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A HYDROGEN MASER FOR LONG-TERM OPERATION IN SPACE

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Introduction

We describe the design of a space-worthy hydrogen maser capable of four or more years of continuous operation in space. This maser system can be adapted for several future space applications, such as very long baseline interferometry, high precision time transfer, and tests of relativistic gravitation. The maser clock system is described, including details on its design for surviving very high levels of launch stress, operating with frequency stability, $\sigma_y(\tau) = 1 \times 10^{-15}$ for $\tau = 24$ hours over ambient temperature variations from 14 to 25 C, and magnetic field variations of ± 0.5 gauss. These specifications are intended to allow it to be used on a wide range of launch vehicles and space platforms. Tests of this maser clock system for approximately 1 year duration will be made in a low orbiting spacecraft by making short pulsed-laser time comparisons with a maser monitored via a common view GPS technique located in a laser-equipped earth station. The timing system and the event timer, with 10 ps time resolution, is described in an accompanying paper at this conference.¹

Operation of the space-borne maser system is controlled and monitored using an on-board microprocessor that implements a number of automated procedures for controlling the maser and testing its operational parameters while in orbit. The entire system, including two reflector-detector-event timer modules, will operate on less than 95 watts. The package, as configured for mounting on the European Space Agency's EURECA spacecraft, weighs less than 110 kg.

Objectives

The purpose of this project is to design, build, and test a spaceborne atomic hydrogen maser clock system and evaluate its performance in space. Three tasks will be performed while in space:

- Measure the maser's frequency relative to international time scales using laser pulses from a ground-based satellite laser ranging station.
- Observe the maser's response to controlled changes in the maser's functions and from variations of its environment. Control and monitoring will be done through the spacecraft's telemetry and telecommand systems.
- Determine from frequency measurements and from monitored data, the maser's frequency stability over the duration of the mission, and the effect of ambient conditions on the maser's long-term frequency performance.

Overview

The main component under test is a hydrogen maser atomic clock system located in a spacecraft in a low earth orbit (altitude of approximately 500 km.) Time kept by the atomic hydrogen maser (H maser) clock will be compared with earth-based clocks by controlling the times of laser pulses sent from a laser ranging station. Their arrival times will be recorded at the spacecraft and the pulses will be reflected back to the ranging station by cube corner retroreflectors mounted on the spacecraft. A photodetector mounted with the retroreflectors will detect the arrival of a laser pulse at the spacecraft and will trigger a timing circuit (an "event timer") that records the pulse's arrival time in terms of the spacecraft maser's time scale. The pulse arrival times at the spacecraft will be corrected for propagation by measuring the two-way time of propagation at the earth station. An overview of the system is shown in Figure 1. Figure 2 shows a block diagram of the major system components.

Systems

The experimental package consists of (i) an H maser physics unit, (ii) one or two laser retroreflector/detector

Hydrogen Maser Clock experiment overview

Figure 1

Fig. 2. Block diagram of major HMC experiment components

MASER SYSTEMS

VACUUM SYSTEMS
 MAGNETIC SHIELDS AND SOLENOID
 HYDROGEN SOURCE
 HYDROGEN DISSOCIATOR/STATE SELECTOR
 TEMPERATURE CONTROL
 RESONANT CAVITY/STORAGE BULB

Cross section of maser and support structure on mounting plate, showing main maser systems.

Figure 3

units that detect the arrival of a laser pulse at the spacecraft and reflect the pulse back to the ranging station, and (iii) the electronics required to operate the maser, interface with the spacecraft and measure the arrival time of laser pulses.

The physics package

The H maser physics unit consists of a microwave resonant cavity assembly, an RF dissociator that creates a beam of hydrogen atoms, a permanent magnet state selector system, and vacuum pumps to remove expended hydrogen and other gases. The physics package is shown in cross-section in Figure 3.

The hydrogen beam that operates the maser is formed in a dissociator-state selector system mounted in the vacuum envelope opposite the entrance to the cavity resonator. The RF dissociator converts molecular hydrogen (H_2) into a beam of atomic hydrogen (H), and the state selection magnet focuses atoms that are in the desired quantum state into the quartz storage bulb. The vacuum manifold that contains the dissociator, state selection magnet, and sorption pumps is connected to the vacuum belljar by a titanium neck tube. Figure 3 shows the locations of the dissociator and hexapole state selection magnet.

The H_2 is supplied from (40 grams) of lithium aluminum hydride ($LiAlH_4$), contained in a stainless steel container whose temperature is controlled to maintain a constant hydrogen pressure. Hydrogen flow from the $LiAlH_4$ source into the maser is controlled by sensing the hydrogen pressure in the dissociator with a thermistor Pirani gauge, and regulating the temperature of a palladium silver diaphragm to keep the pressure constant.

In the dissociator, molecular hydrogen at a pressure of approximately 10^{-1} torr is led from a hydrogen source to a cylindrical glass bulb (~6 cm long, ~3 cm diameter) mounted within the vacuum chamber. An RF coil that is connected through the vacuum envelope surrounds the dissociator bulb. Five watts of RF power at about 90 MHz is applied to produce a plasma discharge that dissociates the H_2 . Atomic hydrogen is directed as a highly collimated beam of about 10^{14} H atoms per second into the hexapole state selection magnet which selectively focuses atoms in the desired atomic hyperfine state into the storage bulb. The hexapole magnet is approximately 8 cm long with a bore of about 3 mm and has a field between its pole tips of approximately 9 kilogauss.

Expendable hydrogen is absorbed in two sorption cartridges operating at room temperature. These pumps scavenge only H_2 . A small ion pump removes the usual non-hydrogen outgassing products from the metallic vacuum system and maintain a 10^{-6} torr vacuum.

The cylindrical vacuum tank is made of titanium alloy (6%Al-4%V) and contains a cylindrical microwave resonant cavity, within which is mounted the quartz hydrogen storage bulb. The three-part cavity (cylinder and two end plates) is made of Cer-Vit, a glass-ceramic material of a type often used for highly stable telescope mirrors. Its inner surface is coated with silver to create a conductive surface. A double Belleville spring clamps the cavity endplates to the cylinder with an axial force of approximately 480 lbs. The compression of the Belleville spring is adjusted so that the compressive force is nominally independent of the length of the hold-down can. Under these conditions, the clamping force on the cavity, and thus the cavity's resonance frequency, is approximately independent of the thermal expansion of the hold-down can. The cavity mounting baseplate is attached near its center to the base of the vacuum tank, making the cavity structure essentially independent of dimensional changes in the outer vacuum envelope.

The spherical, 18-cm diameter, thin-walled fused silica (quartz) storage bulb with a mass of about 200 grams is epoxied to one end of the microwave cavity. Its inner surface is coated with a thin layer of Teflon. Hydrogen atoms enter and leave the bulb through a narrow tubular aperture. While in the storage bulb the atoms produce a very weak microwave signal at a frequency of 1.42 GHz that is coupled by a loop in the cavity and led, at a level of approximately -100 dBm, to a heterodyne receiver that phase-locks a 100 MHz VCXO. A second loop within the cavity incorporates a reverse-biased varactor tuning diode to adjust the cavity resonance frequency.

The magnetic field within the maser's resonant cavity is carefully controlled by an assembly of magnetic shields and a solenoid, shown in Figure 3. Four nested cylindrical molybdenum magnetic shields surround the vacuum belljar. A magnetic field compensation system² is located within the outermost shield which consists of a small fluxgate magnetometer to operate a magnetic field servo system to null the axial field by controlling current to a coil wrapped around the next-to-outermost shield. This system attenuates ambient magnetic fields of ± 0.5 gauss to a level of a few microgauss within the belljar. A shielding factor, $S = \Delta H_{\text{external}} / \Delta H_{\text{internal}}$ in excess of 2×10^6 is

achieved by this system. A two-layer three section printed circuit solenoid closely fitted to the inside of the innermost shield is used to provide a uniform longitudinal magnetic field of about 5×10^{-4} gauss within the cavity.

The temperature of the resonant cavity and storage bulb is held constant by a 7-zone heat-added thermal control system. The vacuum tank constitutes the inner isothermal control surface and is controlled in three zones. The innermost magnetic shield surrounding the tank serves as the inner oven and two heaters are located at the joints near the neck. An outer oven consisting of three zones surrounds the tank and two additional zones control the temperature of the mounting plate and the uppermost end of the tank attachment structure. Figure 3 shows the locations of the heaters.

The inner magnetic shield is mounted to the outside of the titanium tank. The belljar is supported by a pair of tubular titanium necks, one connected to the main mounting flange and the other to an aluminum support can that surrounds the outer magnetic shield. The bottom of the support can is fixed to the main mounting flange. The three outer magnetic shields are separated by segments of open-celled foam that provide a semi-rigid support. This support scheme is designed to damp out shock and vibration in order to prevent work-hardening of the shields, which could lead to loss of magnetic shielding effectiveness. The outermost magnetic shield completely surrounds the maser physics package. The weight of the outer magnetic shields is transferred to the outer aluminum support can, and thence to the main mounting flange.

The main mounting plate is the primary point of attachment of the H maser. It supports the near belljar neck directly, and the far neck through the outer support can. It also supports the stainless steel vacuum manifold that houses the dissociator, the sorption pumps, and the state selector magnet. The main mounting plate is connected to the spacecraft by an aluminum structure that also houses the maser's electronics, the H₂ supply-flow controller and the ion pump. This assembly is shown conceptually in Figure 3.

Retroreflector and Photodetector Arrays

Time kept by the spaceborne hydrogen maser will be compared with time kept by clocks on the earth will be done using laser pulses. A description of the reflector-detector array and the 10 picosecond resolution event timer that encodes the arrival times of the pulses is given in reference 1.

Electronics

The electronics comprise the following:

- Power conditioning circuits
- Computer and associated digital circuits for interfacing with the spacecraft's telecommand systems
- Circuits for controlling and monitoring the functions of the physics unit
- High-voltage (~2.5 kV) power supply for operating the maser's ion vacuum pumps
- RF oscillator and amplifier (~80 MHz, ~5 watts) for dissociating H₂ molecules into H atoms
- Heterodyne RF receiver and frequency synthesizer for phase-locking a crystal oscillator to the maser's output signal
- Photodetector and event timer for laser pulse timing

Power Conditioning

The experiment uses 28-volt DC power supplied by the spacecraft power systems. Isolated switching DC-DC converters produce ± 15 volt and +5 volt power for operating the circuitry. Pulse-width modulated switching circuits are used to supply power to the physics unit's temperature control heaters. The power circuits are filtered to reduce radiated and conducted electromagnetic interference (EMI) to required levels. Average power, including electronic circuits as well as temperature-control heaters, is approximately 95 watts.

Computer and Spacecraft Interface

Standard digital circuitry provides the interface between the experiment and the spacecraft's telemetry and telecommand functions. A dedicated experiment microprocessor buffers signals between the experiment and the spacecraft, receiving telecommands and sending data to the spacecraft's mass storage system for telemetry to the ground station. The microprocessor also controls some of the physics unit's functions, acts upon telecommands, and preprocesses and formats information from the monitoring systems and event timer.

Three types of telecommand information are required by the experiment: (a) commands to adjust internally controlled parameters, such as magnetic field current or hydrogen beam flux; (b) commands that cause the computer to start an autonomous sequence of activities, such as measuring the maser's internal magnetic field; and (c) sets of data that update information in the computer's memory, such as opening gating circuits at the expected times of laser pulse arrivals. In addition, it

will be possible to upload revised programs to the experiment's computer if desired.

Control and Monitoring Circuits

Several functions of the HMC are controlled during the mission, as shown in Table 1.

The heater elements are bifilar-wound wires or flexible printed circuit heaters, depending upon location in the physics unit. Operation of the maser's circuits is monitored by converting controlled or measured parameters into voltages in a standard range and changing these voltages into digital form by a multiplexer and a digital-to-analog converter. Monitored voltages are read by the computer at preset intervals and transferred to the spacecraft's mass memory system for telemetry to the ground.

High-voltage Power Supply

The vacuum within the maser is maintained by a passive (non-powered) sorption cartridge pump that absorbs hydrogen, and by a small ion pump that removes residual gasses resulting from outgassing of internal surfaces. The ion pump is operated by a 2.5 kV, 100 microampere high-voltage power supply (HVPS) mounted integrally with the pump body. The HVPS provides a monitor voltage that is related to the current drawn by the ion pump. The HVPS is a sealed unit, and its high-voltage output is insulated to prevent corona discharge, EMI, and shock hazard.

Dissociator

The hydrogen dissociator uses RF power to make a plasma in low-pressure hydrogen gas that dissociates H₂ molecules into hydrogen (H) atoms. The frequency and amplitude of the dissociator oscillator are controlled to maintain a condition of optimum match. The dissociator oscillator and amplifier, which are located outside of the vacuum system are shielded to prevent EMI, while the matching circuit is shielded by the sealed metal vacuum envelope. The brightness of the red line in the atomic hydrogen spectrum is measured by a photodetector and dielectric interference filter mounted outside of a small quartz window in the vacuum envelope. The dissociator bulb's support structure carries heat dissipated in the plasma to the outside of the vacuum envelope. The dissociator bulb is pressed by Belleville springs between two aluminum plates that are mounted to the vacuum manifold by aluminum rods with sufficient cross sectional area to carry the heat with minimum temperature gradient.

Receiver/Synthesizer

The output signal from the maser's resonant cavity is at a frequency of approximately 1.42 GHz and a power of approximately -90 to -100 dBm. A multiple-heterodyne receiver phase-locks a 100 MHz voltage-controlled crystal oscillator (VCXO) to the maser signal, producing a standard receiver output frequencies of 100 MHz at 0 dBm. An adjustable-frequency direct-digital synthesizer operating at approximately 405 kHz provides adjustment of the VCXO frequency.

Photodetector and Event Timer

The arrival of a laser pulse at a retroreflector is sensed by a photomultiplier tube (PMT) mounted within the array package. The PMT's output pulse is sent to a constant-fraction discriminator and event timer also located in the array package. Because the expected pulse length is considerably longer than the desired measurement precision of 10 picoseconds, and the pulse height can vary from pulse to pulse, the constant-fraction discriminator circuit is needed to produce a standardized logic pulse at a time that is independent of the laser pulse's amplitude.

The standardized pulses produced by the discriminator go to an event timer that records pulse arrival times in terms of a 100 MHz clock signal with a precision of 10 ps. The event timer consists of standard digital gates and registers, and a hybrid analog time interpolation circuit that provides 10 ps measurement resolution.

Summary of Size Weight and Power

The physics unit is a cylindrical structure 43 cm dia, 83 cm long weighing 74.5 kg. The electronics control box has dimensions 30 x 30 x 33 cm and weighs 11.4 kg. The maser receiver package has dimensions 16 x 15 x 12 cm and weighs 2.5 kg. The microprocessor has dimensions 26 x 16 x 14 cm. and weighs 3.8 kg.

The entire experiment will be located on a heat conducting support plate kept at about 20°C; it will consume on average approximately 95 watts of 28 VDC power.

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Table 1 – Controlled Functions

Function	Sensor	Controlled parameter
Temperature (8 zones)	Thermistor	Heater current (pulse width modulated) (~50°C max)
Hydrogen flux	Thermistor	Heater current (pulse width modulated) (~50°C max)
Magnetic field in Cavity	None	Coil current (resistor ladder via relays) (~50 mA max)
Varactor diode volts	None	Diode voltager (resistor ladder via relays) (10 volts max)
Dissociator operation	RF diode	Frequency, power
Synthesizer frequency	None	Direct digital synthesizer setting

¹ E.M. Mattison et al., *A Time Transfer Technique using a Space-borne Hydrogen Maser and Laser Pulse Timing* this publication.

² We gratefully acknowledge helpful discussions on active magnetic compensation systems with Mr. H.E. Peters of the Sigma Tau Corp.