IN ORBIT DEMONSTRATION OF A H-MASER CLOCK SYSTEM

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ABSTRACT

The ESA-NASA technology demonstration flight of a pair of hydrogen masers on the EURECA III mission is planned for 1998. The ESA part of the experiment will have a maser built by Neuchâtel Observatory and a microwave T&F transfer system derived from the existing PRARE system. The NASA part of the experiment will have a maser built by the Smithsonian Astrophysical Observatory and a laser T transfer system. The technology demonstration experiment is described with its expected outcomes and applications.

1.0 INTRODUCTION

This paper reports a proposal submitted by Neuchâtel Observatory (ON) in cooperation with the Deutsche Forschungsanstalt für Luft und Raumfahrt (DLR) to the European Space Agency (ESA) for the space technology demonstration of a H-maser with a microwave Time & Frequency Transfer (T&FT) system to be flown on the EURECA III spacecraft which will be launched in 1998.

The Smithsonian Astrophysical Observatory (SAO) have submitted a similar proposal to the National Space Administration (NASA) for the flight of a SAO built maser with a laser Time Transfer (TT) system to be flown on the same mission. This project was reported in this 23rd PTTI meeting [1].

The high level of redundancy provided by the joint NASA-ESA technology demonstration flight of 2 masers with both a laser TT system and a microwave T&FT system obviously gives a high reliability level to the experiment but, most of all, makes possible a complete evaluation of the contribution of each maser and each transfer system to the overall T&F stability performance.

EURECA III will be a 6 month mission after which the EURECA spacecraft will be retrieved by the Space Shuttle. The ON maser will be designed for a 10 year lifetime in order to demonstrate the level of performance achievable in future T&F applications in space.

The ESA project will involve Neuchâtel Observatory for the ESA maser physics package and electronics design, DLR and the Institute of Navigation of Stuttgart (INS) in Germany for the microwave T&FT system design and industries for the space qualification of the equipments.

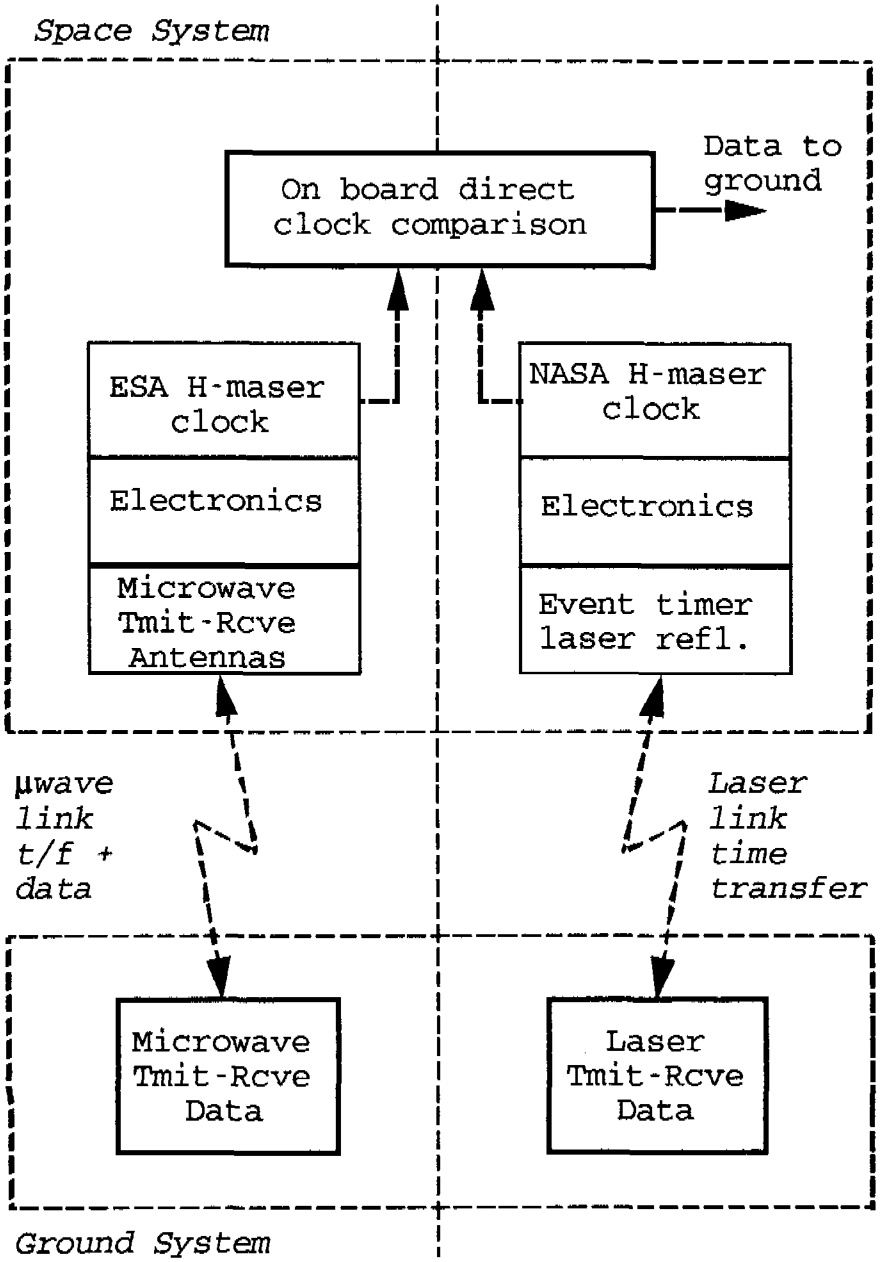

Figure 1
Proposed 2 H-maser T&F Transfer Experiment

The microwave T&FT system will be an extended version of the NAVEX microwave link demonstrated in the 1985 Shuttle mission D1 as a powerful tool for the control of two atomic clocks onboard the Shuttle. This method comprises a precise PRN-code time transfer combined with a simultaneous spread-spectrum data transmission. The extended version with higher carrier frequencies and larger signal bandwidths will be based on existing hardware-facilities of the PRARE ranging system developed by INS for use in ESA ERS-1 satellite.

The T&FT microwave system will be signal compatible with the ground equipment of PRARE and, as the latter, will use both X and S band 1-way links for real time ionospheric correction. Compatibility with PRARE makes the network of already existing PRARE ground stations usable for the present spaceborne masers T&F transfer experiment at the cost of only small modifications to the PRARE ground stations.

2.0 LOCAL & REMOTE T&F TRANSFER & MEASUREMENT CAPABILITIES

Fig.1 shows the schematic diagram of the planned NASA-ESA maser mission on EURECA III.

2.1 LOCAL COMPARISON OF SPACEBORNE H-MASERS

The frequency difference between the ESA and NASA masers is measured continuously during the whole mission (6 to 9 months) using the on board direct clock comparison system. The comparison data is stored locally and transmitted to ground on the telemetry link when tracking stations are visible. The direct comparison will allow the estimation of the relative frequency stability between the 2 H-maser clocks (characterized in the time domain by the classic and modified Allan variances) for averaging periods τ in the range from 1 second to 1 week with a very good statistic confidence.

2.1 LASER REMOTE TIME TRANSFER

The laser TT system [1] allows the remote measurement of the time stability of the space masers. The time comparison is made between a ground maser and the spaceborne maser with a sampling interval equal to the time interval between 2 successive passes of the EURECA spacecraft, i.e. $\tau \geq 5400$ s. These time stability measurements will also make possible the estimation of the long-term frequency stability of the spaceborne masers.

The NASA spaceborne TT system is equipped with a corner laser reflector, a laser detector and a time tagging counter. The laser ground station measures the 2 way time propagation time of the laser pulse using the passive corner reflector. The spaceborne laser detector and time tagging counter determine the time of arrival of the laser pulse in terms of the spaceborne clock local time.

A propagation time error of ≈ 10 ps is estimated to be achievable in the laser TT system [2]. The time error accumulated by the spaceborne H-maser clock over a full orbit is also ≈ 10 ps. Therefore time transfers with a precision of the order of 10 ps is possible from one laser station ground clock to another even if the EURECA spacecraft is not in common view. State-of-the-art time transfers between ground clocks, using already existing laser ground stations, is indeed a highly attractive application of the spaceborne masers experiment.

2.2 MICROWAVE REMOTE T&F TRANSFERS

The microwave T&F transfer system allows the remote measurement of both the short-term and long-term stability of the spaceborne H-masers. During each contact period, the short term stability is measured continuously from the ground stations that are equipped with both a H-maser and a modified PRARE receiver.

The typical contact period is 10 minutes. Several frequency samples averaged over a $\tau = 100$ s averaging interval can be acquired in a single pass. This allows a frequency transfer to the $1\text{x}10^{-14}$ level over a single pass. Frequency averaging over the whole 10 minutes pass yields a single $\tau = 600$ s frequency sample. In this way the spaceborne H-maser frequency stability with respect to a ground H-maser reference can be measured with a few parts in 10^{15} uncertainty by using multi-pass statistics.

The long-term stability of the spaceborne H-maser is estimated by means of time transfers. The time interval error accumulated by the spaceborne H-maser clock with respect to a ground H-maser clock is sampled at every pass over a ground station equipped with a maser and a PRARE receiver. Note that the time interval error accumulated by the spaceborne H-maser clock during a 600 s contact interval is only 1 ps.

The transmission through the telemetry link of the local frequency comparison between the 2 spaceborne H-masers together with the T&F microwave remote comparison between the spaceborne H-masers and the ground H-maser reference make possible a real time measurement of the microwave T&FT system noise.

The contributions of residuals of the ionospheric propagation model, of the geometric doppler and delay cancellation model, and of the relativistic correction model to the microwave T&FT system accuracy are estimated in the following sections below.

The schematic of the PRARE system, modified to provide two X band channels instead of one, permitting the evaluation of 2 spaceborne hydrogen maser clocks, is shown on Fig.3 and Fig.4.

The standard PRARE T&FT system works as follows. Two one-way signals, one in S band and one in X band, are generated from the spaceborne maser and sent to the ground stations. The signals carry both time information, contained into the spread spectrum PRN code modulation, and frequency information, contained into the carrier phase. By measuring the differential delay and the differential doppler between the same signal propagated simultaneously through X and S bands, the actual ionospheric delay and doppler can be determined by the ground stations. A coherent transponder in the ground station sends the signal back to the spaceborne PRARE system in X band. Again both time and frequency information are transmitted through the PRN code and carrier. The transponded signal is received and processed by the PRARE system aboard the space vehicle and yields the one-way delay and the one-way doppler which are estimated to be half the 2-way delay and half the 2-way doppler respectively. The computed 1-way doppler and delay are transmitted in real time to the ground station via the data link.

In standard PRARE applications, the information provided by the system is used for geodetic purposes. In our application, on the other hand, the knowledge of the 1-way doppler and delay, corrected for the actual ionospheric propagation effects and for the relativistic effects discussed in next sections are used by the ground station in order to compare to a high precision the time and frequency of its reference clock with respect to the space clock.

Note that the PRARE system, contrary to the doppler cancellation system of [7], [8] or to the doppler and delay cancellation system proposed in [9], does not try to compensate in real time and by hardware the ionospheric and geometric delay and doppler. Instead these effects are first measured and then corrected by software.

3.3 PRESENT STATUS AND FORESEEN IMPROVEMENTS OF PRARE

The time transfer error achievable with the standard PRARE ground station of the first generation ERS-1 PRARE, which uses a 60 cm dish antenna, is limited by the S/N ratio to a level of 50 ps for an averaging time of 1 s. By increasing the averaging time to > 10 s, the error can be reduced to a limiting value of about 5 ps [10]. This level of performance is comparable or better than that achievable with a laser TT system. On the other hand the frequency transfer error of the ERS-1 PRARE system is limited by the resolution of the counter on board which is 5×10^{-12} for an averaging time of 1 s. This is not acceptable in view of the maser stability performance which is 1×10^{-13} over the same interval. However the counter resolution can be increased by 1 order of magnitude by a minor modification of the PRARE spaceborne equipment. This modification of the counter would yield a white noise floor of 5×10^{-13} for an averaging time of $\tau = 1s$, improving as $1/\tau$ with the averaging time, and the FT

The laser TT system is expected to track the EURECA spacecraft with a millimeter level range accuracy. The tracking data will be used to calibrate the non-dispersive tropospheric delay in the microwave T&FT system to the corresponding level of time accuracy.

3.0 DETAILED DESCRIPTION OF THE SPACE AND GROUND SYSTEMS

The next sections report the detailed description of the space and ground systems used in the ESA part of the experiment.

3.1 ESA SPACEBORNE MASER

Fig.2 shows a drawing of the spaceborne H-maser to be produced by ON. This preliminary design of the spaceborne physics package is based on our 10 year experience with the original EFOS ground masers [3], that are used in VLBI applications, in addition to our on going recent experience gained in the development of the EFOS-B ground maser for ESTEC [4]. Only the features related specifically to the adaptation of the physics package to the space environment are reported below.

The main design features of the ESA spaceborne maser are as follows. The vacuum system uses a passive getter system for pumping hydrogen. A small ion pump is also necessary in order to pump the residual non-getterable gases present in the vacuum enclosure. The high thermal insulation between the cavity and the base plate that is required by the use of an aluminium microwave cavity is naturally provided by the space vacuum environment. A solid state hydrogen supply is used which is much more reliable and lightweight than the conventional hydrogen bottle and pressure regulator.

An auxiliary mode cavity oscillator is used in the Automatic Cavity Tuning (ACT) system [5]. The output frequency of the TE_{013} auxiliary mode oscillator is measured using a counter. By stabilizing the frequency of the TE_{013} auxiliary mode, the frequency of the TE_{011} main mode is automatically stabilized due to the fact that the frequency ratio of the 2 modes is constant. This type of ACT does not perturb at all the maser signal because it uses a mode of the cavity far from the TE_{011} mode. It has no ambient temperature sensitivity since the oscillator amplifier is secured to the cavity and is thermally controlled by the ACT loop to the same level of thermal stability as the cavity itself.

The size and mass limitations imposed by the space qualification requirements can be satisfied by a careful mechanical design. The main trade-off issue in the mass budget is the choice of the thickness to be used for the 5 layers of magnetic shields. The preliminary overall characteristics of the spaceborne maser are

- 35 cm diameter and 70 cm length
- 70 kg mass including electronics
- 70 W power consumption

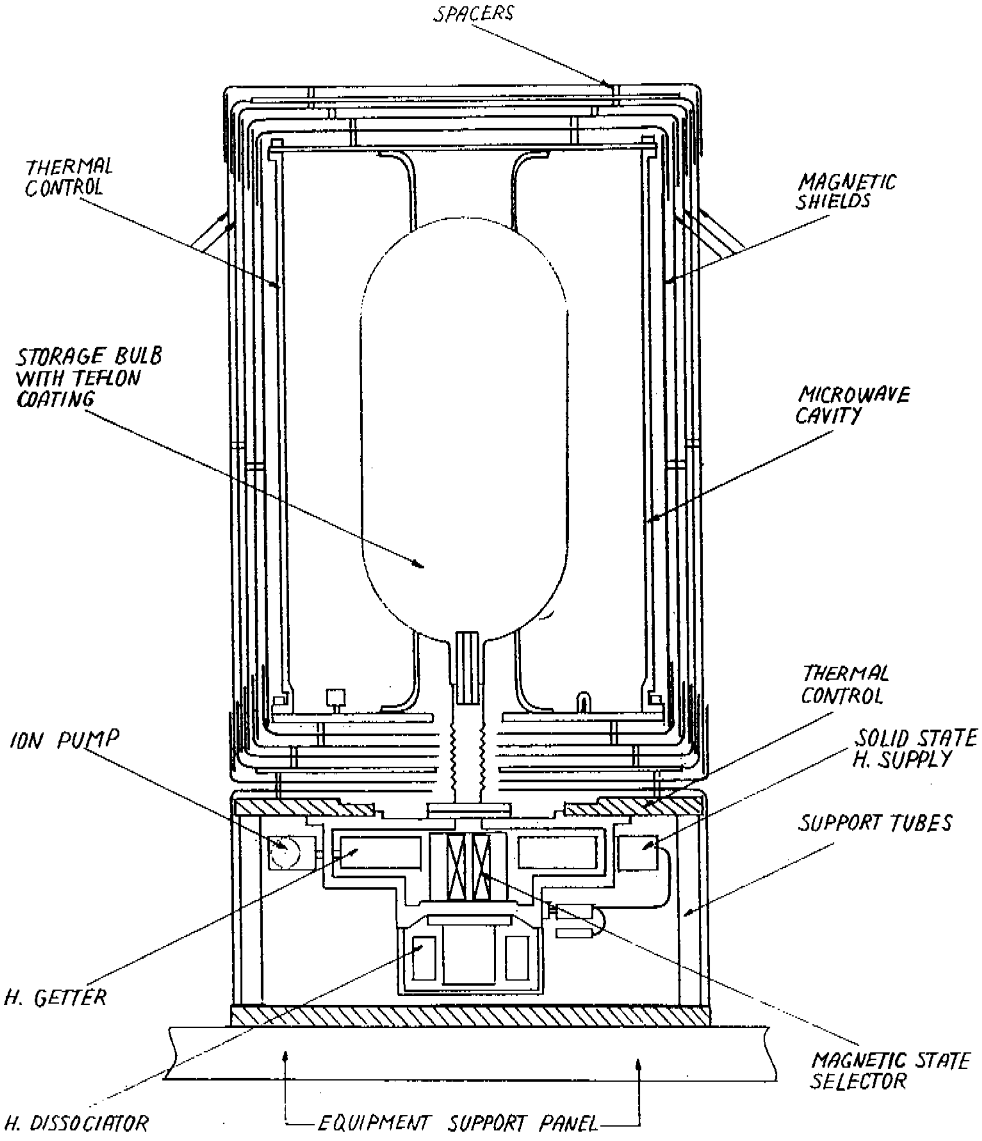

Figure 1
Sketch of Spaceborne H-maser Physics Package

In addition to the drastic vibration and acceleration specifications on the mechanical design imposed by space qualification, the main environmental constraints that are foreseen are thermal and magnetic.

The temperature of the instrument mounting base plate on the EURECA platform is specified to be within a [0 C°, 40 C°] range. Therefore the temperature coefficient of the maser must be very small in order to maintain state-of-the-art frequency stability.

An extremely low thermal sensitivity will be achieved actively by the use of the ACT system.

The magnetic torquers used to control the attitude of the EURECA spacecraft produce magnetic pulses which intensity can reach up to 3 Gauss on the worst area of the instrument mounting panel. In the most favorable area of the panel the pulse strength reaches 50 mGauss. This is to be compared to the 1 mGauss field variations encountered by ground masers under normal operating conditions.

3.2 PRARE T&F MICROWAVE TRANSFER SYSTEM

The development of the microwave T&FT system will be managed by DLR which already has a working experience in this field [6]. The adaptation of the existing PRARE system, which was developed by DLR for use in the ERS-1 satellite, to the requirements of the present maser experiment is a cost-effective alternative to the development of a completely new T&FT system not only from the point of view of the production of the space qualified equipment but also because existing PRARE ground stations become usable for the T&F monitoring of the spaceborne masers at the price of minor modifications.

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It would be possible to further improve the FT performance of the PRARE system but at the cost of a major redesign. The white phase noise floor due to the S/N alone is $1\times10^{-14}\ 1/\tau$.

The temperature sensibility of the internal delay is about 30 ps/C° and can be compensated with a 20 fold improvement factor by the internal delay calibration system. Therefore a < 10 ps delay stability can be achieved over a full orbital period.

In conclusion the PRARE system happens to match the requirements of our spaceborne masers experiment at the cost of minor modifications. The latter include the addition of a second channel in X band since 2 masers are to be evaluated.

3.4 T&FT SYSTEM DESIGN OPTIONS

Many design options of the T&FT system are open. For reliability reasons the H-maser clocks signals will be cross-switchable. Therefore the clock labeled N°1 in the S band 1-way link of figure 3 may may be switched to either H-maser signal in case the other maser fails. For the same reliability reasons the use of 2 redundant transmitter chains sharing the same antenna is considered.

The use of 2 channels in the X band downlink allows a continuous and simultaneous comparison between the H-maser spaceborne clocks N°1 and N°2. This is necessary for the ground measurement of the relative short-term stability between clock N°1 and clock N°2. The spaceborne hardware could be simplified by the use of only one X band downlink channel, like in the standard PRARE package, but then the clock N°1 vs clock N°2 data is obtained from non-simultaneous clock N°3 vs clock N°2 and clock N°3 vs clock N°1 measurements.

The modification options for the accommodation of the existing PRARE ranging ground equipment to both internal delay calibration and T&FT requirements are still open.

4.0 CINEMATIC AND RELATIVISTIC ASPECTS

The true 1-way delay and 1-way doppler are not half the measured 2-way delay and doppler because of the asymmetry due to the fact that the space vehicle moves during the signal propagation. It can be shown that the frequency offset measured on ground is given by

$$\Delta f/f = \delta f/f + DA^{(1)} + DA^{(2)} + D^{(2)} + GS \qquad (1)$$

where $\Delta f/f$ is the normalized frequency offset between the ground and the spaceborne maser after correction for ionospheric propagation effects, $\delta f/f$ is the true frequency offset between the clocks, $DA^{(1)}$ is the first order doppler asymmetry term, $DA^{(2)}$ the second order doppler asymmetry term, $D^{(2)}$ the second order doppler and GS the gravitational frequency shift.

The different terms are given by

$$DA^{(1)} = \frac{1}{2}\left(\left(\vec{\beta}_1 - \vec{\beta}_G\right)\cdot \vec{r}_{1G} - \left(\vec{\beta}_G - \vec{\beta}_2\right)\cdot \vec{r}_{G2}\right) \qquad (2)$$

$$DA^{(2)} = \left(\left(\vec{\beta}_1 \cdot \vec{r}_{1G}\right)^2 - \left(\vec{\beta}_1 \cdot \vec{r}_{1G}\right)\left(\vec{\beta}_G \cdot \vec{r}_{1G}\right) - \left(\left(\vec{\beta}_2 - \vec{\beta}_G\right)\cdot \vec{r}_{G2}\right)^2\right) \qquad (3)$$

$$D^{(2)} = \frac{1}{2}\left(\beta_G^2 - \beta_1^2\right) \qquad (4)$$

$$GS = \frac{\phi_G - \phi_1}{c^2} \qquad (5)$$

The $\vec{\beta}_i = \frac{\vec{v}_i}{c}$ are velocity vectors normalized by the velocity of light c. The $\vec{r}_i$ are position vectors. ϕ is the gravitation potential. Index 1 refers to the position and velocity of the satellite, in an inertial system of coordinates, at the time a synchronization pulse is generated in the satellite and sent to the ground. Index G refers to the position and velocity of the ground station at the time the pulse arrives to the ground. Index 2 refers to the position and velocity of the satellite at the time the pulse transponded from the ground arrives to the satellite.

In the planned experiment the gravitational shift is nearly constant, due to the circular orbit, and equal to $\approx 6\text{x}10^{-11}$. The second order doppler shift is of the same order of magnitude and nearly constant for the same reason. These conditions are radically different from the conditions of the 1976 red-shift experiment [11] in which the gravitation shift and second order doppler changed by order of magnitudes in the course of a ballistic flight. In the present experiment it is the doppler asymmetry terms that show a high dynamic change in the course of every pass of the space vehicle over a ground station. The first order term $DA^{(1)}$ will reach maximum values of the order of $1\text{x}10^{-10}$. It will be possible to check the relativistic model of the asymmetry terms to the order of $1\text{x}10^{-15}$.

5.0 GROUND SEGMENT

At present the only ground station committed to the laser TT aspect of the experiment is the NASA station of Maoi in Hawaii. The Matera station in southern Italy and the Shanghai station in China are showing interest to join. The scientific benefit of the participation of several laser tracking stations is the possibility of time transfer to a 100 ps level of accuracy between distant ground clocks.

As for the microwave T&FT aspect, the commitment of the Mas Palomas station is expected. The participation of ground stations equipped with both laser tracking and PRARE systems allows the precise calibration of the microwave tropospheric delay.

All VLBI stations use hydrogen maser clocks and those located within the EURECA III visibility region could be equipped with mobile PRARE ground equipment. The relevant European stations are Matera and Noto in Italy.

Besides, all existing PRARE stations located within ±30° of latitude, i.e. about 10 stations, could participate. The PRARE stations are committed to geodesy work and the benefit they could draw from the experiment is the mm level position determination accuracy provided by the use of a spaceborne maser reference clock. A very precise tracking of the EURECA III orbit is required in order to make possible the accurate position determinations of the ground PRARE stations. This could be easily achieved if a space qualified GPS receiver is carried aboard the EURECA III spacecraft in addition to the laser ranging system. As a matter of fact, part of the original goals of the ERS-1 PRARE experiment, that failed because of a destructive latch-up in the memory subsystem of the ERS-1 PRARE space package, could be achieved by means of the EURECA III maser experiment.

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REFERENCES

[1] Vessot R.F.C., Mattison, E.M., Decher R., "Test of an Orbiting Hydrogen Maser Clock System Using Laser Time Transfer", to be published in Proc. 23rd Annual PTTI Planning and Applications Meeting, December 3-5, 1991, Pasadena, CA.

[2] Veillet C., "Lasso: The New Transatlantic Phase", to be published in *Proc. 23rd Annual PTTI Planning and Applications Meeting*, December 3-5, 1991, Pasadena, CA.

[3] Schlüter W., Nottarp K., Feil D., Busca G., "First Experiences with the H-Maser EFOS-1", *Proc. of the 14th Annual PTTI Applications and Planning Meeting*, Greenbelt, November 1982, pp. 393-408.

[4] Bernier L.G., Busca G., "Recent Progress in the Development of the EFOS-B Hydrogen Maser at Neuchâtel Observatory", *Proc. 5th EFTF*, Besançon, March 1991, pp.404-406.

[5] Busca G., Johnson L., "A New Automatic Cavity Tuning for Active H Masers", *Proc. 1st European Time and frequency Forum*, Besançon, March 1987, pp.339-341.

[6] Starker S., Arko D., Hammesfahr J., Nau N., Sappl E., Schild H., Schimmel R., Stelzel F., *Navigation Experiment NAVEX on Spacelab Mission D1*, Final Report, DLR, Institute of Radio Frequency Technology, D-8031 Wessling.

[7] Vessot R.F.C., Levine M., Mueller L., Baker M., "The Design of an Atomic Maser System for Satellite Experiments", *Proc.*

21st Annual Symposium on Frequency Control, Atlantic City, April 1967, pp. 512-542.

[8] Vessot R.F.C., Levine M.W., "Performance Data of Space and Ground Hydrogen Masers and Ionospheric Studies for High-Accuracy Comparisons Between Space and Ground Clocks", *Proc. 28th Annual Symposium on Frequency Control*, Atlantic City, May 1974, pp. 408-414.

[9] Penfield H., Imbier E.,Vessot R.F.C., "Design of the STIFT Time and Frequency Transfer Microwave Ground Terminal", *Proc. 14th Annual PTTI Applications and Planning Meeting*, NASA Goddard Space Flight Center, Greenbelt, Maryland, November 30,December 1-2, 1982, pp. 223-241.

[10] Schäfer W., Institute of Navigation of the University of Stuttgart, private communication.

[11] Vessot R.F.C., Levine M.W., Mattison E.M., Hoffman T.E., Imbier E.A., Têtu M., Nystrom G., Kelt J.J., Trucks H.F., Vaniman J.L., "Space-Borne Hydrogen Maser Design", *Proc. 8th Annual PTTI Applications and Planning Meeting*, Washington, December 1976, pp. 277-233.

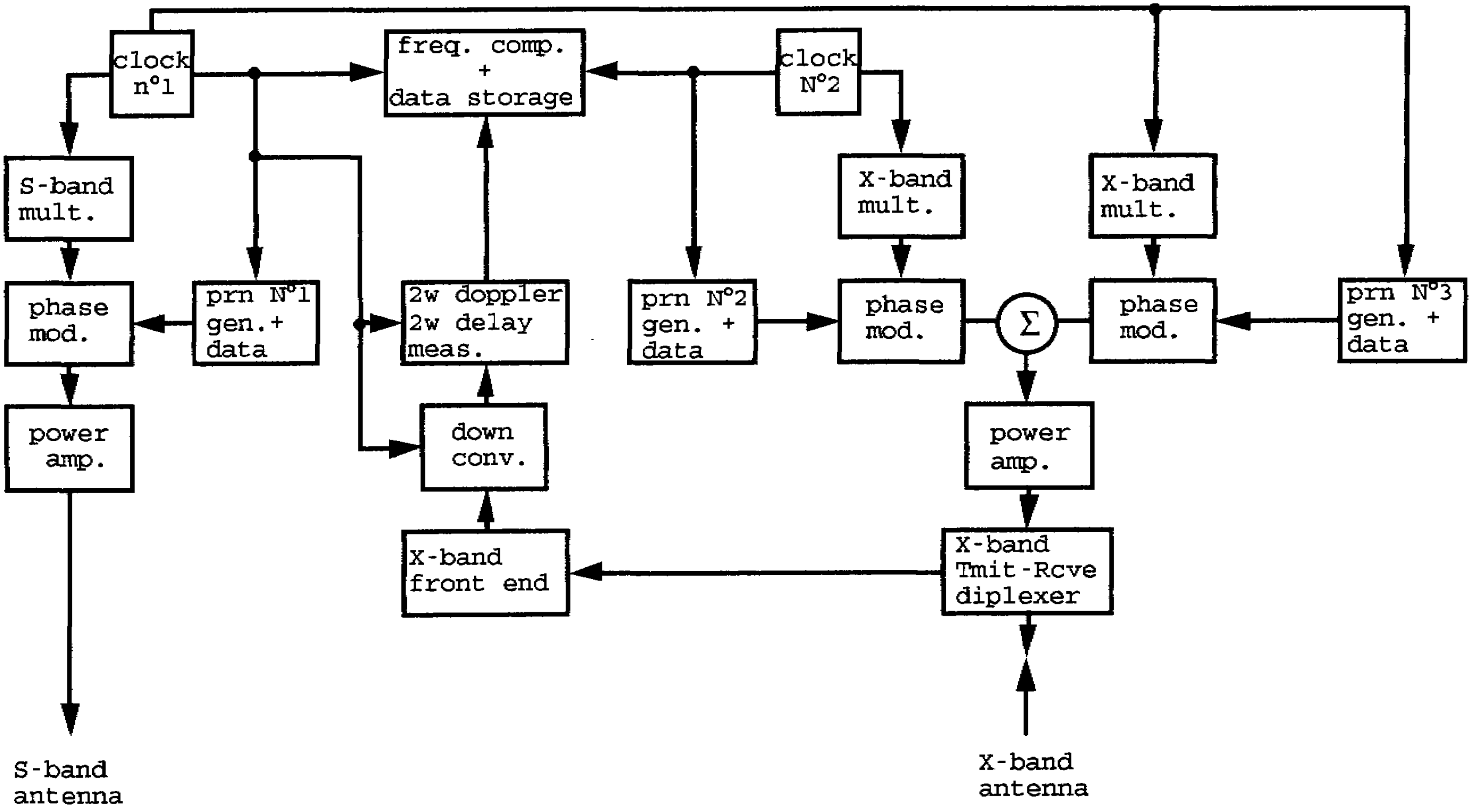

Figure 3
Modified Spaceborne PRARE

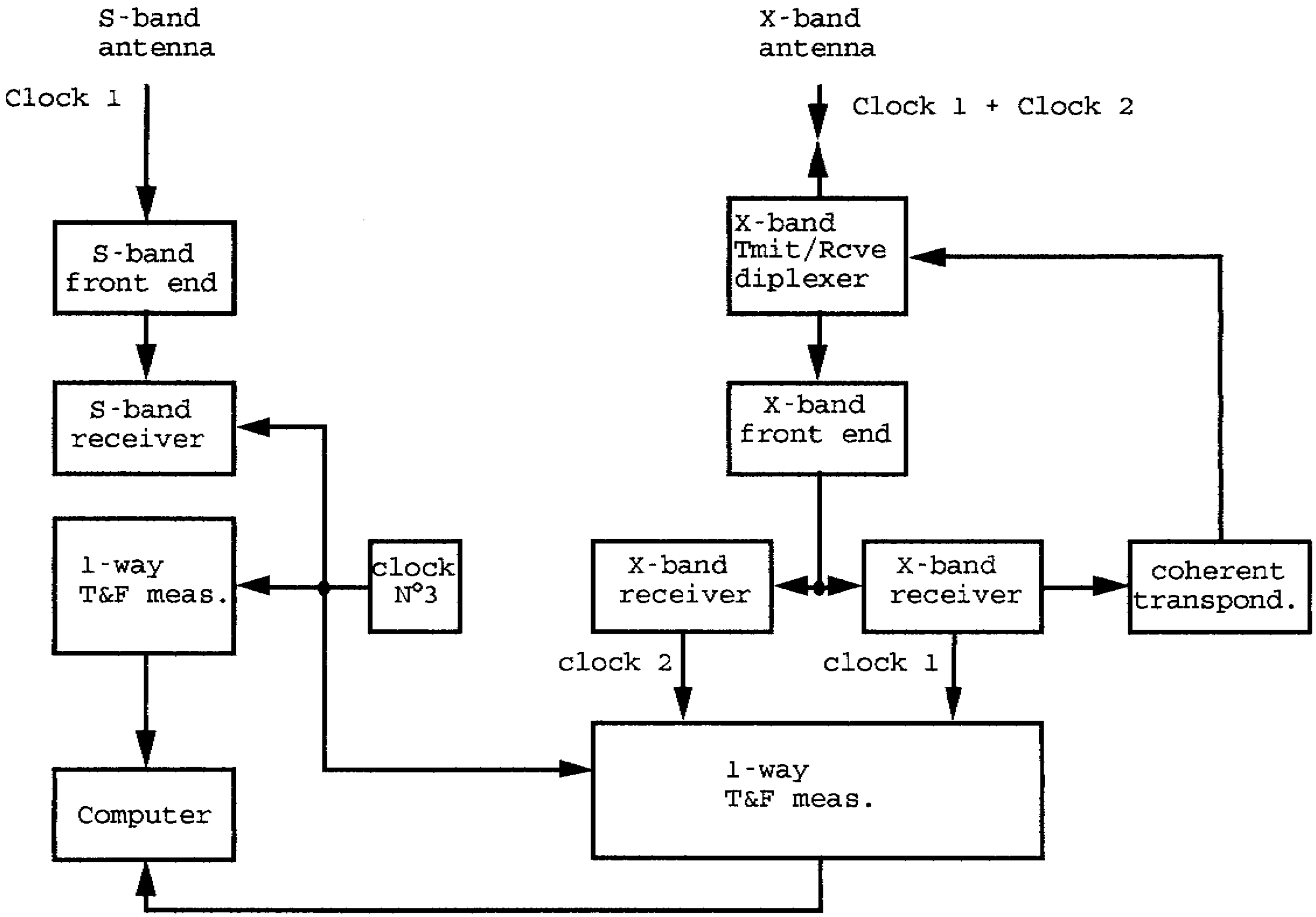

Figure 4
Modified Ground PRARE