

# DEVELOPMENT OF A SPACEBORNE HYDROGEN MASER ATOMIC CLOCK FOR QUASI-ZENITH SATELLITES

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## Abstract

*A Bread Board Model of a spaceborne hydrogen maser atomic clock for the satellite positioning system using Quasi-Zenith Satellites has been developed. Analysis and experiments for technical problems such as miniaturization, achievement of long life, mechanical vibration proofing, and space environment characteristics have been performed, and technical data necessary for EM development have been obtained.*

## INTRODUCTION

In space application programs, the weight and size of onboard mission instruments are crucial issues, as well as power consumption. The instruments are also required to operate in harsh space environment with high reliability, where the changes in temperature or magnetic field may be much larger than those on the earth. The National Institute of Information and Communications Technology (NICT) has continued the research and development of a Spaceborne Hydrogen Maser (SHM) that satisfies these requirements, collaborating with Anritsu Corporation since 1997.

In the early basic research phase, the design principle of a sapphire-loaded cavity, optimized from the viewpoint of frequency stability and weight, was established. NICT has developed a small-sized prototype model of SHM using the sapphire-loaded cavity based on this design principle, and evaluated the basic characteristics, such as frequency stability and temperature and magnetic sensitivities of the model.

In Japan, a program of satellite positioning using Quasi-Zenith Satellite System (QZSS)

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started in 2003, and NICT has developed the Bread Board Model (BBM) of SHM for QZSS. Though the BBM is based on the prototype model, its reliability, such as lifetime and mechanical vibration performance, has been greatly improved, as well as its weight and environmental performance. In this paper, the main features of the BBM are reported.

## THE CONCEPT OF QZSS

The idea of the quasi-zenith satellites was proposed by Radio Research Laboratory (currently NICT) in 1972. Takahashi [1] claimed that an elliptical orbit with an inclination of 45 degrees would provide high elevation to users located in mid-latitude regions like Japan. Research about orbit and communication mission followed [2].

Considering the increasing reliance on GPS for positioning/navigation applications, the Japanese government reported in 1997 that three basic technologies for satellite positioning should be researched and developed by the Japanese themselves. Those are:

1. development of an onboard atomic clock;
2. time management of the satellites;
3. precise orbit determination of the satellites.

Japan started a project of QZSS in 2003. The most possible orbit has an “asymmetric figure 8” footprint on the earth to satisfy the requirements of both communications and positioning. In Tokyo, for example, where the maximum elevation for a geostationary satellite is 48 degrees, at least one satellite is visible with elevation higher than 78 degrees. The QZSS works as a regional complement system to the modernized GPS when the number of visible GPS satellites or their DOP is not sufficient [3].

The positioning mission is to be developed by four ministries: the Ministry of Education, Culture, Sports, Science, and Technology; the Ministry of Internal Affairs and Communications; the Ministry of Economy, Trade and Industry, and Land; and the Infrastructure and Transportation Ministry. Timing related missions are assigned to institutes related to those ministries to establish the technology essential to a satellite positioning system.

The Japan Aerospace Exploration Agency (JAXA) will develop the total system for positioning including onboard navigation equipment, the master control station, and several monitoring stations in and out of Japan and also to determine the orbits of the satellites precisely. JAXA also develops advanced technologies such as an experimental L-band signal.

NICT will develop an SHM and time management system, including onboard equipment and related ground systems, such as time management stations. An SHM has

been chosen to be developed as an experimental onboard atomic clock, since it has significant stability compared to other atomic clocks. The QZS possesses two more commercially available atomic clocks (rubidium and/or cesium atomic clocks) for practical use.

## MINIATURIZATION OF THE SHM

The most significant factor determining the dimensions of the hydrogen maser is size of the cavity resonator. If the cavity can be reduced in size, the vacuum enclosure and the magnetic shields that surround the cavity may in turn be made smaller, and the entire hydrogen maser can be made to be small and lightweight. From this point of view, we have developed a sapphire-loaded cavity, which is shown in Figure 1. It is 161.9 mm in diameter and 161.9 mm high, and its volume is reduced by 1/7th compared to a conventional maser cavity that is about 300 mm in diameter and 300 mm high.

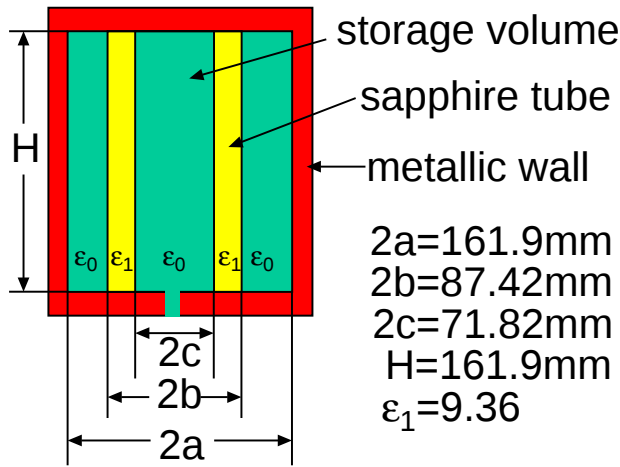


Figure 1: The structure of the sapphire-loaded cavity.

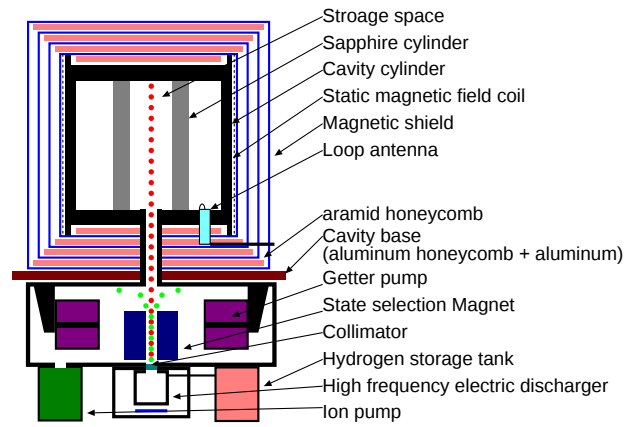


Figure 2: The BBM structure of the SHM.

In order to miniaturize the BBM, the metallic cylinder of the cavity is also used as the vacuum enclosure in the new design. The new design minimizes the use of outgassing materials in vacuum, which results in improved lifetime of SHM as stated later. With this new design, the weight of BBM, shown in Figure 2, is reduced from 72 kg to 52.6 kg, compared to prototype model

## IMPROVEMENT OF LIFETIME

The operational lifetime of an SHM is mainly limited by the vacuum pump that absorbs the hydrogen gas. The amount of hydrogen consumption of the prototype model is  $1.08 \times 10^{-4}$  torr liter/s or 34,000 torr liter for 10 years operation. A conventional hydrogen

maser for ground use usually uses an ion pump, which is heavy and requires electric power. For this reason, we have developed a Non-Evaporable Getter (NEG) pump with a pumping capacity for 10 years of operation.

Though the NEG pump is lightweight and requires no electric power, it is necessary to be activated before use. In the activation process, the NEG must be kept at 500 °C for 45 minutes or more. The NEG must be thermally isolated so that other components of SHM will not be damaged by activation heat. The activation process has been thermally analyzed. Based on the analysis, an experiment has shown that the NEG can be successfully activated, keeping the temperature of the vacuum enclosure less than 70 °C.

The improvement of the hydrogen atom beam efficiency is also effective in reducing the hydrogen consumption, which may result in a longer lifetime of the pump. The efficiency of new beam optics that use a quadrupole magnet has been estimated by calculation, which agrees with the experimental results with error less than 25%, as shown in Figure 3. In the prototype SHM, a six-pole magnet is used, and the distance between the magnet and the oscillator is 150 mm. In order to obtain the maser oscillation power of -103 dBm, the hydrogen supply pressure of about 50 mtorr is required. On the other hand, in the BBM, which uses a quadrupole magnet and a distance between the magnet and the oscillator of 100 mm, an equivalent oscillation intensity could be obtained by the supply pressure of 20 mtorr.

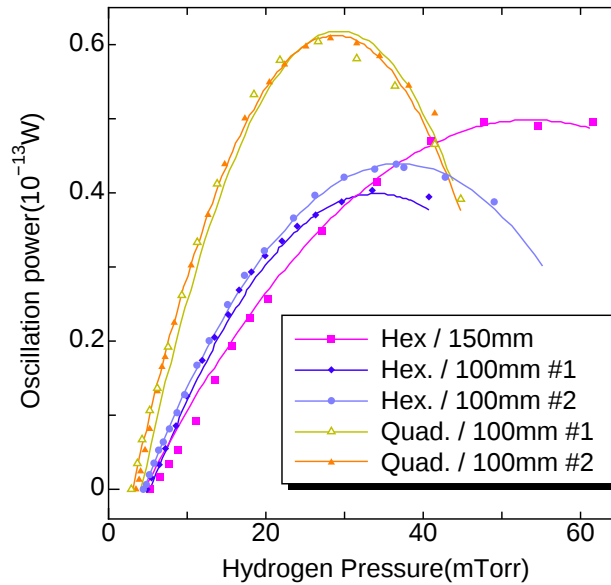


Figure 3: Maser oscillation power vs. hydrogen pressure.

## IMPROVED PERFORMANCE IN A SPACE ENVIRONMENT

An SHM is required to have far better temperature and magnetic characteristics to achieve the superior maser frequency stability in a space environment, where the changes in temperature or magnetic field are much larger compared to those on the earth.

The change in the magnetic field at the QZSS orbit, which is 36,000 km from the earth on average, is expected to be less than 1 mG. The prototype model has four concentric magnetic shields, each of which is 1 mm thick, and has a magnetic shielding factor of more than 200,000.

In terms of temperature resistance, in the sapphire-loaded dielectric cavity, the temperature variation in the dielectric constant of sapphire is large. It is, therefore, almost impossible to stabilize the frequency of the microwave cavity  $f_c$  with temperature isolation alone; instead, stabilization of  $f_c$  by active, automatic control becomes indispensable.

Because a temperature change of the cavity causes not only fluctuation of  $f_c$ , but fluctuation of the secondary Doppler frequency shift, it is necessary to stabilize the cavity temperature to within at least  $0.001^\circ\text{C}$  to realize frequency stability of  $10^{-15}$ . The temperature fluctuation of a fourth magnetic shield was estimated as about  $4^\circ\text{C}$  in 1 day.

We have developed a temperature control test model of SHM, which has the same structure as the BBM, and estimated the temperature change of the microwave cavity with precise temperature control. From this experiment, the change of cavity temperature was less than  $0.005^\circ\text{C}$ , when the temperature of a fourth magnetic shield change  $3.5^\circ\text{C}$ . In the experiment, the upper surface and the bottom of the cavity were not independently controlled from the restrictions on a circuit, but we think it is possible to control the cavity temperature change to within  $0.001^\circ\text{C}$  with independent control of those two heaters.

## IMPROVEMENT OF MECHANICAL STRENGTH

It is also necessary to devise a structure that endures the mechanical vibration of a lift-off. A number of mechanical vibration tests have been made to measure the mechanical characteristics and the reliability of vacuum seals. In the tests, an acceleration of vibration up to 5 G was applied to the BBM in three directions. The frequency of the vibration was swept upward and then downward between 5 Hz and 300 Hz in 4 minutes. As shown in Figure 4, mechanical resonance points were found at about 90 Hz for the X direction, 185 Hz for the Y direction, and 230 Hz for the Z direction vibration, each of which has a transmissivity more than ten. Based on the results, the mechanical design has been reviewed to make the resonance frequency higher than 100 Hz and to reduce the transmissivity.

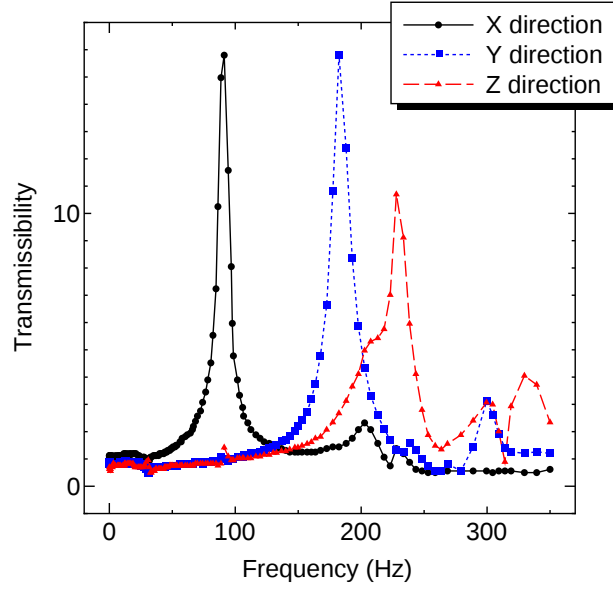


Figure 4: The mechanical response of the microwave cavity.

During the vibration tests, no vacuum seal leak was observed, except for a negligibly small leak of about  $10^{-7}$  torr liter/s.

## CONCLUSIONS

We have developed the BBM of a SHM for the QZSS. We estimate many technical problems such as miniaturization, improvement of lifetime, temperature characteristics, magnetic-field sensitivities, and vibration. We are now planning to evaluate the performance of the BBM, such as frequency stability and temperature sensitivity. These data, obtained from experiments, will be used for development of the engineering model.

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## REFERENCES

- [1] K. Takahashi, 1972, “*Suitable Orbits for Various Satellite Missions*,” **Review of RRL**, **18**, (97), 345-353 (in Japanese).
- [2] For example, K. Kimura, *et al.*, 1999, “*Optimum constellations using elliptical inclined synchronous orbits for mobile and fixed satellite communications*,” in Proceedings of the 50th International Astronautical Congress, 4-8 October 1999, Amsterdam, the Netherlands, IAF-99-A.2.10.
- [3] I. Kawano, M. Mokuno, S. Kogure, and M. Kishimoto, 2004, “*Japanese Experimental GPS Augmentation Using Quasi-Zenith Satellite System (QZSS)*,” in Proceedings of the ION GNSS Meeting, 21-24 September 2004, Long Beach, California, USA (Institute of Navigation, Alexandria, Virginia), in press.
- L.-G. Bernier, 1994, “*Preliminary Design and Breadboarding of a Compact Qualified Hydrogen Maser Based on a Sapphire Loaded Microwave Cavity*,” in Proceedings of the European Frequency and Time Forum (EFTF), 9-11 March 1994, Weihenstephan, Germany (VDI, Düsseldorf), pp. 965-980.
- H. Ito, M. Hosokawa, J. Umezu, T. Morikawa, K. Takahei, M. Uehara, K. Mori, and M. Tsuda, 2003, “*Development and Preliminary Performance Evaluation of a Spaceborne Hydrogen Maser*,” in Proceedings of the Asia-Pacific Workshop on Time and Frequency (ATF), November 2002, Daejeon, South Korea, pp. 103-110.
- T. Morikawa, J. Umezu, K. Takahei, M. Uehara, K. Mori, and M. Tsuda, 2001, “*Development of Small Hydrogen Maser with a Sapphire Loaded Cavity for Space Application*,” in Proceedings of the Asia-Pacific Workshop on Time and Frequency (ATF), 31 October-2 November 2000, Tokyo, Japan, pp. 224-228.
- F. S. Rusin, B. A. Gaygerov, and S. F. Ponomarenko, 1985, “*Calculation of a Cylindrical Cavity Partially Filled with a Dielectric*,” **Measurement Techniques**, **28**, (5) 396-398.

## Questions and Answers

**HUGO FRUEHAUF (FEI-Zyfer):** Is it a maser?

**HIROYUKI ITO:** It is an active maser.