# DEVELOPMENT OF A PRIMARY REFERENCE CLOCK

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**Abstract**

***Quartzlock is engaged in research to improve the generation, measurement, and distribution of accurate frequency sources that are stable with environmental changes. The elements in this progress report are both active and passive masers, quartz frequency standards, measurement systems, GPS/Glonass receiver, GPS CVTT, and rubidium standards. Space-qualified passive hydrogen masers and rubidium oscillators are considered. A new measurement system is detailed and the first noise floor results are reported.***

## ACTIVE AND PASSIVE MASERS, GPS-GLONASS, AND GPS CVTT

NIST-traceable measurements have been made of a passive hydrogen maser with GPS, rubidium, and other elements for a new primary reference clock being developed with European Union assistance.

IEM Kvarz provided an ensemble of active hydrogen masers to measure the GPS carrier-phase tracking RX performance of $5x10^{-14}$ over 3 to 33 days. This figure was confirmed at PTB. The active maser performance has been significantly improved at 1 day to $3x10^{-16}$ for drift after 1 year of operation ($5x10^{-16}$ in the first month).

The H masers used as a reference are CH1-75's. Results include the CH1-75 active hydrogen maser frequency stability measurement, which has an automatic cavity frequency control (ACFC) system. Two ACFC systems were investigated. The first system was non-autonomous, because another hydrogen maser was required for its operation; the second system was autonomous. The atom line quality modulation method was used in both systems.

The ACFC system is based on measurement of the frequency difference of masers at two atom-line quality values by means of a frequency comparator and a reversible counter and cavity frequency control versus the value and sign of this difference. In the non-autonomous system, a cavity autotuning was produced by cycles with a 2300-s duration (a count time of the reversible counter in one direction was 1000 s); atom-line quality was changed by beam intensity.

10 s was used. The modulation was performed by introduction of an inhomogeneous magnetic field into the storage bulb. The tuning was performed by cycles with 25-s duration (the count time of reversible counter was 10 s). An additional digital filter (the second reversible counter) was introduced after the first reversible counter.

The experimental frequency stability of the hydrogen maser with autonomous ACFC was $5x10^{-15}$ per day. Using a more stable crystal oscillator having a frequency stability of $1.5x10^{-13}$ at 1 s to 10 s will improve maser frequency stability approximately by 3 times and using a microprocessor or a personal computer as a digital filter improves dynamic performance of the ACFC loop.

The Autonomous Autotune (AAT) system employed enables close to Cavity Autotune (CAT) performance with two active hydrogen masers, which achieve Allan variances of $2x10^{-13}$ at 1 s, $3x10^{-14}$ at 10 s, and $2x10^{-15}$ at 1 d, but without the advantage of a redundant system needed for HiRel timing. IEM KVARZ is providing active H masers for qualification and specification analysis of a new passive maser, a GPS/Glonass RX measurement system, and GPS, CVTT, and rubidium elements. The passive H maser target performance meets the European Space Agency PM specification requirement.

GPS size, weight, and power reductions are significant. A new low-cost GPS element result is illustrated. It is not expected to be reproducible in production quantities as a product spec, but is a typical test result.

## MEASUREMENT SYSTEM

The current measurement system A7 has the highest resolution available in the shortest measurement time: $1.5x10^{-15}$ in only 100 s and $1.5x10^{-16}$ in 1000 s. For the new passive maser this is the development tool used. However, in a system where the new PHM is the standard against which the DUT is measured, a low cost, smaller size, lighter weight module is required for it to be a component part in a complete system. The performance required is not as high as the current A7, but innovative solutions enabling substantial cost size and weight were required. A completely new approach was adopted that met the need of the Alpha project in all respects – the results achieved are plotted.

## RUBIDIUM OSCILLATOR

The rubidium oscillator element has to be the most rugged because this link in the redundancy chain must survive longest, and telecom component applications in both civil and defense use have differing environmental requirements.

Current HSRO, LPRO, SRAFS, and LCRO specs are tabled below.

## LABORATORY ENVIRONMENTAL DATA

Mechanical/physical environmental testing revealed the following results during tests of the rubidium element.

# REFERENCES

V. A. Logachev 1999, it "The hydrogen maser cavity step autotuning: theoretical analysis and experimental results," Proceedings of the Joint Meeting of the 13th European Frequency and Time Forum and 1999 IEEE International Frequency Control Symposium, 13-16 April 1999, Besançon, France, pp. 129-132.

N. Demidov, private communication.

European Space Agency

| Specifications | Active Hydrogen Maser CH1 – 75 | Active Hydrogen Maser +AAT CH1 – 75A Autonomous Auto Tune Version | Active Hydrogen Maser +CAT CH1-75 (2 units) CH1-75B | Passive Hydrogen Maser CH1-76 | S-PHM Space Qualified Passive Hydrogen Maser @10-s mBar | S –RAFS Space Qualified Rubidium Atomic Frequency Standards |
|---|---|---|---|---|---|---|
| Sine wave | | | | | | |
| Frequency, MHz | 5,100 | 5,100 | 5,100 | 5,100 | 10 | 10 |
| Voltage at 50 Ohm load, V | 1±0.2 | 1±0.2 | 1±0.2 | 1±0.2 | 7dBm±1 | |
| Harmonic distortion dB | -30 | -30 | -30 | -30 | -60 | -40 |
| Non-harmonic distortion in 10 MHz – 10kHz range dBc | -120 | -120 | -120 | -100 | -84<br>&<br>-60 | -84<br>&<br>-60 |
| Phase noise dBc/Hz | | | | | | |
| 1 Hz | -110 | -110 | -110 | -100 | -124 | -90 |
| 10 Hz | -130 | -130 | -130 | -120 | -146 | -110 |
| 100 Hz | -140 | -140 | -140 | -140 | -155 | -130 |
| 1000 Hz | -150 | -150 | -150 | -150 | -155 | -150 |
| 10000 Hz | -150 | -150 | -150 | -150 | -155 | |
| - pulse | | | | | | |
| Frequency Hz | 1 | 1 | 1 | 1 | | |
| Amplitude at 50 Ohm load V | >2.5 | >2.5 | >2.5 | >2.5 | | |
| Width ns | 10 – 20 | 10-20 | 10-20 | 10-20 | | |
| Rise time ns | 15 | 15 | 15 | 30 | | |
| Jitter ns | 0.1 | 0.1 | 0.1 | 0.1 | | |
| Frequency accuracy (within 1 year period) | $\pm 3.10^{-12}$ | $\pm 1.10^{-12}$ | $\pm 5.10^{-13}$ | $\pm 1.5.10^{-12}$ | | $1.0 \cdot 10^{-10}$ |
| 1s | $2.10^{-13}$ | $3.10^{-13}$ | $2.10^{-13}$ | $1 \cdot 5.10^{-12}$ | $1.10^{\cdot 12}$ | $5 \cdot 10^{-12}$ |
| 10s | $3\ 10^{-14}$ | $1 \cdot 10^{-13}$ | $3\ 10^{-14}$ | $5 \cdot 10^{-13}$ | $3.2 \cdot 10^{-13}$ | $1.5 \cdot 10^{-12}$ |
| 100s | $5\ 10^{-15}$ | $1 \cdot 10^{-14}$ | $1\ 10^{-14}$ | $1.5 \cdot 10^{-13}$ | $1 \cdot 10^{-13}$ | $5 \cdot 10^{-13}$ |
| 1000s | $2.5 \cdot 10^{-15}$ | $5 \cdot 10^{-15}$ | $5 \cdot 10^{-15}$ | $5 \cdot 10^{-14}$ | $3.2 \cdot 10^{-14}$ | $1.5 \cdot 10^{-13}$ |
| 1h | $1 \cdot 10^{-15}$ | $3 \cdot 10^{-15}$ | $3 \cdot 10^{-15}$ | $3 \cdot 10^{-14}$ | $1 \cdot 10^{-14}$ | $7 \cdot 10^{-14}$ |
| 1 day | $1 \cdot 10^{-15}$ | $3\ 10^{-15}$ | $2 \cdot 10^{-15}$ | $1\ 10^{-14}$ | | $5 \cdot 10-^{14}$ |
| Frequency drift per 1 day | $3\ 10^{-15}$ | $5 \cdot 10^{-15}$ | $2 \cdot 10^{-15}$ | $1\ 10^{-14}$ | | |
| At launch | $5 \cdot 10^{-15}$ | $5 \cdot 10^{-16}$ | $5\ 10^{-16}$ | $2 \cdot 10^{-15}$ | | |
| After 1 year | $3 \cdot 10^{-15}$ | $3\ 10^{-16}$ | $3 \cdot 10^{-16}$ | $2\ 10^{-15}$ | $3 \cdot 10^{-12}$ | $3.0 \cdot 10^{-11}$ |
| Temperature frequency coefficient 1/°C | $2 \cdot 10^{-15}$ | $2 \cdot 10^{-15}$ | $1 \cdot 10-^{15}$ | $2 \cdot 10^{-14}$ | | $1 \cdot 10^{-13}$ |
| External magnetic field effects, 1/Gauss | $1 \cdot 10^{-14}$ | $1 \cdot 10^{-14}$ | $1 \cdot 10^{-14}$ | $2.5 \cdot 10^{-14}$ | $2 \cdot 10^{-14}$ | $1 \cdot 10^{-13}$ |
| Frequency corrector resolution | $1 \cdot 10^{-15}$ | $1 \cdot 10^{-15}$ | $1 \cdot 10^{-15}$ | $1 \cdot 10^{-14}$ | | |

Fig.1 NIST traceability of A8-B

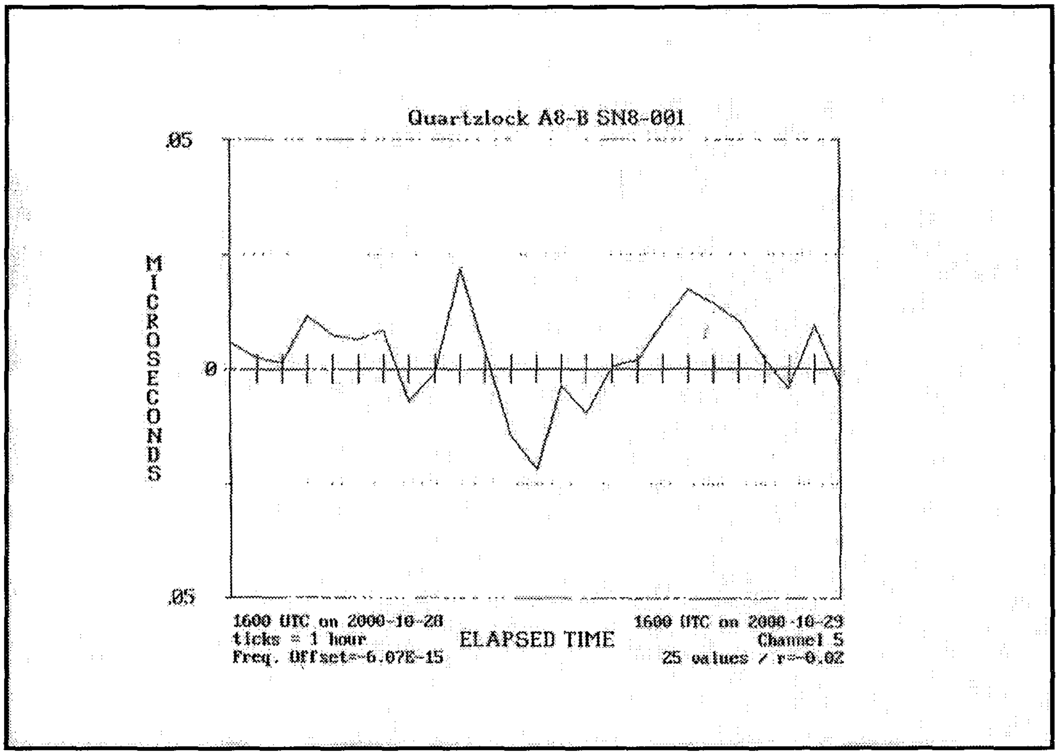


Fig.2 NIST traceability of Passive Hydrogen Maser

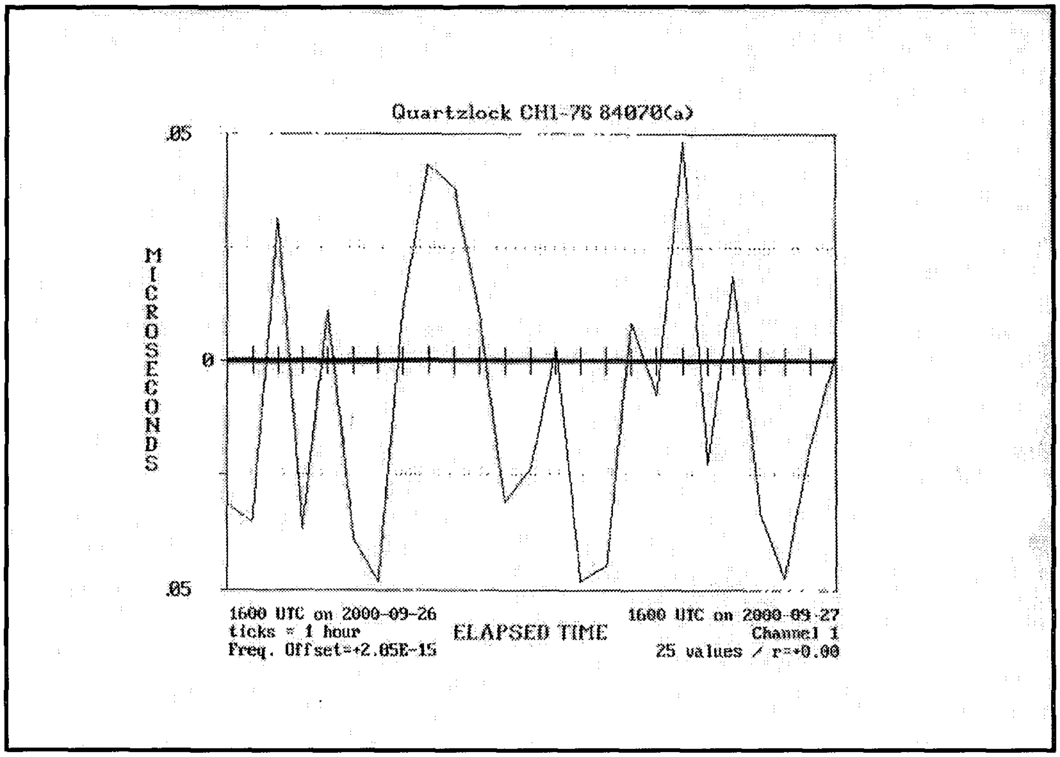


Fig.3:
Resonance Search - Axis 1.
Monitor Accelerometer on Rubidium Module.
Pre –Endurance Testing

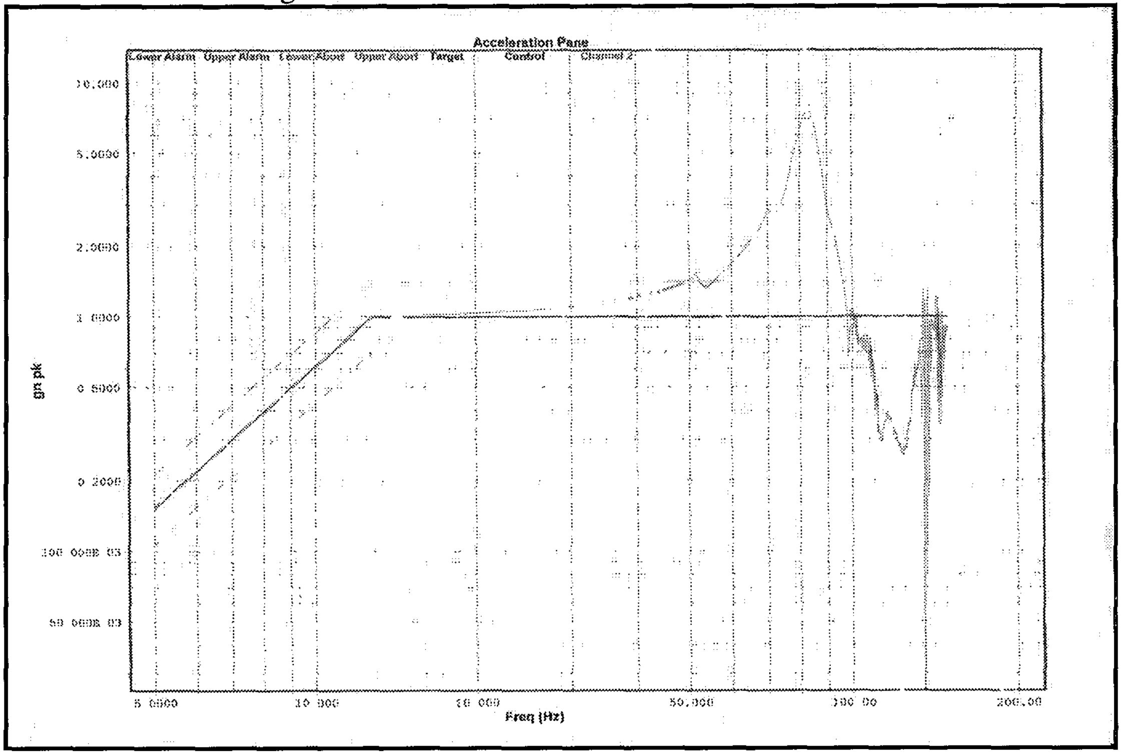


Fig.4 Applied Shock Pulse – 25gn for 6ns

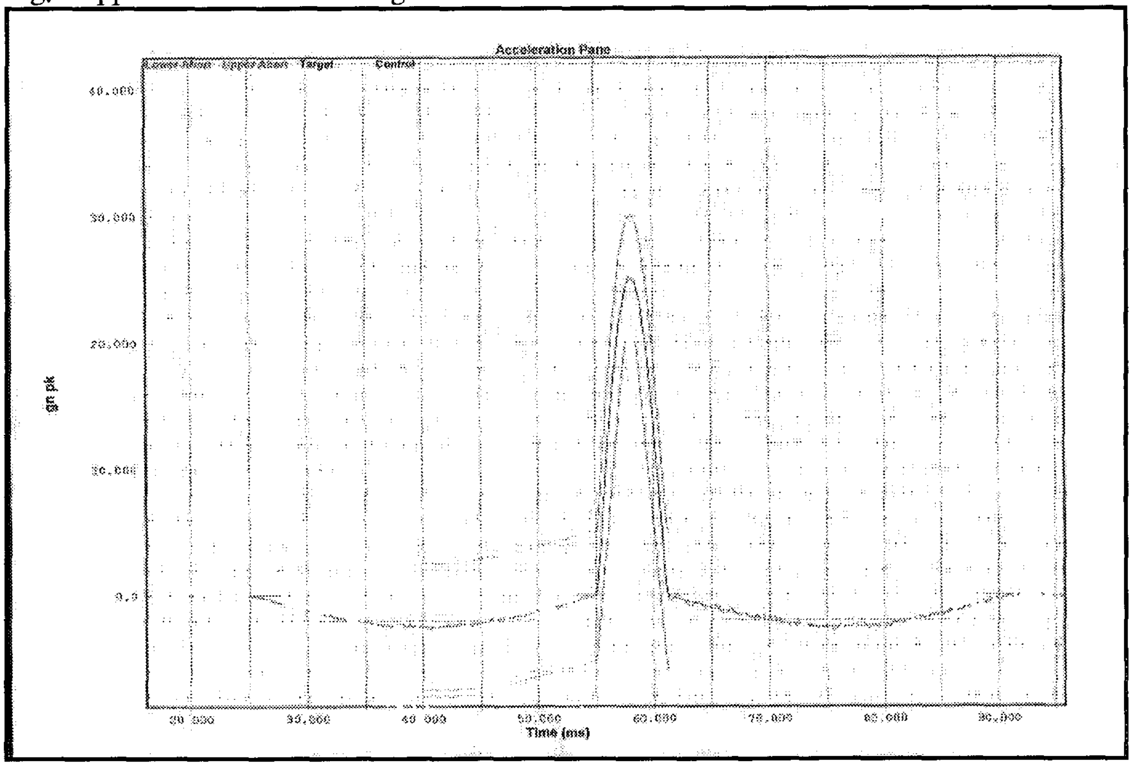
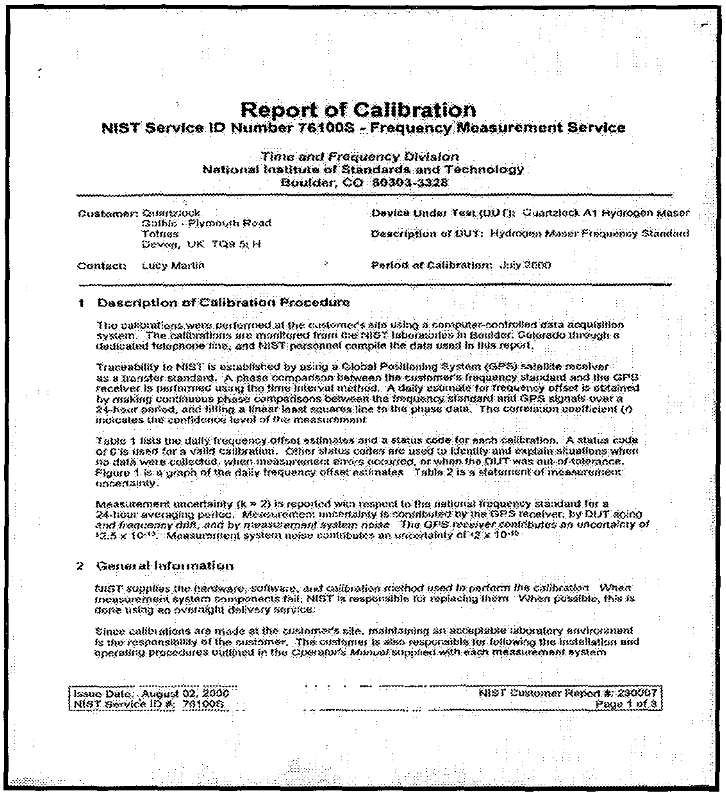


Fig.5



# Report of Calibration

## NIST Service ID Number 76100S - Frequency Measurement Service

*Time and Frequency Division*
National Institute of Standards and Technology
Boulder, CO 80303-3328

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**Customer:** Quartzlock
Gothic - Plymouth Road
Totnes
Devon, UK TQ9 5LH

**Contact:** Lucy Martin

**Device Under Test (DUT):** Quartzlock A1 Hydrogen Maser

**Description of DUT:** Hydrogen Maser Frequency Standard

**Period of Calibration:** July 2000

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### 1 Description of Calibration Procedure

The calibrations were performed at the customer's site using a computer-controlled data acquisition system. The calibrations are monitored from the NIST laboratories in Boulder, Colorado through a dedicated telephone line, and NIST personnel compile the data used in this report.

Traceability to NIST is established by using a Global Positioning System (GPS) satellite receiver as a transfer standard. A phase comparison between the customer's frequency standard and the GPS receiver is performed using the time interval method. A daily estimate for frequency offset is obtained by making continuous phase comparisons between the frequency standard and GPS signals over a 24-hour period, and fitting a linear least squares line to the phase data. The correlation coefficient (*r*) indicates the confidence level of the measurement.

Table 1 lists the daily frequency offset estimates and a status code for each calibration. A status code of 0 is used for a valid calibration. Other status codes are used to identify and explain situations when no data were collected, when measurement errors occurred, or when the DUT was out-of-tolerance. Figure 1 is a graph of the daily frequency offset estimates. Table 2 is a statement of measurement uncertainty.

Measurement uncertainty ($k = 2$) is reported with respect to the national frequency standard for a 24-hour averaging period. *Measurement uncertainty is contributed by the GPS receiver, by DUT aging and frequency drift, and by measurement system noise. The GPS receiver contributes an uncertainty of* $<2.5 \times 10^{-13}$. Measurement system noise contributes an uncertainty of $<2 \times 10^{-13}$.

### 2 General Information

*NIST supplies the hardware, software, and calibration method used to perform the calibration. When* measurement system components fail, NIST is responsible for replacing them. When possible, this is done using an overnight delivery service.

Since calibrations are made at the customer's site, maintaining an acceptable laboratory environment is the responsibility of the customer. The customer is also responsible for following the installation and operating procedures outlined in the Operator's *Manual* supplied with each measurement system.

Issue Date: August 02, 2000
NIST Service ID #: 76100S

NIST Customer Report #: 230007
Page 1 of 3

Fig.6

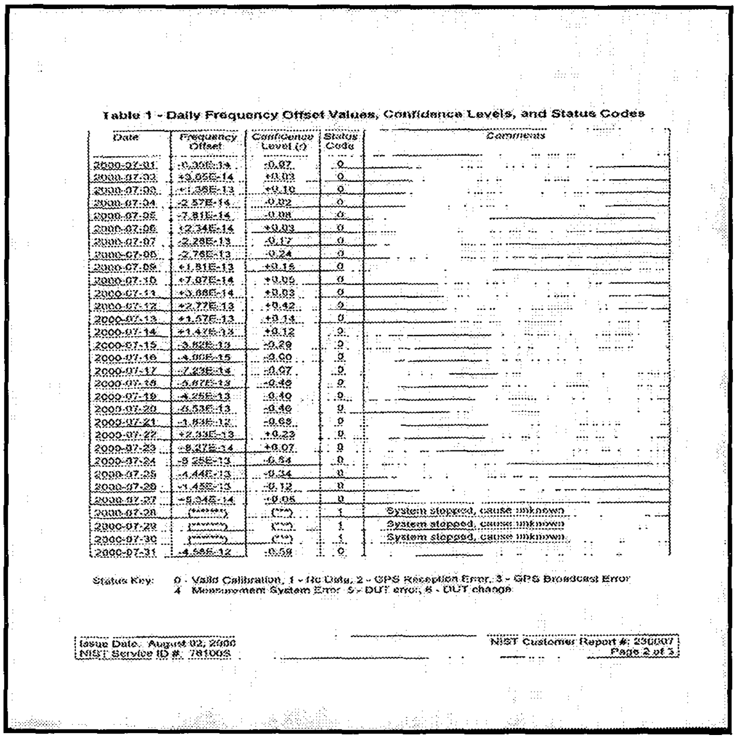

**Table 1 - Daily Frequency Offset Values, Confidence Levels, and Status Codes**

| Date | Frequency Offset | Confidence Level (*r*) | Status Code | Comments |
|---|---|---|---|---|
| 2000-07-01 | -0.39E-14 | -0.07 | 0 | |
| 2000-07-02 | +3.05E-14 | +0.03 | 0 | |
| 2000-07-03 | +1.38E-13 | +0.10 | 0 | |
| 2000-07-04 | -2.57E-14 | -0.02 | 0 | |
| 2000-07-05 | -7.81E-14 | -0.08 | 0 | |
| 2000-07-06 | +2.34E-14 | +0.03 | 0 | |
| 2000-07-07 | -2.28E-13 | -0.17 | 0 | |
| 2000-07-08 | -2.76E-13 | -0.24 | 0 | |
| 2000-07-09 | +1.81E-13 | +0.15 | 0 | |
| 2000-07-10 | +7.07E-14 | +0.05 | 0 | |
| 2000-07-11 | +3.88E-14 | +0.03 | 0 | |
| 2000-07-12 | +2.77E-13 | +0.42 | 0 | |
| 2000-07-13 | +1.57E-13 | +0.14 | 0 | |
| 2000-07-14 | +1.47E-13 | +0.12 | 0 | |
| 2000-07-15 | -3.62E-13 | -0.29 | 0 | |
| 2000-07-16 | -4.00E-15 | -0.00 | 0 | |
| 2000-07-17 | -7.23E-14 | -0.07 | 0 | |
| 2000-07-18 | -5.87E-13 | -0.46 | 0 | |
| 2000-07-19 | -4.25E-13 | -0.40 | 0 | |
| 2000-07-20 | -6.53E-13 | -0.46 | 0 | |
| 2000-07-21 | -1.83E-12 | -0.68 | 0 | |
| 2000-07-22 | +2.33E-13 | +0.23 | 0 | |
| 2000-07-23 | +8.27E-14 | +0.07 | 0 | |
| 2000-07-24 | -9.25E-13 | -0.54 | 0 | |
| 2000-07-25 | -4.44E-13 | -0.34 | 0 | |
| 2000-07-26 | -1.45E-13 | -0.12 | 0 | |
| 2000-07-27 | -5.34E-14 | -0.05 | 0 | |
| 2000-07-28 | (*****) | (**) | 1 | System stopped, cause unknown |
| 2000-07-29 | (*****) | (**) | 1 | System stopped, cause unknown |
| 2000-07-30 | (*****) | (**) | 1 | System stopped, cause unknown |
| 2000-07-31 | -4.58E-12 | -0.58 | 0 | |

Status Key: 0 - Valid Calibration, 1 - No Data, 2 - GPS Reception Error, 3 - GPS Broadcast Error
4 - Measurement System Error, 5 - DUT error, 6 - DUT change

Issue Date: August 02, 2000
NIST Service ID #: 76100S

NIST Customer Report #: 230007
Page 2 of 3

Fig.7

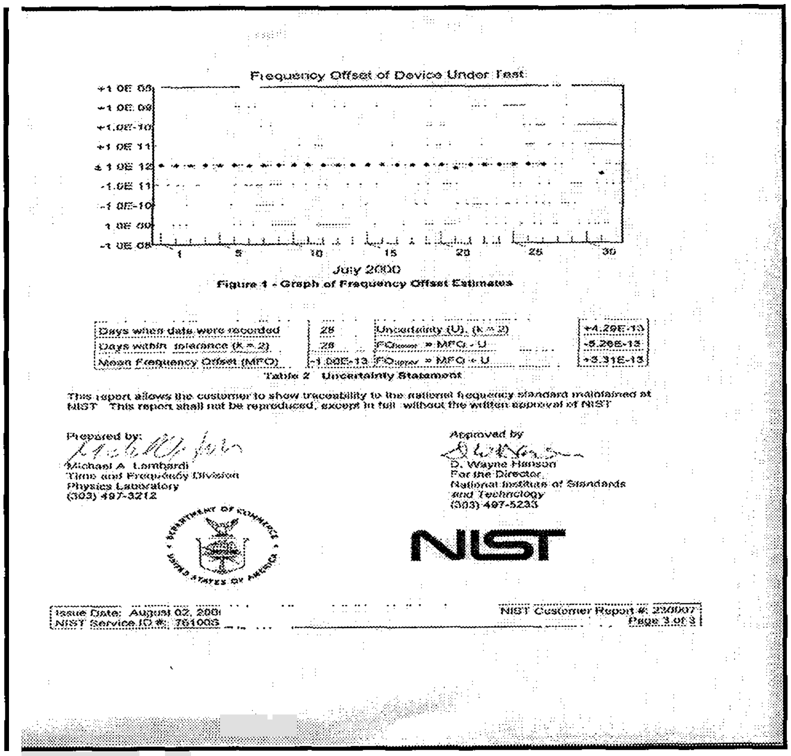

Figure 1 - Graph of Frequency Offset Estimates

| | | | |
|---|---|---|---|
| Days when data were recorded | 28 | Uncertainty (U), (k = 2) | +4.29E-13 |
| Days within tolerance (k = 2) | 28 | $FO_{lower}$ = MFO - U | -5.26E-13 |
| Mean Frequency Offset (MFO) | -1.00E-13 | $FO_{upper}$ = MFO + U | +3.31E-13 |

Table 2 Uncertainty Statement

This report allows the customer to show traceability to the national frequency standard maintained at NIST. This report shall not be reproduced, except in full, without the written approval of NIST.

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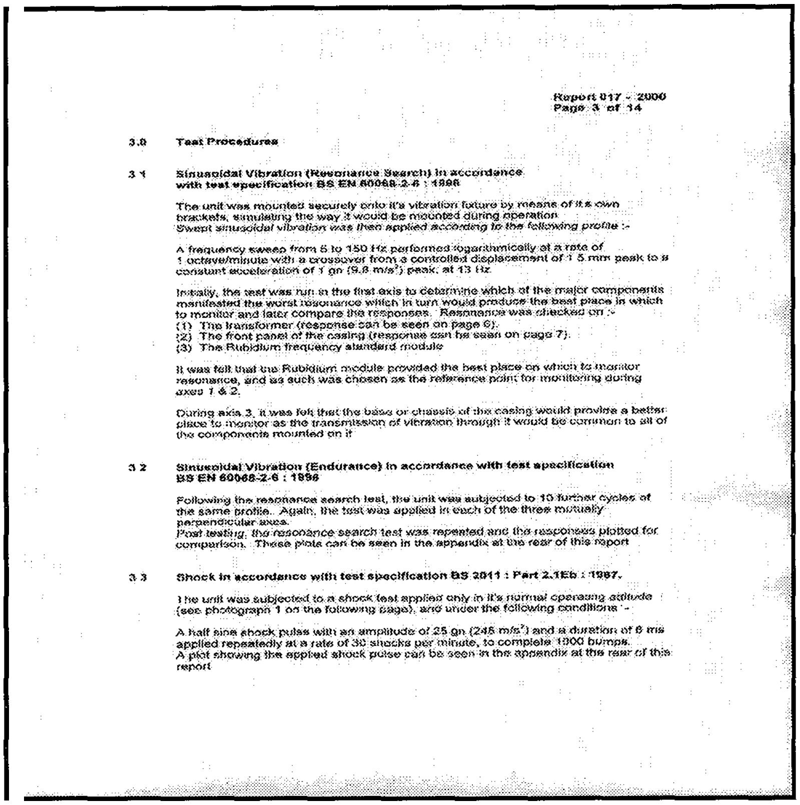
NIST

Issue Date: August 02, 2000
NIST Service ID #: 761005

NIST Customer Report #: 230007
Page 3 of 3

Fig.8



Report 017 - 2000
Page 3 of 14

**3.0 Test Procedures**

**3.1 Sinusoidal Vibration (Resonance Search) in accordance with test specification BS EN 60068-2-6 : 1996**

The unit was mounted securely onto it's vibration fixture by means of it's own brackets, simulating the way it would be mounted during operation.
*Swept sinusoidal vibration was then applied according to the following profile :-*

A frequency sweep from 5 to 150 Hz performed logarithmically at a rate of 1 octave/minute with a crossover from a controlled displacement of 1.5 mm peak to a constant acceleration of 1 gn ($9.8\ m/s^2$) peak, at 13 Hz.

Initially, the test was run in the first axis to determine which of the major components manifested the worst resonance which in turn would produce the best place in which to monitor and later compare the responses. Resonance was checked on :-
(1) The transformer (response can be seen on page 6).
(2) The front panel of the casing (response can be seen on page 7).
(3) The Rubidium frequency standard module

It was felt that the Rubidium module provided the best place on which to monitor resonance, and as such was chosen as the reference point for monitoring during axes 1 & 2.

During axis 3, it was felt that the base or chassis of the casing would provide a better place to monitor as the transmission of vibration through it would be common to all of the components mounted on it.

**3.2 Sinusoidal Vibration (Endurance) in accordance with test specification BS EN 60068-2-6 : 1996**

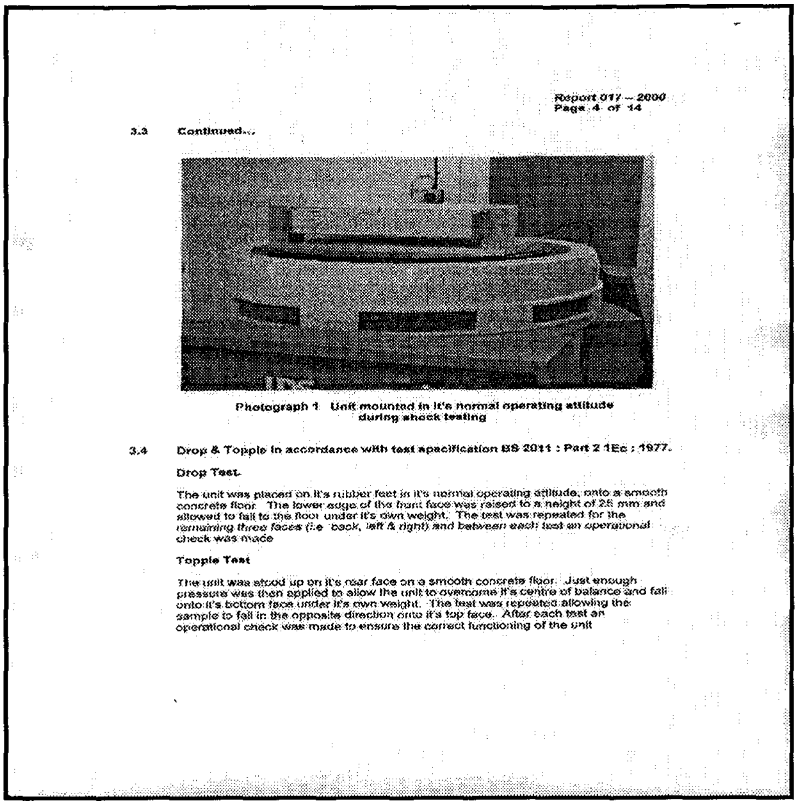
Following the resonance search test, the unit was subjected to 10 further cycles of the same profile. Again, the test was applied in each of the three mutually perpendicular axes.
*Post testing,* the resonance search test was repeated and the responses plotted for comparison. These plots can be seen in the appendix at the rear of this report.

**3.3 Shock in accordance with test specification BS 2011 : Part 2.1Eb : 1987.**

The unit was subjected to a shock test applied only in it's normal operating attitude (see photograph 1 on the following page), and under the following conditions :-

A half sine shock pulse with an amplitude of 25 gn ($245\ m/s^2$) and a duration of 6 ms applied repeatedly at a rate of 30 shocks per minute, to complete 1000 bumps.
A plot showing the applied shock pulse can be seen in the appendix at the rear of this report.

Fig.9



Report 017 – 2000
Page 4 of 14

**3.3 Continued...**

Photograph 1 Unit mounted in it's normal operating attitude during shock testing

**3.4 Drop & Topple in accordance with test specification BS 2011 : Part 2 1Ec : 1977.**

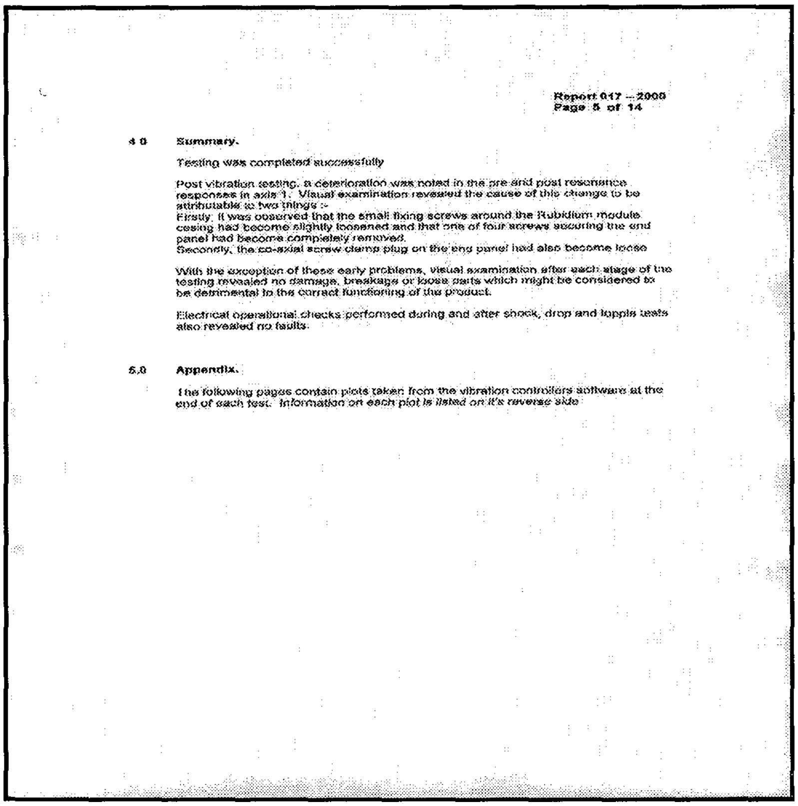
**Drop Test.**

The unit was placed on it's rubber feet in it's normal operating attitude, onto a smooth concrete floor. The lower edge of the front face was raised to a height of 25 mm and allowed to fall to the floor under it's own weight. The test was repeated for the *remaining three faces (i.e back, left & right) and between each test an operational* check was made

**Topple Test**

The unit was stood up on it's rear face on a smooth concrete floor. Just enough pressure was then applied to allow the unit to overcome it's centre of balance and fall onto it's bottom face under it's own weight. The test was repeated allowing the sample to fall in the opposite direction onto it's top face. After each test an operational check was made to ensure the correct functioning of the unit

Fig.10



Report 017 – 2000
Page 5 of 14

**4.0 Summary.**

Testing was completed successfully

Post vibration testing, a deterioration was noted in the pre and post resonance responses in axis 1. Visual examination revealed the cause of this change to be attributable to two things :-
Firstly, it was observed that the small fixing screws around the Rubidium module casing had become slightly loosened and that one of four screws securing the end panel had become completely removed.
Secondly, the co-axial screw clamp plug on the end panel had also become loose

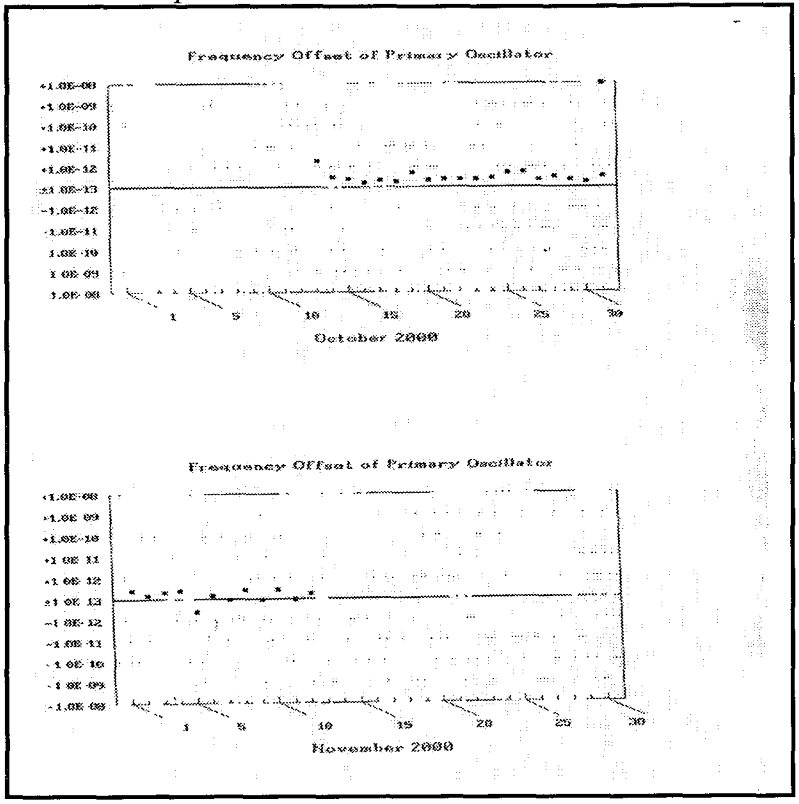
With the exception of these early problems, visual examination after each stage of the testing revealed no damage, breakage or loose parts which might be considered to be detrimental to the correct functioning of the product.

Electrical operational checks performed during and after shock, drop and topple tests also revealed no faults.

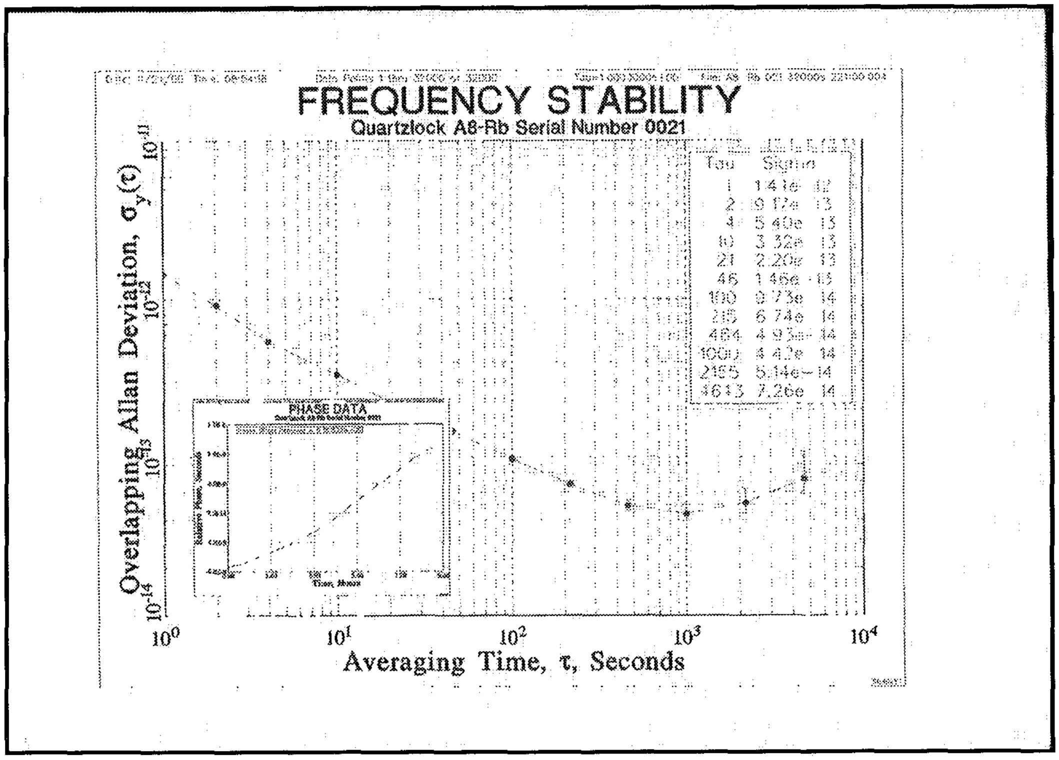
**5.0 Appendix.**

The following pages contain plots taken from the vibration controllers software at the end of each test. *Information on each plot is listed on it's reverse side*

Fig.11 NIST-traceable passive maser offset

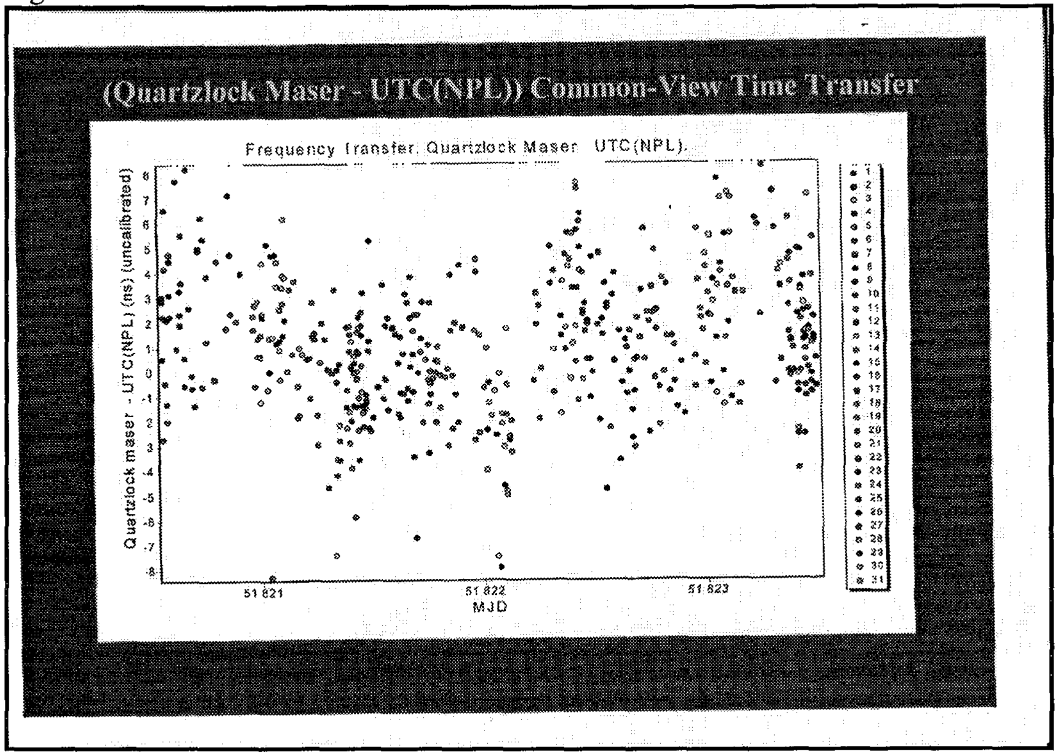


Synthesizer adjustment end Oct.



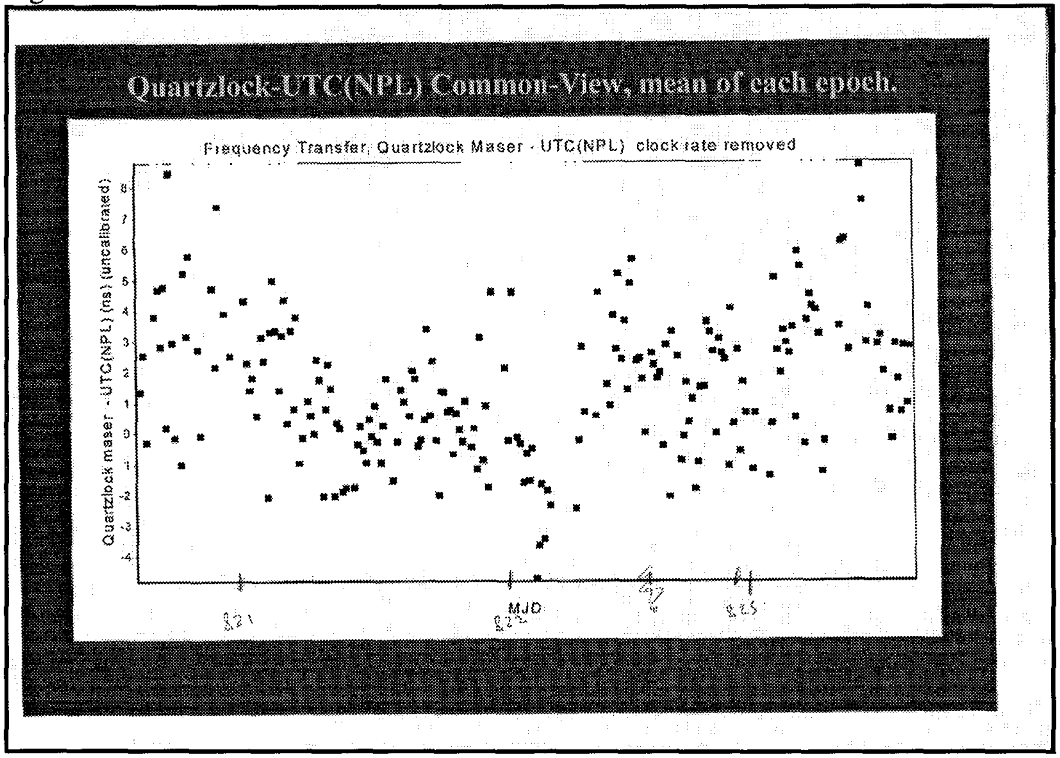
| Tau | Sigma |
|---|---|
| 1 | 1.41e-12 |
| 2 | 9.17e-13 |
| 4 | 5.40e-13 |
| 10 | 3.32e-13 |
| 21 | 2.20e-13 |
| 46 | 1.46e-13 |
| 100 | 9.73e-14 |
| 215 | 6.74e-14 |
| 464 | 4.93e-14 |
| 1000 | 4.42e-14 |
| 2155 | 5.14e-14 |
| 4613 | 7.26e-14 |

Fig.12



(Quartzlock Maser - UTC(NPL)) Common-View Time Transfer

Fig.13



Quartzlock-UTC(NPL) Common-View, mean of each epoch.