MHM-2020

Active Hydrogen Maser - In Depth

INTRODUCTION

Expanding upon the heritage of the world's most widely installed active Hydrogen Maser, the Microchip MHM-2020 has enhanced the unique Auto-Tune design of the MHM-2010 by re-engineering the electronics and software to attain even better stability.

Capable of achieving <3 × 10^{-16} daily drift rates along with improved environmental stability, the MHM-2020 has been designed for applications requiring extreme frequency stability and low phase noise.

Microchip's MHM-2020 and its predecessor are the world's most widely installed active hydrogen maser for a reason. They offer a combination of features and are 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. The MHM-2020 leverages several proprietary technologies to enable Microchips highest performance commercially available clock, including:

- A patented Magnetic Quadrapole state selector 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 long-term standalone stability
- A specialized Low Noise Quartz oscillator built specifically for this product in-house
- A proprietary Teflon™ storage bulb coating technique that virtually eliminates any recoating requirement, extending maintenance free life
- A low-phase noise option for superior short-term stability in an active hydrogen maser
- Drift Compensation software algorithms to enable < $3E^{-16}$/day drift (typical, after 3 month's)

The MHM-2010 is the only commercially available active hydrogen maser with stand-alone cavity switching auto tuning manufactured in the U.S. Now, by pairing this technology with the new integrated Drift Compensation software, daily aging rates can achieve an almost 10x improvement over the predecessor MHM-2010.

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 makes the MHM-2020 the logical choice for applications like VLBI, which require extremely high resolution images.

Finally, the Maser may be configured with a variety of features that provide flexibility to the user.

Features

- Telemetry monitoring via touch screen and secure Ethernet
- Dedicated keypad or USB/serial port (secure) allow flexibility in instrument control
- Internal time-of-day clock for internal data time stamping
- 1PPS synchronization option for precise calibration to GNSS
- Multiple 1PPS and RF output options (5, 10 or 100 MHz)
- Battery backup
- CE compliant

FIGURE 1: *MHM-2020 Active Hydrogen Maser*

MASER DESIGN

Hydrogen Masers operate on the principle that hydrogen atoms, in the proper environment, emit microwaves at a precise frequency (1420405751 Hz). This is the well-known atomic hydrogen wavelength of 21 cm. Phase locking this extremely small power and 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-2020 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 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-2020 to deliver long-term stability normally only attributed to the most stable of cesium atomic standards.

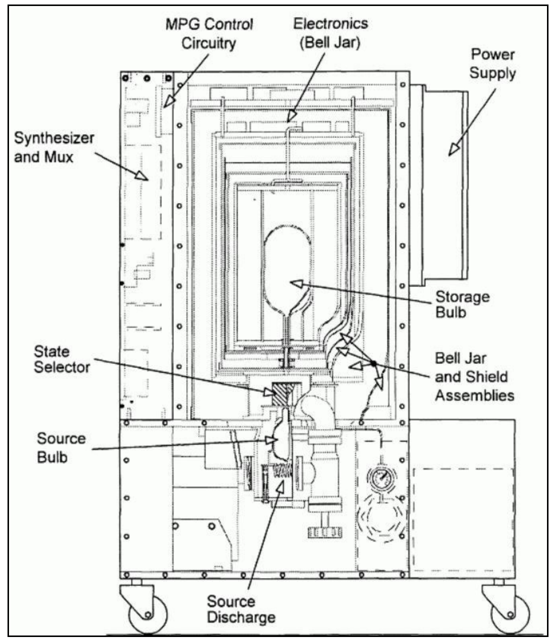

FIGURE 2: *MHM-2020 Active Hydrogen Maser - Internal View*

MHM-2020 APPLICATIONS

Applications that employ Microchip 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 precision 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 2×10^{-15}. Better stability enables higher resolution imaging.

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

In April 2019, images from the largest VLBI survey (taken in 2017) were compiled to produce the first image of a black hole via the Event Horizon Telescope project. The Microchip Maser played a small but critical part in this project by providing the timing necessary to image such a distant phenomenon.

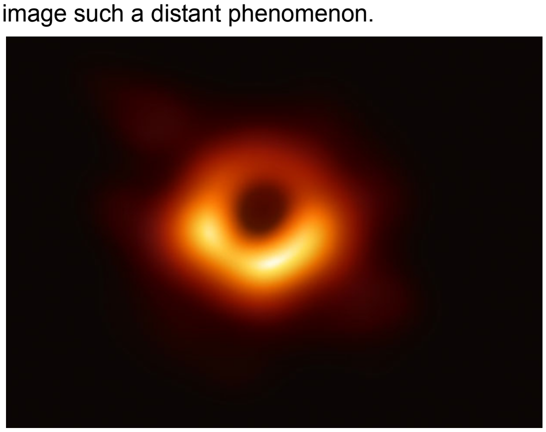

FIGURE 3: *Image of a Black Hole*

Credit: EHT Collaboration

https://www.eso.org/public/images/eso1907a/

OBSERVATORIES

Microchip 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 with the Westerbork site beginning operations in 1956.

The Westerbork Synthesis Radio Telescope is one of the most powerful radio observatories in the world. It enables astronomers to study a wide range of astrophysical problems: from pulsars to kinematics of nearby galaxies to the physics of black-holes. It is also part of the European VLBI network EVN.

Korea Astronomical Observatory

The Korea Astronomical Observatory (KAO) provides observation and meteorology 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) and the National Science Foundation (NSF) operated under cooperative agreement by the University of Central Florida. 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.

The site has contributed to VLBI investigations into Quasars and other research.

Jodrell Bank Observatory

Jodrell is home to e-MERLIN (enhanced Multi Element Remotely Linked Interferometer Network), which is an array of seven radio telescopes spanning 217 km across the UK connected by optical fiber network to its headquarters at Jodrell Bank Observatory. It has a unique position in the world with an angular resolution comparable to that of the Hubble Space Telescope and carrying out centimeter wavelength radio astronomy.

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

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.

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.

Paris Observatory

Founded in 1667, the Observatoire de Paris is the largest national research center for astronomy. 30 % of all French astronomers are working in it five laboratories and its institute. Situated on the Paris, Meudon and Nançay campuses, they are all "Unités Mixtes de Recherche (UMR)" associated with the CNRS and, in many cases, with the major scientific universities in the Paris area. The work of the Observatoire is also carried out in two major scientific services. The Observatoire de Paris is an academic centre (Grand établissement) under the aegis of the Ministère de l'Enseignement supérieur et de la Recherche.

The research done at the Paris observatory covers all the fields of contemporary astronomy and astrophysics including:

- The study of the Sun and Sun-Earth relations
- Planets and planetary systems
- Star formation, the interstellar medium
- The formation and evolution of galaxies
- Astroparticles and cosmology
- Time and space metrology
- The history and philosophy of science

The Observatory develops and implements national and international services, and contributes to the major projects for the observation of the Universe.

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.

NOTES:

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