MHM 2010™ Active Hydrogen Maser... In Depth

The world's most widely installed active hydrogen maser employs the ideal timekeeping technologies for applications that require extreme frequency stability, low phase noise and long service life.

The Symmetricom® MHM 2010™ is the world's most widely installed active hydrogen maser for a reason. It offers a combination of features and is ideally suited for applications like national timekeeping and VLBI (very long baseline interferometry) that require extreme frequency stability, long life and maintenance-free operation in a single instrument:

- A patented Magnetic Quadrapole that provides superior atomic beam focusing
- A very low Hydrogen usage (< 0.01 mole per year) for extended maintenance-free operation
- A unique Cavity Auto Tuning feature for "as good as cesium" long-term standalone stability
- A proprietary Teflon coating technique that virtually eliminates any recoating requirement, extending maintenance free life
- CE compliance
- A low-phase noise option for superior short-term stability in an active hydrogen maser

The MHM 2010 is the only commercially available active hydrogen maser with stand-alone cavity switching auto tuning manufactured in the U.S. This technique enables the MHM 2010 to deliver long-term frequency stability normally only attributed to the most stable cesium atomic standards.

The availability of a low phase noise option means that users looking for extreme long-term stability must no longer trade off short-term stability. In combination with all the instrument's other industry-leading features, this option make the MHM 2010 the logical choice for applications like VLBI, which require extremely high resolution images.

Maser Design

Hydrogen masers operate on the principal that when hydrogen atoms are provided the proper environment, they emit radiation of a precise frequency (1420 MHz) and spectral line width (21 cm). Phase locking this extremely small power, high purity signal to a very high performance quartz oscillator, provides the user with incredible long-term stability, as well as excellent phase noise. The MHM 2010 implements this principal as follows:

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

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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. When the low-phase noise option is selected, the maser is configured so the VCO itself contributes a greater weight to stabilizing the output signal — taking advantage of the VCO's inherently greater phase noise performance relative to the maser.

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 supplied to the system. 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 Enhances Long-Term Stability

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 enables the MHM 2010 to deliver long-term stability normally only attributed to the most stable of cesium atomic standards.

AOG-110 Auxiliary Offset Generator

It is often desirable to synchronize and syntonize (run at the same frequency) the signal from a frequency standard (e.g., the MHM 2010) and a reference (e.g., the USNO Master Clock). This raises the issue of how to offset the maser's output frequency without actually changing the frequency of the device itself. The AOG-110 Auxiliary Offset Generator solves this problem by reading the reference frequency and generating the offset. The AOG-110 provides a 5 MHz output, programmable over a broad frequency range with extremely high resolution and precise phase control. It facilitates adjustment of the MHM 2010 output to a slightly different operating point without compromising the maser's stability. It leaves the maser completely unperturbed, thereby maintaining the maser's optimum performance.

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 signal (1PPS), which is available as an output. The 1PPS output can be periodically synced to an external 1PPS reference by the AOG-110 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 x 10^{-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 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-110 are independently controlled through a menu-driven interface on the front panel. The interface also provides operational status information. The local interface consists

Figure 1. MHM 2010 Active Hydrogen Maser

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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 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 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 the remote console without affecting the 5 MHz output.

Although intended for use with the Symmetricom MHM 2010 Active Hydrogen Maser, the AOG-110 can be used with any highly stable high performance 5 MHz 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-way satellite time transfer or GPS common mode common view.

MHM 2010 Applications

Applications that employ Symmetricom active hydrogen masers benefit from, and typically require, the most stable frequency reference signals commercially available coupled with a lengthy record of reliability and a demonstrated life of over 20 years. Two such applications are VLBI and national timekeeping.

Very Long Baseline Interferometry (VLBI)

VLBI is a technique in which multiple radio telescopes, separated by perhaps thousands of miles, operate in precise time sync. The sharpness of the resulting image can be measured in microarcseconds —higher than any other astronomical instrument. In fact, it's the same level of detail that a single telescope might achieve if its diameter were equal to the distance separating the antennas farthest apart in the array.

Time syncing with the maser allows data from the multiple telescopes to be integrated, creating a composite of what all telescopes "saw" at each instant in time. Digitally recorded data files with the time stamped data are shipped to a single VLBI coordinator and then played back simultaneously to create the composite. In order for the timing data to be precisely aligned, each maser has a stability typically less than 2 x 10^{15}.

Figure 2. AOG-110 Auxilliary Output Generator

VLBI sites employing Symmetricom active hydrogen masers include those operated by the U.S. National Radio Astronomy Observatory, the Westterbork Synthesis Radio Telescope, the Korean Research Institute of Science and Standards, the National Astronomy and Ionosphere Center, and Multi-Element Radio Linked Interferometer Network.

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Observatories

Symmetricom MHM 2010 Active Hydrogen Masers are still currently in use by these organizations to further their research.

U.S. National Radio Astronomy Observatory (NRAO)

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.

Westerbork Synthesis Radio Telescope

The fourteen 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 timekeeping station A Legacy of Performance

Part of the upgrade was to replace the original (30 year old) maser system by a Symmetricom active hydrogen maser, in order to accommodate the future requirements of the VLBI, pulsar and geodetic communities.

The Korea Astronomical Observatory

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

National Astronomy and Ionosphere Center

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 astronomy. It also maintains an Ionospheric Interactions facility consisting of 32 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.

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Nuffield Radio Astronomy Laboratories
MERLIN, the Multi-Element Radio Linked Interferometer Network, consists of seven separate telescopes in the United Kingdom, including the Lovell or Mark II at Nuffield Radio Astronomy Laboratories (NRAL) at Jodrell Bank. Others are the Mark III telescope and two 25-m telescopes elsewhere in Cheshire, another two 25-meter telescopes in Shropshire and Worcestershire, and a 32-meter 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, the Lovell Telescope routinely works with radio observatories all over the world.

National and International Timekeeping

Paris Observatory
The Paris Observatory is one of the principal centers of the French Ministry of Higher Education and Research. 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 advance international cooperation.

The Observatory consists of nine departments, a scientific service and five common services, which comprise a dozen CNRS units. As part of the service responsibilities assigned to it on an international and national level, it accommodates the Principal Laboratory of Time and Frequency (LPTF), whose responsibilities include keeping the French civil time, watching over solar activity, and operating the International Service of Earth's Rotation.

Built around 1665, it is the oldest observatory still functioning, and the latitude of the south face defines the Paris latitude (48° 50' 11'' N) while the meridian line passing through its center defines the Paris longitude (2° 20' E). The foundations are as deep (27m) as the building is high. In this deep basement, the Bureau Internationale de l'Heure (International Time Bureau) sets the coordinated universal time (UTC) with 10^{-6} sec. of accuracy.

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 true for such ground-based systems as well as GPS. In the communications and 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 are more stable than cesium beam atomic clocks in the short term, and mercury ion frequency standards, which are more stable than either cesium or hydrogen in the long run. These represent the most advanced technologies available to date.

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National Institute of Standards and Technology (NIST)
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: 1) developing and operating the standards of time and frequency and coordinating them with other world standards;
2) providing time and frequency services to the United States; and 3) undertaking basic and applied research in support of future standards, services and measurement methods. The Division also undertakes a number of advanced development programs for advanced atomic frequency standards for industrial and scientific applications.

National Physical Laboratory (U.K.)
Home of the United Kingdom's atomic time scale, UTC, 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.

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