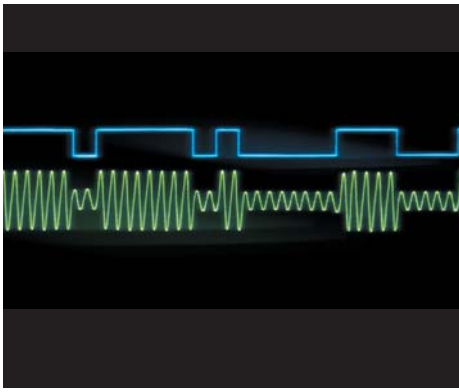
Symmetricom

Symmetricom Sigma Tau Standards Group

Active Hydrogen Maser MHM 2010



WHITE PAPER

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Company Overview

Mr. Harry Peters founded *Sigma Tau* Standards Corporation in 1977. The company's focus from the outset was to build the best performing Active Hydrogen Masers in the world. A background in physics complemented by a number of years experience in Hydrogen Maser engineering design and manufacture at NASA's Goddard Space Flight Center, positioned Harry ideally for this task.

By assembling a team of highly competent engineers and technicians the company was able to develop a premium product, with strong emphasis on superior performance and high reliability. Over the past twenty years the company has delivered more than forty active masers to a worldwide customer base, including institutions at the forefront of time and frequency excellence such as the Observatoire de Paris (France), NIST (USA), NPL (United Kingdom), and USNO (USA).

The company has made a number of product improvements over the years resulting in a product that boasts an estimated life in excess of twenty years coupled with stability performance to < 1 x 10-16 after a sufficient period of unperturbed operation.

In 1997 *Sigma Tau* Corporation was acquired by the Timing, Test and Measurement (known then as Frequency and Time Systems) subsidiary of Datum Corporation, a $120M publicly held US Corporation. Founded in 1971, Datum - Timing, Test and Measurement manufactures Cesium and Rubidium Atomic Time and Frequency Standards, GPS receivers, Quartz Oscillators, Distribution Amplifiers and Bus Level Time and Frequency Processors. These products are utilized in a wide range of applications that include, Satellite tracking stations, military communications, telecommunications testing and timing equipment and spaced based reference clocks.

Datum Corporation was acquired by Symmetricom, a $180M publicly held US Corporation, in 2003. The combination of these companies forms a unique team with the expertise to build the best frequency standards in the world. A manufacturing, sales and service organization with worldwide presence that is able to respond to and support an extensive International customer base, backs the Symmetricom *Sigma Tau* Standards Group.

MHM 2010 Active Hydrogen MASER Overview

MHM 2010 Active Hydrogen Maser

The MHM 2010 epitomizes the performance and reliability of the best in American technology manufacturing.

The MHM 2010 contains a number of critical features that contribute to the excellent performance over other units including:

- Patented Magnetic Quadrapole providing superior atomic beam focussing
- Very low Hydrogen usage (< 0.01 mole per year) gives extended maintenance-free life
- Unique, stand-alone, Cavity Auto Tuning feature
- Proprietary Teflon coating technique eliminates re-coating requirement, extending maintenance free life

The Maser Operation

A small storage bottle supplies molecular hydrogen under electronic servo control to the source discharge bulb where the molecules are dissociated into atoms. Atoms emerge from the source through a small elongated hole known as the source collimator and then pass through a magnetic state selector that directs a beam of atoms in the correct quantum state to a Teflon coated quartz storage bulb. A microwave cavity, resonant at the hydrogen transition frequency, provides the proper environment to stimulate maser action that causes the atoms to produce microwave emissions. A small loop couples the microwave signal from the microwave cavity to the receiver/synthesizer system through a coaxial cable.

The signal from the cavity passes to a low noise, heterodyne receiver system containing a high resolution frequency synthesizer, and a phase-locked loop locks a voltage controlled crystal oscillator (VCO) to the maser output. Integral multipliers, dividers and buffer amplifiers under temperature control provide several isolated outputs at standard frequencies. To insure proper environment for maser action and minimize systematic perturbations of the maser output frequency, sputter-ion pumps maintain a high vacuum and getter the hydrogen. Magnetic shielding surrounds the cavity and a multi-level thermal control system provides isolation from external temperature variations. An axial magnetic field coil wound on the inside of the first shield provides control of the internal magnetic field also known as the C Field.

Auto-Tuning

The maser incorporates an automatic frequency control system to maintain the cavity at a constant frequency relative to the hydrogen emission line. This cavity servo, using the cavity frequency-switching method, requires no other stable frequency references in its operation. Unlike conventional automatic spin-exchange tuning, the maser does not require beam intensity switching, so the cavity servo system does not significantly degrade the maser short term stability or phase noise. Organizations requiring the best long term stability and reproducibility will find the auto-tuning system crucial to realizing their goals

This product was the first commercially available Active Hydrogen Maser in the world with stand-alone Cavity Auto Tuning. This technique, developed by Symmetricom's Sigma Tau, enables the MHM 2010 to deliver long-term stability normally only attributed to the most stable of cesium 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 being shipped from the Symmetricom's Sigma Tau facility each unit has undergone months of testing and performance monitoring to insure that specifications are met.

Features

- Outputs 5,10,100MHz & 1PPS
- 1PPS auto sync input
- Remote monitor interface
- <2E-16 per day aging
- Low environmental sensitivity
  - Humidity: <2e-17 per % of relative
  - Temperature: <1.4e-15/degree C
  - Magnetic Field: <5.5e-15/Gauss, ±0.5 Gauss
  - Pressure: 1.6e-16/kPa, for 5 kPa change

AOG 110 Auxiliary Offset Generator Overview

The Symmetricom 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.

Output frequency is controlled by directly offsetting a phase accumulator (synthesizer) in the PLL chain. The maximum synthesized fractional frequency range is + 1 e-7, with a resolution of 2 x 10-19 . 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 fre quency offset and precise time interval. Direct control over both frequency and time interval is available.

FIGURE 1 AOG 110 Auxialiry Offset Generator

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 Symmetricom 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:

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or visit our web site at
http://www.symmetricom.com/ttm

AOG 110 Auxiliary Offset Generator Overview > continued

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

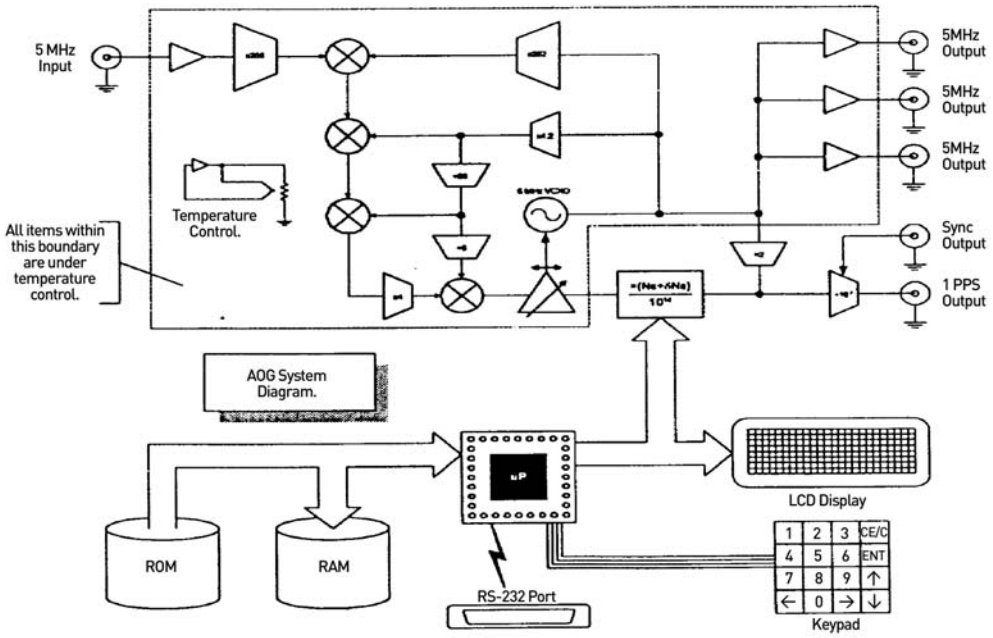

FIGURE 2 AOG 110 Auxialiry Offset Generator- Schematic

MHM 2010 Active Hydrogen Maser – Typical Performance

Stability

1 < t < 1,000 seconds	$1.5 \times 10^{-13}\ t^{-1/2}$
1,000 < t < 10,000 seconds	2.5×10^{-15}
Floor	1.5×10^{-15}
Long term	$< 2 \times 10^{-16}$ per day *
Auto tuning	no external reference required

*after extended period of unperturbed, continuous operation

Environmental

Temperature Sensitivity	$< 1 \times 10^{-14}$ °C.	For reduced sensitivity temperature chamber can be supplied
Magnetic Sensitivity	$< 1 \times 10^{-14}$ / Gauss	
Power source sensitivity	$< 1 \times 10^{-14}$	when switching to auxiliary supply

Control

Synthesized frequency resolution	7×10^{-17}
Frequency control range	1×10^{-8} (1×10^{-6} possible with offset of VCO coarse control)

note : synthesizer maintains continuous phase throughout frequency change

Available Outputs

Frequency Outputs	5MHz, 10MHz, 100 MHz
Amplitude	> 1V rms
Load Impedance	50 ohms
Timing Input	1PPS (auto sync)
Synchronization input to output	<15ns
Isolation	100dB
Timing Output	1PPS
Amplitude	> 3V (TTL Compatible)
Load Impedence	50 ohms

Power

Operating voltage	85 to 264 VAC
Frequency Range	47 to 440 Hz
Peak power	150 W
Operating power	75 W
External DC input	22 to 28 VDC

AOG 110 – Typical Performance

	3.1A (typical)
Standby battery	> 8 hours operation
Stability	
1 second	3 x 10-13
> 1 second	approximately 1 / t to noise floor
Steering	
Resolution	2 x 10-19
Range	± 1 x 10-7
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	(3) 5 MHz, (1) 1PPS
Amplitude	+13 dBm
Load Impedance	50 Ohms
Output isolation	> 80 dB
Environmental	
Temperature sensitivity	< 10 pico second per 0C
Other	
5 MHz input range	+6 dBm to +15 dBm
VCXO range	> 1e-6 fractionally
Sync Input	1PPS (TTL Compatible)
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)
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

Active Hydrogen Maser Applications

Introduction

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

During this time, Symmetricom *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:

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

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 radio telescope is used to observe galaxies, quasars, gravitational lenses, and other objects, at milliarcsecond resolution.

The NRAO currently has **fourteen, Symmetricom *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.

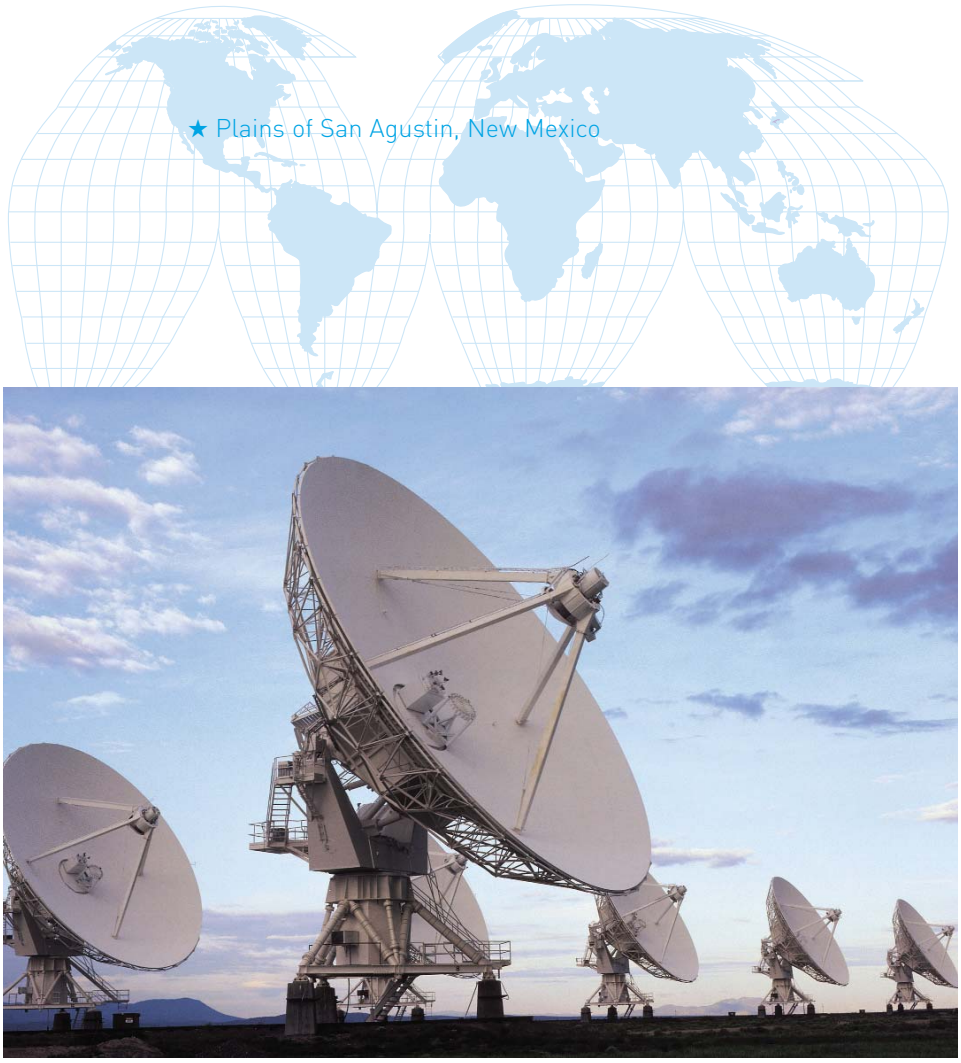


FIGURE 3 National Radio Astronomy Observatory (NRAO) USA - Very Large Array

Very Long Baseline Interferometry (VLBI) and Very Long Baseline Arrays (VLBA) > continued

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 H2O 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 **Symmetricom *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.

FIGURE 4 Westorbork Synthesis Radio Telescope (WSRT) NetherlandsWestorbork Synthesis Radio Telescope (WSRT) Netherlands

Very Long Baseline Interferometry (VLBI) and Very Long Baseline Arrays (VLBA) > continued

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 **Symmetricom *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.

FIGURE 5 Taeduk Radio Astronomy Observatory

Very Long Baseline Interferometry (VLBI) and Very Long Baseline Arrays (VLBA) > continued

The Arecibo Observatory is part of the National Astronomy and Ionosphere Center (NAIC), operated by Cornell University with the National Science Foundation (NSF). The National Aeronautics and Space Administration (NASA) provide extra support. 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 sub reflectors and new electronics greatly increases the capability of the telescope.

The Arecibo Ionospheric Observatory uses a **Symmetricom *Sigma Tau* MASER** as a key component of the Observatory's capabilities.

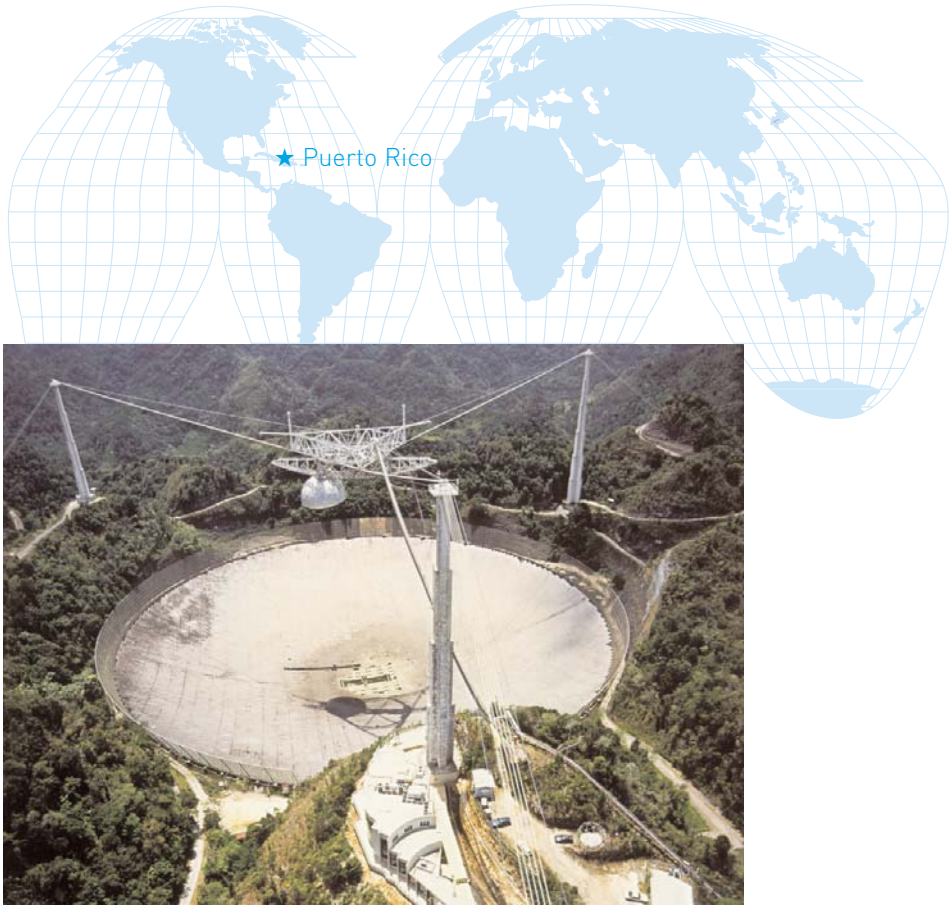


FIGURE 6 Arecibo Ionospheric Observatory (AIO) - Arecibo, Puerto Rico

Very Long Baseline Interferometry (VLBI) and Very Long Baseline Arrays (VLBA) > continued

MERLIN, the Multi-Element Radio-Linked Interferometer Network, consists of seven separate telescopes in the United Kingdom: 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 arc sec; 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 **Symmetricom *Sigma Tau* MASER** within the laboratories as the precise timing for data recording, a critical aspect of the Observatory's capabilities.

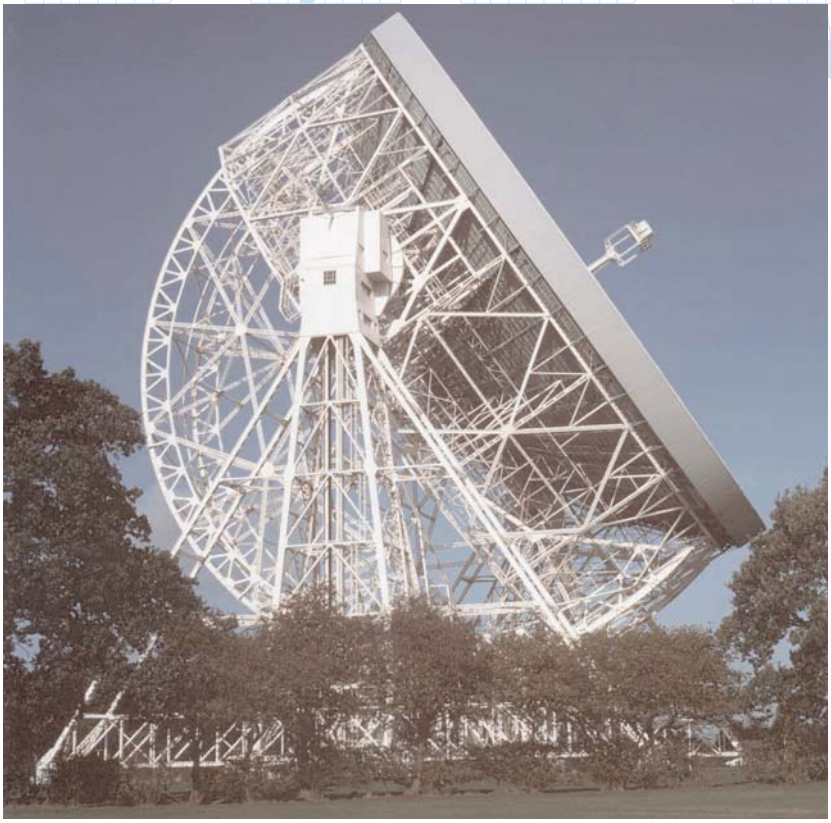
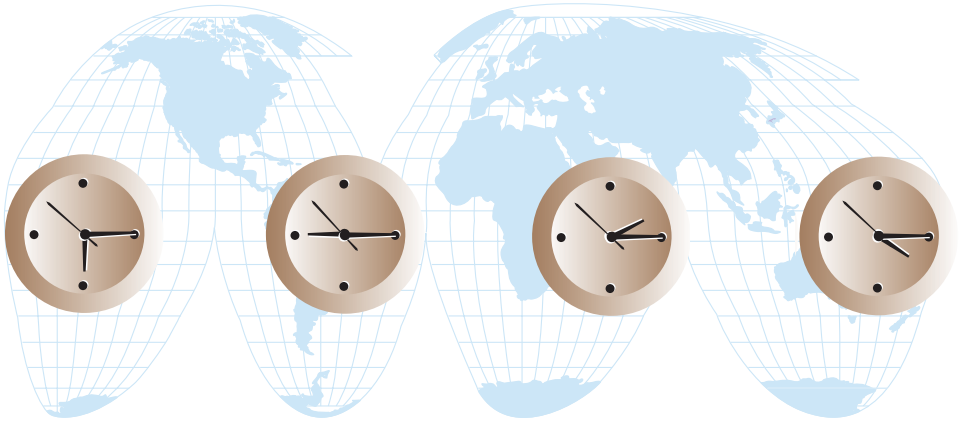


FIGURE 7 The 76 m Lovell Telescope at Nuffield Radio Astronomy Laboratories (NRAL), UK

National and International Timekeeping



Paris Observatory

The Paris Observatory is one of the principal centers of the French Ministry of Higher Education and Research, and a 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 two **Symmetricom *Sigma Tau* MASER** as part of the critical reference equipment employed.

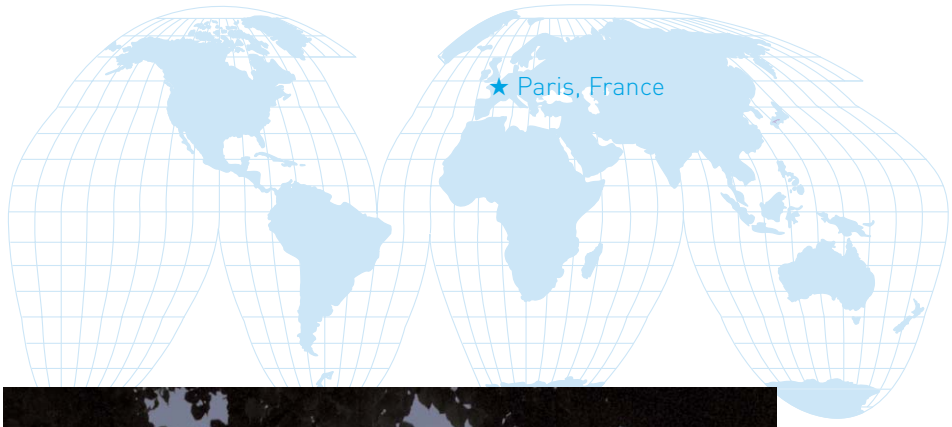


FIGURE 8 Observatoire de Paris, Paris, France

U.S. Naval Observatory

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 twenty **Symmetricom *Sigma Tau* MASER's** as part of this critical Master Clock system.

FIGURE 9 U.S. Naval Observatory (USNO) - Washington D.C.

FIGURE 10 one of the USNO clock vaults containing Symmetricom's masers and cesium instruments

National Institute of Standards and Technology

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 and 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 six, **Symmetricom *Sigma Tau* MASER's** which contribute to the precise time and frequency reference capability vital for this work.

FIGURE 11 National Institute of Standards and Technology, Boulder, Colorado, USA

National Physical Laboratory

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 three; **Symmetricom *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.

FIGURE 12 National Physical Laboratory, Teddington, England

References

Customer	Masers Delivered
US Naval Observatory	20
US National Radio Astronomy Observatory	14
US National Institute of Standards and Technology (NIST)	6
US Naval Research Laboratory	4
National Physical Laboratory (UK)	3
Johns Hopkins Applied Physics Laboratory	3
Shanxi Astronomical Observatory (China)	2
SP Swedish National Testing and Research Institute (Sweden)	2
Instituto Elettrotecnico Nazionale (Italy)	1
Instituto y Observatorio de la Armada (Spain)	1
Korea Research Institute of Standards and Science (Korea)	1
Shanghai Astronomical Observatory (China)	1
Urumqi Astronomical Observatory (China)	1
Arecibo Observatory (US)	1
Other	22
Total Installed base	82

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