CPEM '88 DIGEST

# IN SEARCH OF THE BEST CLOCK

by

David W. Allan, Marc A. Weiss and Trudi K. Peppler
Time and Frequency Division
Boulder, Colorado 80303

## ABSTRACT:

Because of the increased need for better clock performance than is currently available, this paper addresses some fundamental questions regarding clock metrology. Heretofore, most work has focussed on improving the clocks to meet the increased need. Though this is fundamental and will be addressed in the paper, we will also show that significant gains are available through the algorithms which process the clock readings and through international comparisons now available via satellite. Proper algorithms for processing seem to be more important than the proportionate attention generally given them. In fact, to date, the only way we have been able to investigate some of the long-term performance aspects of the millisecond pulsar, PSR 1937+21, is by using such optimization algorithms. Since there are indications in the pulsar data of variations which could be explained as arising from the influence of gravity waves, these long-term stability studies take on a new importance. Years of study will probably be necessary to confirm these initial indications, but clearly improved long-term stability of earth-bound clock systems would significantly assist this study.

## SUMMARY:

In the search for a best clock, we explicitly mean the clock with the best long-term frequency stability, which in turn can be shown to lead to the minimum long-term time dispersion. There are three important steps in time and frequency metrology for producing a best clock. Step one is to have an accurate primary frequency standard; the better the frequency accuracy the better will be the achievable long-term frequency stability. Step two is to have a precise and accurate method of accumulating the time intervals defined by the available frequency standards. Step three is the optimum use by some computer algorithm of the time differences among all the clocks involved and of the frequency calibrations with the primary frequency standards.

Since errors in clocks can be well modeled by systematic deviations and by random deviations, we optimally estimate the systematic deviations in the presence of the random deviations. We also estimate the characteristics of the random deviations in the presence of the systematic deviations. Because of this semi-circular nature of the error analysis in clocks, the combining computer algorithms have to be approached judiciously -- paying attention to confidence of the estimates and to correlations. That the systematic deviations are somewhat orthogonal to the random deviations assists in the tractability of the error analysis. One of the significant benefits of the output of step three is in regard to the random deviations: We have shown that the deviations of the optimally computed time and frequency are less than those of the best contributing member clock.

In studying the long-term stability of clocks there are now sufficient data available from high accuracy satellite time and frequency comparison techniques that we can view most of the best clocks in the world as if they were in the same laboratory. Therefore, we are now at a point in international time and frequency metrology that we can combine the time differences and frequency calibrations from the best clocks and frequency standards in the world and generate a "world's best clock" using an optimization algorithm. This study in long-term stability of clocks and of ensemble outputs using various algorithms has led to some very interesting findings -- including some possible causes of annual variations and of cross-correlations between clocks. The clocks studied were primary cesium beam frequency standards, hydrogen masers, mercury ion frequency standards and various commercial atomic clocks. All of the primary timing center's outputs, which are available to NBS via the Global Positioning System common-view measurements, were used in the study. The millisecond pulsar signal from PSR 1937+21 was used as well. The efforts to search for the "best clock" in this study have the advantage that post analysis better helps us characterize and deal with systematic deviations.

This investigation has been driven in large measure by the observed outstanding long-term clock performance of the millisecond pulsar, discovered in 1984. The millisecond pulsar has already turned out to be an extremely useful timing tool, and improving the performance of earth-bound atomic clocks has the potential for opening up several important measurements -- not the least of which is the measurement of gravity waves.

Theoretically, a perfect clock cannot be built, because of quantum mechanical limits in any given atomic resonance and because of the noise inherent in all physical systems. Even if we could imagine having a perfect clock, as soon as its time was transformed to some other frame of reference, the uncertainties of that transformation would limit the accuracy of its apparent reading. In addition, the interrogating electronics and associated measurement system(s) will also limit a clock's apparent performance. However, in counter-perspective, there is no known theoretical limit to how nearly perfect a clock or a clock system can be. This paper investigates both the performance of the best clocks known, as well as some ways to gain significant improvements. We show that steps one, two and three, properly combined, help considerably in moving us toward the ideal clock.

Since the construction of the first atomic frequency standard, the accuracy of determining an atomic resonance for step one has improved by about an order of magnitude every seven years. This trend is expected to continue, and we should be prepared to take advantage of the new standards as they become available. In dealing with steps two and three it is necessary to deal with not only the stochastic behaviors of the contributing clocks, but also with their systematic behaviors, for example, sensitivities to environmental perturbations, frequency drifts, frequency offsets, time offsets and correlated effects.

The figure shows the estimated frequency stability of the millisecond pulsar and of the output of the NBS time scale algorithm. With longer averaging times, improved frequency standards and optimum combining algorithms, the resulting long-term stability improvements should prove beneficial. To date, our search for the "best clock" has already paid significant dividends.

MILLISECOND PULSAR VERSUS UTC(NBS) AND AN ESTIMATE OF THE STABILITY OF THE NBS TIME SCALE ALGORITHM'S OUTPUT

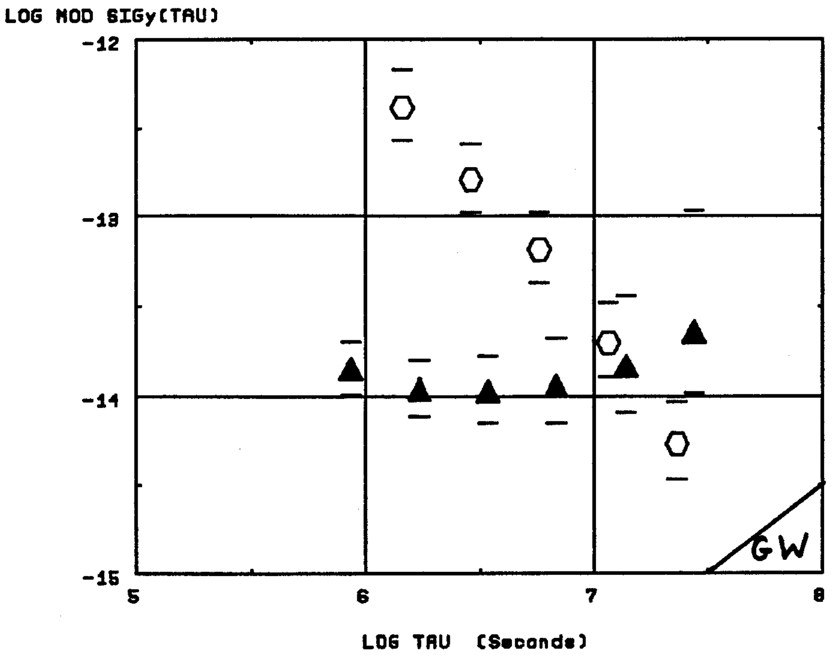

Fig. 1 The data plotted as the open hexagons are the fractional frequency stabilities calculated from the square root of the modified Allan variance of the millisecond pulsar, PSR 1937+21, versus UTC(NBS) for the period October 1984 through February 1987. The data plotted as the solid triangles are the stability estimates of the NBS time-scale algorithm's output with respect to the world's "best clock" calculated using the same algorithm for the period 29 February 1984 through 23 June 1987. Also plotted is an indication of the estimated level at which gravity waves (GW) might be observed.