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APPLICATION OF VERY-LONG-BASELINE INTERFEROMETRY TO ASTROMETRY AND GEODESY: EFFECTS OF FREQUENCY-STANDARD INSTABILITY ON ACCURACY

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ABSTRACT

The accuracy of geodetic and astrometric information obtained from very-long-baseline interferometry (VLBI) observations is dependent upon the stability of the frequency standard, or clock, used at each site of a VLBI array. The sensitivities of two hydrogen-maser frequency standards of different design to pressure, temperature, and magnetic field variations were measured and, for one of the standards, found to be severe enough to degrade the information content of VLBI measurements. However, the effect on the geometric and astrometric information of such clock instabilities, with time scales of hours or greater, can be sharply reduced through the use of differencing techniques.

INTRODUCTION

Very-long-baseline interferometry (VLBI) was made possible by the development in the 1950's and 1960's of high-stability frequency standards. A stability of about 1 part in 10^{12} was needed, for example, to detect many extragalactic sources when VLBI observations were made at a radio frequency of 10 GHz using the so-called Mark I recording system. The higher stability, up to about 1 part in 10^{14} for time scales from about 1000 seconds to a day, of hydrogen-maser standards was useful for combining the results from a set of pairs of these three-minute Mark I recordings (each an "observation") to determine source positions, baseline vectors, polar motion, and variations in the rate

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of rotation of the earth (see the review article by P. Bender in these Proceedings for references). If hydrogen-maser standards are used that do not meet such a performance criterion, then the effects on the astrometric and geodetic results of long-term instabilities can be minimized by the use in the data analysis of the differences of the results of observations, made in rapid succession, of sources in widely separated parts of the sky. With the use of such a technique in situations in which signal-to-noise ratios are not a limiting factor, the contributions of the frequency-standard instabilities to the uncertainties in the astrometric and geodetic quantities are, in good approximation, proportional to

$$[\sigma_1^2(T) + \sigma_2^2(T)]^{1/2}\, T$$

where $\sigma_i^2(T)$ is the so-called Allan variance[1] for the frequency standard at Site i, and T, assumed constant, is the time interval between adjacent observations.

In the remainder of this paper we describe the results of a study to evaluate directly the performance of two hydrogen-maser frequency standards, of different design, that have been used in VLBI experiments. The main emphasis was on the sensitivity of these standards to changes in environmental conditions such as temperature, pressure, and magnetic field.

EVALUATION OF FREQUENCY STANDARDS

Two hydrogen-maser frequency standards -- a VLG-10-P2 built by the Smithsonian Astrophysical Observatory and an NP-3 built by the Goddard Space Flight Center -- were operated in separate environments. One of the masers was placed in the standards' room of the Haystack Observatory and the other in a special room at the Westford communications antenna, about 1.2 km distant. The environment at Haystack is well controlled in temperature (to within 0.2°C), but unshielded from variations in magnetic field and atmospheric pressure. The environment at Westford is similar to that at Haystack except the pressure, temperature, and magnetic field can be changed and controlled within certain limits.

The signals from the masers were intercompared at Westford with a phase comparator and the results recorded digitally. Variations in the electrical path of the cable carrying the signal from the standard at Haystack to Westford were nullified by the use of the reflected signal to servocontrol a mechanical "line stretcher". Figure 1 shows the curves for the square root of the Allan variance for various averaging times both for the maser comparison and for the measurement system itself, the comparator and associated cables. (Also shown are intercomparisons carried out earlier between the VLG-10 and both a Model HP-5065A rubidium standard and an old Model H10-1 hydrogen maser in rather poor condition.) During periods when the atmospheric pressure remained nearly constant, a relative stability of 5 parts in 10^{15} was observed. Figure 2 shows the comparison between the time kept by the two standards during such a period of exceptional stability. Tests made by changing the temperature, pressure, and magnetic field show that the hydrogen-maser standards exhibit appreciable sensitivity to their environment as indicated by the entries in Table 1. For VLBI, the most detrimental of these is the large sensitivity of the frequency of the signal from the VLG-10 maser to variations in atmospheric pressure. A pressure coefficient of $-3.5 \pm 0.2 \times 10^{-13}$ per inch of mercury (" Hg) was found for the VLG-10 maser from an analysis of the data obtained by modulation of the pressure by 0.15" Hg at the Westford site. (In particular, the pressure coefficient was obtained by cross correlation of the measured frequency changes with the measured pressure changes.) The base plate of the bell jar in the VLG-10 maser is apparently not sufficiently decoupled from the cavity to prevent pressure variations from affecting the cavity resonant frequency and shifting the frequency of the signal from the maser. Tests made in a barometric chamber[2] yielded a coefficient of -4.3×10^{-13}/"Hg. Figure 3 shows the frequency variations produced by variations in the atmospheric pressure during the passage of a weather "front". The pressure coefficient derived by cross correlation from these atmospheric changes is -6×10^{-13}/"Hg and is considerably larger than that obtained from modulation of the pressure at Westford. This comparison suggests that the NP-3 maser might have a positive pressure coefficient; however, separate tests conducted with the maser locations interchanged have shown that the NP-3 maser has a pressure coefficient less than 4×10^{-14}/"Hg. The differences between the coefficients obtained for the VLG-10 maser may be explained by the presence of mechanical hysteresis or by some non-linear behavior. Other evidence for such behavior comes from the observation that the frequency of the signal from the VLG-10 maser does not follow the pressure modulation smoothly and often jumps in frequency when the atmospheric pressure change reverses in sign, as can be seen in Figure 3.

CONCLUSION

The appreciable environmental sensitivity of some hydrogen-maser frequency standards used in VLBI experiments can severely limit the interpretation of VLBI measurements unless a suitable differencing technique can be employed. Although frequency stability of a few parts in 10^{15} can sometimes be attained with hydrogen-maser standards, their performances are often degraded by more than an order of magnitude by changes in the environment. If these standards can not be made insensitive to the environment, it may be necessary to control carefully the temperature, pressure, and magnetic field in their vicinity in order to use them most effectively in VLBI experiments.

ACKNOWLEDGEMENT

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REFERENCES

1. D. W. Allan, Proc. IEEE, 54, 221 (1966).

2. R. F. C. Vessot, private communication.

Table 1

Environmental Sensitivities of Hydrogen-Maser Frequency Standards

Frequency Standard	Pressure	Temperature	Magnetic Field (vertical component)
VLG-10-P2 (SAO)	-3.5×10^{-13}/"Hg to -6×10^{-13}/"Hg	1×10^{-13}/°C	1×10^{-12}/Gauss
NP-3 (NASA/GSFC)	4×10^{-14}/"Hg	2×10^{-14}/°C	5×10^{-12}/Gauss

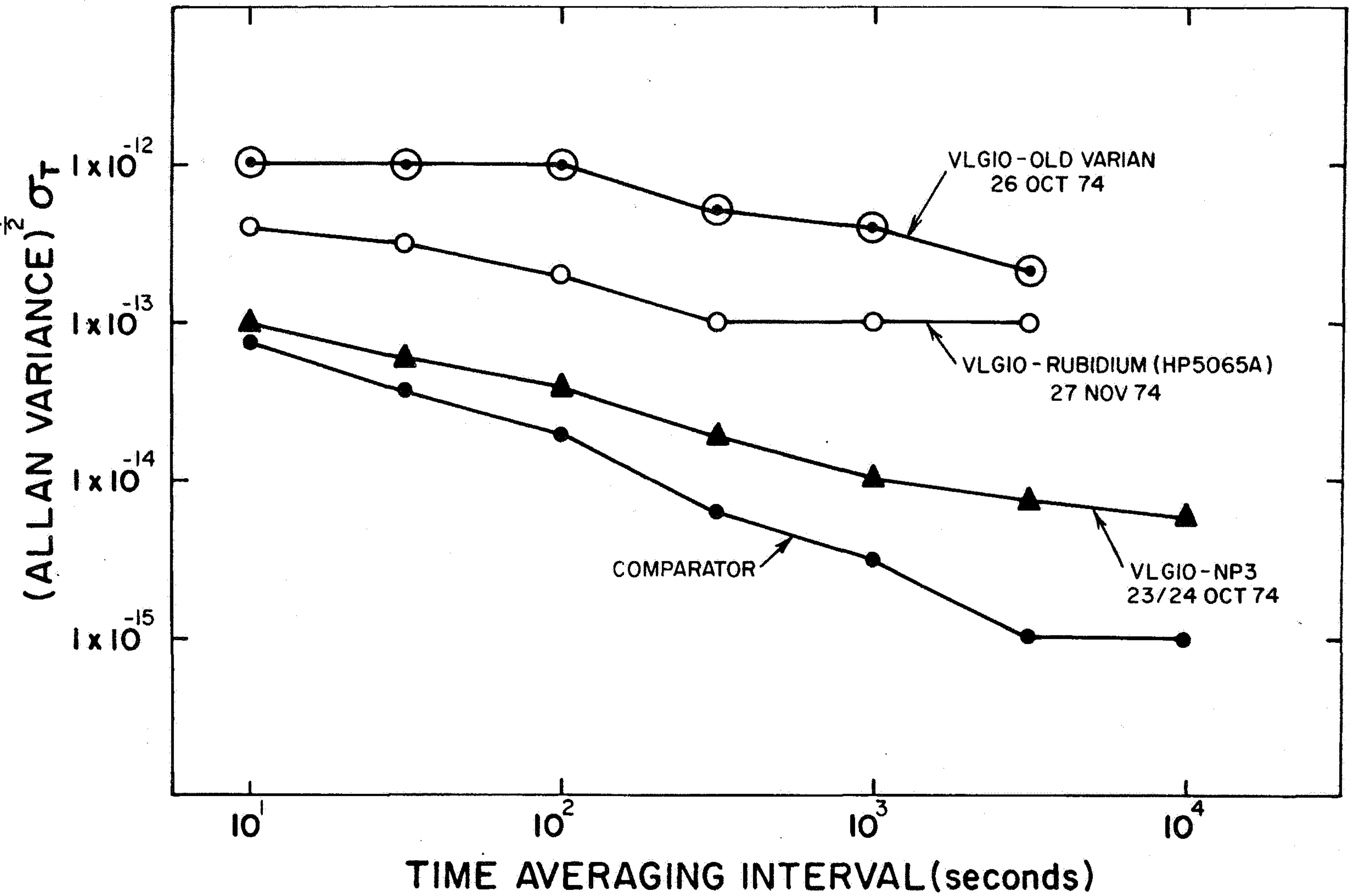

Figure 1. Relative stability of different frequency standards observed during periods of near-constant atmospheric conditions.

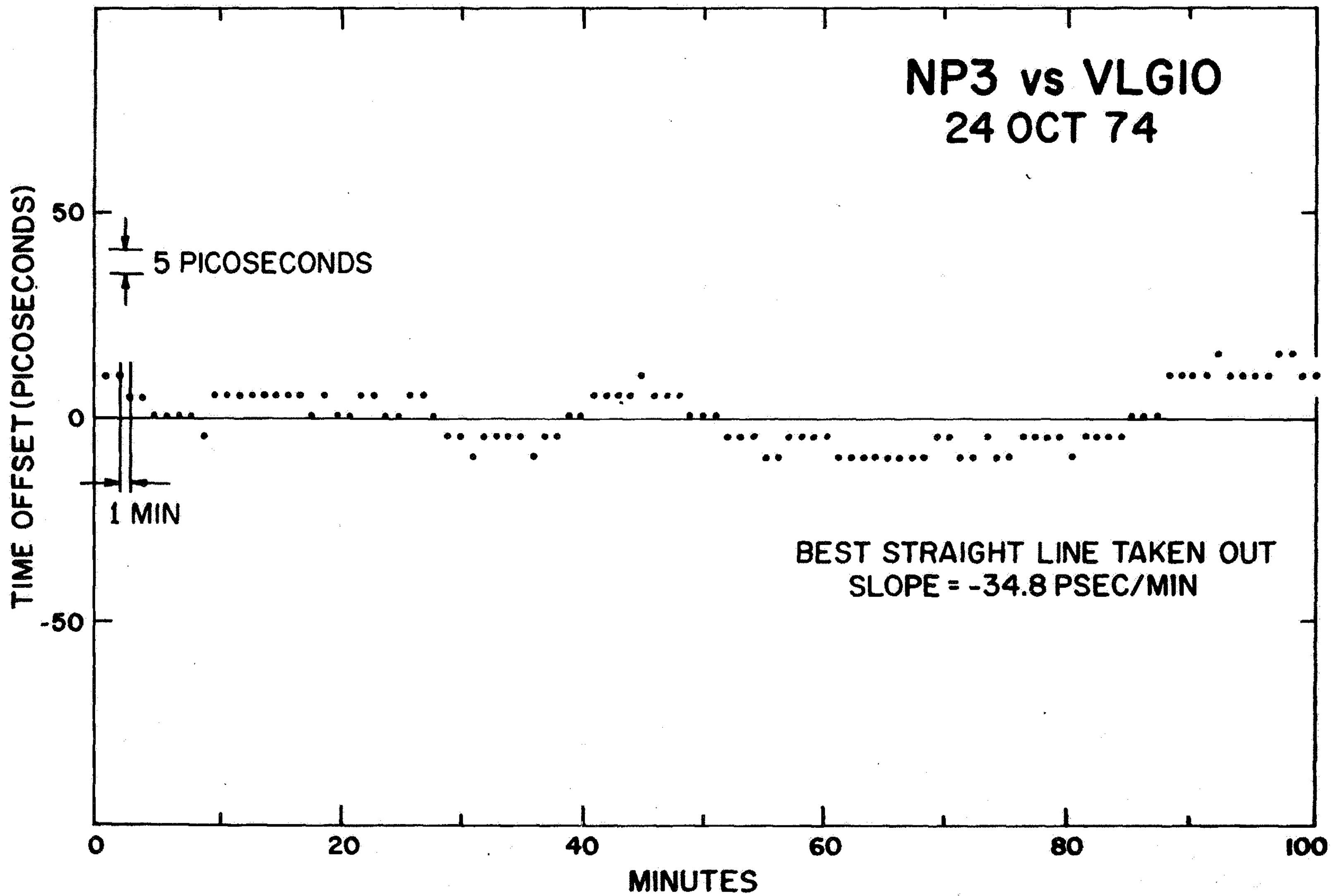

Figure 2. Selected period showing exceptional stability between two hydrogen-maser frequency standards. The 5-picosecond quantization is introduced by the computer program used to generate the graph.

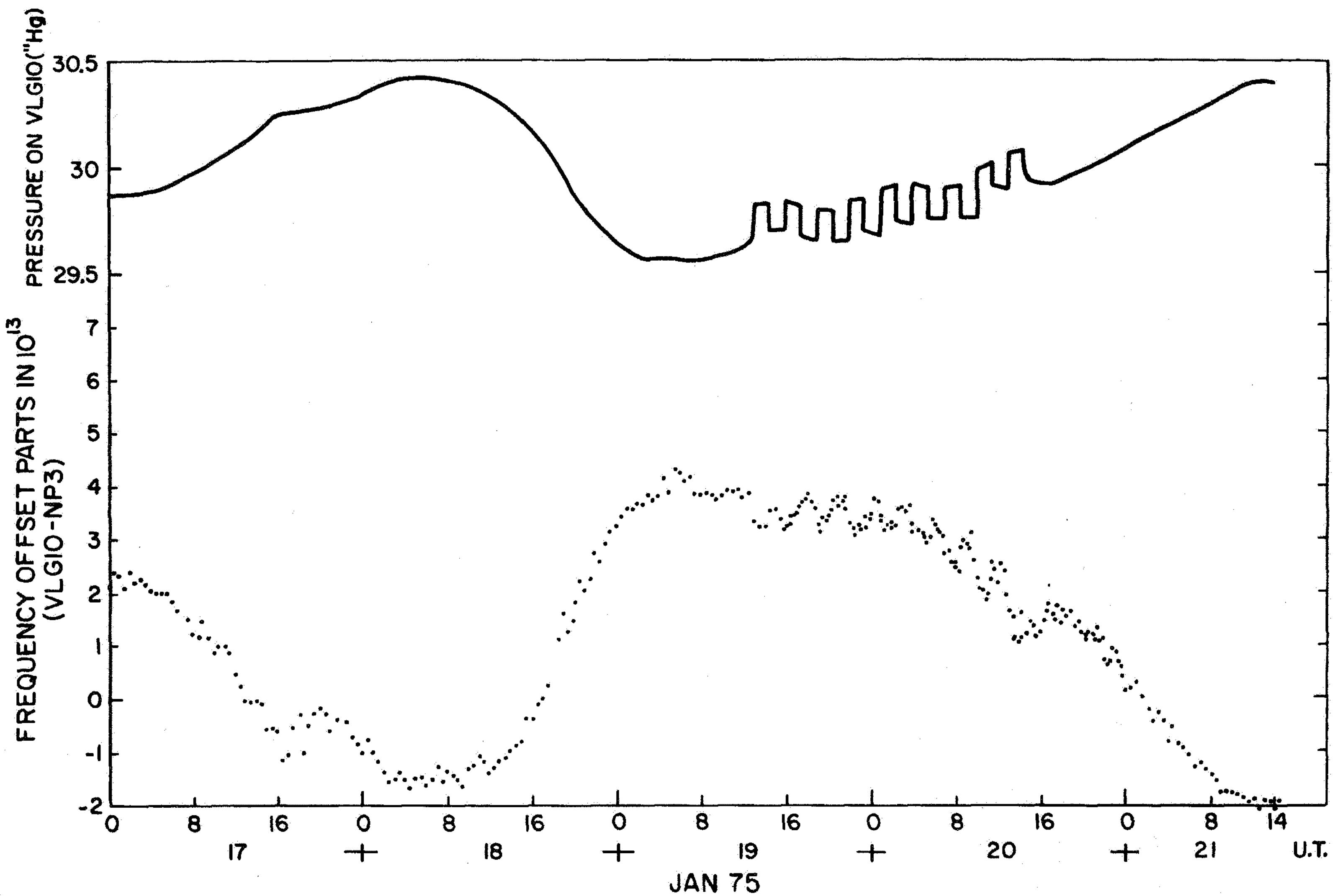

Figure 3. The effect of atmospheric pressure changes on the frequency offset between two hydrogen-maser standards with different sensitivities to pressure variations (see text).