REFERENCE GUIDE

Active Hydrogen Masers MHM 2010

Auxiliary Offset Generators AOG 110

It takes a long time to bring excellence to maturity.

-Publius Syrus

datum

Timing, Test & Measurement

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ACTIVE HYDROGEN MASERS MHM 2010
AUXILIARY OFFSET GENERATOR AOG 110

Intro

In 1997, Datum–Timing, Test & Measurement (known then as Frequency and Time Systems) acquired Sigma Tau Corporation. The Sigma Tau Active Hydrogen Masers operation had been founded twenty-years earlier by Mr. Harry Peters.

From the outset Mr. Peters focused on building the best performing instruments in the world. Years of experience in Hydrogen Maser engineering design and manufacture at NASA's Goddard Space Flight Center positioned him ideally for this task.

By assembling a team of highly competent engineers and technicians, the company developed a premium product, with a strong emphasis on superior performance and high reliability.

In twenty years the company delivered more than forty active hydrogen masers to a worldwide customer base, including institutions at the forefront of time and frequency excellence such as the USNO (USA), Observatoire de Paris (France), NIST (USA) and NPL (United Kingdom).

A number of product improvements made through the years resulted in a product that boasts a demonstrated life of >15 years coupled with frequency drift performance to <2E-16/day after a sufficient period of unperturbed operation.

Today, Datum–Timing, Test & Measurement offers one of the most complete ranges of time, timing and frequency technology available. Already well known for the successful installation of Caesium Clocks in the GPS NAVSTAR satellite system, Datum TT&M now provides the best active hydrogen maser available in the world.

The combination of these two operations forms a unique team with the expertise to build the best frequency standards in the world. The Datum Sigma Tau Standards Group is backed by a manufacturing, sales, and service organization with worldwide presence, able to respond to and support an extensive international customer base.

MHM 2010 ACTIVE HYDROGEN MASER

Features

A patented Magnetic Quadrapole for superior atomic beam focusing.

A very low Hydrogen usage (< 0.01 mole per year) for extended maintenance-free operation.

A unique, stand-alone, Cavity Auto Tuning feature.

A proprietary Teflon coating technique, eliminating any re-coating requirement and extending maintenance free life.

MHM 2010 ACTIVE HYDROGEN MASER

Microwave
Amplification
Stimulated
Emission of
Radiation

Overview

This product is the only commercially available Active Hydrogen Maser in the world with stand-alone Cavity Switching Auto Tuning. This technique, developed by Sigma Tau, enables the MHM 2010 to deliver long-term stability normally only attributed to the most stable of caesium atomic standards.

Each MHM 2010 is manufactured to exacting quality standards and carefully checked at each stage to insure a top quality product. Once built, the units are subjected to extensive performance testing, verifying all aspects of operation.

Before shipment from the Datum Sigma Tau facility, each unit goes through rigorous testing and performance monitoring to insure that the unit meets or exceeds all specifications.

Specifications

Stability

Allan Deviation (measured in 1Hz Bandwidth)

1s	2E-13
10s	5E-14
100s	1.3E-14
1000s	3.2E-15
Floor	3E-15

Long term	<2E-16 per day*
Auto tuning	no external reference required

*Achieved after extended period of unperturbed, continuous operation.

Environmental

Temperature Sensitivity	<1E-14/°C
Magnetic Sensitivity	<3E-14/Gauss
Power source sensitivity	<1E-14

Control

Synthesized frequency resolution	7E-17
Frequency control range	7E-10

Note : The synthesizer maintains continuous phase throughout frequency change.

Available Outputs

Frequency	Amplitude
5 MHz	13dBm (3 each)
10 MHz	10dBm
100MHz	13dBm

Load Impedance 50 Ω

Phase Noise

5MHz Outputs

1Hz	-90 dBc
10Hz	-110dBc
100Hz	-130dBc
1KHz	-140dBc
10KHz	-150dBc
100KHz	-155dBc

Operating voltage 85 to 264 VAC

Power

Operating voltage	85 to 264 VAC
Frequency Range	47 to 63 Hz
Peak power	150 W
Operating power	75 W
External DC input	22 to 28 VDC 3.1A (typical)
Standby battery	8 hours operation

Options	Option P/N
• 100 MHz Output / 13dBm	102

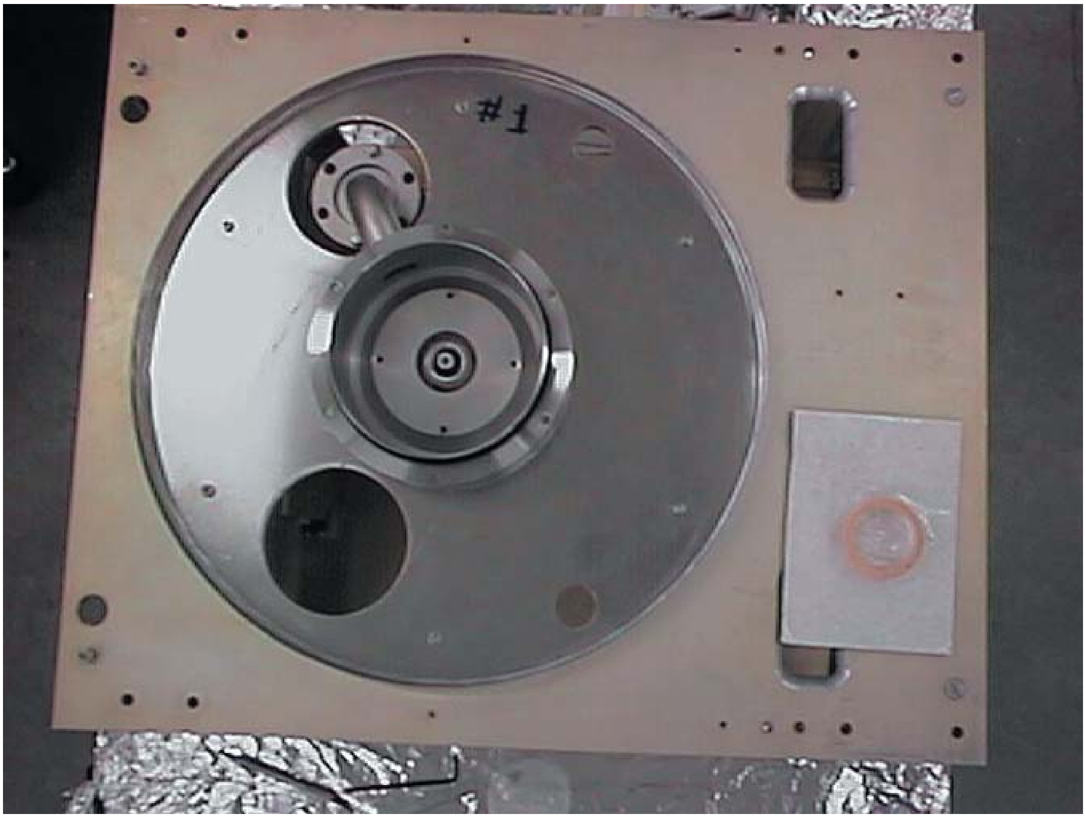
Specifications subject to change without notice.

Datum-TT&M • 34 Tozer Road • Beverly, MA 01915-5510 • Tel: +1-978-927-8220 • Fax; +1-978-927-4099
USA Toll Free: 1-800-544-0233 • Web: www.datum.com • E-mail: ttmsales@datum.com

The dissociator converts molecular Hydrogen (H2) into atomic Hydrogen. The atomic beam emerges from the collimator (shown in the center of the picture) and the proper atomic hyperfine states are directed into the microwave cavity by the quadrapole magnetic state selector.

The quadrapole magnetic state selector design gives a very high concentration of flux at the pole tips which allows extremely precise focussing of the atoms. Due to its small size and low level of stray fields caused by the magnet, the state selector may be placed close to the magnetic shields, reducing path length and improving efficiency of the Maser.

The improved efficiency translates into a lower usage of hydrogen for the same performance, which helps to extend the trouble-free operating life of the Maser.



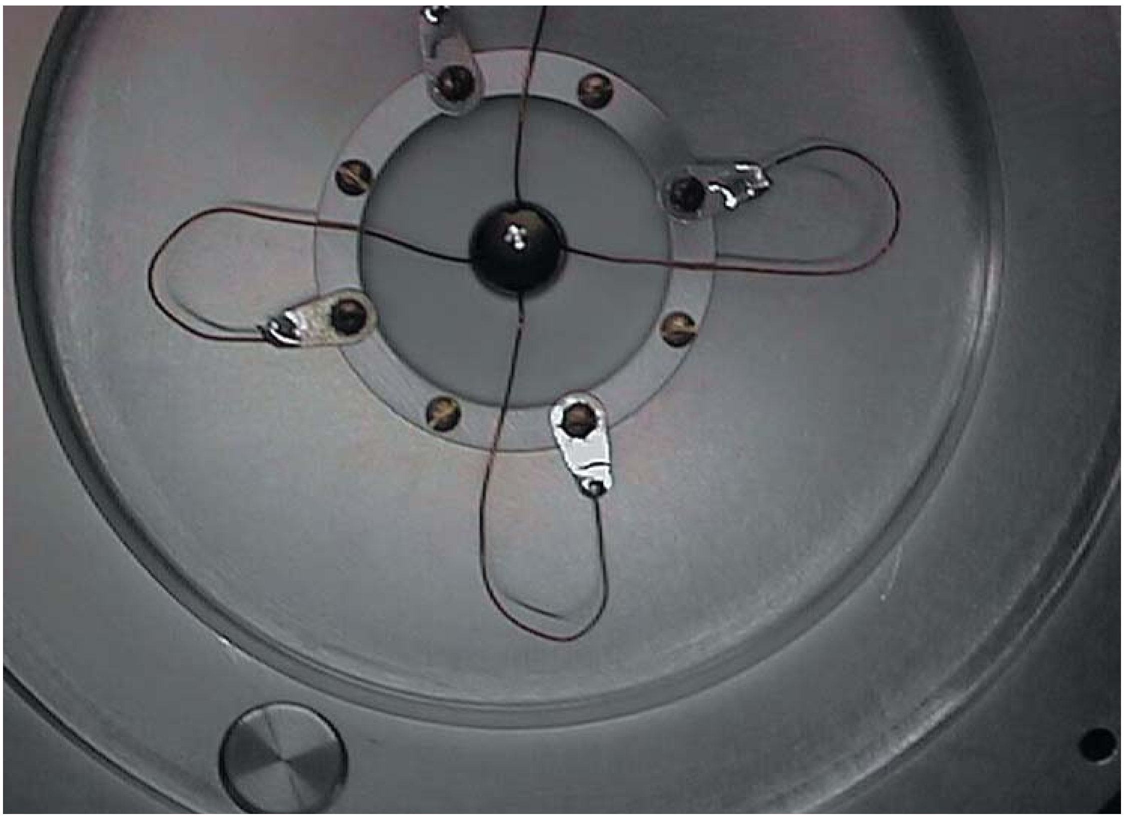
Top View of Source Chamber, Collimator, and Dissociator

CAVITY SUPPORT PLATE

This picture shows the cavity support plate with degaussing spider emerging from the plate bottom.

This technique insures electrical conductivity needed for degaussing, while maintaining thermal isolation of the microwave cavity.

Thermal isolation of the cavity is a critical aspect of maintaining a constant temperature operating environment, resulting in improved Maser stability.



Cavity Support Plate

The picture below shows the Hydrogen storage bulb prior to fitting within the solid copper microwave cavity.

Teflon coating helps preserve the properties of the Hydrogen atom despite around 104 collisions with the coated bulb surface. The Sigma Tau technique used for coating the bulb insures high line Q and practically eliminates bulb re-coating as a wear out mechanism.

It is within the storage bulb that the atoms are stimulated by the microwaves to emit at the precise frequency of the hydrogen line at 1,420,405,751.xxx Hz. On average each atom travels several kilometers within this bulb before exiting!

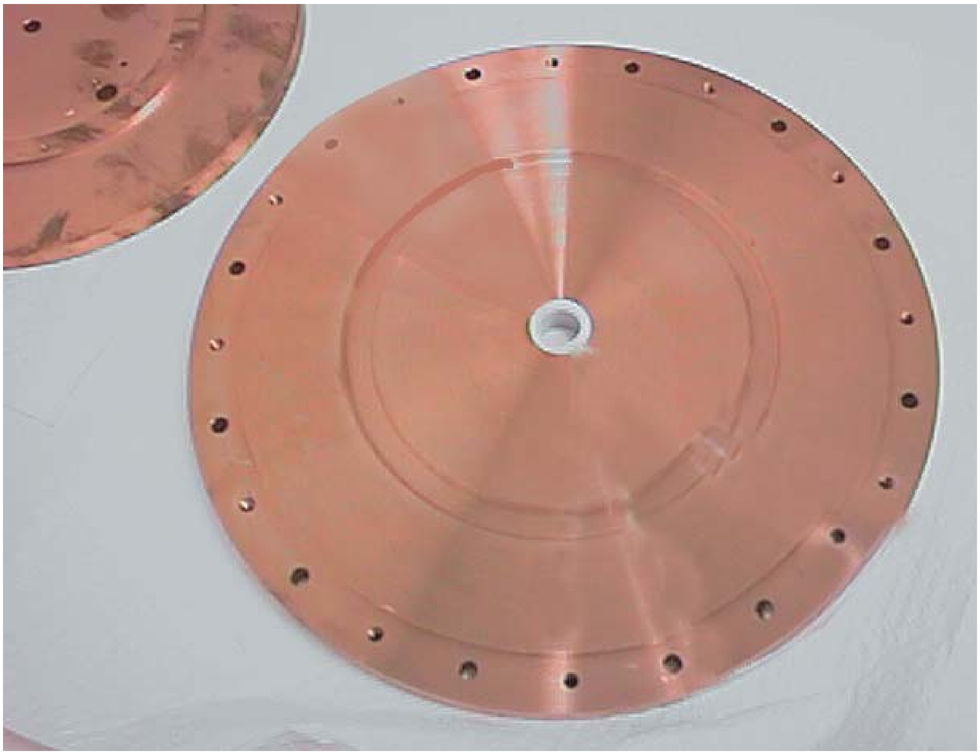
One of the key aspects for maintaining the superb long term stability characteristics of the Maser is consistency and stability of the internal components themselves. This storage bulb is designed to maintain a repeatable, stable, performance for many years.

Hydrogen Storage Bulb

The precision machined, solid copper microwave cavity bottom plate gives an example of the rugged construction and engineering that goes into the manufacture of each Sigma Tau maser.

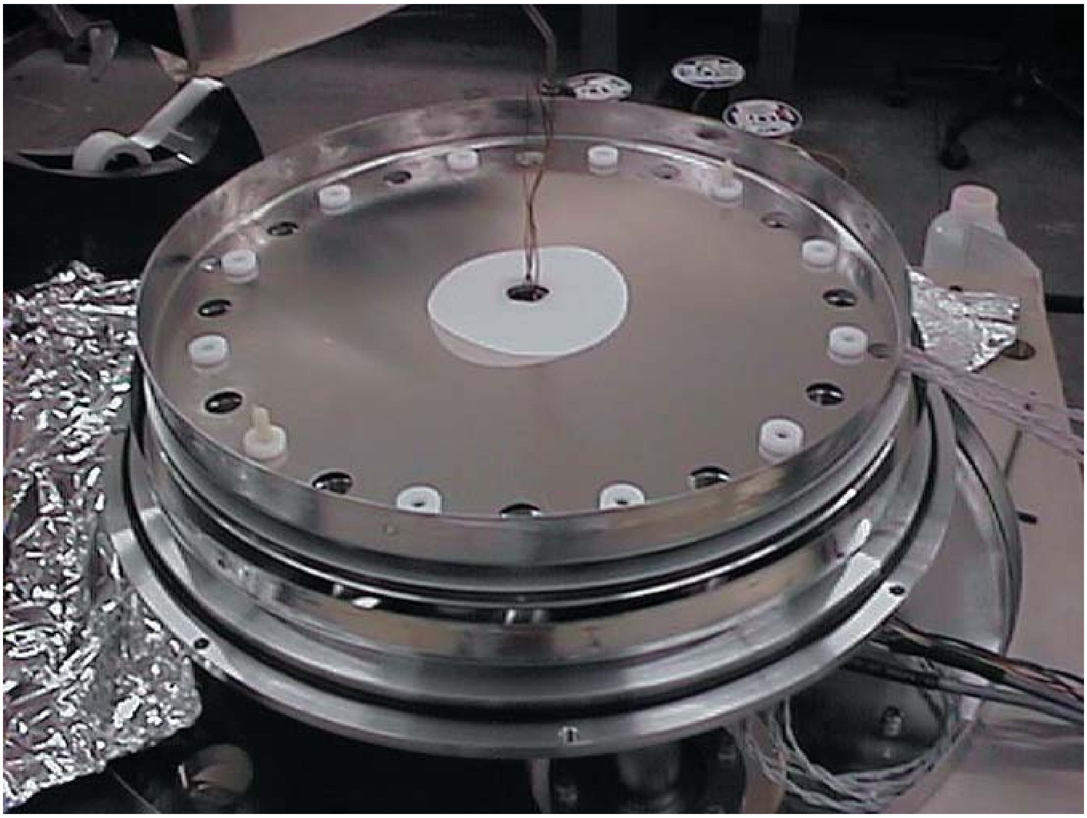
There are many similar parts incorporated in the design, all carefully examined and inspected for compliance to drawing detail before being assembled into the end product.

Building a reliable network of skilled suppliers is just one of the aspects of manufacturing repeatability which makes the Sigma Tau masers stand apart from other designs.



Microwave Cavity Bottom Plate

The high μ metal cover plate for magnetic shielding is an example of the special materials used within the Maser for achieving the absolute best from the desired function, in this case shielding the unit from the effects of any external magnetic fields.



Hypernom Cover Plate

Critical to achieving the stability levels associated with Active Hydrogen Masers is thermal stability of all of the active components and assemblies.

The picture below shows the overall thermal shield of the MHM 2010, which encloses the inner magnetic shield and the microwave cavity of the Maser.

There are several levels of thermal control built into the unit to assure that any ambient temperature variations have a minimal affect on Maser performance.

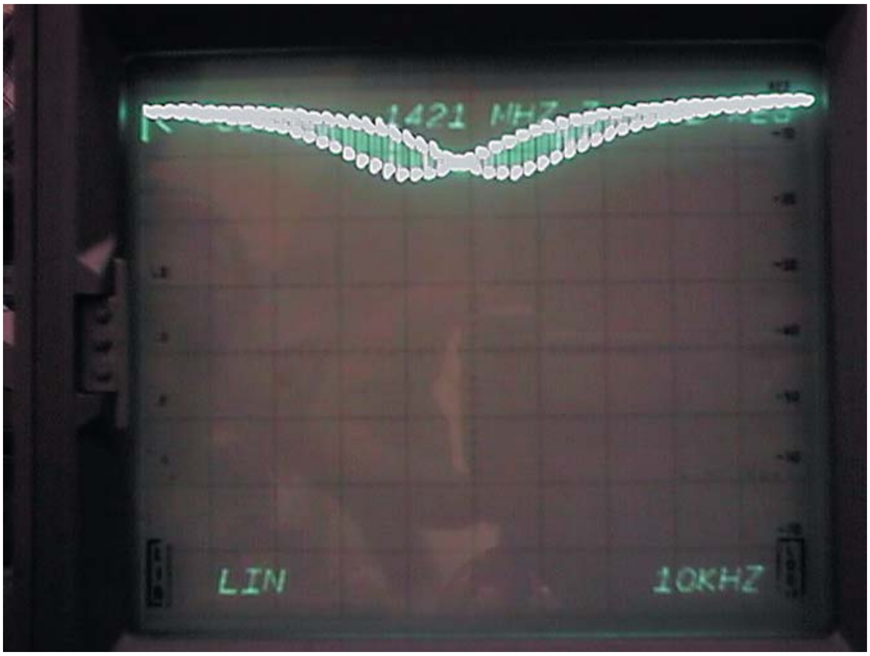
Even so, Active Hydrogen Masers are often placed within temperature controlled chambers in order to meet such stability values as 1E-16 per day!

Thermal Shield

One of the unique aspects of the MHM 2010 is the Cavity Auto Tuning feature which enables the unit to constantly verify that it is centered on the Hydrogen peak at 1,420,405,751.xxx Hz.

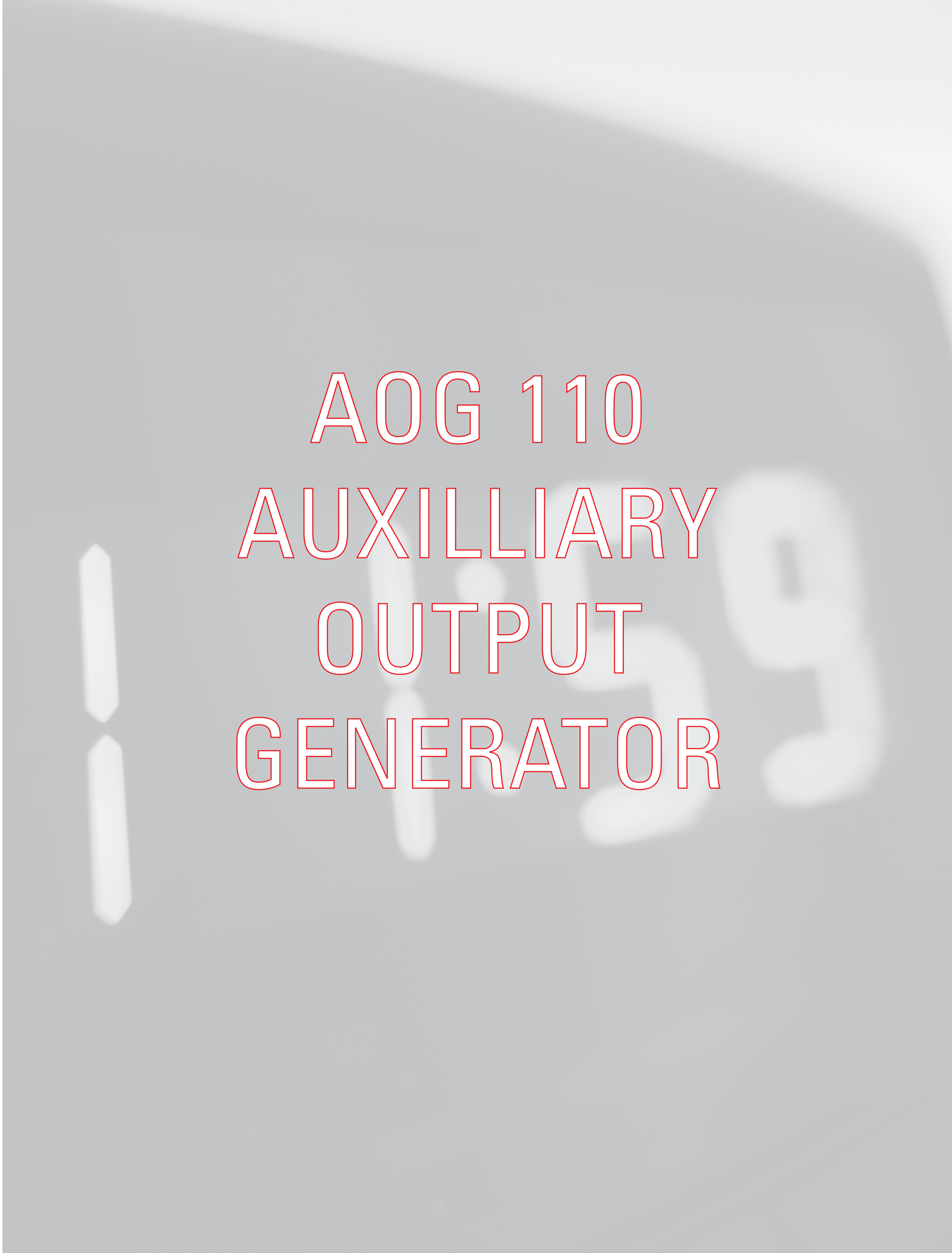
Based upon the cavity frequency-switching method, the cavity servo requires no external frequency references in it's operation, and unlike conventional spin exchange tuning, the maser does not require beam intensity switching which could degrade the short term stability and phase noise characteristics.

The Cavity Auto Tuning insures that the long term stablity of the unit is highly controlled. With other designs of Active Hydrogen Masers this level of performance can only be met by using two Masers to Auto Tune against each other.



Display of Cavity Auto Tuning

Typical performance parameters are shown in the back of this booklet. Further technical information on the performance of the MHM 2010 can be obtained by contacting Datum-Timing, Test & Measurement.



AOG 110 AUXILLIARY OUTPUT GENERATOR

Features

High Precision

- 5 MHz low phase noise outputs
- Outputs phase offset programmable to 1 picosecond
- Output frequency programmable to 1E-19 fractionally over 5E-8 range
- Temperature control insures thermal stability

Proven Design

- RF subsystem developed from hydrogen maser technology
- Second generation microprocessor control
- Digital phase and frequency control

Easy-to-use Hardware

- Menu driven interface with keypad access
- LCD display provides easy access to configuration and performance information
- Full system control via RS-232 compatible interface

Versatile Control Functions

- Password protected remote operation provides security
- Absolute and relative frequency control
- Dual-mode, timed frequency control allows interval frequency and final frequency settings
- Output relative phase control over user defined intervals
- Suspend and resume available on programmed intervals
- Real-time clock set and adjust

AOG 110 AUXILIARY OUTPUT GENERATOR

Overview

The Datum Auxiliary Output Generator, designated the AOG-110, solves performance and capability issues associated with the use of high stability frequency standards. Until now, intermediate offset generators that extended a standard's frequency range without a performance sacrifice were difficult or impractical to obtain. Now the AOG-110 is available with a 5 MHz output, programmable over a broad frequency range with extremely high resolution and precise phase control at an economical price.

The 5 MHz output, available on three buffer-isolated output ports, features a high performance crystal oscillator phase-locked to the external standard's output reference and employs heterodyne techniques developed for the Datum TT&M Atomic Hydrogen Maser. Internally, the 5 MHz is used to develop one pulse per second (1 PPS) which is available as an output. The 1 PPS output can be synchronized to an external 1 PPS reference by the AOG's operator controls.

Specifications

The output frequency is controlled by directly offsetting a phase accumulator (synthesizer) in the PLL chain. The maximum synthesized fractional frequency range is ± 1E-7, with a fractional resolution of 1E-19. By altering the frequency output over a precise time interval, output phase control is achieved. Typically, the user defines the desired phase offset and time interval within which the offset is made. Once set, the AOG-110 automatically implements the appropriate frequency offset and precise time interval. Direct control over both frequency and time interval is available.

The frequency, phase and 1 PPS synchronization of the AOG are independently controlled through a menu-driven interface on the front panel. The interface also provides operational status information. The local interface consists of an LCD display, a real-time clock display, and a 16-key keypad coupled to a microprocessor. An RS-232 serial port is available for remote operation. Generally the operator uses either exclusive local control or exclusive remote control. Shared control between local and remote interface is available. Remote control supports password protection that requires entry of a code before the use of local controls is possible. Numerous other options include: baud rate, parity and data format; unit identification number; settable VCO phase-locked loop (PLL) bandwidth and real time clock format. Storage of these options in a nonvolatile memory prevents loss due to power failure or removal.

The AOG-110 remote command set includes 11 commands for frequency, phase control, security control, status, on-line help and 1 PPS synchronization control. All commands are parsed for correct syntax and operational range prior to execution. Commands that contain errors are rejected and reported to the remote console without affecting the 5 MHz output.

Performance

- One second stability better than 3E-13
- Approximate 1/t stability from one second
- Phase noise <3 dB over Maser
- Three 5 MHz outputs, +13 dBm into 50 Ohms
- VCXO range, >1E-6
- Output isolation >80 dB
- 5 MHz input range, +3 dBm to +15 dBm

Temperature sensitivity <0.1 picosecond per degree C

Power Requirements

- Universal supply, 85-265 VAC, 47-440 Hz
- Secondary DC input, 18-30 Vdc
- 20 Watt operational power, 40 Watt start-up

Dimensions

- 7.0” x 16.75” x 21.0” rack-mount chassis
- Approximately 40 lbs.

Computer Interface

- RS-232 compatible control port
- Supports 1200, 2400, 4800, 9600 and 19200 baud rates
- Remote lockout mode requires password for keypad control
- All frequency, phase and clock controls available remotely
- Operational data and identification available remotely

The AOG110 (above) is used by calibration laboratories, engineering facilities and metrology laboratories with high stability frequency standards such as Masers to generate high quality RF sine wave signal offsets without sacrificing performance.

Overview

The Sigma Tau AOG 110 Auxiliary Offset Generator solves performance and capability issues associated with the use of high stability 5 MHz frequency standards such as the MHM 2010 Active Hydrogen Maser. The AOG-110 provides a 5 MHz output, programmable over a broad frequency range with extremely high resolution and precise phase control.

It is often desirable to synchronize and syntonize the signal from a frequency standard to a source, for example the USNO Master Clock.

The AOG 110 facilitates adjustment of the reference to a slightly different operating point and allows the user to apply the benefit from the stability of the the reference. At the same time it leaves the reference source completely unperturbed, therefore maintaining best performance from the Maser.

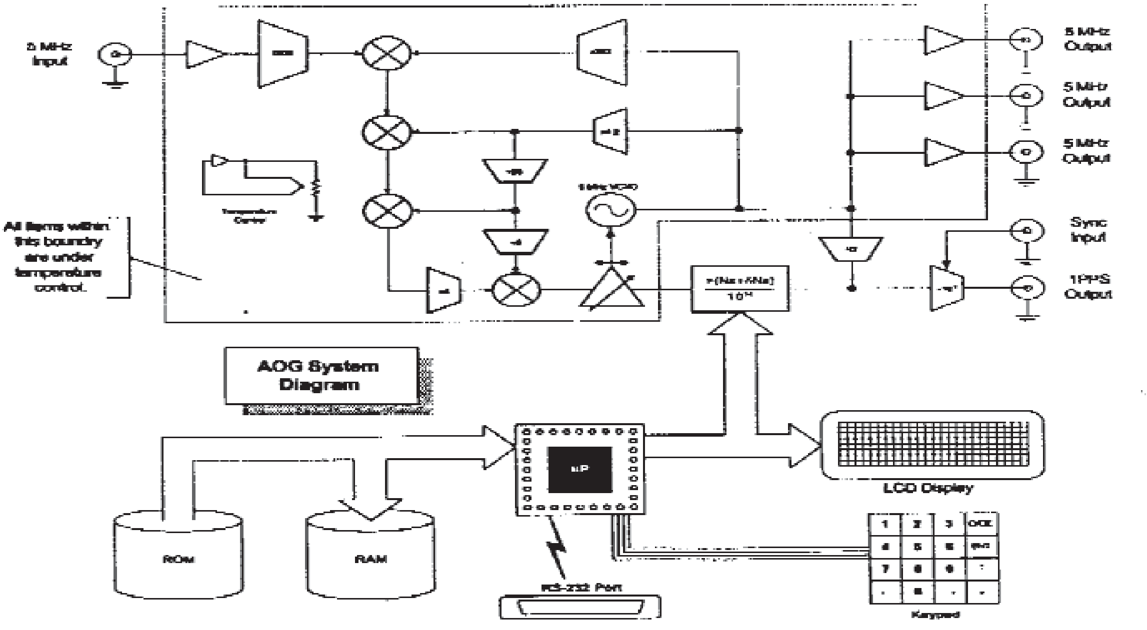
The 5 MHz output, available on three buffer-isolated output ports features a high performance crystal oscillator phase-locked to the external standard?s output reference and employs the heterodyne techniques developed for the MHM 2010 active hydrogen maser. Internally, the 5 MHz is used to develop a one pulse per second output (1PPS) which is available as an output. The 1PPS output can be periodically synced to an external 1PPS reference by the AOG's operator controls.

Overview

Output frequency is controlled by directly offsetting a phase accumulator (synthesizer) in the PLL chain. The maximum synthesized fractional frequency range is + 1E-7, with a resolution of 2E-19 . By altering the frequency output over a precise time interval output phase control is achieved. Typically, the user defines the desired phase offset and time interval within which the offset is made. Once set the AOG-110 automatically implements the appropriate frequency offset and precise time interval. Direct control over both frequency and time interval is available.

The frequency, phase and 1PPS synchronization of the AOG are independently controlled through a menu-driven interface on the front panel. The interface also provides operational status information. The local interface consists of an LCD display, a real-time clock display, and 16-key keypad coupled to a microprocessor. An RS-232 serial port is available for remote operation. Generally the operator uses either exclusive local control or exclusive remote control. Shared control between local and remote interface is available.

Remote control supports password protection that requires entry of a code before the use of local controls is possible. Numerous other options include: baud rate, parity and data format; unit identification number; VCO phase-locked loop (PPL) bandwidth and real time clock format. Storage of these options in a nonvolatile memory prevents lost due to power failure or removal.



The AOG-110 remote command set includes 11 commands for frequency, phase control, security control, status, on-line help and 1PPS synchronization control. All commands are parsed for correct syntax and operational range prior to execution. Commands that contain errors are rejected and reported to remote console without affecting the 5 MHz output.

Although intended for use with the Sigma Tau MHM 2010 Active Hydrogen Maser the AOG 110 can be used with any highly stable high performance source.

Typically phase or frequency adjustments are necessary when matching the output of the Maser to some other reference. For example implementing precision timing synchronized to international time scales by means of such techniques as two satellite time transfer or GPS common mode common view.

Technical specifications are shown in the back of this booklet. Further technical information on the performance of the MHM 2010 can be obtained by contacting Datum-Timing, Test & Measurement.

Features

High precision

- 5 MHz low phase noise outputs
- Outputs phase offset programmable to 1 pico second
- Output frequency programmable to 1E-19 fractionally over 5E-8 range
- Temperature control insures thermal stability

Proven design

- RF subsystem developed from hydrogen maser technology
- Second generation micro-processor control
- Digital phase and frequency control

Easy to use hardware

- Menu driven interface with keypad access
- LCD display provides easy access to configuration and performance information
- Full system control via RS-232 compatible interface

Versatile Control Functions

- Password protected remote operation provides security
- Direct and incremental frequency control
- Dual-mode, timed frequency control allows interval-frequency and final-frequency settings
- Output-relative phase control over user defined intervals
- Suspend and resume available on programmed intervals
- Real-time clock set and adjust

Typical Performance

Stability

1 second	3E-13
> 1 second	approximately 1 / τ to noise floor

Steering

Resolution	2E-19
Range	± 1E-7

SSB Phase Noise @ 5 MHz (using MHM 2010 as reference source)

Offset from Carrier	
1 Hz	< -126 dBc
10 Hz	< -130 dBc
100 Hz	< -147 dBc
1000 Hz	< -153 dBc

Outputs

Frequency	5 MHz	three outputs
Amplitude	+13 dBm	
Load Impedance	50 Ω	
Output isolation	>80 dB	

Environmental

Temperature sensitivity	<0.1 pico second per 0C

Other

5 MHz input range	+3 dBm to +15 dBm
VCXO range	>1E-6 fractionally

Power Requirements

Operating Voltage	85 to 264 VAC
Frequency Range	47 to 440 Hz
Peak power	40 W
Operating power	20 W
External DC input	18 to 30 VDC, 1A (typical)

Typical Performance

Dimensions

Height	7.0 inches
Depth	16.75 inches
Width	19 inch rack-mount chassis
Weight	Approximately 40 lbs.

Computer Interface

RS-232 compatible control port

Baud rates :	1200
	2400
	4800
	9600
	19200

Remote lockout mode	password for keypad control
Remote controls	Frequency Phase Clock
Remote Monitors	Operational data Identification

FROM THE PEOPLE WHO PUT CESIUM INTO THE GPS NAVSTAR SATELLITE...

VERY LONG BASELINE INTERFEROMETRY, TIME-KEEPING AND OTHER APPLICATIONS FOR SIGMA TAU ACTIVE HYDROGEN MASERS

INTRODUCTION

The following pages provide just a small sample of some of the many Active Hydrogen MASERs, delivered by the Sigma Tau Standards Group over the past 20 years.

During this time, Sigma Tau MASERs have gained a reputation for providing the most stable frequency reference signals commercially available anywhere in the world. This, coupled with a superb record of reliability, exemplifies the dedication and design attention to detail that is the product of a lifetime of experience working with precision frequency standards.

For further information regarding these and other precision frequency reference standards including, Cesium, Rubidium and Quartz technologies for commercial, military, and space environments, please contact
Datum, Timing, Test & Measurement at:

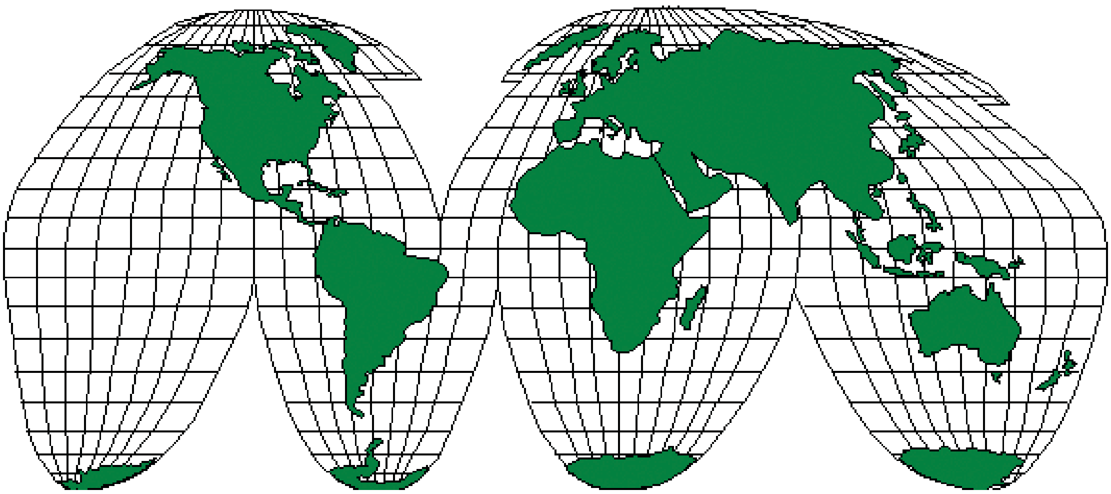
34 Tozer Road
Beverly, MA 01803
USA

Tel: (+1) 978 927 8220
TollFree: (+1) 800-544-0233
Fax: (+1) 978 927 4099

E-mail : ttmsales@datum.com

or visit our web site
http://www.datum.com

VERY LONG BASELINE INTERFOROMETRY (VLBI) & LONG BASELINE ARRAYS (VLBA)



Very Long Baseline Interferometry (VLBI) & Very Long Baseline Arrays (VLBA)

National Radio Astronomy Observatory (NRAO) USA - Very Large Array

The NRAO is a facility of the National Science Foundation (NSF). The Very Large Array (VLA) is one of the world's premier astronomical radio observatories. The VLA consists of 27 antennas arranged in a huge Y pattern 36km (22 miles) across.
The VLA was completed in January 1981 and is located on the Plains of San Agustin, west of Socorro, New Mexico, USA. The VLA is tremendously versatile and observing time is in extremely high demand among astronomers. The 27 VLA antennas work together as 351 different interferometer pairs, linked in real time, which allows production of extremely high quality images of celestial objects.

Also operated by NRAO, in Socorro, is the Very Long Baseline Array which is a set of 10 identical antennas spread across the United States from Hawaii to the U.S. Virgin Islands. This radiotelescope is used to observe galaxies, quasars, gravitational lenses, and other objects, at milliarcsecond resolution..

The NRAO currently has **twelve, Datum-TT&M *Sigma Tau* MASERs**. The MASERS have been procured over the past 15 years and are used within the VLBA facility to provide the precise timing synchronization and stability essential to these measurements.

Westorbork Synthesis Radio Telescope (WSRT) Netherlands


The 14 telescopes comprising the Westerbork Synthesis Radio Telescope (WSRT) form a major National resource for The Netherlands and have been undergoing a major upgrade since 1994.

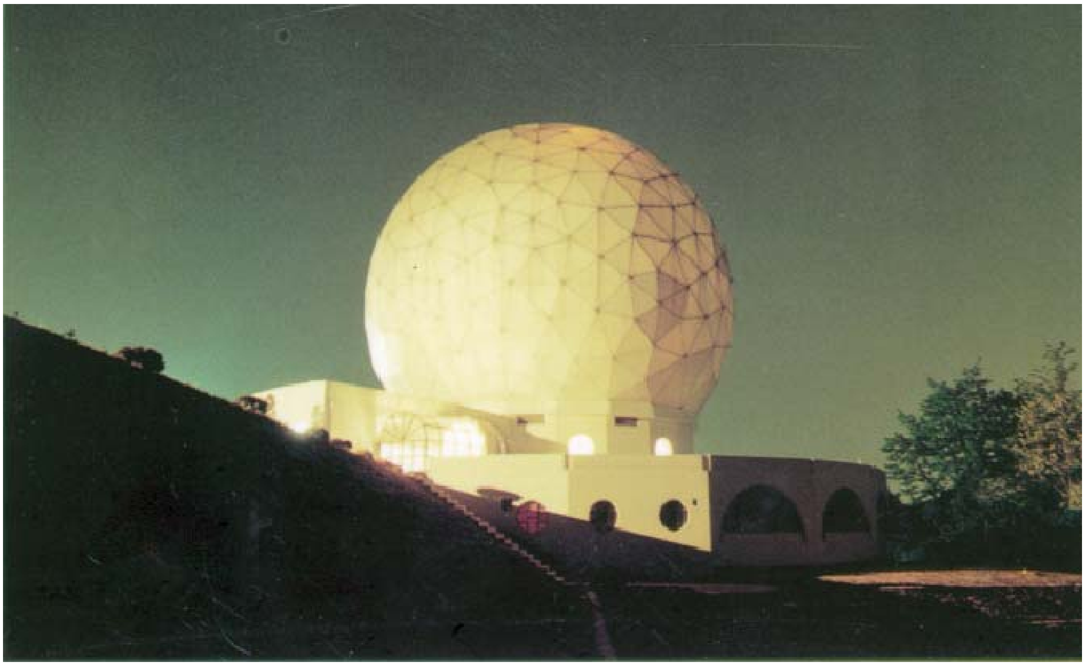
The result of the upgrade is a fundamental change in the operation and the scientific capabilities of the telescope. The expanded observing capacity allows new and innovative science over a wide range of frequencies. Complementary studies across the vast frequency range now accessible to the WSRT allows spectral line observations of HI, OH, formaldehyde, and even H_2O in large portions of the early Universe.

The current and proposed uses for the WRST MASERs are :

- Local synthesis observations
- Astronomical VLBI
  (requires 2E-15 stability in 1000 seconds for 3.6cm observations)
- Geodetic VLBI
- Pulsar Research
  (currently requires 10ns accuracy, future goal 1ns accuracy)
- Connection to Geodesy framework
- Absolute time keeping station

Part of the upgrade was to replace the original (30 year old) MASER system by a **Datum-TT&M *Sigma Tau* MASER**, in order to accommodate the future requirements of the VLBI, pulsar and geodetic communities. This should also ensure a time-keeping system second to none.

Very Long Baseline Interferometry (VLBI) & Very Long Baseline Arrays (VLBA)



The Korea Astronomical Observatory (KAO)

The Korea Astronomical Observatory (KAO) provides observation and metrology facilities for South Korea. The Taeduk Radio Astronomy Observatory (shown above) is also in joint cooperation for Very Long Baseline Interferometry (VLBI) observations with facilities in Japan and other Asian countries.

KAO has utilized a Datum-TT&M Sigma Tau MASER, in cooperation with the Korean Research Institute of Science and Standards (KRISS) for many years, and now, as part of an upgrade project has recently taken delivery of a second MASER for use in this work.

The Arecibo Observatory is part of the National Astronomy and Ionosphere Center (NAIC), operated by Cornell University with the National Science Foundation (NSF). Extra support is provided by the National Aeronautics and Space Administration (NASA). Following three years of construction the Arecibo Ionospheric Observatory (AIO) went into operation in 1963.

Operating on a continuous basis, 24 hours a day, it is the site of the world's largest single-dish radio telescope. The Observatory is recognized as one of the most important national centers for research in radio astronomy, planetary radar and terrestrial aeronomy. It also maintains an Ionospheric Interactions facility consisting of thirty-two log-periodic antennas and transmitters capable of concentrating energy in the ionosphere. The Arecibo site offers the advantage of being located in Karst terrain, with large limestone sinkholes which provided a natural geometry for the construction of the 305 meter reflector.

In 1974 a new high precision surface for the reflector (the current one) was installed together with a high frequency planetary radar transmitter. The second and major upgrade to the telescope was completed in 1997. A ground screen around the perimeter of the reflector was installed to shield the feeds from ground radiation. The gregorian dome with its subreflectors and new electronics greatly increases the capability of the telescope.

The Arecibo Ionospheric Observatory uses a Datum-TT&M Sigma Tau MASER as a key component of the Observatory's capabilities.

The 76 m Lovell Telescope at Nuffield Radio Astronomy Laboratories (NRAL), UK MERLIN, the Multi-Element Radio-Linked Interferometer Network, consists of seven separate telescopes in the United Knigdom: the Lovell or Mark II at Jodrell Bank, the Mark III telescope and two 25-m telescopes elsewhere in Cheshire, another two 25-m telescopes in Shropshire and Worcestershire, and the far-flung 32-m telescope at Cambridge.

MERLIN has a resolution of around 0.05 arcsec; about the same as the Hubble Space Telescope at visible wavelengths. The Lovell Telescope is an important part of MERLIN, since its large collecting area provides the sensitivity that the smaller telescopes lack.

Together with large telescopes in Germany and the Netherlands, the Lovell Telescope forms the core of the European VLBI Network (EVN) which has regular programs of collaborative observing. On a larger scale still, the Lovell Telescope routinely works with radio observatories all over the world.

NRAL use a Datum-TT&M Sigma Tau MASER within the laboratories as the precise timing for data recording, a critical aspect of the Observatory's capabilities.

NATIONAL & INTERNATIONAL TIMEKEEPING

The Paris Observatory is one of the principal centers of the French Ministry of Higher Education and Research, and a so-called public institution of scientific, cultural and professional nature. Its goals are to contribute to our growing knowledge of the Universe, to provide services related to its research activities to the national and international community, to contribute to basic and advanced education, to assist in the distribution of knowledge and to implement international cooperation.

The Observatory consists of nine departments, a scientific service and 5 common services which comprise a dozen CNRS units. As part of the service responsibilities assigned to it on international and national level, it accommodates the Principal Laboratory of Time and Frequency (LPTF), which is responsible, among other things, for keeping the French civil time, watching over solar activity, as well as for the International Service of Earth's Rotation.

It is the oldest observatory still serving (built around 1665) and the latitude of the south face defines the Paris latitude (48° 50' 11'') while the meridian line passing through its center defines the Paris longitude. The foundations are as deep (27 m) as the building is high. In this deep basement is the Bureau Internationale de l'Heure (International Time Bureau) who sets the coordinated universal time (UTC) with 10-6sec. of accuracy. Since 1933, the speaking clock (tel. 3699) gives the accurate time. The basement is connected with the Paris catacombs (visits forbidden). The catacombs consist of 65 km of underground galleries.

The Observatory is responsible for many highly important scientific works and has just added a second Datum-TT&M Sigma Tau MASER as part of the critical reference equipment employed.

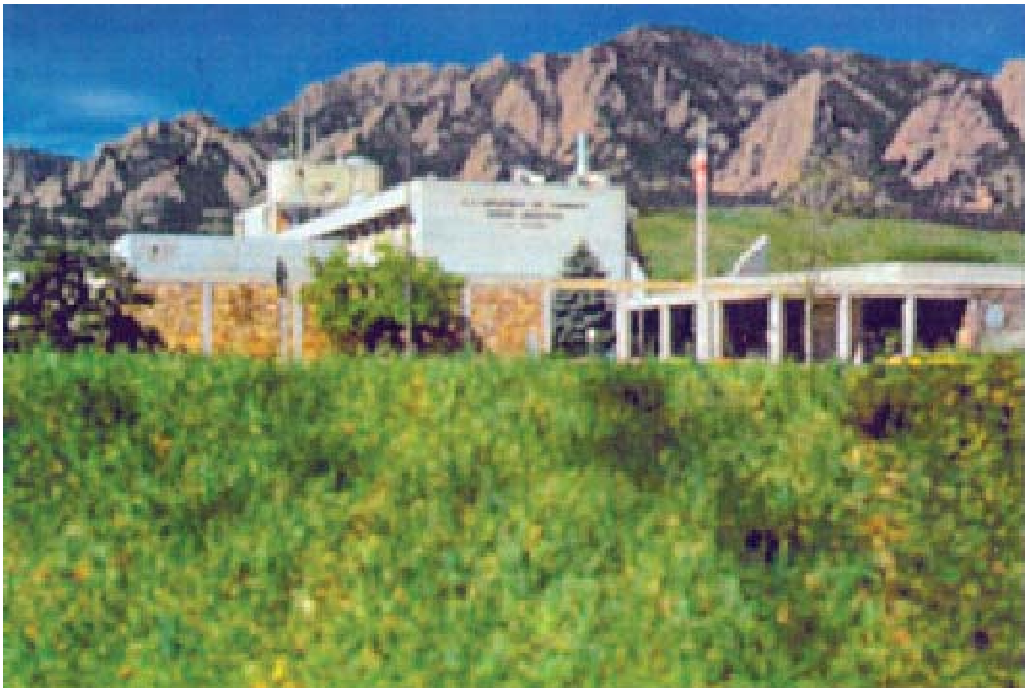
A US Department of Defense (DoD) directive charges the U.S. Naval Observatory with maintaining the DoD reference standard for Precise Time and Time Interval (PTTI).

The Superintendent is designated as the DoD PTTI Manager. The U.S. Naval Observatory has developed the world's most accurate atomic clock system. Increasingly accurate and reliable time information is required in many aspects of military operations. Modern navigation systems depend on the availability and synchronization of highly accurate clocks. This holds for such ground-based systems as LORAN-C as well as for the Department of Defense satellite-based NAVSTAR Global Positioning System (GPS). In the communications and the intelligence fields, time synchronized activities are essential.

The U.S. Naval Observatory Master Clock is the time and frequency standard for all of these systems. The Master Clock system must be at least one step ahead of the demands made on its accuracy, developments planned for the years ahead must be anticipated and supported.

The Master Clock system now incorporates hydrogen masers, which in the short term are more stable than cesium beam atomic clocks, and mercury ion frequency standards, which are more stable in the long run. These represent the most advanced technologies available to date.

The US Naval Observatory has ten Datum-TT&M Sigma Tau MASER's as part of this critical Master Clock system.



The Time and Frequency Division of NIST is responsible for the standards of time and frequency. Since length is now derived from the second, the Division has an additional responsibility to develop optical frequency standards in support of programs in the Manufacturing Engineering laboratory, Precision Engineering Division, which has the primary responsibility for length.

The Division's three primary functions are: developing and operating the standards of time and frequency and coordinating them with other world standards; providing time and frequency services to the United States; and undertaking basic and applied research in support of future standards, services, and measurement methods.

The Division undertakes a number of advanced development programs for advanced atomic frequency standards for industrial and scientific applications. Integral to the Division's capability are two, Datum-TT&M Sigma Tau MASER's which contribute to the precise time and frequency reference capability vital for this work.

Home of the United Kingdom's atomic time scale, UTC(NPL), the National Physical Laboratory (NPL) is the focus for time and frequency measurements in the UK. NPL's responsibilities are both international, in relating the UK and international time scales, and national, in providing the reference against which time and frequency broadcast signals in the UK can be monitored.

Funded by the UK's Department of Trade and Industry, the NPL follows a three year National Measurement System Program for Time and Frequency Measurement, which includes extensive activities in evaluating and developing the latest techniques for generating precise frequency and time references.

NPL uses two, Datum-TT&M Sigma Tau MASER's to provide not only the basis for UTC (NPL) but also the precise frequency reference for other key experiments and programs undertaken at the NPL facility.

DATUM 7/13 WARRANTY PROTECTION PROGRAM

4/18/01

Datum Timing, Test & Measurement's limited 7/13 warranty covers the MHM 2010 against any defect in material and workmanship for a period of up to thirteen (13) years. Datum will repair any defect free of charge during the first seven (7) years of ownership. Starting with year eight (8) and ending with year eleven (11) Datum will be responsible for the prorated percentage of repairing the unit as indicated in Table I.

During years eleven (11) through thirteen (13) the owner has the option of paying 100% of any repair charge or trading-in the malfunctioning maser towards the purchase of a refurbished maser at the pricing indicated in Table II. If the owner elects to purchase a refurbished maser, Datum will repair any defect in material or workmanship for a period of up to five (5) years free of charge. Warranty coverage for the refurbished maser varies depending on what year of ownership the original maser is replaced.

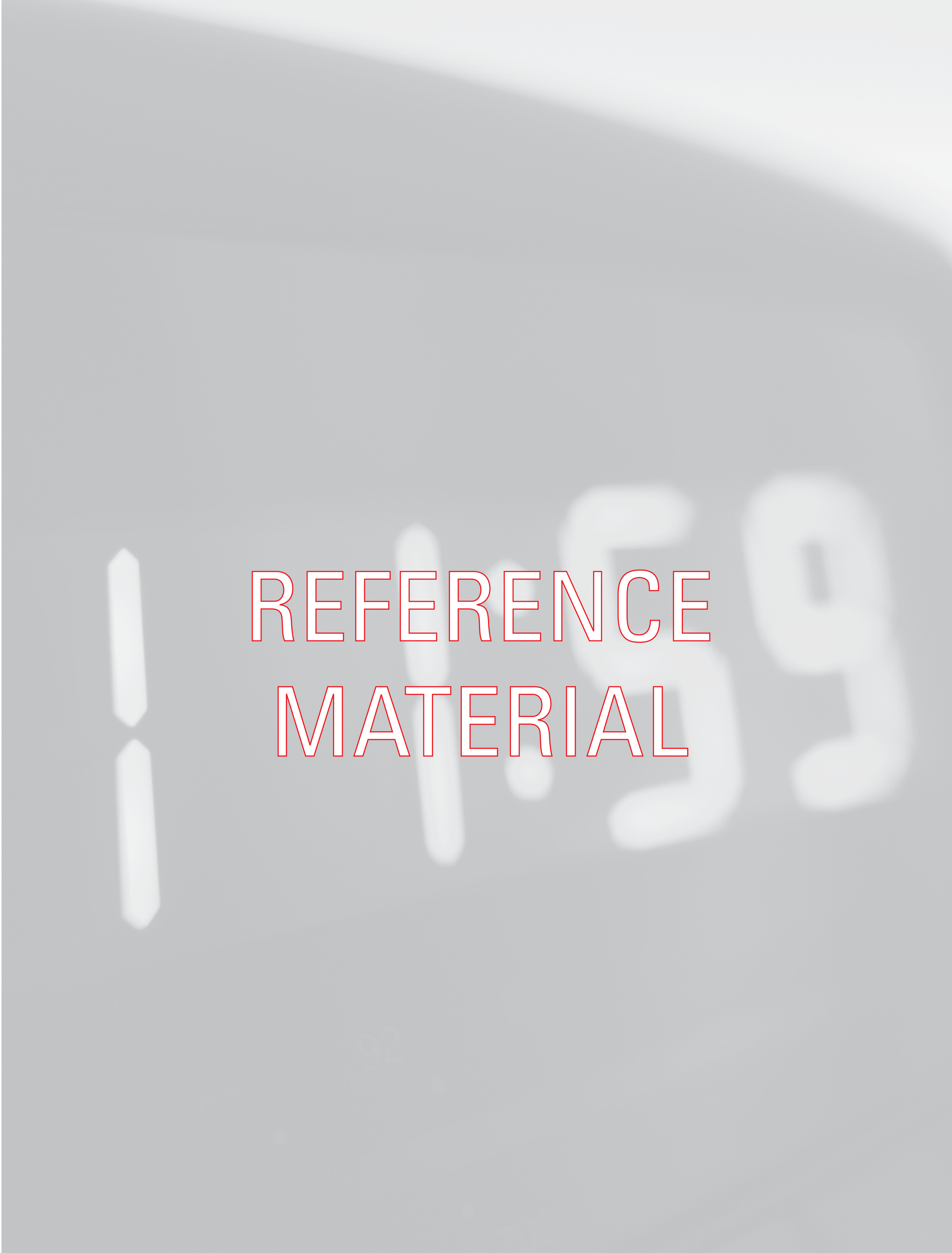
All warranties are null and void upon conclusion of the thirteenth year of ownership of the original maser.

TABLE I

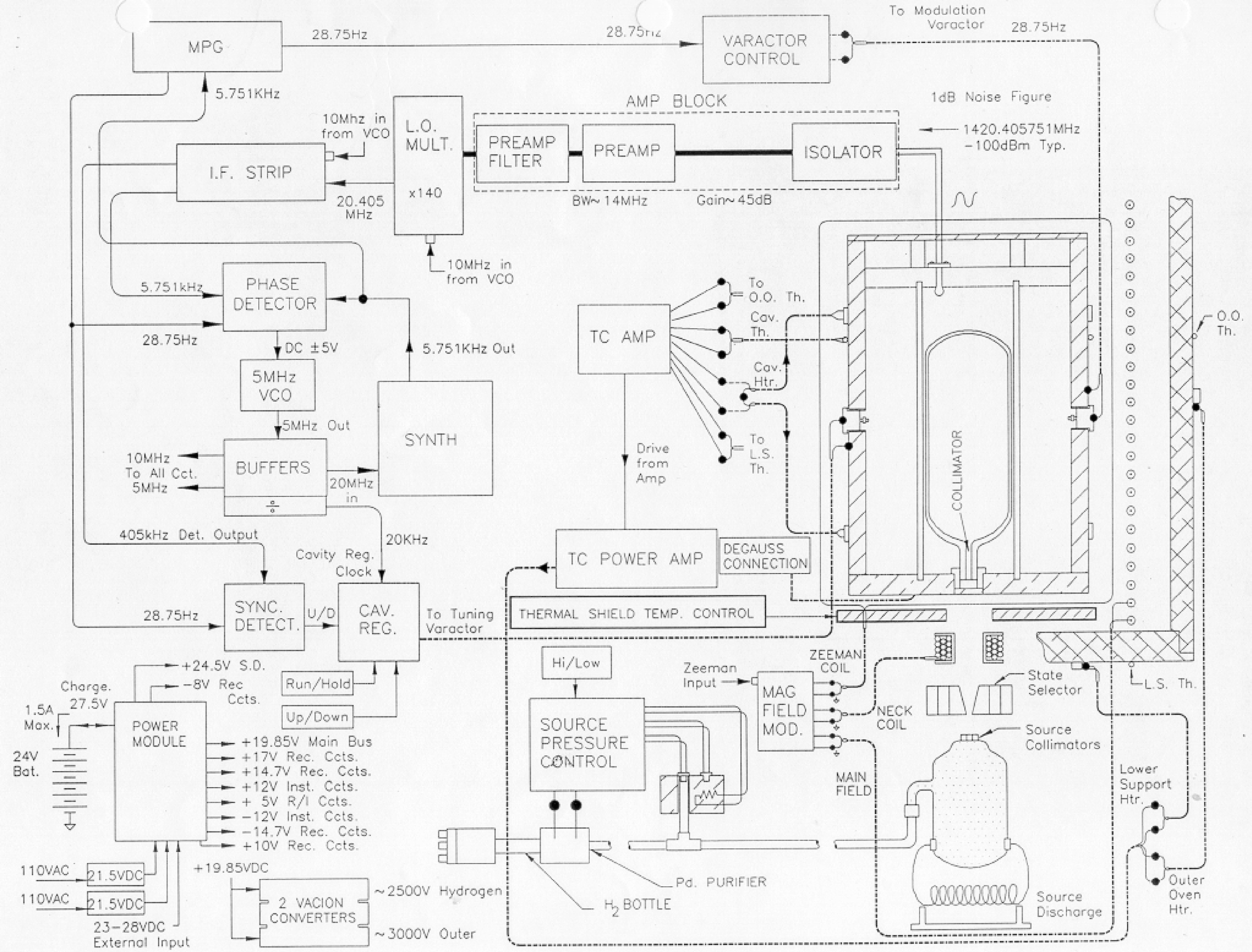
Year of Ownership	Datum Cost	Owner Cost
1 Thru 7	100%	0%
8	75%	25%
9	50%	50%
10	25%	75%
11	0%	100%

TABLE II

Year of Ownership	Owner Cost	Warranty
11	50% of list price of MHM2010	3 years
12	60% of list price of MHM2010	4 years
13	70% of list price of MHM2010	5 years



REFERENCE MATERIAL


MPG
28.75Hz
5.751KHz
VARACTOR CONTROL
To Modulation Varactor
1dB Noise Figure
1420.405751MHz
-100dBm Typ.
AMP BLOCK
PREAMP FILTER
PREAMP
ISOLATOR
BW~ 14MHz
Gain~ 45dB
L.O. MULT.
x140
10Mhz in from VCO
10MHz in from VCO
I.F. STRIP
20.405 MHz
PHASE DETECTOR
5.751kHz
DC ±5V
5MHz VCO
5MHz Out
BUFFERS
10MHz To All Cct. 5MHz
20MHz in
SYNTH
5.751KHz Out
405kHz Det. Output
Cavity Reg. Clock
20KHz
SYNC. DETECT.
U/D
CAV. REG.
To Tuning Varactor
Run/Hold
Up/Down
TC AMP
To O.O. Th.
Cav. Th.
Cav. Htr.
To L.S. Th.
Drive from Amp
TC POWER AMP
DEGAUSS CONNECTION
THERMAL SHIELD TEMP. CONTROL
COLLIMATOR
O.O. Th.
L.S. Th.
State Selector
Source Collimators
Lower Support Htr.
Outer Oven Htr.
Source Discharge
ZEEMAN COIL
NECK COIL
MAIN FIELD
Zeeman Input
MAG FIELD MOD.
Hi/Low
SOURCE PRESSURE CONTROL
Pd. PURIFIER
H2 BOTTLE
+24.5V S.D.
-8V Rec Ccts.
Charge. 27.5V
1.5A Max.
24V Bat.
POWER MODULE
+19.85V Main Bus
+17V Rec. Ccts.
+14.7V Rec. Ccts.
+12V Inst. Ccts.
+ 5V R/I Ccts.
-12V Inst. Ccts.
-14.7V Rec. Ccts.
+10V Rec. Ccts.
110VAC
21.5VDC
110VAC
21.5VDC
23-28VDC External Input
+19.85VDC
2 VACION CONVERTERS
~2500V Hydrogen
~3000V Outer

WORKING APPLICATION OF TWSTT FOR HIGH PRECISION REMOTE SYNCHRONIZATION

Paul Koppang, Datum Inc., Tuscaloosa, AL

Paul Wheeler, United States Naval Observatory, Washington, DC

Abstract

Two-way satellite time transfer (TWSTT) is the primary method implemented to determine the synchronization error between the United States Naval Observatory (USNO) Alternate Master Clock (AMC) located in Colorado and the USNO Master Clock located in Washington, DC. A hydrogen maser at the AMC is controlled to the USNO Master Clock within 1 ns RMS as determined by low noise (< 300 ps) TWSTT measurements. A Kalman filter utilizes the TWSTT time difference data to give real time synchronization and syntonization error estimates that are used in a linear quadratic Gaussian control design. Calibration runs using a mobile earth station monitor the long term performance of the TWSTT method. Results of a closed loop TWSTT calibration experiment will be discussed.

Introduction

In this paper we describe how two-way satellite time transfer (TWSTT) is utilized in the remote realization of the United States Naval Observatory (USNO) Master Clock at the USNO Alternate Master Clock facility (AMC). The USNO Master Clock is located in Washington, DC and the AMC is located in Colorado. A Kalman filter utilizes the TWSTT time difference data to give real time synchronization and syntonization error estimates that are used in a linear quadratic Gaussian control design.

The first section gives an overview of the AMC purpose along with a description of the system. The next section briefly covers the TWSTT method followed by a summary of the AMC TWSTT link. Stochastic control of frequency standards is the topic of the following section. Data are then given on the performance of the AMC system.

USNO Alternate Master Clock (AMC)

The AMC is located at Falcon Air Force Base near Colorado Springs, CO. The AMC serves as a backup facility for the USNO Master Clock system and can take over the highest priority tasks conducted at the USNO facility in Washington, DC should the need arise [4]. The AMC also acts as a precision remote realization of the USNO Master Clock. The AMC Master Clock signal is used as a frequency standard at the GPS monitor station at Falcon AFB.

The AMC is a state of the art facility with a system that is comprised of 2 atomic hydrogen masers, 14 cesium standards, several GPS receivers, 4 environmental chambers, and 10 racks of precise timing equipment.

Two-way Satellite Time Transfer (TWSTT)

TWSTT is the most precise method being utilized for disseminating time at the present ([8],[9]). It has the capability of performing time transfer with a precision on the order of 300 picoseconds. One of the great advantages of TWSTT is the fact that atmospheric and other potential perturbations are seen simultaneously in each path and therefore cancel to a high degree during the measurement cycles. This technique has been in use since 1962 when the precision was at the 0.1 to 20 microsecond level [8].

TWSTT measurements are accomplished by both participating laboratories measuring the time interval difference between the local reference standard 1 pulse per second (PPS) and that which is being received via the satellite link using a spread spectrum technique [6]. If all the path delays are reciprocal, that is that the delay from station 1 to station 2 is same as the delay from station 2 to station 1, the time difference between the two laboratories is the time difference measured by the modems. Due to non-reciprocal time delays in the system, reciprocity cannot be assumed. The time difference between the stations is given as

$$
\begin{aligned}
T_1 - T_2 = &\frac{1}{2}(\Delta T_1 - \Delta T_2) \\
&+ \frac{1}{2}[(\tau_1^U + \tau_2^D) - (\tau_2^U + \tau_1^D)] \\
&+ \frac{1}{2}(\tau_{12} - \tau_{21}) \\
&+ \Delta\tau_R \\
&+ \frac{1}{2}[(\tau_1^{Tx} - \tau_1^{Rx}) - (\tau_2^{Tx} - \tau_2^{Rx})].
\end{aligned}
$$

The first term corresponds to the time difference measured at each station. The second term pertains to the signal delays from the up and down satellite links. The satellite transponder delays make up the third term. $\Delta\tau_R$ is due to the relativistic Sagnac effect. The last term corresponds to the delays in transmitting and receiving at each of the stations [9].

A calibration run using a mobile earth station or portable fly-away dish with known properties and delays is necessary to calibrate the total system [15]. The AMC was calibrated during the initial system setup. A follow up calibration approximately one year later was within 300 ps of the original measurement.

AMC TWSTT Link

The TWSTT link between USNO and AMC is shown in block diagram form in Fig. 1. The USNO Master Clock provides the reference 5 MHz and 1 pulse per second signals that are required for the TWSTT modem at USNO. A commercial satellite operating in the Ku band is used for AMC TWSTT link. An attempt is made every hour to measure the synchronization error between the AMC and the USNO Master Clock. The historical success rate of obtaining a measurement is approximately 80%, with most of the failures occurring due to older generation modems not properly locking. New modems that are planned to be installed should increase the success rate.

After the time difference data have been analyzed at USNO, a computer at AMC collects the data via the Internet or by other means such as dial up modems should the Internet connection fail. The measured data point is then used as the input for a Kalman filter estimate calculation. This Kalman estimate is used in conjunction with a linear quadratic Gaussian (LQG) calculated gain to produced the necessary frequency steer to be applied to the AMC Master Clock.

An Auxiliary Output Generator (AOG) frequency synthesizer is used to give the frequency steer a physical realization. A hydrogen maser 5 MHz signal is the reference input into the AOG. The frequency steers adjust the maser reference input signal so that it is synchronized to the USNO Master clock as determined by the TWSTT measurements. The output of the AOG provides the reference 5 MHz and 1 pulse per second signals that are required for the TWSTT modem at AMC.

Stochastic Control of Frequency Standards

Noisy measurements combined with stochastic noise inherent in processes make real time parameter estimation both difficult and interesting. In the AMC system the disturbances come in the form of the TWSTT measurement system noise and the random characteristics of the frequency standards being compared. Kalman filtering ([1],[2],[3],[13], and [14]) is used to estimate the AMC offsets in time and frequency with respect to the USNO Master Clock. In Kalman filter theory the state equation is

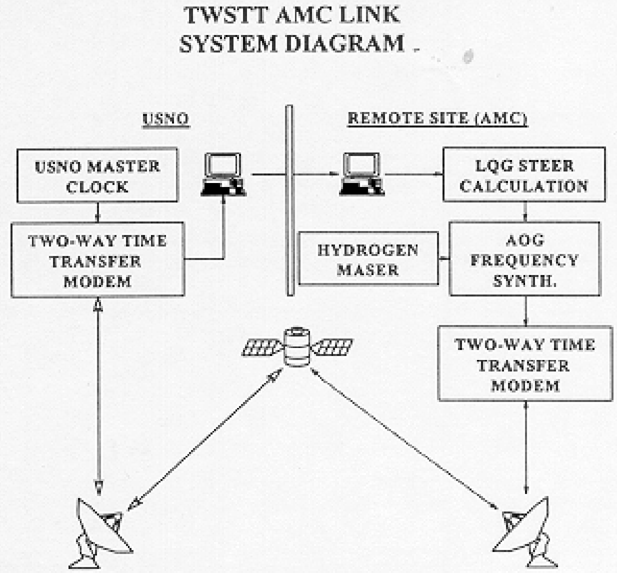


Fig. 1. AMC TWSTT link block diagram

assumed to be given as a linear function of a state vector, **x**(k), a control vector, **u**(k), and a noise vector **w**(k):

$$x(k+1) = \Phi x(k) + Bu(k) + w(k),$$

where for the two state frequency standard model,

$$\Phi = \text{transition matrix} = \begin{bmatrix} 1 & \tau \\ 0 & 1 \end{bmatrix}, \tau \text{ is the time interval}$$

between measurements,

$$x(k) = \text{state vector} = \begin{bmatrix} x_1(k) \\ y_2(k) \end{bmatrix},$$

$x_1(k)$ is the time difference, and $y_2(k)$ is the fractional frequency difference, between the reference and the steered standard,

$$\mathbf{B} = \begin{bmatrix} \tau \\ 1 \end{bmatrix},$$

$u(k)$ = control vector which is a scalar corresponding to the fractional frequency change of the synthesizer controlling the steered standard,

$w(k)$ = Gaussian white process noise

The noisy measurement $z(k)$ is related to the state vector

$$z(k) = Hx(k) + v(k)$$

where

$z(k)$ = measurement, in our case a scalar time difference,

H = connection matrix = [1 0], and

$v(k)$ = Gaussian white measurement noise.

After the state comprised of the phase and frequency offsets has been estimated, the data are used with an LQG calculated control gain in order to produce a frequency steer value. The LQG method ([2],[3],[5],[7],[10] and [12]) calculates a gain such that the cost function

$$J = E[\sum_k[\hat{x}(k)^T W_Q \hat{x}(k) + u(k)^T W_R u(k)]]$$

is minimized.

W_Q and W_R are matrices that are chosen in order to set the relative penalties assessed to the state vector estimate $\hat{x}(k)$ and control vector $u(k)$ as they vary from zero. The optimal control for the given cost function is given by the linear equation

$$u(k) = -\hat{G}_0 \hat{x}(k),$$

where $\hat{G}_0$ is calculated by solving a Ricatti equation.

AMC Performance Data

The AMC has been synchronized to the USNO Master Clock within 700 ps RMS as given by TWSTT data over approximately a two year period. A Kalman filter is used to estimate the time and frequency offsets between AMC and the USNO Master Clock. The Kalman filter calculates an optimal estimate based on given process and measurement system noise parameters. The real time Kalman estimates of the data are also plotted in Fig. 2.

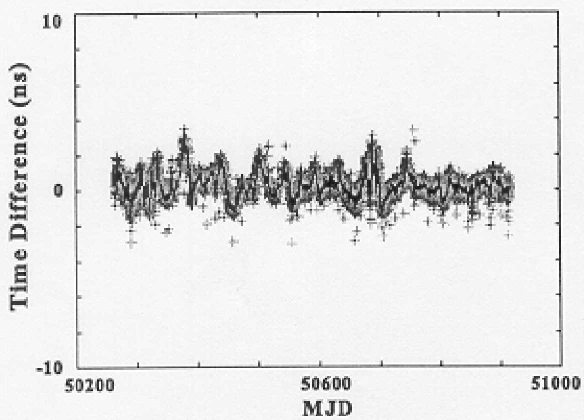


Fig. 2. Time difference between USNO Master Clock and AMC via TWSTT. Dashed crosses are the measured data and the black line is the real time Kalman estimate.

A one step ahead prediction is made from the time and frequency estimates as given by the Kalman filter. The difference between this estimate and the corresponding measurement is referred to as the innovation. More formally the definition of the innovation , $\nu(t)$, is

$$\nu(t) = Z(t) - E\{Z(t)|Z(1)Z(2) \dots Z(t-\tau)\},$$

where the second term reads the expectation of the noisy measurement Z(t) given all the data up to and including the previous measurement of Z. Fig. 3 is a plot of the Kalman filter innovations of the data measured at AMC. The innovations are dominated by the noise of the TWSTT link.

The innovations are utilized as a real time outlier detector. In the present design all measurements that cause the innovation to be larger than +/- 3 ns are thrown away. It appears that the filter could be tightened up to +/- 1 ns. It is interesting to note that most of the outlying points tend to be in the negative sense. The reason for this is unknown at present.

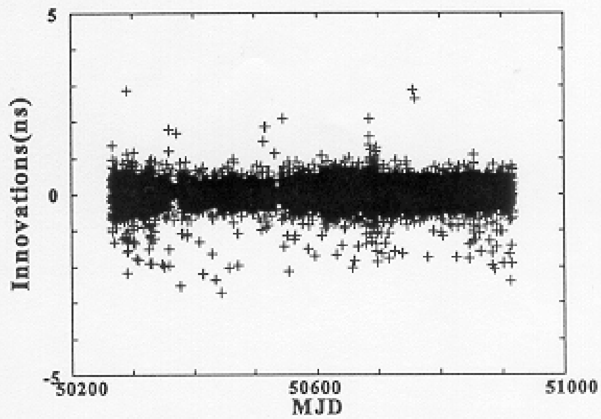


Fig. 3 Innovations of the measured data given in Fig. 2.

Frequency steers are calculated using the Kalman estimates of the time and frequency offsets along with a linear quadratic Gaussian calculated control gain. A gain has been chosen so that the time and frequency offsets and the frequency perturbations due to the steers are all within acceptable performance parameters. This determination was

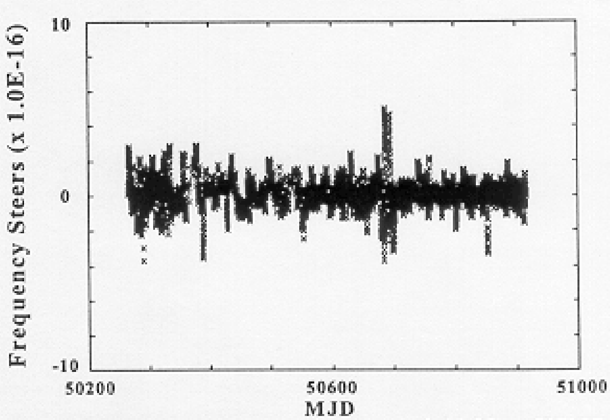


Fig. 4. Frequency steers used to control AMC to USNO Master Clock.

made possible by steering simulations that were conducted on real archived data. A plot of the frequency steers needed to control the AMC Master Clock to the USNO Master Clock is given in Fig. 4.

A plot of the frequency offset generated by the AOG over approximately a year is given in Fig. 5. The reference for the AOG is Sigma Tau hydrogen maser N13. The plot shows the short term variations caused by the steering and also the relative drift of less than $1.0*10^{-16}$ per day between N13 and the AMC Master Clock.

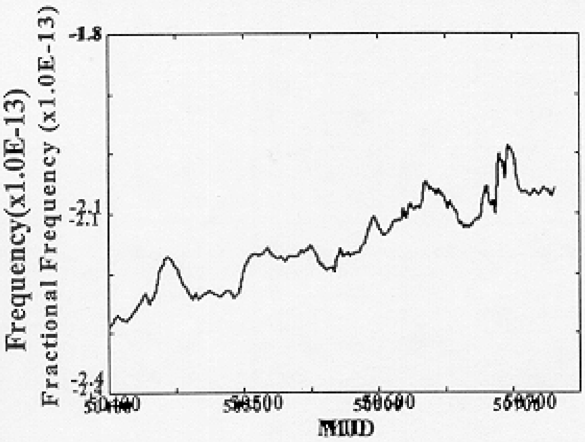


Fig. 5 Relative frequency of the input vs. output of the frequency synthesizer. Reference is hydrogen maser N13.

The frequency stability performance of the AMC Master Clock along with the time and frequency errors with respect to USNO Master Clock are the main parameters of concern. The frequency stability perturbation of the N13 maser output caused by controlling it to the USNO Master Clock is shown in Fig. 6. The Allan deviation of the AMC Master Clock remained below $2.0*10^{-15}$ for averaging times from 1 hr to 42 days with respect to the free running maser N14. The disturbance at 10^6 second averaging time was predicted by simulation [10].

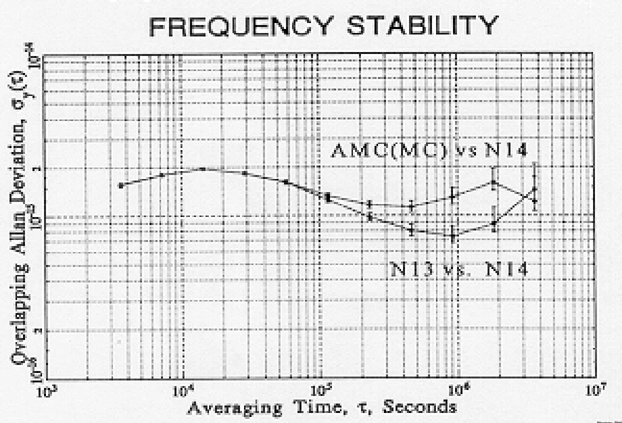


Fig. 6. Allan deviation of AMC Master Clock vs. hydrogen maser N14 and masers N13 vs. N14

Calibration Testing

Fig. 7 shows a block diagram of an experiment ongoing at USNO in Washington, DC. The test utilizes a common reference, the USNO Master Clock, and two satellite dishes located near each other at USNO. By using the common reference and having independent communications systems, the characteristics of the noise due to the TWSTT method may be studied. Monitoring any bias or calibration change over the long term is of particular interest. Fig. 8 gives initial test results of the experiment.

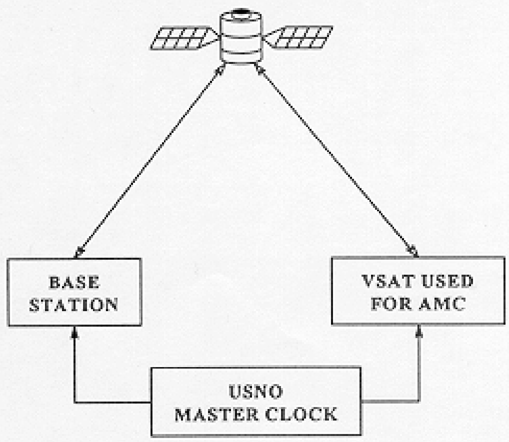


Fig. 7. Calibration monitoring experiment at USNO.

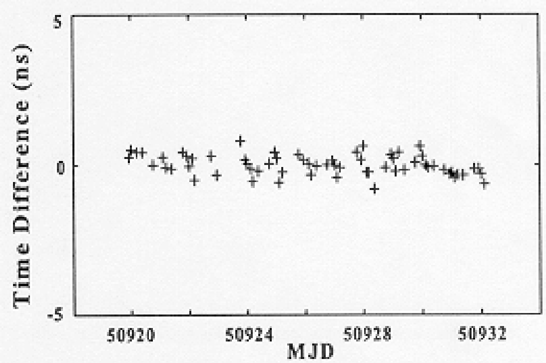


Fig. 8. Initial calibration test data.

Conclusion

TWSTT is being utilized to remotely control the AMC Master Clock in Colorado to within 1 ns RMS of the USNO Master Clock located in Washington, DC. The parameters of the control system where chosen so that the AMC Master Clock would exhibit excellent frequency stability characteristics while being steered to be on time and frequency to the USNO Master Clock. Tests to characterize TWSTT calibrations are ongoing.

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ENVIRONMENTAL SENSITIVITIES OF CAVITY-TUNED HYDROGEN MASERS

T. E. Parker, J. E. Gray and T. K. Peppler

National Institute of Standards and Technology
Time and Frequency Division, 847.5
325 Broadway
Boulder, CO 80303 USA

Abstract

With the increasing number of cavity-tuned hydrogen masers in use around the world in time scales and as reference oscillators for primary frequency standards, it is necessary to have a complete understanding of the environmental sensitivities of the masers. Common-mode frequency fluctuations are of great concern and the degradation of maser frequency stability due to environmental fluctuations should be minimized. Measurements of environmental sensitivities (temperature, relative humidity, atmospheric pressure, line voltage and magnetic field) have demonstrated that the frequency stability of cavity-tuned hydrogen masers is not significantly degraded if the masers are contained in a reasonably controlled environment.

KEY WORDS - Environmental sensitivities, hydrogen maser, cavity tuned

Introduction

The number of hydrogen masers being used in time scales around the world has increased significantly over the last ten years [1-3]. The Bureau International des Poids et Mesures (BIPM) now uses data from 33 masers in the generation of International Atomic Time (TAI). Masers are also now commonly used as reference oscillators for primary frequency standards since they offer fractional frequency stabilities below 1×10^{-15} at time intervals on the order of hours to days. With cavity tuning this stability can be extended to tens of days. The National Institute of Standards and Technology (NIST) has five cavity-tuned masers [4] at its site in Boulder, Colorado, USA, three of which are currently in the NIST AT1 time scale [1]. The remaining two masers will very likely be in the scale by the end of 1997. One of the masers is also routinely used as the reference oscillator for the primary frequency standard NIST-7 [5], and for research on new technologies for primary frequency standards. Each maser at NIST is contained in its own environmental chamber to control temperature (~ ± 0.1 °C peak to peak) and relative humidity (~ ± 2 % peak to peak).

With the increased role of masers in time scales and as references for primary frequency standards it is important to have accurate knowledge concerning the environmental sensitivities of the masers for time intervals up to at least several days. In most laboratories the only frequency source with short-term frequency stability comparable to that of a maser is another maser. Therefore, it is necessary to know if there are any common-mode frequency fluctuations which would not be visible in a comparison between masers. Since common-mode fluctuations generally come from environmental sensitivities, these sensitivities must be known. Pressure sensitivity is of particular concern since controlling pressure is very expensive and, if not controlled, all of the masers at a given site will respond to the same fluctuations in atmospheric pressure. Furthermore, the lowest pressure sensitivity currently guaranteed by the manufacturer [4] would result in frequency fluctuations larger than 1×10^{-14} occurring simultaneously in all of the masers just due to normal barometric pressure fluctuations. These fluctuations would not be observable in comparisons among masers at the same site. Previous measurements of the pressure sensitivity of hydrogen masers without cavity tuning have shown evidence of frequency fluctuations as large as 1×10^{-13} [6]. Fortunately, we have found that the pressure sensitivity in the cavity-tuned masers is at least 10 times smaller than the manufacturer's specification.

In a more general sense, it is also desirable to know to what extent environmental fluctuations degrade the maser stability even if the frequency fluctuations are not common-mode. To accomplish these goals a program is underway at NIST to measure the environmental sensitivities of the masers, and where possible to do this in the same type of chamber they are normally operated in. The sensitivities of the maser frequencies to (a) temperature, (b) relative humidity (RH), (c) barometric pressure, (d) line voltage, and (e) vertical magnetic field (the most sensitive direction) have been measured on several masers. Previous measurements of environmental sensitivities of cavity-tuned hydrogen masers have been made [7] but not over the appropriate time interval or at the level of accuracy required for use in time scales or as references for primary frequency standards.

Environmental Sensitivities

Frequency sensitivities to temperature, relative humidity, line voltage, and magnetic field were all measured in the same type of chamber in which the masers normally operate. This was done to ensure that gradients in temperature and humidity present in the chambers used for normal operation are also present during the measurements of the sensitivities. However, pressure sensitivity had to be measured in a specially constructed chamber that has approximately the same internal dimensions as the other chambers. This chamber is capable of pressures changes up to +/- 15% of an atmosphere about the ambient barometric pressure. The frequency sensitivity for each environmental parameter was measured by changing the appropriate parameter and recording simultaneously the frequency difference between the test maser and at least two other reference masers that were held in a constant environment. In each case every effort was made to change only one parameter at a time. It is important to note that no attempt was made to understand the physical cause of any particular environmental sensitivity, but simply to characterize its value. Apparent sensitivities to pressure, humidity, and line voltage may in fact be caused partially or entirely by changes in temperature or temperature gradients inside the maser. Knowing these details is important to reducing the environmental sensitivities of the masers, but is not necessary in order to quantify the sensitivities.

Measurement of Temperature Sensitivity

Figure 1 illustrates how the temperature sensitivity measurements were carried out. The lower trace shows the temperature as measured by a sensor mounted on the outside of Maser 5 and the upper trace shows the frequency difference between Maser 5 and one of the reference masers. Data were taken at 2 hour intervals. Over the course of thirty five days the temperature was increased above normal by two degrees for a period of seven days and also decreased below normal for a seven

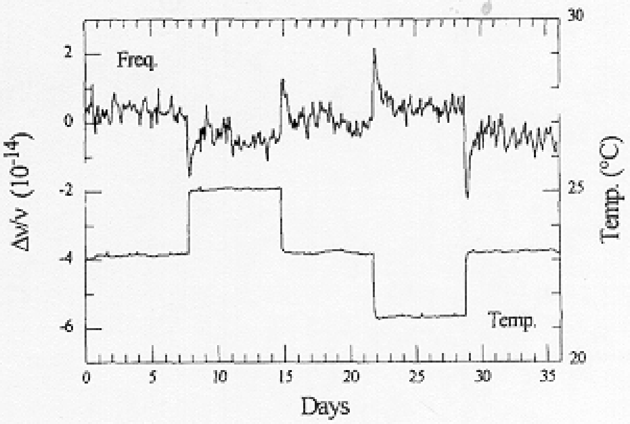

Figure 1 Influence of temperature steps on the frequency of Maser 5.

day interval. The average frequency drift between the two masers has been removed from the data in Fig. 1. The frequency of the test maser shows a transient shift at the time of each temperature transition, which lasts for about 16 hours, followed by a steady-state shift which correlates with the steady-state temperature. These characteristics indicate the presence of both dynamic and a static temperature coefficients. The static temperature coefficient was determined by comparing the average frequency over the final six-day interval of each temperature deviation period with the average of the frequencies in the periods immediately before and after the temperature excursion. Using only the last six days of each seven day cycle eliminates the dynamic effects from the measurement. The measured frequency shift was then divided by the change in temperature to give the static temperature sensitivity, which is $-3.4\pm0.2 \times 10^{-15}$/°C in this case. A complete measurement cycle takes thirty five days. There was a significant amount of frequency noise in the data, so the same analysis was performed with two or three different reference masers. The average of these results serves to reduce the influence of the reference maser noise.

A precise value for the dynamic temperature coefficient cannot be obtained since the internal temperature of the maser was not measured. The temperature measured on the outer surface of the maser changes much more rapidly than that of the internal maser parts that actually affect the frequency. However, a transient frequency shift of approximately 2×10^{-15} occurred at each 2 °C temperature change.

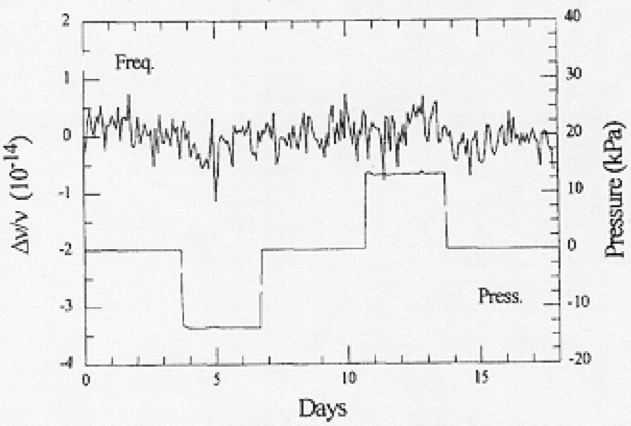

Figure 2 Influence of pressure steps on the frequency of Maser 4.

Measurement of Pressure Sensitivity

Figure 2 shows data from Maser 4 for changes in pressure about the ambient atmospheric pressure. The corresponding frequency changes are less obvious here, but a pressure sensitivity of $+0.8\pm0.2 \times 10^{-15}$ per 5 kPa of pressure change was observed (0.1 kPa = 1 millibar). It was necessary to repeat the cycle shown in Fig. 2 several times to reduce the measurement uncertainty to a reasonable level. Since no dynamic effects are present, the measurement cycle here was reduced to only sixteen days, with three day pressure steps and a four day interval between steps. The four day interval was chosen simply to keep the measurements in synchronization with the normal work week.

Summary of Results

Table 1 summarizes the results of all the tests performed to date. Table blocks with no values indicate that those parameters have not yet been measured in our laboratory. This is also true for the magnetic field sensitivities of Masers 3 and 4, where only the values measured by the manufacturer are shown. Line-voltage and magnetic field sensitivities were determined using the same measurement cycle as shown for pressure in Fig. 2. The measurement of sensitivity to relative humidity used a longer cycle as discussed below. No data is available for Masers 1 or 2 since they have been in the NIST time scale since 1994 and cannot be used for environmental testing.

Temperature: All of the measured static temperature sensitivities (S_T) are within the manufacturer's specifications. The smaller value observed on Maser 5 reflects an additional level of temperature stabilization added by the manufacturer to that maser. Masers 3 and 4 also exhibited dynamic temperature effects of about the same magnitude as that observed on Maser 5, but they were less significant and more difficult to observe because of the larger static coefficients on these masers. Since relative humidity is also controlled in these chambers, there was no change in relative humidity during the temperature tests. However, this does result in a change in absolute humidity that is coherent with the temperature changes. No attempt was made to correct for this situation since the same coherence would also be present for the smaller temperature fluctuations that exist in normal

Table 1 Summary of Environmental Sensitivities

Sensitivity	Maser 3	Maser 4	Maser 5
$S_T(10^{-15}/°C)$	-9±1	-8±1	-3.4±.2*
$S_{RH}(10^{-15}/\%)$	+0.4±.1	-0.2±.1	–
$S_P(10^{-15}/5\ kPa)$	+0.4±1.8	+0.8±.2	–
$S_V(10^{-15}/volt)$	$<\lvert 0.1 \rvert$	–	–
$S_H(10^{-15}/100\ \mu T)$	17†	6†	47±14

* Dynamic temperature response is not included

† As measured by manufacturer at ± 100 μT (± 1 gauss)

operation.

Relative Humidity: Sensitivities to relative humidity (S_{RH}) are quite small and large steps (+/- 9%) in humidity had to be used to measure them. Small changes in temperature were sometimes observed to coincide with the humidity steps, but no corrections for temperature were made in calculating the values in Table 1. If corrections are made for the temperature changes the humidity sensitivities are slightly reduced. A humidity step length of fourteen to twenty one days was used with the humidity measurements to ensure that processes with long time constants would be observed. Test cycles much longer than this are of limited value since frequency drift or aging in masers is usually large enough to make environmental parameters irrelevant in the long term.

Pressure: The manufacturer guarantees a pressure sensitivity (S_P) of less than $15x10^{-15}/5$ kPa and the observed values are smaller than this by at least a factor of ten. This effectively eliminates one potential major cause of common-mode frequency fluctuations. The large uncertainty for the pressure sensitivity of Maser 3 in Table 1 stems from the fact that this maser exhibited occasional erratic frequency transients during the course of the measurements. These transients were not reproducible like the dynamic frequency effects in Fig. 1, and did not always occur simultaneously with the pressure steps. Sometimes they would occur many hours after the pressure change, or not at all. Also, the signs of the frequency transients were not consistent with the signs of the pressure steps. It is clear however, that the transients are related to relatively sudden pressure excursions since they do not occur at all in extended periods when there are no deliberate pressure changes. No significant coherent temperature changes were observed during the pressure tests, but there were small changes (~1%) in the relative humidity that coincided with the pressure changes. Making corrections for coherent variations in temperature and/or relative humidity has little impact on the observed pressure sensitivities.

Line-voltage: Virtually no frequency sensitivity to line-voltage (S_V) changes was observed and the entry in Table 1 simply represents the measurement uncertainty. This measurement will be made more precisely on Masers 4 and 5. None of the other environmental parameters showed any coherent variations with the line-voltage variations.

Magnetic field: Sensitivity to magnetic field (S_H) was measured by placing a set of Helmholtz coils around one of the environmental chambers. The coils were oriented to create a vertical magnetic field since this is the most sensitive direction of the masers. Calibration was accomplished by measuring the field strength and uniformity as a function of electrical current with nothing inside the coils. This process needs to be repeated with the coils located around an empty environmental chamber; however, this is not expected to significantly affect the calibration since the chamber is constructed mostly of non-magnetic material. Nevertheless, until this is accomplished our results for magnetic field sensitivity should be considered as preliminary. During testing with the maser in the chamber the vertical field strength is monitored on the top surface of the maser. The field on the maser in the test chamber is typically around -73 μT (100 μT = 1 gauss) just due to the Earth's magnetic field. Changes about this value caused by current in the Helmholtz coils were found to be about twice the magnitude of those observed in the empty coils. For the purposes of calculating the magnetic field sensitivity, however, the field values for the empty coils were used. Tests were performed for field changes of +/- 10 μT and +/- 5 μT. S_H appears to be nonlinear since the magnitude of the observed frequency change is about 65% larger when the total field strength is increased as opposed to when the field is decreased by the same amount. The value listed in Table 1 is the average of the responses for the two directions.

Sensitivity to vertical magnetic field is of particular interest since the value for Maser 5 measured in our laboratory is almost an order of magnitude larger than that measured by the manufacturer on the same maser ($5x10^{-15}/100$ μT) and is substantially larger than that of any of the other masers. Even a calibration error could not account for this discrepancy. However, the effectiveness of passive magnetic shielding is known to be highly nonlinear and our measurements are consistent with this. The manufacturer's measurements were made for field changes of +/- 100 μT, while our measurements were made for much smaller values (all relative to the empty Helmholtz coils). Another possible reason for the discrepancy is that the magnetic shielding may have degraded during the transportation of the masers from the manufacturing site to our facility. Unfortunately we have not yet been able to duplicate the manufacturer's test conditions in our laboratory because of the close proximity of the magnetic-field test chamber to other masers that are in the NIST time scale. The lower field variations of our tests are more meaningful for our situation since the normal field fluctuations in our laboratory are on the order of ± 1 μT or less. Except for magnetic field sensitivity, no significant nonlinearity was observed in any of the other environmental sensitivities, even though a range of values in the steps were used.

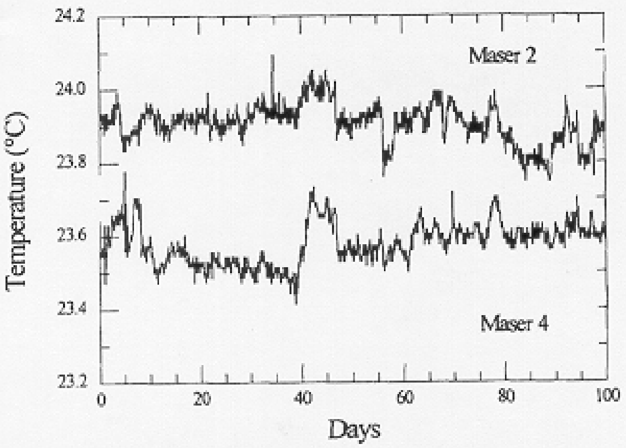

Figure 3 Temperature in two environmental chambers for a 100 day period.

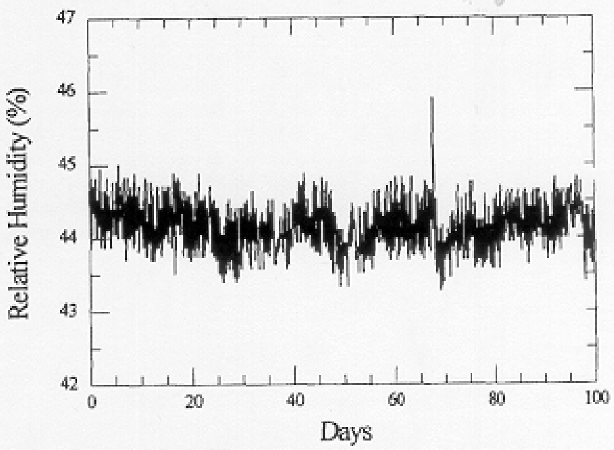

Figure 5 Relative humidity in the environmental chamber of Maser 2.

Impact of Environmental Factors on Maser Frequency Stability

In addition to the determination of the maser environmental sensitivities, the stabilities of the environmental parameters in the maser chambers and maser room are also being monitored. Temperature, relative humidity, and vertical magnetic field (the most sensitive axis of the masers) are all monitored in the chambers in which the masers normally operate. Barometric pressure and power-line voltage are monitored in the maser room. Figure 3 shows typical temperature values in the chambers of Masers 2 and 4 for a period of 100 days in early 1997. The temperatures are measured every 2 hours by sensors on the outside surface of the masers. These are the same sensors used in the temperature-sensitivity tests. Typical variations are on the order of +/- 0.1 °C, with occasional larger swings. There is only a moderate level of correlation between the temperatures in the two chambers. The rise in temperature in both chambers between the 40th and 47th day correlates with the room temperature; otherwise, most of the structure does not correlate between chambers or with the room. The correlation coefficient at a time interval of a few days is only about +0.4 between the two chambers. In contrast, the correlation coefficients between changes in frequency and changes in an environmental parameter over a time interval of a few days are respectively -0.8 and +0.5 for the data in Figs. 1 and 2.

Figure 4 is a plot of the barometric pressure in the maser room for the same 100-day period as that in Fig. 3. Figures 5 and 6 are respectively the relative humidity in the chamber for Maser 2 and the power-line voltage in the

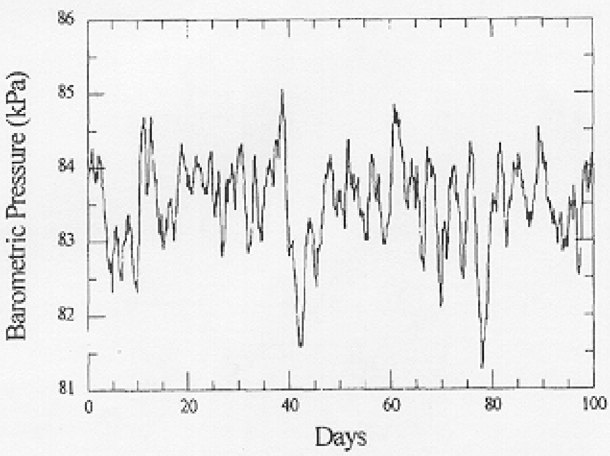

Figure 4 Barometric pressure in the maser room.

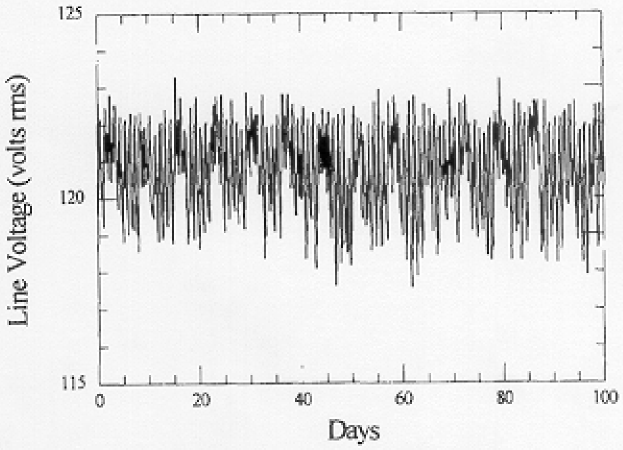

Figure 6 Line-voltage fluctuations in the maser room.

maser room for the same 100-day period. The line voltage clearly has a periodic daily variation of about 5 volts peak to peak. On weekends the amplitude of the variation is less. Figure 7 shows the vertical magnetic field in the chamber of Maser 2 for the same time interval. The obvious quantization is caused by the analog-to-digital converter. Long-term field changes as large as 1.5 μT were observed in some other chambers that were closer to objects being moved.

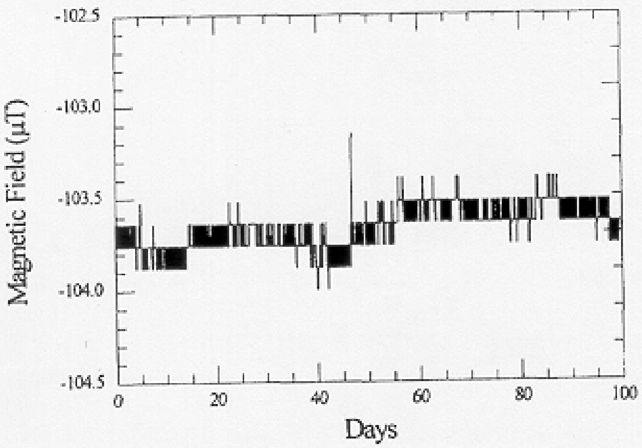

Figure 7 Vertical magnetic field in the environmental chamber of Maser 2.

A two-sample variance analysis of the observed environmental parameter fluctuations, along with the measured sensitivities, allows one to estimate the influence of the environment on the observed FM noise levels of the masers. Figure 8 shows the Allan deviation, $\sigma_y(\tau)$, of Maser 4 as determined from a 3 corner hat measurement with Masers 1 and 2. The value for $\sigma_y(\tau)$ at τ = 20 days is not shown since it has a negative variance. Also shown in Fig. 8 are the estimated levels of frequency instabilities caused by the five environmental parameters being monitored. These levels of instability were quantified by first doing a two-sample variance on the environmental parameters measured either in the environmental chamber of Maser 4, or in the maser room. The effective level of frequency fluctuations induced by each of the environmental parameters was then calculated by multiplying the environmental two-sample deviations by the Maser 4 sensitivities in Table 1. Since the line-voltage sensitivity of Maser 4 has not been measured, the value for Maser 3 was used. Also a magnetic field sensitivity of 2×10^{-14}/100 μT was used. The data in Fig. 8 is for the same 100 day period shown in Figs. 3 - 7.

Figure 9 shows the same type of plots for Maser 2, one of our most stable masers. Since the environmental sensitivities of Maser 2 have not been measured, the

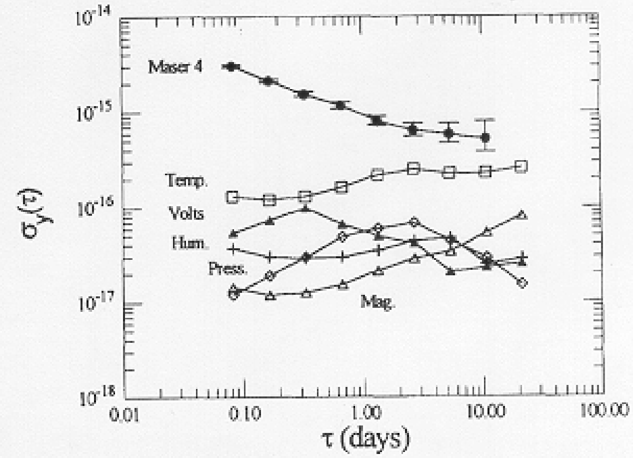

Figure 8 Allan deviation of Maser 4 •, along with environmental contributions from temperature □, line voltage ▲, relative humidity +, pressure ◊, and magnetic field Δ.

largest observed sensitivity of any maser in Table 1 was used for each of the five parameters. The increasing value of $\sigma_y(\tau)$ at τ = 20 days reflects the impact of frequency drift in the maser.

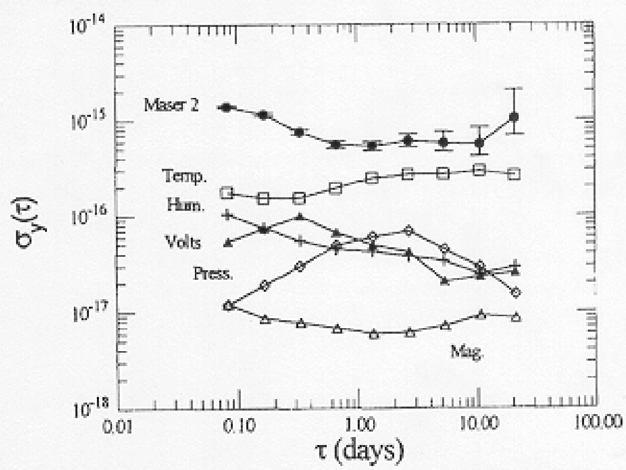

Figure 9 Allan deviation of Maser 2 •, along with environmental contributions from temperature □, line voltage ▲, relative humidity +, pressure ◊, and magnetic field Δ.

Though the maser noise reaches levels as low as 5×10^{-16}, it is clear from the data in Figs. 8 and 9 that fluctuations in environmental parameters do not play a significant role in determining the frequency stability of the masers in our laboratory. Temperature effects are the largest contributor but they are at least a factor of two below the maser noise. All of the other environmental fluctuations are below 1×10^{-16}. Even combining all of the environmental contributions in a root-sum-square process does not change the situation. An improvement to maser stability of only about 15 % would be achieved at some values of τ if all of the environmental instabilities were eliminated. It is also clear that large common-mode frequency fluctuations are not a problem since all of the environmental contributions are small. Temperature effects have the largest impact but the correlation between temperature fluctuations in different chambers is not high. Also the correlation between maser frequency and chamber temperature at time intervals of a few days is less than 0.2.

Conclusions

The flicker floors of the best masers in our laboratory are about $\sigma(\tau) = 5\times10^{-16}$ at τ of a few days, and our analysis indicates that none of the environmental fluctuations are large enough to be a significant contributor to this level of frequency fluctuations. However, the frequency fluctuations induced by fluctuations in temperature, barometric pressure, relative humidity, line voltage and magnetic field on maser frequency are only a factor of 2 to 10 below the measured maser noise levels, indicating that care must be exercised in controlling the environment of the masers. Of these five parameters, temperature fluctuations are the largest contributor to frequency fluctuations in the masers. There is no evidence of any significant common-mode frequency fluctuations in the masers.

Acknowledgments

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HYDROGEN MASER ENSEMBLE PERFORMANCE AND CHARACTERIZATION OF FREQUENCY STANDARDS

Thomas E. Parker

National Institute of Standards and Technology
Time and Frequency Division
325 Broadway, Boulder, CO 80303, USA

ABSTRACT

The performance of a post-processed clock ensemble dominated by active, cavity-tuned, hydrogen masers has been evaluated. The ensemble has an average frequency drift of less than $\pm 3\times10^{-15}$ per year, and an Allan deviation less than 1×10^{-15} for τ between 4 hours and 100 days. This ensemble has been used to help characterize the frequency stability of a number of commercially available, high performance frequency standards.

1. INTRODUCTION

A complete evaluation of the frequency stability of commercial, high-performance cesium beam and hydrogen maser frequency standards is very difficult to perform because there is no single standard consistently available that is better in all aspects of stability. Therefore, the National Institute of Standards and Technology (NIST) has developed a post-processed ensemble of high performance standards that is intended to serve as a stable frequency reference in both short and long term.

The ensemble, referred to as AT1E, consists of five active, cavity-tuned, hydrogen masers [1] and four high-performance cesium beam standards [2]. The AT1 algorithm [3], [4] is used in a post-processed mode, and the maximum weight of any standard in the scale is limited to ~30 %. We also make use of modeled frequency drift parameters to handle the relatively high drift rates of the hydrogen masers. Post-processing helps in determining the drift parameters and in handling unusual events, such as equipment failures or environmental disruptions. We have not yet found it necessary to model the frequency drift of the cesium standards. Though four cesium standards are present in the ensemble, their total weight, both short and long term, is less than 5 %. Thus they play a relatively small role in the performance of the scale. AT1E has been calculated since April 27, 1997 (MJD 50565), which is the earliest point in time from which at least four masers have always been available. The goal for AT1E is to provide continuity and to be comparable to, or more stable than any of the individual standards in the ensemble. Its purpose is to serve as a convenient frequency reference for evaluating the stability of various frequency standards such as commercial devices, or even the short and medium-term stability of primary standards. In Section 2 we discuss the performance of the ensemble, and in Section 3 we use the ensemble to help characterize the frequency stability of the high-performance, commercial frequency standards that are in the ensemble.

2. ENSEMBLE PERFORMANCE

The long-term stability of AT1E is evaluated with data from primary frequency standards such as CS1 and CS2 at the Physikalisch-Technische Bundesanstalt (PTB) and NIST-7. AT1E is not steered directly, but uses information from primary standards to model the long-term frequency drift of the hydrogen masers. Figure 1 shows the fractional frequency difference of AT1E relative to three primary standards for the entire period of its calculation. Data for CS1 and CS2 were obtained from publications of the Bureau International des Poids et Mesures (BIPM), including Circular T and the Annual Report of the BIPM Time Section. All of the primary standards have uncertainties near 1×10^{-14}. For convenience the initial frequency offset of AT1E was arbitrarily set to 0.

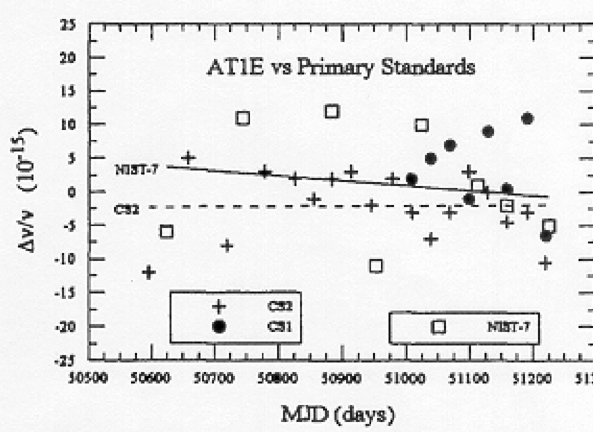

Figure 1. Frequency of AT1E relative to primary frequency standards.

Our primary interest is in the frequency stability of AT1E. The solid line indicates the average frequency drift of AT1E relative to NIST-7, and its slope is $-2.6(\pm 6)\times 10^{-15}$ per year. The slope was obtained by the method of linear regression. The dashed line indicates the average frequency drift of AT1E relative to CS2, which is $+0.2(\pm 2)\times 10^{-15}$ per year. There is not yet enough CS1 data from Circular T to make a meaningful estimate of frequency drift. The conclusion drawn from the data in Fig. 1 is that the drift modeling has been successful with the average frequency drift of AT1E being less than $\pm 3\times 10^{-15}$ per year. (The lowest overall individual maser drift rate is $+1.2\times 10^{-14}$ per year.)

The stability of the primary frequency standard data is not good enough to provide meaningful information on the stability of AT1E for time intervals less than about one year. Changes in maser drift rates that occur over intervals shorter than one year can only be estimated by comparison to the ensemble itself. This requires some care since the masers being evaluated are also in the ensemble. However, since AT1E is a post-processed scale the modeled drift rates can be iterated to provide an overall low drift rate. More accurate evaluation of short-term changes in maser drift rates will become possible when data from cesium fountain standards is available at regular intervals.

Figure 2 shows Allan deviation plots as calculated by two different methods. The curves with triangles and diamonds are for AT1E and were obtained from three-corner-hat calculations using TA(USNO) and EAL, and TA(USNO) and TA(AMC), respectively. EAL is a free atomic scale calculated by the BIPM, TA(USNO) is the independent local atomic time scale calculated at the U.S. Naval Observatory in Washington DC, USA, and TA(AMC) is the independent local atomic time scale calculated at the Alternate Master Clock in Colorado Springs, CO, USA. Data for EAL, TA(USNO), and TA(AMC) were obtained from Circular T and the Annual Report of the BIPM Time Section. The solid circle curve is a comparison of maser 2 with AT1E

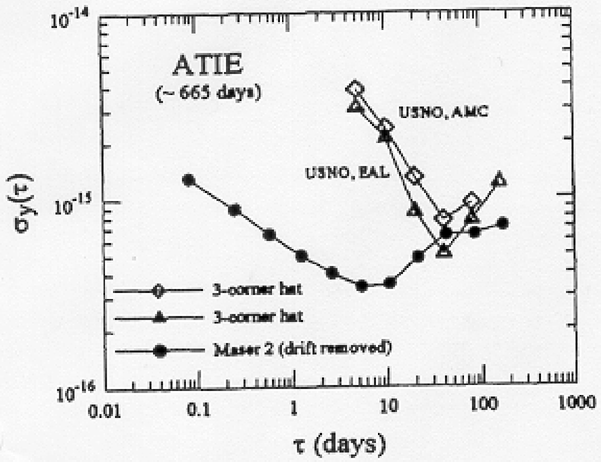

Figure 2. Allan deviation of AT1E.

using internal NIST measurements. The short-term stability (τ less than ~40 days) of the three-corner-hat curves is dominated by common-view GPS noise [5] and therefore does not represent the true performance of AT1E.

A better estimate for the short-term stability of AT1E is obtained from the curve with solid circles. The weight of maser 2 in AT1E is approximately 30 %, which means that the actual ensemble noise is about 65 % of that indicated by the solid circle curve [6]. The data for this curve has not been corrected for this correlation since the short and long-term weights of maser 2 are not the same, and furthermore, the weights are not constant with time. Therefore, the curve should be considered only an approximation of the true behavior of AT1E since a precise correction would be almost impossible to perform. Frequency drift was removed for the solid circle curve because of the relatively high drift rate of maser 2. No frequency drift was removed for the three-corner-hat curves. (The average drift of AT1E relative to EAL is only -4.3×10^{-15} per year.)

There is risk involved in evaluating the stability of an ensemble by comparing it to one of the individual standards in the ensemble, as in the solid circle curve. Some correlation exists between the scale and the standard, as determined by the weight of the standard. This can be approximately accounted for as pointed out above. However, there is also the risk of other unknown common-mode phenomena causing all of the standard frequencies to behave in a similar fashion. Although we have put considerable effort into identifying and eliminating such potential common-mode problems [7], it is always useful to make comparisons to remote, and independent frequency references. That is why the three-corner hat curves are shown. Unfortunately, the noise inherent in a GPS common-view comparison dominates in the short-term as seen in Fig. 2. Therefore, a truly independent evaluation of the short-term stability of AT1E cannot be made until better frequency comparison technology, such as carrier phase GPS, is available. However, the Allan deviation for the three curves is in good agreement for τ longer than about 40 days, indicating that it is a reasonable measure of the long-term stability of AT1E. Table 1 summarizes the estimated performance of AT1E.

Table 1 AT1E Performance

$\sigma_y(\tau = 0.1$ day)	$\sim 1\times 10^{-15}$
$\sigma_y(\tau = 1$ day)	$\sim 4\times 10^{-16}$
$\sigma_y(\tau = 10$ days)	$\sim 2.5\times 10^{-16}$
$\sigma_y(\tau = 100$ days)	$\sim 8\times 10^{-16}$
Frequency Drift	$\leq \pm 3\times 10^{-15}$ per year

3. FREQUENCY STANDARD PERFORMANCE

There are five, active, cavity-tuned hydrogen masers at the NIST facility in Boulder, CO, USA, and all are contained in individual environmental chambers to control temperature and humidity [7]. Figure 3 shows the long-term fractional frequency drift of the five hydrogen masers relative to AT1E for the full 695 days that AT1E has been calculated. Initial frequency values have been arbitrarily offset for viewing convenience. In fact, the maser frequencies are distributed over a range of 8×10^{-12}. The frequency drift clearly differs from maser to maser, and the newer ones generally have higher drift rates. (The masers are numbered in the order in which they were purchased.) There also is a tendency for the larger drift rates to decrease with time. The slopes of the curves in Fig. 3 range from $+3.2\times10^{-13}$ per year (early in the curve for maser 3) to -3.3×10^{-14} per year for maser 4.

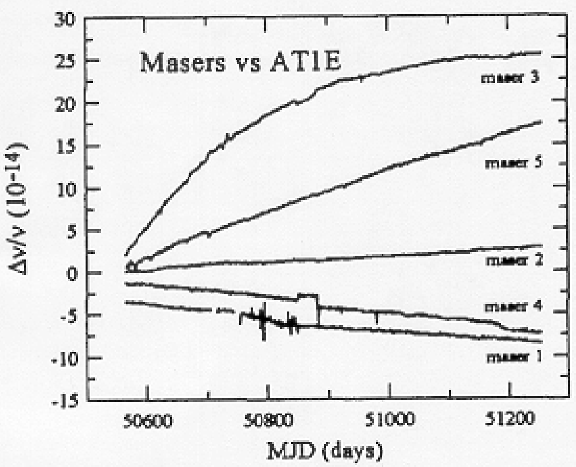

Figure 3. Frequency drift of hydrogen masers.

Nearly all of the transient structure observed in the curves can be identified with environmental testing, failures of environmental chambers, or the moving of masers from one chamber to another. The gaps in the maser 1 data between MJD 50700 and MJD 50800 occurred when the maser was out of service. Maser 2 has been virtually undisturbed for the full time and shows the best overall performance.

The most interesting unexplained event in Fig. 3 started on MJD 50850 when masers 3 and 4 both exhibited frequency steps at the same time. The frequency of maser 4 went up 8×10^{-15} and that of maser 3 went down by 5×10^{-15}. The monitored environmental data (temperature, relative humidity, barometric pressure, power line voltage, and vertical magnetic field strength) showed no obvious cause. Thirty four days later both masers exhibited opposite frequency steps when the maser 4 environmental chamber failed. Note that the two masers are in different chambers and none of the other masers showed any unexplained behavior. At this time we still have no satisfactory explanation for the occurrence.

Figure 4 shows TOTAL deviation (interpreted the same as the Allan deviation) plots for three representative masers compared to AT1E. Allan deviation curves for the other two masers fall within the range of the curves in Fig. 4. Upward corrections to the data ranging from 10 % to 20 % should in principle be made since these masers are all in AT1E. However, as mentioned earlier, these corrections are difficult to make precisely, so no corrections have been applied. A mean second-difference frequency drift has been removed in all cases. For clarity confidence limits are only shown on one curve.

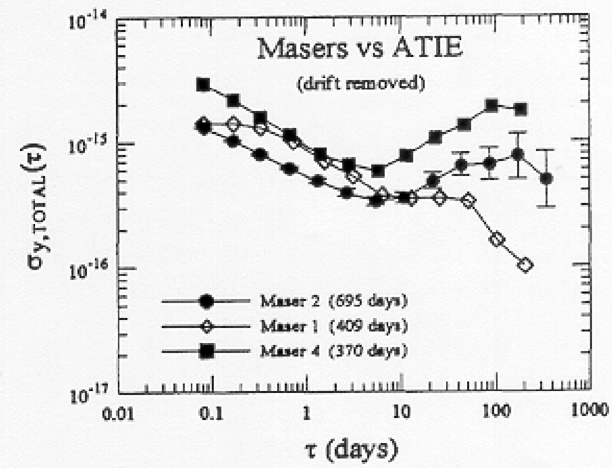

Figure 4. Allan (TOTAL) deviation of hydrogen masers.

Maser 2 has been undisturbed for the full period that AT1E has been calculated so the data in Fig. 4 is for a period of 695 days. For masers 1 and 4 the data covers only the most recent 409 and 370 days respectively. The stability curves vary significantly from maser to maser, not only in level, but also in shape. However, all of the masers show frequency stabilities that drop into the 10^{-16} range between one and ten days. All of the masers except maser 1 show a rise in the TOTAL deviation beyond about ten days. This rise appears in most cases to be caused by changes in the frequency drift rate, although occasionally it can be traced to environmental stability problems. The drop beyond 100 days is caused by the frequency drift removal process.

Figure 5 shows TOTAL deviation plots for two of the cesium standards. Again the standards are numbered in the order in which they were purchased. No frequency drift has been removed for these plots, and no correlation correction is needed because of the low weight of the clocks. The data in Fig. 5 show that the noise of the cesium standards is white frequency out to about 80 days where the level is in the low to mid 10^{-15} range. Beyond 80 days the level either flickers out or begins to rise. The Allan deviation curves of cesium standards 2 and 3 fall between the two curves in Fig. 5.

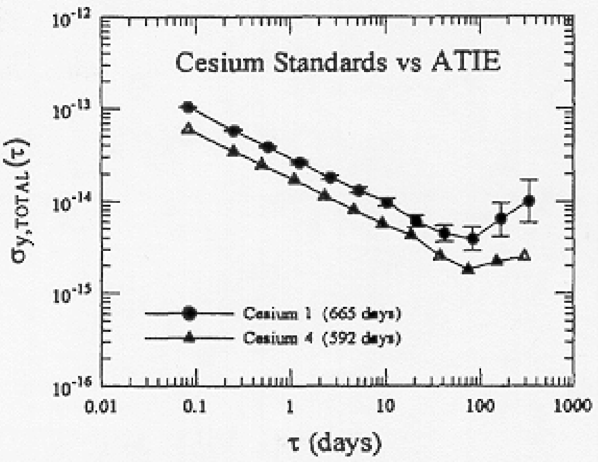

Figure 5. Allan (TOTAL) deviation of cesium frequency standards.

Frequency drift rates of the cesium standards relative to AT1E are generally low and are summarized in Table 2, along with the maser drift rates. The drift rates for cesium standards 2 and 3 were calculated for the entire interval that AT1E has been calculated, while for cesium standards 1 and 4 the period is slightly less. Cesium 4 is the newest device and has not been in operation for the full length of AT1E operation. Cesium standard 1, on the other hand, is the oldest device and it ran out of cesium in March, 1999. It became very noisy during its last 25 days, and the frequency of cesium 1 also exhibited a slight upward trend for the last 100 days before it got noisy. This has resulted in it having the highest overall cesium drift rate.

Table 2. Frequency Drift Rates Relative to AT1E

Standard Number	Freq. Drift Rate
Maser 1	-2.0×10^{-14} per year
Maser 2	$+1.6\times10^{-14}$ per year
Maser 3	$+2.8\times10^{-14}$ per year
Maser 4	-3.3×10^{-14} per year
Maser 5	$+7.5\times10^{-14}$ per year
Cesium 1	$+1.6\times10^{-14}$ per year
Cesium 2	$+5.8\times10^{-15}$ per year
Cesium 3	-4.4×10^{-15} per year
Cesium 4	$+2.9\times10^{-15}$ per year

The maser drift rates in Table 2 apply only to the most recent 300 days. They are generally higher than those of the cesium standards, with only maser 2 having a drift rate equal to the worst cesium.

4. SUMMARY

A hydrogen maser ensemble has demonstrated a frequency drift rate less than $\pm3\times10^{-15}$ per year, and a minimum Allan deviation near 2×10^{-16} at $\tau \approx 10$ days. This ensemble has proven to be very useful in evaluating the frequency stability characteristics of the best commercial frequency standards and also in the evaluation of stability characteristics of primary frequency standards [8].

5. ACKNOWLEDGEMENTS

The author acknowledges the valuable assistance of Jim Gray and Trudi Peppler in maintaining the frequency standards in the ensemble and Judah Levine for creating the computer program for AT1E.

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HYDROGEN MASER PERFORMANCE AT THE UNITED STATES NAVAL OBSERVATORY AND THE NAVAL RESEARCH LABORATORY

E. Powers and A. Gifford
Naval Research Laboratory
Washington D.C. 20375-5000
P. Wheeler
United States Naval Observatory
Washington D.C. 20391-5100

Abstract

The United States Naval Observatory(USNO) has been using hydrogen masers for over six years as part of the USNO Master Clock. The Naval Research Laboratory(NRL) has also been using masers references as part of the NRL Clock testing facility since September 1985. The masers reported on in this paper will include the Smithsonian Astrophysical Observatory VLG-11, VLG-12 and masers from the Sigma Tau Standards Corporation. This paper will describe the operation of the masers at USNO and NRL including stability, aging rates, and reliability.

Introduction

The United States Naval Observatory(USNO) is responsible for time keeping within the Department of Defense(DOD). The USNO Master Clock is a system of several hydrogen masers, cesium beam and mercury ion frequency standards. USNO has up-graded its time scale and in recent years has added an NRL designed 48 channel long term clock measurement system[1], a new full Kalman filter based clock ensemble[2], three trapped Mercury Ion devices[3] and fourteen Hydrogen masers[4, 5].

NRL has been in the forefront of advanced clock development for a variety of DOD systems including the USNO Master Clock upgrade program and the Global Positioning System (GPS) atomic clock development program[6]. Hydrogen masers serve as the primary frequency standard in the NRL clock test facility. Starting from the early 1970's NRL purchased four SAO VLG series masers and two Sigma Tau masers to use as references. The two Sigma Tau masers (NRL-N1 and NRL-N2) and one of the SAO VLG-11 (P-12) series masers were chosen to make up NRL's primary frequency reference ensemble with the other three SAO VLG series masers, including the original VLG-10 P-0, are located at other test sites.

Performance of USNO masers

The new USNO long term clock measurement system was designed to take data in a highly automated fashion, and has proved to be ideal for measurement of a large number of clocks over very long periods of time. This 48 channel dual-mixer system records data every hour with a measurement noise of less than five picoseconds. The computers running the measurement software are available over an ethernet type UNIX network, which makes data handling very easy.

At present USNO is operating twelve Hydrogen Masers with two more expected to arrive later in 1991. Of the twelve masers already at USNO, two are SAO VLG-11 series masers (P-18 and P-19), four are SAO VLG-12 (P-22, 23, 24 and P-25) series masers and six are Sigma Tau masers (N1, N2, N3, N4, N5 and N6). Data on two of the Sigma Tau masers, N1 and N6 was not available for this paper because they have been sent to other USNO sites.

The performance of eight of the USNO masers taken over a period of 264 days was measured against the USNO Master Clock. This 264 day span covers MJD 48104 to MJD 48368 (August 1990 - April 1991). The drift removed frequency stability of each combination of clock pairs was then calculated and used in an N-Cornered hat estimation[7, 8], so the true stability of each clock could be found. Table 1 shows the N-Corner Hat estimates of the frequency stability of the USNO masers. Masers denoted as P are built by SAO and masers with a N prefix were built by Sigma Tau. During a one month period starting in March 1991 P-23 exhibited a 8 $x10^{-15}$ frequency shift which distorts the stability numbers for this clock.

N2, and P18 are being steered to the USNO Master Clock by use of the high resolution synthesizer built into both types of masers. Because of this, only a shorter span of data was available for the calculation of the stability of masers N2 and

N-CORNER HAT FOR A 263 DAY PERIOD COVERING MJD(8104-8367) WITH DRIFT REMOVED.

	1 DAY	2 DAY	4 DAY	8 DAY	16 DAY	32 DAY
N3	1.4	1.5	2.0	2.7	3.8	5.7
N4	1.6	2.1	2.7	3.4	4.9	5.6
N5	1.2	0.85	.75	0.8	0.73	0.9
P19	1.95	2.0	2.05	1.8	1.9	2.2
P22	3.1	3.6	4.4	4.8	6.2	8.7
P23*	5.7	6.9	9.0	11.6	13.0	14.5
P24	0.6	0.97	0.82	0.92	1.05	1.2
P25	1.2	1.4	1.83	3.3	5.49	7.5
N2	1.1	1.36	1.24	2.3		
P18	1.9	2.4	2.7	2.8		

NOTE: All values are times 1 x10^{-15}
*8 x10^{-14} frequency shift greatly influenced data on P-23

P18. The steer amounts were removed from the data and a 3-Corner hat estimate was calculated. This data is also shown in Table 1.

The drift rate was removed by using a simple linear fit to the frequency data which worked well for most pairs of clocks. P-25 had a logarithmic shape to its frequency drift, with the drift rate slowing by almost 50 %. Drift rates for each clocks are shown below versus BIPM.

N3 - BIPM NONE
N4 - BIPM NONE
N5 - BIPM +0.25 x10^{-15}/DAY
P18 - BIPM +0.29 x10^{-15}/DAY
P23 - BIPM +0.99 x10^{-15}/DAY
P19 - BIPM +1.09 x10^{-15}/DAY
N2 - BIPM +1.26 x10^{-15}/DAY
P24 - BIPM +1.82 x10^{-15}/DAY
P22 - BIPM +2.81 x10^{-15}/DAY
P25 - BIPM +3.37 x10^{-15}/DAY

NOTE: NONE IS < (+/-) 1 x10^{-16}/DAY DRIFT

PERFORMANCE OF NRL MASERS

The Sigma Tau corporation delivered two Hydrogen masers (NRL-N1 and NRL-N2) to NRL in the September 1985. These masers have been in almost continuous operation since the day they arrived having been shut off only once because of dead back-up batteries. No adjustments have been made to any of the masers settings for almost six years.

NRL and USNO installed a cesium clock at a local television station (WTTG channel 5) that is used to produce the 77 Mhz carrier frequency of this station[9]. Both NRL and USNO mix their local references with the received television carrier to produce a 2250 Hz beat frequency. USNO feeds their beat frequency to NRL over a dedicated telephone line and NRL compares the phase of these two 2250 Hz signals. The cesium clock at WTTG will cancel, and NRL is left with the phase difference between NRL-reference (NRL-N1) and the USNO Master Clock. The short term noise in this method is good but signal drop outs can cause phase breaks to occur.

Using this television carrier phase comparison system to measure the long term frequency drift in the NRL reference shows that NRL-N1 had a drift rate of less than 5 x10^{-17}/day for almost six years versus BIPM.

NRL-N2 exhibited a non-linear frequency drift rate during the first two and half years of operation at NRL, with the drift rate slowly increasing. This drift rate changed to a constant rate of +4 x10^{-15}/day for the next two years. Approximately one year ago the drift rate shifted again to a constant rate +3.5 x10^{-15}/day and remained at that rate.

The drift removed frequency stability of NRL-N1 versus NRL-N2 is shown below. Because these two clock are similar one may assume that one of the two clocks are at least the square root of two better than shown in below. NRL-N1 versus BIPM stability estimates for 100 day and 200 day sample times are also shown below.

TYPICAL FREQUENCY STABILITY NRL-N1 VERSUS NRL-N2 (DRIFT REMOVED)

1 sec	2.5×10^{-13}
10 sec	3.5×10^{-14}
100 sec	6.0×10^{-15}
1 hour	5.0×10^{-15}
2 hour	4.8×10^{-15}
4 hour	4.6×10^{-15}
8 hour	3.6×10^{-15}
1 day	2.8×10^{-15}
2 day	2.1×10^{-15}
5 day	1.2×10^{-15}
10 day	1.2×10^{-15}

FREQUENCY STABILITY ESTIMATE OF NRL-N1 VERSUS BIPM (NOT DRIFT REMOVED)

100 day	4.7×10^{-15}
200 day	5.6×10^{-15}

RELIABILITY

The reliability of both the VLG-12 and Sigma Tau masers has been excellent. The only systematic problem was in the older SAO VLG-11 series maser's vacuum system. The VLG-11 masers require replacement of the ion pump every two or three years. The SAO VLG-12 series masers high vacuum ion pump system is improved and should last much longer. Also several VLG-11 masers have suffered receivers failures due to an amplifier chip running hot and burning out. This design error has been corrected and all of USNO masers have been modified to correct this error.

All of the USNO Sigma Tau masers needed their quartz oscillators replaced. After consulting the company that manufactures this quartz oscillator, a design flaw was discovered. The company changed their design and future problems are not expected. It is expected that the useful lifetimes of both the VLG-12 and Sigma Tau masers will be greater than 12 years.

CONCLUSION

The USNO clocks with the best frequency stability over the time period reported on in this paper were N5, P19 and P24. N5 and P24 long term drift removed frequency stability at 32 day sample times were less than 1.2×10^{-15} and the stability of P-19 was 2.2×10^{-15}.

The clocks with the least drift were N3, N4, N5 and P18. These drift rates were less than 3.0×10^{-16}/DAY versus BIPM. Over a period of less than one year measuring drift rates smaller than this is very difficult because of measurement uncertainties between BIPM and USNO.

NRL master frequency reference NRL-N1 has shown a net long term frequency drift versus BIPM of less than 5×10^{-17}/day over a six year period.

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Datum - Timing, Test & Measurement 34 Tozer Road • Beverly, MA 01915-5510 • USA

US Toll Free: 1-800-544-0233
Phone: +1-978-927-8220
Fax: +1-978-927-4099

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Datum Operations

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9975 Toledo Way
Irvine, CA 92618

Datum–eBusiness Solutions
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Datum–Austin
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