

Hydrogen Maser Clocks in Space for Solid-Earth Research and Time-Transfer Applications: Experiment Overview and Evaluation of Russian Miniature Sapphire Loaded Cavity

G. Busca, L.G. Bernier
Observatoire de Neuchâtel (ON), Switzerland

P. Silvestrin, S. Feltham
European Space Agency (ESA),
Noordwijk, The Netherlands

B.A. Gaygerov, V.M. Tatarenkov
NPO VNIIFTRI, Mendeleev,
Moscow, Russia

Abstract

The Observatoire Cantonal de Neuchâtel (ON) is developing for ESTEC a compact H-maser for space use based upon a miniature sapphire loaded microwave cavity, a technique pioneered at VNIIFTRI.

Various contacts between West-European parties, headed by ESA, and the Russian parties, headed by RSA, led to the proposal for flying two H-masers on Meteor 3M, a Russian meteorology satellite in low polar orbit.

The experiment will include two masers, one provided by ON and the other by VNIIFTRI. T/F transfer and precise positioning will be performed by both a microwave link, using PRARE equipment, and an optical link, using LASSO-like equipment. The main objectives of the experiment are precise orbit determination and point positioning for geodetic/geophysical research, ultra-accurate time comparison and dissemination as well as in-orbit demonstration of operation and performance of H-masers.

Within the scope of a preliminary space H-maser development phase performed for ESTEC at ON in preparation to the joint experiment, a Russian miniature sapphire loaded microwave cavity, on loan from VNIIFTRI, was evaluated in a full-size EFOS hydrogen maser built by ON. The experimental evaluation confirmed the theoretical expectation that with a hydrogen storage volume of only 0.65 liter an atomic quality factor of 1.5×10^9 can be obtained for a -105 dBm output power. This represents a theoretical Allan deviation of 1.7×10^{-15} averaged on a 1000 s time interval. From a full-size design to a compact one, therefore, the sacrifice in performance due to the reduction of the storage volume is very small.

Introduction

Following many contacts between West-European parties, headed by ESA, and Russian parties, headed by RSA, a proposal for a H-maser experiment was conceived in the form of an

opportunity flight on a Russian meteorology satellite in low polar orbit^{1, 2, 3}. Meteor 3M is a Russian meteorology satellite built by NIEEM, Moscow. The satellite will be launched end of 1996 on a sun-synchronous orbit.

Altitude :	925 km
Inclination :	99.1°
Eccentricity :	0.001
Orbital Period:	103 minutes

Total mass is 3,000 kg and 200 kg are available for the opportunity experiment. The meteor spacecraft is designed for a three year lifetime.

Twenty-five spacecrafts of the Meteor 2 type have been launched so far, as well as five spacecrafts of the new Meteor 3 type. The launch vehicle utilized for the Meteor satellites is the Tsydon launcher and the launch base is Plesetsk, north of Moscow⁴. Meteor 3M is the first of an enhanced version of Meteor 3, optimized to serve as a multipurpose space platform.

The H-maser joint experiment is meant as a scientific experiment. With two very stable spaceborne clocks and the associated microwave and optical T/F transfer equipment it is expected to push back the limits of precise positioning for geodynamic and solid-Earth studies applications as well as for precise time transfer. Complementary scientific applications will possibly be added³. The joint experiment is also meant as a technological demonstration of the spaceborne Hydrogen masers and related T/F transfer equipment. It is as well an opportunity of cooperation between scientists, space agencies and industries of Russia and western Europe.

Development Status of the Spaceborne Hydrogen Masers

A compact hydrogen maser for space based on a miniature sapphire loaded microwave cavity is now in the preliminary design phase at ON. Present activities are concentrating on the breadboarding and testing of the critical maser elements. A proton irradiation test was performed on a fully operating EFOS hydrogen maser at the proton irradiation test facility of the Paul Scherrer Institute. The test, performed under ESTEC contract, has shown that on the Meteor 3M orbit the shielding effect of the microwave cavity and of the magnetic shields is sufficient for protecting the Teflon wall coating in the storage bulb from the damaging effect of space radiations. The test of the miniature sapphire loaded microwave cavity on loan from VNIIFTRI was performed under the same ESTEC contract.

VNIIFTRI, on the other hand, has already a long experience with ground based compact hydrogen masers^{5, 6} including the use of bulk getter pumping for hydrogen. Its task is now to adapt the existing design for space use.

Embarked Equipment

The Meteor 3M spacecraft will carry two hydrogen masers, one provided by ESA and the other by RSA. A local T&F comparison system will measure the relative frequency stability of the

H-maser clocks and downlink the stability data to the ground.

The two way microwave link for T&F transfer between the satellite and ground will be based on the PRARE system^[7, 8]. PRARE (Precise Range and Range Rate Experiment) uses pseudo-noise coded microwave signals in a fully coherent design. The two-way link uses two carrier frequencies in S and X bands and allows correction of the ionospheric delay by evaluation of the total electron content through the dispersion effect. Figure 1 illustrates the basic PRARE operating principles.

The optical link will use LASSO-like equipment^[9, 10], i.e. a corner reflector and a detector on the spacecraft. The laser pulses from the ground are reflected by the corner reflector and the two-way delay is measured at the ground station. Simultaneously the arrival of the laser pulses on the detector is time-tagged with respect to the spaceborne hydrogen maser clock using an embarked counter. Figure 2 shows schematically the optical link. Figure 3 shows the main equipment necessary for the joint experiment.

Complementary equipment such as a DORIS system, a GLONASS/GPS Receiver and an ultra sensitive accelerometer may be added depending on the complementary scientific applications now under study at ESA and RSA. Figure 4 shows the embarked equipment as it could possibly be expanded.

Evaluation of The VNIIFTRI Miniature Microwave Cavity

During a previous feasibility study ON determined that the best compromise between size and performance for a spaceborne hydrogen maser is by the use of a miniature sapphire loaded microwave cavity such as the one used in the VNIIFTRI "Saphir" H-maser^[11]. A collaboration between ON and VNIIFTRI was started in the perspective of using the VNIIFTRI cavity in the ON design. Dr. Gaygerov of VNIIFTRI visited ON in August 1993 with one of the sapphire loaded cavities used in the "Saphir" maser. The VNIIFTRI cavity was installed into an EFOS hydrogen maser and evaluated.

A view of the VNIIFTRI miniature cavity, as mounted in the EFOS-13 full size maser, is shown on Figure 5. For the purposes of the experiment, the molybdenum plate that normally holds the quartz storage bulb in the EFOS maser was replaced by an aluminium interface plate on which the VNIIFTRI cavity was mounted. The interface plate was placed on top of the standard EFOS aluminium cavity baseplate. A special interface tube with o-rings was used to connect the neck of the sapphire storage bulb to the internal vacuum vessel of the EFOS maser.

Table 1 shows the main geometrical parameters of the VNIIFTRI sapphire loaded cavity. Note that from the microwave point of view this cavity does not have a fully cylindrical symmetry because of the sapphire covers that close the sapphire storage bottle. A photograph of the sapphire storage bottle standing on the Titanium cavity bottom plate is shown on Figure 6.

Table 1	
Geometrical Parameters of VNIFFTRI Sapphire Cavity	
sapphire I.D.	80 mm (r1 = 40 mm)
sapphire O.D.	93 mm (r2 = 46.5 mm)
sapphire length	172 mm
inner length of sapphire bulb	130 mm
thickness of sapphire covers	6 mm

Table 2				
VNIIFTRI Cavity Modes in Air at Room Temperature				
as Measured at ON				
Theoretical Modes Computed by ON				
ν_0 [kHz]	approx. Q	Mode	theor. ν_0	theor. Q
1,118,394	4,500			
1,421,214	55,000	TE011	1.4212 GHz	48,000
1,517,714	17,000			
1,650,470	46,000	TE012	1.6442 GHz	66,000
1,883,549	5,600			
1,883,882	5,600			
1,940,788	43,000	TE013	1.9398 GHz	87,000

Table 2 shows the resonant modes of the cavity as measured by ON in air and at room temperature. The theoretical resonant frequencies were computed by ON by assuming a fully symmetrical symmetry, i.e. a sapphire cylinder without covers, and by adjusting the external diameter of the sapphire cylinder in order to obtain the right frequency for the TE011 mode.

Figure 7 shows the experimental determination of the TE011 mode thermal coefficient. Table 3 shows the experimental temperature coefficient of the TE011 mode as determined by a best fit of the slope on the plot of figure 7. The theoretical thermal expansion coefficient of Titanium, and sapphire as well as the temperature dependence of the dielectric constant of sapphire are also shown. It appears that the dominant factor in the temperature dependence of the TE011 mode is due to the variation of the dielectric constant of sapphire.

Table 3	
Parameters of Theoretical Model for Thermal Coefficients	
Normalized thermal coefficient of TE011 mode [1/C]	3.3×10^{-5}
Thermal Expansion Titanium [1/C°]	9.4×10^{-6}
Thermal Expansion Sapphire [1/C°]	5.4×10^{-6}
Dielectric Constant Sapphire [1/C°]	6×10^{-5}

The atomic quality factor was measured for different hydrogen pressures in the dissociator. The slope

$$s = \frac{\Delta f_{\text{atomic}} [\text{Hz}]}{\Delta f_{\text{cavity}} [\text{Hz}]}$$

produced by the cavity pulling effect is proportional to the γ_2 relaxation rate. Both the relaxation rate and the slope s are proportional to the atomic linewidth and increases proportionally to the hydrogen flux because of the spin-exchange line broadening effect. The slope without the spin-exchange contribution is obtained by extrapolating to zero the slope versus hydrogen pressure curve. An extrapolation by linear regression yields

$$s(p = 0) = 1.76 \times 10^{-5}$$

and therefore the atomic quality factor without spin-exchange broadening is

$$Q_{\text{atomic}}(p = 0) = \frac{Q_{\text{cavity}}}{s(p = 0)} = \frac{47,000}{1.7584 \times 10^{-5}} = 2.67 \times 10^9$$

The VNIIFTRI storage bulb collimator is

4.2 mm diameter
60 mm length

The time constant of the storage bulb is

$$T_b = \frac{4V}{K v_v A_h} = 1.01 \text{ s}$$

where

$V = 0.65 \times 10^{-3} \text{ m}^3$ is the volume of the storage bulb,

$K = 0.0797$

the Clausing factor in molecular flow for a 60/2 length to radius ratio,

$v_v = 2564 \text{ m/s}$

the average velocity of atomic hydrogen at 45 C° and

$A_h = 12.57 \times 10^{-6} \text{ m}^2$

the cross-section of the collimator.

The escape rate is therefore

$$\gamma_b = \frac{1}{T_b}$$

and the storage bulb contribution to the quality factor

$$Q_b = \frac{\pi \nu_0}{\gamma_0} = 4.51 \times 10^9$$

Neglecting the contribution of magnetic relaxation, the atomic quality factor with spin–exchange broadening removed is the sum of the escape rate and wall relaxation contributions.

$$\frac{1}{Q(p=0)} = \frac{1}{Q_b} + \frac{1}{Q_w}$$

Therefore the Teflon contribution to the quality factor is obtained by removing the contribution of the storage bulb escape rate.

$$Q_w = \frac{1}{\frac{1}{2.67 \times 10^9} - \frac{1}{4.51 \times 10^9}} = 6.51 \times 10^9$$

This figure can be converted into an equivalent EFOS Teflon quality factor by taking into account the surface to volume ratio which is

$$\frac{A_b}{V_b} = \frac{4.22 \times 10^{-2} \text{ m}^2}{6.54 \times 10^{-4} \text{ m}^3} + 65.38 \text{ m}^{-1}$$

in the case of the VNIIFTRI storage bulb and

$$\frac{A_b}{V_b} = 33.14 \text{ m}^{-1}$$

in the case of the EFOS storage bulb.

The VNIIFTRI Teflon used in an EFOS storage bulb would yield

$$Q_w = 6.53 \times 10^9 \times \frac{65.38}{33.14} = 1.29 \times 10^{10}$$

This value is very high and is comparable to the quality factor obtained in the most recent EFOS storage bulbs. This indicates that the VNIIFTRI Teflon coating has a relaxation probability per collision similar to the Teflon coating used at ON in recent EFOS masers.

The operating quality factor of the VNIIFTRI cavity is 1.5×10^9 for a -105 dBm output power as measured 10.8.93. Figure 8 shows the atomic quality factor versus the maser output power. The circles indicate the experimental values while the solid line represents the theoretical model. The model is the same as in [11] and the theoretical parameters are set to the values of Table 4.

Table 4	
Parameters used in the Theoretical Model	
V_b	= 0.65 liter
β	= 0.1
Q_c	= 47,000
η'	= 0.45
γ_b	= 0.988 s ⁻¹
γ_w	= 0.683 s ⁻¹

The correspondence between experimental values and the model is very good. note that the filling factor of a dielectric loaded cavity is larger than the assumed $\eta' = 0.45$. However, the fitting of the model is not improved if the value of η' is increased.

The frequency stability of the hydrogen maser is determined by the atomic quality factor and by the signal output power.

Assuming that there is an isolator between the cavity and the receiver, the theoretical Allan deviation of the maser is given by

$$\sigma_y(t) = \sqrt{\frac{3f_c kt}{2\pi\nu_0^2 P_0} \left(\frac{\beta}{1+\beta} + \frac{F}{4} \right) \frac{1}{\tau^2} + \frac{kT}{2P_0 Q^2} \left(\frac{\beta}{1+\beta} \right) \frac{1}{\tau}}$$

where f_c is the bandwidth of the measurement, P_0 the maser output power, b the coupling factor of the cavity, F the noise figure of the receiver and Q the quality factor of the atomic line. Assuming the parameters of Table 5 that correspond to the conditions of the frequency measurement of 10.8.93,

Table 5	
Operating Parameters of Measurement 10.8.93	
Q	= 1.5×10^9
P_0	= 3.16×10^{-14} W (-105 dBm)
F	= 2
f_c	= 1 Hz
β	= 0.1

the fundamental limit to frequency stability is shown in Table 6 and Figure 9. Note that the theoretical limit does not include the flicker noise floor and other environmental effects.

tau [s]	Allan dev.
1	1.5×10^{-13}
10	2.2×10^{-14}
100	5.5×10^{-15}
1000	1.7×10^{-15}
10,000	5.4×10^{-16}

Conclusion

The experimental evaluation confirms the theoretical expectation^[11] that with a hydrogen storage volume of only 0.65 liter an atomic quality factor of 1.5×10^9 can be obtained for a -105 dBm output power. This represents a theoretical Allan deviation not very far from what is normally obtained in a full-size hydrogen maser. From a full-size design to a compact one, therefore, the sacrifice in performance due to the reduction of the storage volume is very small.

References

- [1] Protocol of the First Working Meeting, H-Maser in Space Project, Mission Control Center, Kaliningrad, March 22-24 1993.
- [2] Meteorological Satellite Meteor - 3M - Hydrogen Maser Mounting and Flight Exploitation - an Engineering Memo (translated from preliminary specification in Russian)
- [3] First Working Meeting on Hydrogen Maser Clocks in Space for Solid-Earth Research and Time-Transfer Applications, Collected Papers and Presentations, June 29th and 30th 1993, ESTEC, Noordwijk.
- [4] P. Silvestrin, unpublished internal ESTEC document.
- [5] Gaygerov B.A., Rusin F.S., Sysoev V.P. "Portable Atomic Clock on the Basis of an Active Hydrogen Maser 'Sapphir', ", Proc. 5th EFTF, Besançon, March 1991, pp. 293-294.
- [6] Boyko A.I., Gaygerov B.A., Yelkin G.A., Jestkova N.D., Kurnikov G.P., Sysoev V.P., "Hydrogen Time and Frequency Standard 'Sphere', " Proc. 5th EFTF, Besançon, March 1991, pp. 296-299.
- [7] Busca G., Bernier L.G., Starker S., Feltham S., "In Orbit Demonstration of a H-Maser Clock System, " Proc. 23rd PTTI Applications and Planning Meeting, Pasadena, December 1991, pp. 385-397.
- [8] Schäfer W., "The Application of the PRARE Principle for Two-Way Time Transfer to Space-Based Atomic Clocks, " Proc. 6th EFTF, ESTEC Noordwijk, March 17-19, 1992, ESA-SP 340, pp.41-47.
- [9] Veillet C., Fridelance P., "Time Transfer Between USA and France through LASSO", Proc. 7th EFTF, Neuchâtel, March 16-18, 1993, pp. 637-640.

- [10] Baumont F., Fridelance P., Grüdler P., Veillet C., "*Preliminary Report on the Comparison of LASSO and GPS Time Transfers*", Proc. 7th EFTF, Neuchâtel, March 16–18, 1993, pp. 641–643.
- [11] Bernier L.G., "*Optimization of the Escape Rate for Best Frequency Stability in the Atomic Hydrogen Maser,* " 7th European Frequency and Time Forum, Neuchâtel, March 16–18, 1993, pp. 373–377.

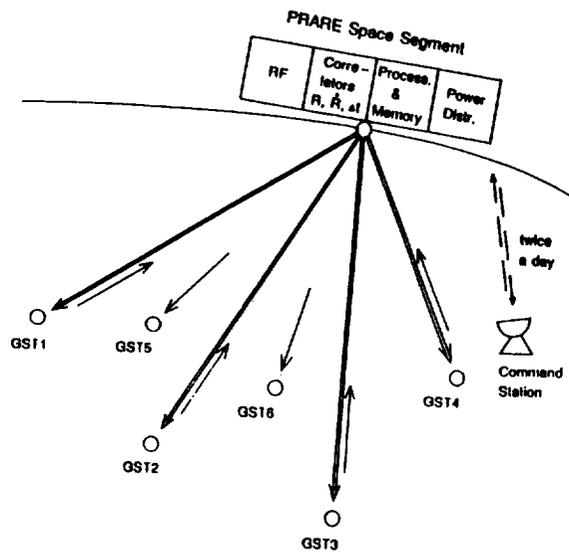
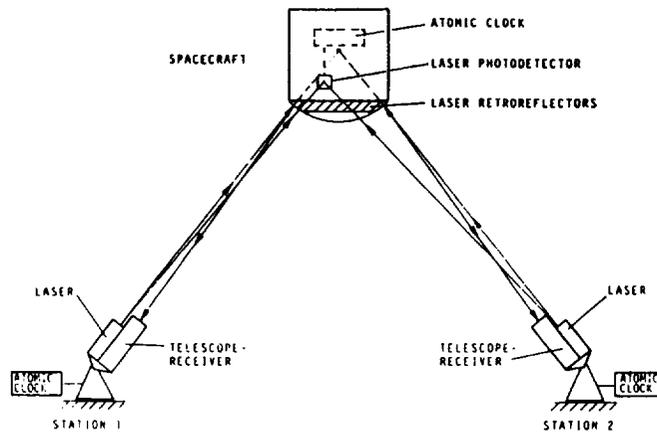


Figure 1
Basic PRARE Operation



Schematics of Time Synchronisation Experiment

Figure 2
Basic Optical Link Operation

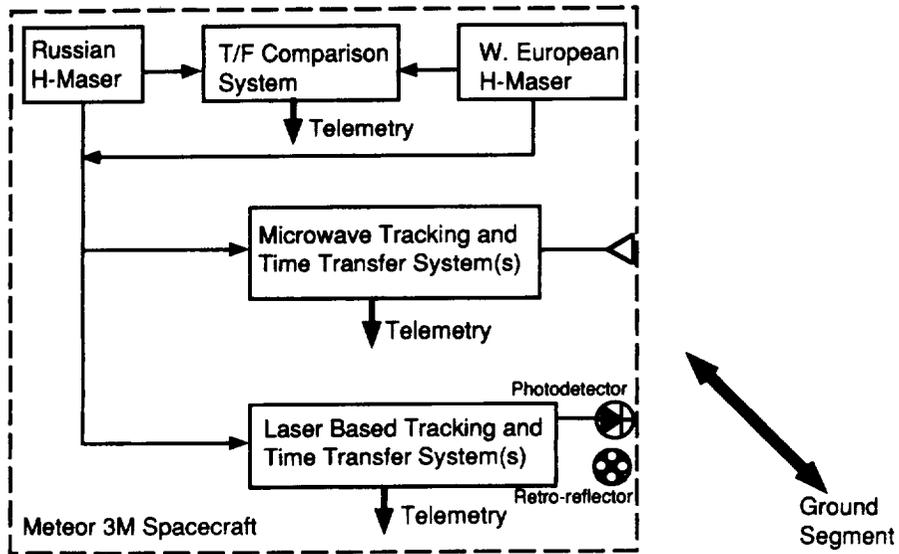


Figure 3
Main Payload for Joint Experiment

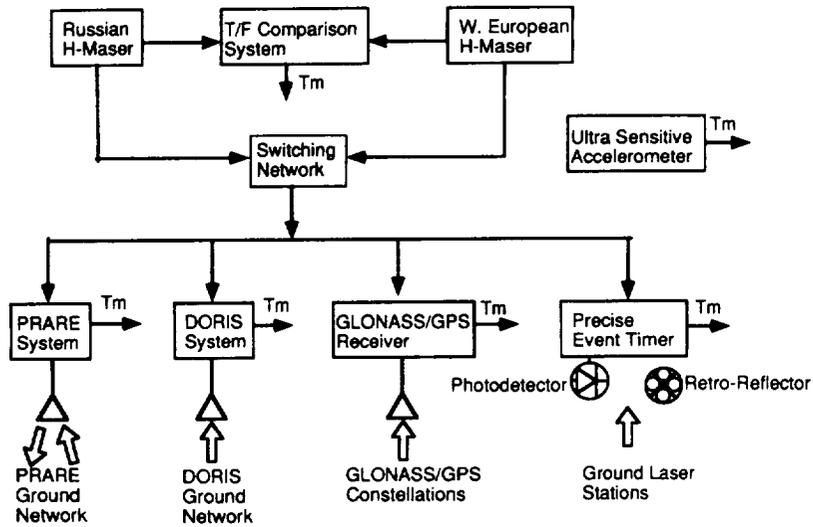


Figure 4
Extended Payload for Joint Experiment

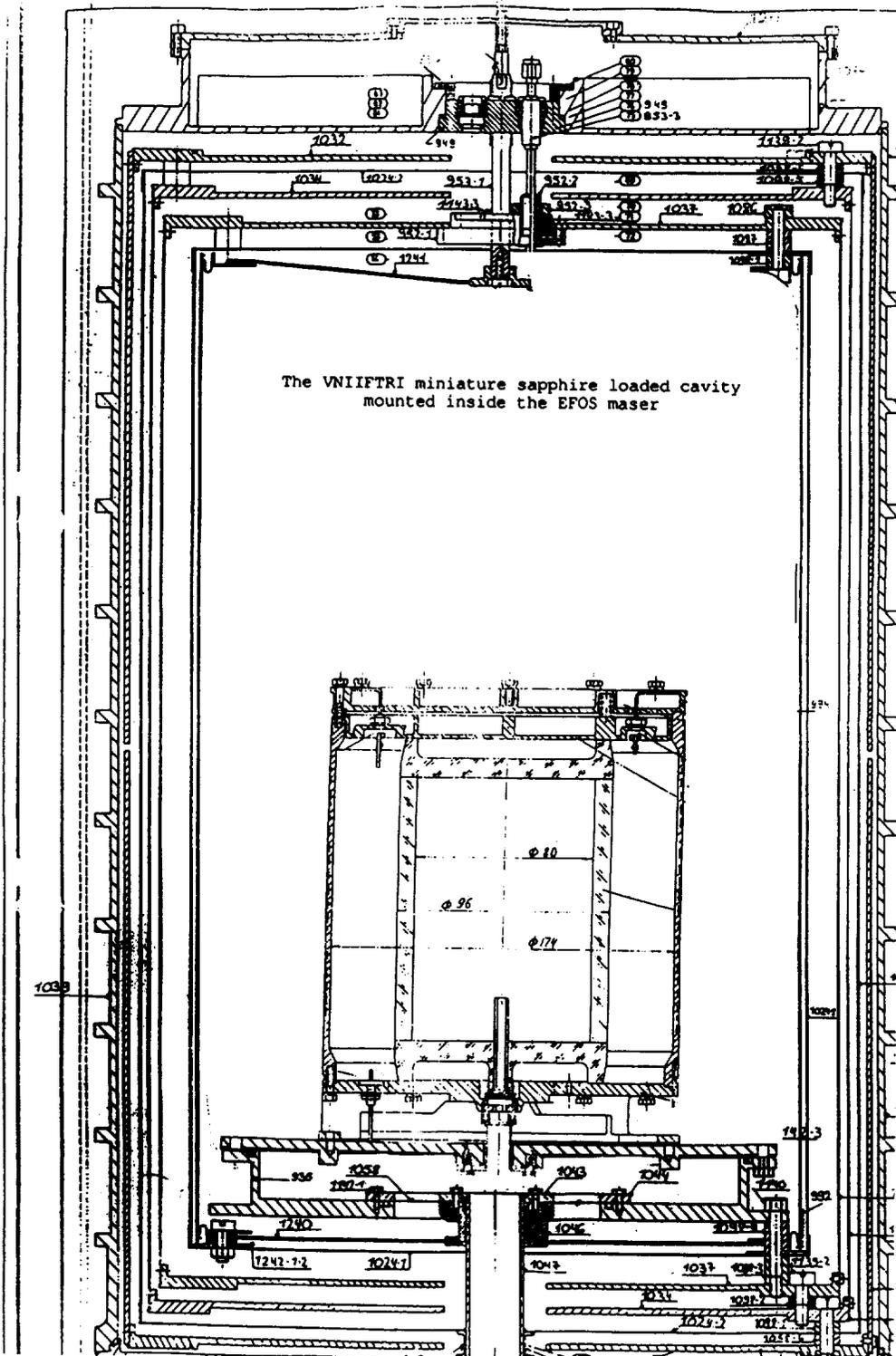


Figure 5
 VNIIFTRI Miniature Sapphire Loaded Cavity
 Mounted Inside the ON EFOS Hydrogen Maser

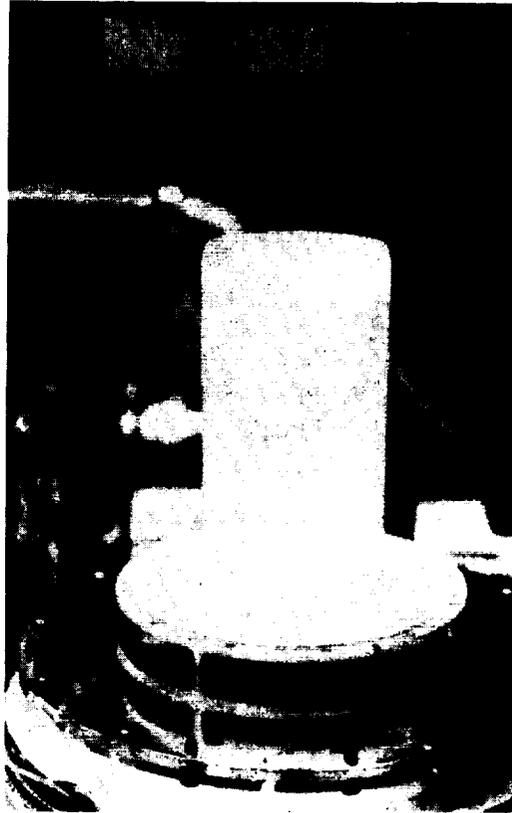


Figure 6
 VNIIFTRI Sapphire Storage Bulb on the Titanium Cavity Base

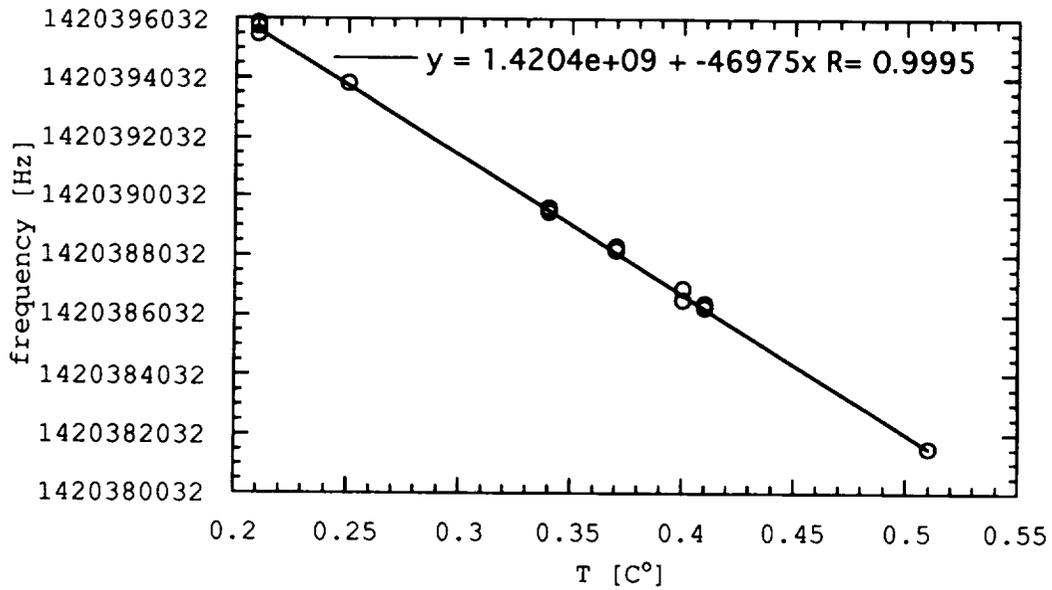


Figure 7
 Determination of TE₀₁₁ Mode Thermal Coefficient

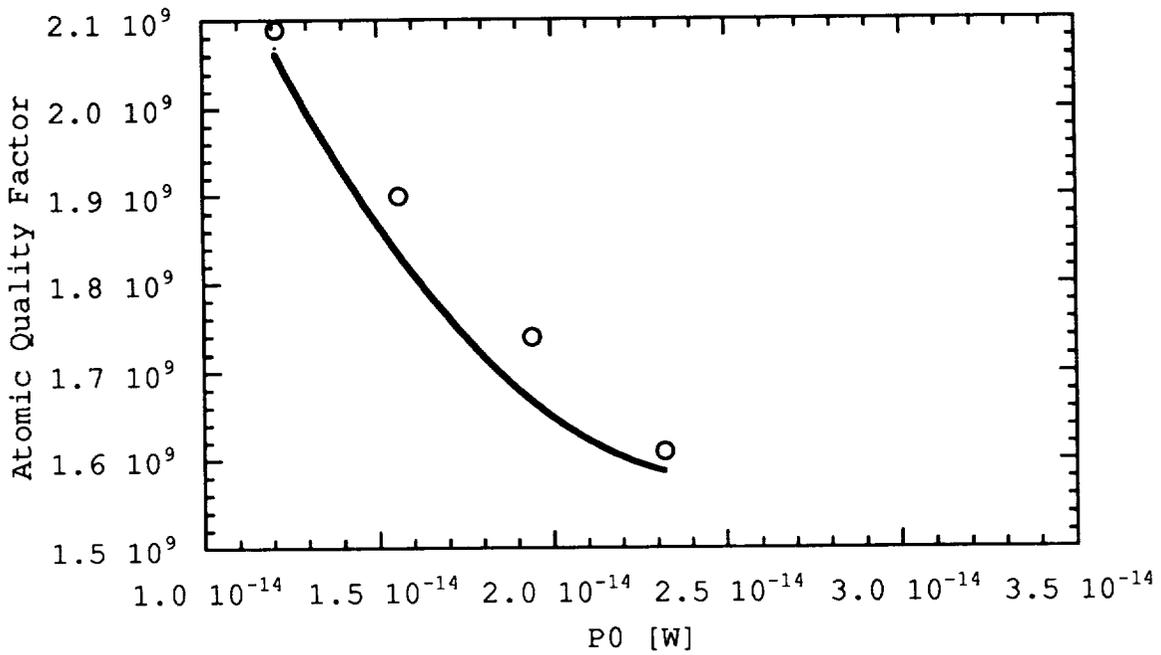


Figure 8
Atomic Quality Factor versus Output Power
Theoretical Model and Experimental Values

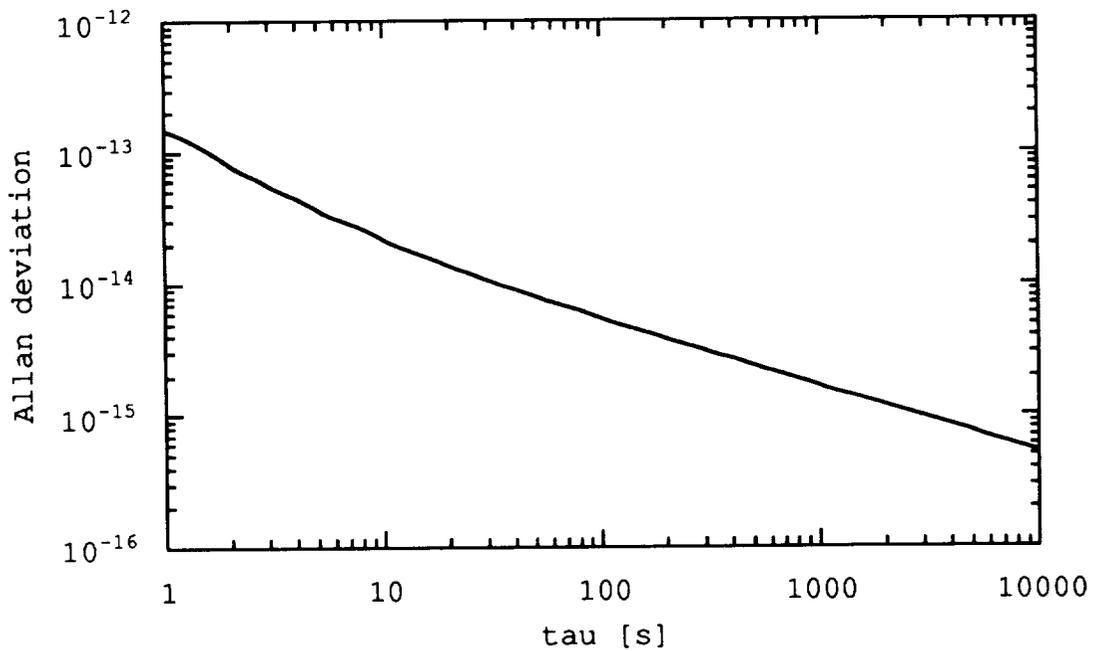


Figure 9
Theoretical White Phase Noise and White Frequency Noise Limits
Associated with Parameters of Table 5