, the link of UTC(CRL) to UTC and the published Circular T data, we can compare the frequency of any of the standards in CRL Tokyo and Ohtakadoya-yama LF station with UTC.

A Cs frequency standard, HP5071A normal tube, has been transported by car from CRLTokyo head quarter to LF station on 27 April, 2000. During the transportation, the Cs standard was kept working by the battery.

After the transportation, we have observed that the frequency of the Cs standard become higher in about 9×10^{-14} with respect to UTC. According to General Theory of Relativity, 710 m altitude difference will cause a 7.7×10^{-14} frequency difference.

Considering the stability of the Cs Standard and the accuracy of time transfer, the observed frequency shift shows a good agreement with the theoretically calculated gravitational red shift.

Poster 8

MULTI-PURPOSE TIME ANALYZER AND MONITOR FOR DEEP SPACE NETWORK TIME SYNCHRONIZATION

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ABSTRACT

The NASA Deep Space Network (DSN) is an international network of antennas that supports interplanetary spacecraft missions and radio and radar astronomy observations. The DSN consists of three tracking stations at Goldstone, in California's Mojave Desert; near Madrid, Spain; and near Canberra, Australia. Independent master clocks at each station are synchronized to UTC using traditional GPS common view techniques. Each station contains up to 10 different antennas separated by up to 30 kilometers. Within each station, time code translators (TCT's) are used to convert distributed frequency and serial time code signals generated from the online frequency standard and master clock into a stable and synchronous 1 pps reference signal for approximately 120 separate users. These TCT's also compensate for distribution related timing delays.

We report the development of a multi-purpose, automated, and continuously operating time analyzer to measure and monitor distributed 1 pps signals. The instrument consists of a PC to control a VXI based time interval counter and multiplexer with a Labview based user interface and LINUX OS. The instrument performs three major functions needed for operation of the DSN Frequency and Timing Subsystem.

1) Performance tests and monitor of timing offsets and jitter of 1 pps timing outputs of 120 TCT's relative to the station master clock. Time offset data from each TCT is summarized in histogram form. Additional test channels to monitor 1 pps from any other source (e.g.; the GPS time synchronization receivers) against the master clock are also provided
2) Captures any anomalies and alerts station operators in event of performance or operational failure. Archives timing configuration, station performance, and status.
3) Provides monitor of frequency offsets and long term stability of backup frequency standards with respect to the online frequency standard (which drives the master clock). Time and frequency offset data between online and backup frequency standards are analyzed over a twenty-four hour period and displayed numerically.

The user interface is designed to provide a high level summary of the entire timing system performance and to alert station operations in the event of an anomaly. Raw data is fully archived and network accessible if detailed analysis is warranted.

This work was carried out at the Jet Propulsion Laboratory, California Institute of Technology, under a contract with the National Aeronautics and Space Administration.

Poster 9

ON-ORBIT FRACTIONAL FREQUENCY SHIFTS OF PRECISION CRYSTAL OSCILLATORS

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ABSTRACT

The combination of Solar activity and the Earth's own geomagnetic shielding modulates the energetic proton environment. Over the past three years, the ambient integral proton flux with energy greater than 10 MeV in the free space between the Earth and the Sun has been small and even declining from 2 to 1 particles/($cm^2 \cdot s \cdot sr$). However, during the same period, there have been at least ten times when the integral flux of protons with energy greater then 10 MeV has greatly exceeded 10 particles/($cm^2 \cdot s \cdot sr$) by two to three orders of magnitude for periods of time ranging from hours to days. These periods of increased proton flux are a concern to space missions with precision timing applications using crystal oscillators. We present a look at some crystal oscillator on orbit performance during the last three years concentrating on the known high flux times and compare to ground measurements.

Quartz crystal oscillators are arguably the most widely used timing and synchronization sources for microelectronics applications. In general, crystal oscillators have many features which make them very desirable for use in space applications including relatively stable performance, inherent rugged design, low cost, small size, and low power requirements. Over the past 30 years or so, crystal oscillators have been successfully used in many space applications, and we anticipate their use to continue. However, future space applications will demand more timing and synchronization performance to meet mission needs and requirements.

It has been observed that proton radiation introduces fractional frequency drift in measurable amounts that may exceed not only long term system timing drift requirements but also the instantaneous timing drift requirements usually expressed as the fractional frequency drift, *Df/f*, per minute. Therefore in precision timing and synchronization space applications that use crystal oscillators, it becomes important to understand the crystal response to proton radiation.

This is a first look at on-orbit crystal oscillator performance directly correlated with known times of increased proton flux. While oscillator performance has been reasonably acceptable, we anticipate the future timing and synchronization requirements to challenge crystal oscillator performance in the proton radiation environment for space applications.

Poster 10

CURRENT STATUS OF MILLISECOND PULSAR OBSERVATION AT CRL

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ABSTRACT

We will report the current status of millisecond pulsar timing observations at Communications Research Laboratory (CRL). We have been observing a millisecond pulsar, PSR1937+21, for three years by using our 34m antenna, and have obtained the frequency stability of 10^{-13} over one year. Millisecond pulsars are known to have extremely stable pulse timing in long term, and expected to be used as new sources of frequency standards. The Communications Research Laboratory (CRL) aims to apply millisecond pulsars to the construction of a new time scale, and perform research on millisecond pulsars; theoretical research, VLBI observation, and timing observation.

As for the timing observation since November 1997, we have developed an original observation system using the 34m antenna at Kashima Space Research Center, and started the regular observation of PSR1937+21, which is the brightest millisecond pulsar in the northern sky. Regular observations have been carried out once a week, eight hours per day.

Although the observed pulse phases have shown systematic trends over a day and in the long term (reported in PTTI'98), we have checked our observation system and analysis program carefully. Through these checks, recently we have succeeded in removing the systematic trends. The phase shifts in one day were removed by a correction of the earth rotation parameter. The trend in a long term was improved by using the DE200 ephemeris for the analysis in a consistent way. Some other causes of the strange trends, such as the program bugs and the insufficient corrections of the observation time and frequency, have also been corrected.

Finally we succeeded in estimating the pulsar parameters of PSR1937+21 from our own data with the timing precision of 6.4 microseconds. In our analysis, the frequency stability of PSR1937+21 is 10^{-13} at averaging time of one year, which shows the possibility of constructing the pulsar time scale with even a rather small antenna.

We will present our observation system, analysis methods, and observation results of PSR1937+21 for about three years.

Poster 11

GPS COMMON-VIEW AND MELTING-POT TIME TRANSFER USING ONCORE UT+ RECEIVERS

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ABSTRACT

For three or four years, the Motorola VP oncore GPS receiver has been utilized in several experiments that have proven its ability to achieve time transfer with a precision roughly equivalent to those offered by other commonly used time-dedicated receivers. Motorola's decision to replace the VP by the UT+, has several important drawbacks among these are:

1. impossible to follow the standard BIPM common view schedule
2. no access to the raw navigation data

In this paper we present the results of the time transfers performed via UT+ receivers located at the Observatoire de Paris (OP) and at the Observatoire de Besançon (OB) which are 324 km apart. Both sites operate HP5071A-001 cesium clocks.

First, measurements made in a "melting pot" mode, all visible satellites being tracked at the same time by two stations will be presented.

In a second step, we will show how it is possible to overcome the first point for two stations up to around 1000 km apart.

Data collected between OP and OB will be presented; for both methods data consist in standard 13 minute measurement sessions. For the melting pot, data acquisition were synchronized with the standard BIPM schedule. For the common-view data, around 60 sessions were made daily, but at non-standard dates.

The two methods show very similar results, with a small advantage to the common-view method in terms of precision. These results are also compared to those simultaneously obtained at the same sites using time-dedicated GPS receivers.

Poster 12

GPS-BASED TIME ERROR ESTIMATES PROVIDED BY SMOOTHING, WIENER AND KALMAN FILTERS: A COMPARATIVE STUDY

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ABSTRACT

GPS timing signals play a critical role in the modern practice of time error estimation and synchronization. The major difficulty in this practice is the large noise on the measured data provided by the GPS receiver that requires the use of the proper filtering method to achieve adequate accuracy. Statistically, the most accurate results are achieved by the use of Kolmogorov-Wiener filtering (Wiener filter) for stationary random signals and Kalman-Bucy filtering (Kalman filter) for non-stationary signals. A non-optimal smoothing filter is used as the simplest way from an engineering point of view.

Despite the differences in theoretical application of the filters (stationary and non-stationary), GPS applications require a practical method of separation. What processes may be practically considered as stationary and what processes considered as non-stationary?

In this report we answer this question and obtain a practical method of separation of the stationary and non-stationary time error signals based on the variance and the rate of the time process. Simulation shows that, for the same transient time, the following filters should be used to obtain the best accuracy, depending on a fractional frequency offset (time error rate) y_0 for times where:

$0 \leq |y_0| < r_1$ for a Smoothing Filter,
$r_1 \leq |y_0| \leq r_2$ for a Wiener Filter, and
$r_2 < |y_0|$ for a Kalman Filter.

We determine the critical offsets r_1 and r_2. These offsets are dependent on the filter transient.

Digital processing of a GPS-based time error signal is carried out simultaneously by all three filters. Depending on y_0, the proper estimate should be taken as the most accurate. It follows that the Smoother and Wiener filters give the most accurate estimates for the relatively stationary signals of a precise synchronization system and the time error of an atomic oscillator with a small frequency offset. On the other hand, for a large initial offset for the tested quartz oscillator, the Kalman filter provides the best results.

We present comparative results for all three filters for rubidium and crystal oscillators based on the reference timing signals of the Motorola GPS UT+ Oncore Timing Receiver. Many examples of the original and filtered processes are discussed.

Poster 13

ROA TWSTFT STATION - SETUP AND FIRST RESULTS

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ABSTRACT

Real Observatorio de la Armada (ROA) has finished the installation and set-up of a Two-Way Satellite Time & Frequency Transfer (TWSTFT) station to join the European and Trans-Atlantic Links.

In this paper we will provide a description of the main components of the station and will present very preliminary results derived from the recent incorporation of the TWSTFT system.

Poster 14

CLOCK SYNCHRONIZATION USING GPS/GLONASS CARRIER PHASE

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ABSTRACT

In this paper, the clock synchronization via GPS/GLONASS (Global Positioning System/GLObal Navigation Satellite System) is proposed. By performing the double differences on carrier phase observables, the remote Oven-Controlled Crystal Oscillator (OCXO) clock can be synchronized with the primary cesium atomic clock. Two GPS/GLONASS receivers with the external frequency option are used in our system. While the remote OCXO clock and the primary cesium atomic clock are connected to the receivers, the frequency offset of the remote clock with respect to the primary clock can be estimated via the double differences on carrier phase observables. The Proportional-Derivative (PD) controller is adopted in our system for tuning the OCXO in real time. Through the D/A converter, the remote clock is then steered to synchronize with the primary clock. For averaging times of one day under the configuration of about a 30-meter baseline, our experimental results show that the accuracy of the remote clock can be improved from about 1×10^{-10} to about 3×10^{-14}, and the stability of the remote clock can be improved from about 2×10^{-10} to about a few parts in 10^{14}. Comparing with the GPS Disciplined Oscillator (GPSDP) system, the scheme adopted in this paper can achieve the traceability of frequency dissemination. The potential applications of the proposed architecture include the frequency sources system for calibration laboratories, telecommunication networks and power transmission system.

Poster 15

MODERNIZATION OF THE GLOBAL POSITIONING SYSTEM

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ABSTRACT

More than two decades have now passed since the construction of the GPS Operational Control Segment (OCS), including the Master Control Station (MCS) at Schriever AFB, Colorado and worldwide monitoring stations, and launch of the first GPS satellites. During that time, several generations of satellites have been designed, built, and launched, and operations are routinely supported by the OCS.

Today, the Global Positioning System (GPS) is entering into the new millennium with a far-reaching program to modernize the system on the ground and in space. This paper describes the goals, requirements, design objectives, and plans for implementing a $1 billion-plus modernization program in the coming decade.

Poster 16

PRIMARY REFERENCE CLOCK DEVELOPMENT

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ABSTRACT

The National Institute of Standards and Technology traceable measurements of a passive hydrogen maser, GPS receiver, rubidium standard and other elements of a new Primary Reference Clock being developed with European Union Assistance are reported. A new measurement system is detailed and first noise floor results are also reported.

Paper 27

ISSUES NECESSITATING A COMMON TIME REFERENCE IN THE U.S. NAVY

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ABSTRACT

This briefing discusses the impact of incorrect implementation of the United States of America Chairman of the Joint Chiefs of Staff timing policy. The brief systematically addresses each policy area and shows the associated level of compliance. Finally, with regard to the United States Navy, calls for the implementation of a common time reference making time a utility on board U.S. Naval vessels.

Paper 28

COMMON TIME REFERENCE TECHNOLOGY FOR SYSTEMS INTEROPERABILITY

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ABSTRACT

The Global Positioning System (GPS) has become the primary and most accurate means of disseminating time and frequency information. A growing and diverse mix of military positioning, communications, sensor, and data processing systems are using precise time and frequency from GPS. The precise accuracies required for their operation is also becoming more stringent. A new system architecture for providing a Common Time Reference to the operating forces and their related subsystems is being developed. This architecture is to provide a robust enhancement to implementations of GPS time and frequency subsystems. Through its implementation, interoperability between systems are to be enabled by providing a Common Time Reference and the means for systems to operate synchronously as a foundation for common interfaces and data exchange.

The Common Time Reference approach and its relationship to present GPS time and frequency usage will be described to show the concept and approach of this architecture. A robust architecture utilizing distributed time standards and existing standards within individual systems is to provide new capabilities for existing fielded systems without the impact of requiring a major retrofit. This combination of enabling existing and new resources to be used in a common reference will reduce the sensitivity to GPS anomalies and lack of continuous contact for precise updating. These systems would then be interconnected at the fundamental level of internal time and frequency generation, which would provide an inherent basis for functional interoperability. The elements necessary for implementation of this architecture with generic systems will be discussed. Technical developments necessary for implementation of the concept and the impact on interoperability will be discussed.

Paper 29

OVERVIEW AND COMPARISON OF EMERGING CLOCK TECHNOLOGIES

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ABSTRACT

Recent research results in the area of high stability clocks and oscillators have been remarkable. This paper provides a brief overview of several emerging clock technologies.

Different confinement and manipulation techniques will be covered, including ion traps and cold atom traps, along with laser and buffer gas cooling. Different interrogation schemes will be analyzed as well, with an emphasis on passive standards in the microwave and optical regimes.

Throughout, we will outline enabling technologies and key technological limitations.

Paper 30

DEVELOPMENT AND EVALUATION OF GPS SPACE CLOCKS FOR GPS III AND BEYOND

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ABSTRACT

The current GPS has exceeded its globally averaged position and timing accuracy of 16 m (50 % spherical error) and 100 ns (one sigma) as stated in the 1990 GPS System Operation Requirements Document (SORD). The 1999 GPS Operational Requirements Documents (ORD) set a new goal for the GPS III and beyond. The 1999 ORD specifies the position and timing accuracy at any location as: range rms accuracy threshold and objective of 1.5 m and 0.5 m, respectively, and 95 % time transfer accuracy threshold and objective of 20 ns and 10 ns, respectively. This paper will evaluate how the current clocks and the clocks being developed can support the ORD threshold and objective. The paper will include the following topics: (1) Atomic clocks on the GPS Block II space vehicles, (2) Estimated accuracy of the IIF Rb clock by Perkin Elmer and digital Cs clocks by Datum-Beverly and assessment of their performance against the ORD threshold range requirements. (3) Description of the new space clocks being developed jointly by the GPS JPO, Aerospace and NRL, and evaluation of their predicted performance to see if they can support the ORD objective of 0.5 m (rms). (4) Prediction of the GPS signal-in-space accuracy, including all the space and control segments errors, using IIF Rb and Cs clocks. The predictions are based on replacing the National Imagery and Mapping Agency (NIMA) estimated GPS II/IIA/IIR clock data, contained in the actual tracking data of the GPS monitor stations and the NIMA tracking stations, by simulated IIF Rb and Cs clock data. A Kalman filter similar to that of the Operational Control Segment (OCS) then processes the resulting tracking data and the estimated results are compared with NIMA estimates treated as truth. (5) Evaluation of the various options to see whether the ORD objective can be achieved based on the predicted signal-in-space accuracy.

Paper 31

GLOBAL POSITIONING SYSTEM (GPS) MODERNIZATION

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ABSTRACT

The Global Positioning System (GPS) signal is now the primary means of obtaining precise time to an internationally accepted standard. Precise timing applications have become dependent on this space-based source of precise time and, therefore, depend on the constellation of satellites that provide it worldwide, anytime. This paper describes the efforts by the GPS Joint Program Office within the U.S. Department of Defense to modernize the GPS signal services to meet future military and civil user requirements. GPS timing users and timing receiver developers and integrators need to be aware of these new capabilities and when they will be available. This paper starts with a brief review of the system design and an overview of the current constellation status. The GPS Modernization program to modify the current block of satellites being placed into service and the next generation currently in design to provide additional system capabilities will be described. Next, the paper discusses the GPS-III program to look at future user requirements beyond the next twenty years for precise positioning and timing services. The paper summarizes what these new capabilities will mean to the GPS timing users and provides some suggestions on what GPS timing users can do to make their future needs known. The paper concludes with some challenges to the user community to support the continued mission of GPS to provide precise positioning and time to all users free of direct charge.

Paper 32

FREQUENCY STABILITY REQUIREMENTS FOR NARROW BAND RECEIVERS

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ABSTRACT

Very narrow band Global Positioning System (GPS) receivers have recently been proposed in order to help mitigate the effects of scintillation. This paper will re-visit the stability requirements placed on the local oscillator of such receivers.

Paper 33

THE NANOKERNEL

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ABSTRACT

Internet timekeeping has come a long way since first demonstrated almost two decades ago. In that era most computer clocks were driven by the power grid and wandered several seconds per day relative to UTC. As computers and the Internet became faster and faster, hardware and software synchronization technology became much more sophisticated. The Network Time Protocol (NTP) evolved over four versions with ever better accuracy now limited only by the underlying computer hardware clock and adjustment mechanism.

Several years ago the software algorithms to discipline the Unix system clock were overhauled to provide improved accuracy, stability and resolution. In addition, a means was added to discipline the clock directly from a precision timing source, such as a cesium oscillator. The software was integrated with several operating system kernels of the day and eventually adopted as standard in Digital Alpha, Sun Solaris, Linux and FreeBSD. The performance achieved with workstations of the day was a few hundred microseconds in time and a PPM or two in frequency, so the resolution of one microsecond seemed completely adequate.

With PCs and workstations and networks of today reaching speeds in the gigahertz range, it is clear the solution of several years ago is rapidly becoming inadequate. This paper describes new algorithms and implementations providing a 1000-fold improvement in time and frequency resolution, together with a more agile and accurate precision discipline. The paper discusses the analysis and design of the algorithms, implementation details, and the results of proof-of -performance experiments. A testbed using a 450-MHz Intel PC with an uncompensated clock oscillator, but disciplined to a rubidium oscillator, has achieved RMS jitter less than 50 ns. The software has been implemented and tested in Digital Alpha and SunOS operating systems and is now distributed with Linux and FreeBSD.

Paper 34

USING THE NETWORK TIME PROTOCOL (NTP) TO TRANSMIT INTERNATIONAL ATOMIC TIME (TAI)

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ABSTRACT

Although Coordinated Universal Time (UTC) is the time scale that is transmitted by almost all time services, this scale is awkward to use in the vicinity of a leap second. Many computer systems cannot represent the epoch corresponding to a positive leap second (23:59:60), and remain synchronized to UTC by stopping the clock at 23:59:59 for 1 extra second whenever a leap second is to be added. This makes it impossible to assign unambiguous time tags to events that happen during this period. In addition, computing the length of a time interval that includes a leap second of either sign is difficult because simply subtracting the two UTC time stamps at the end-points of the interval does not account for the time interval occupied by the leap second itself.

To address these issues, we have augmented the Network Time Protocol (NTP) to allow a client system to reconstruct TAI from UTC and a table of leap seconds. This time scale has no discontinuity during the leap second. Intervals computed using TAI are unaffected by the additional time occupied by the UTC leap second, and the TAI time scale provides an unambiguous time tag to any event -- even one that happens during a UTC leap second. Although our solution is unique to servers that support the Network Time Protocol (NTP), it could be adapted to other time services and formats. Such systems could support time tags using either UTC or TAI, and would significantly reduce the problems that result from using UTC alone.

Paper 35

USNO GPS/ATOMIC NTP STRATUM-1 SERVERS

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ABSTRACT

The U.S. Naval Observatory (USNO) has been contracted by the Defense Information Systems Agency (DISA) for the production of Network Timing Protocol (NTP) Stratum 1 network time servers for worldwide deployment. These will be based on the design of the present high-performance USNO NTP servers, capable of handling greater than 100 NTP requests/second. Significant improvements will include integration of the Rockwell-Collins MPE 1.12 dual-frequency keyed GPS module and a TEMEX RMO-1 internal rubidium. The P(Y) code receiver meets DoD requirements for military applications, and will be integrated into Brandywine's VME synchronized generator. The rubidium will allow sustained NTP service in the event of loss of GPS signal for up to a year with 1-millisecond flywheel accuracy.

Paper 36

PRIMARY REFERENCE CLOCKS USING INDOOR ANTENNAS

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ABSTRACT

This paper discusses a new technology of synchronizing clocks and disciplining oscillators using CDMA cellular transmissions. Like cellular telephones, these receivers will operate in most buildings without rooftop antennas. They are reported accurate to within microseconds to UTC with stable frequencies available.