EVOLUTION OF THE INTERNATIONAL ATOMIC TIME TAI COMPUTATION

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ABSTRACT

The International Atomic Time TAI is a worldwide time reference. Its computation has changed during the last 10 years. Further changes would essentially depend on the improvement of the atomic clocks.

The International Atomic Time TAI as computed by the Bureau International de l'Heure (BIH) is a worldwide time reference officially adopted in 1971 [1]. It has been made available for the scientific community for 24 years. The time signals transmit Universal Time Coordinated UTC which is closely related to TAI. The TAI computation has involved atomic clocks, comparisons between the clocks and mathematical algorithms. It is intended to outline the main recent changes concerning the above three points and to have a look to some future possibilities of computing TAI.

Atomic clocks

The computation of TAI has been performed from the data of cesium clocks*. Some significant modifications, quantitative as well as qualitative, must be noted in the devices involved in it over the last decade as shown by the Figure 1. In 1962, about 45 commercial cesium clocks entered this computation, all of them being manufactured by the Hewlett-Packard company-models 5060A and 5061A-. The Hewlett-Packard option 4 clocks were introduced into the TAI clocks ensemble at the end of 1972. Then the introduction of the Oscilloquartz

* Data from other devices with cesium comparable performances could be used.

cesiums -model OSA 3200- led to an interesting deversification of this ensemble. Nowadays, in 1979, TAI is composed of about a hundred cesium clocks. On the other part, three laboratory cesium clocks have been used in the computation of TAI: the NRC-CsV of the National Research Council since May 1975 [2], the NBS-4 of the National Bureau of Standards since the end of 1975 [3] and more recently the PTB-CS1 of the Physikalisch-Technische Budesanstalt [4]. These clocks offer at the same time * very good stability for sample times up to several months and excellent accuracy.

Time intercomparisons between clocks

The time intercomparisons between distant clocks play an important role in the computation of TAI. In 1979, as 10 years before, the LORAN system ensures the connection between the clocks of various laboratories ; so the international time TAI appears strongly dependent on the qualities and defects of this system. The LORAN transmissions delays change with respect to time and they have to be calibrated from time to time by the clock transportations results. The US Naval Observatory carries out most of these transportations, especially between America and Europe ; it allows to limit the inaccuracy of the LORAN time comparisons down to about 1 microsecond, the precision being of the order of 300 nanoseconds or better. Many experimental time intercomparisons were performed during the last decade using satellites [5]. The NTS campaign results [6] showed interesting promises for the Global Positioning System; an inaccuracy of less than 100 nanoseconds is expected. Some precise time comparisons were performed between 2 or 3 laboratories through the satellites ATS-1 [7], Hermes and Symphonie [8]; precisions up to a few nanoseconds were obtained on a regular basis. As soon as precise time comparison results via a satellite system are routinely available, they will be used to compute the TAI.

Computation of TAI

From 1969 till 1979, the TAI computation was concerned with two main concept changes. The first one took place in 1973 as a conse-

*The NBS-4 works either as a clock or as a frequency standard.

quence of the 1972 Consultative Committee for the Definition of the Second (CCDS) meeting. A new TAI algorithm was implemented where each clock participates with a weight which is a function of its past and present frequency* . On a practical point of view, the mean frequency of each clock over a two-month interval is computed with respect to TAI ; and the weight of a clock is proportional to the reciprocal of the variance of 6 mean frequencies : it takes into account the changes of frequency or, generally speaking, the short term instability of the clock. The other change is concerned with the accuracy concept. The laboratory cesium standards give the best realization of the SI (International System) second. Their improvement has been quite remarkable during the last decade; in 1976, their accuracy capability was of the order of 1×10^{-13} or better and three laboratory cesium standards at NBS, NRC and PTB agreed that the frequency of TAI was too high by 10^{-12}. The International Astronomical Union, in 1976, recommended that the TAI frequency be corrected by exactly -10×10^{-13} on 1977 January 1. This adjustment was made and was the first direct input of the laboratory standards on TAI.

Taking into account the uncertainty of 1×10^{-13} of the laboratory standards and the possible change of the TAI frequency by 1 to 2×10^{-13} per year (already observed) if TAI is solely based on commercial cesium clocks, one comes to the conclusion that rather frequent adjustments of the TAI frequency could be required in order to avoid significant errors. It was recognized that a frequency steering by frequent small adjustments (of the same order as the variations which can be expected from random noise) were better than noticeable corrections at less frequent intervals. The implementation of the steering was recommended by the Consultative Committee for the Definition of the Second in April 1977 and it was immediately put into effect.

The current computation of TAI results from these concepts and is carried out in two steps as shown by the Figure 2. The first step introduces the short term stability concept. The algorithm ALGOS computes a "free" time scale from the data of the cesium clocks running independently from each other. The second step introduces the accuracy concept. Starting from the laboratory cesium standards

*the term frequency is used instead of normalized frequency a frequency reference is obtained through the algorithm A. The inaccuracy of the "free" time scale is measured with respect to the reference and is partially corrected through a defined procedure. The correction of the inaccuracy leads to an improvement of the long term stability. The choice of the correction procedure is important to avoid any stability deterioration of the "free" time scale.

From now on

A worldwide time reference must be a) available for the users - b) reliable so that it is not upset or stopped by any local incident - c) stable for any sample times, i.e. uniform - d) accurate with respect to the SI second. The fulfillment of these qualities is strongly dependent on the clocks which are or could be involved in the TAI computation.

The current situation is given by the Figure 3. A hundred commercial cesium clocks contribute mostly to the availability, reliability and short term stability while the accuracy and long term stability are ensured by the 3 laboratory cesium clocks and 1 laboratory cesium standard. Development of new laboratory cesium clocks, such as the NRC-CsVI ones, is in progress. They are the first metrological devices for specific time purposes featuring stability and accuracy qualities. It could be imagined that a new situation for the TAI computation would arise when a large enough number -may be 6? - of such units would be running in various laboratories. It would be wise to utilize these devices to fulfill the stability and accuracy qualities as shown by the Figure 4. The commercial cesium clocks would ensure the availability and the reliability of TAI.

Another potential situation would appear if some clocks were developed whose stability in a limited range of sample times would be better than that of the cesium clocks -it could be, for example, H-masers (passive) [9] -. In this case, the qualities of availability reliability, stability and accuracy would be fulfilled by three various kinds of clocks: commercial cesiums, superstable clocks and laboratory cesiums as Figure 5 indicates. There would be a clear similitude between this last situation and the current one.

The TAI results from the combination of the data of atomic clocks and/or standards. In the past decade, two changes occurred coming first from the algorithm itself and then from the introduction of the laboratory cesium standards data. Different modifications are possible in the future.

References

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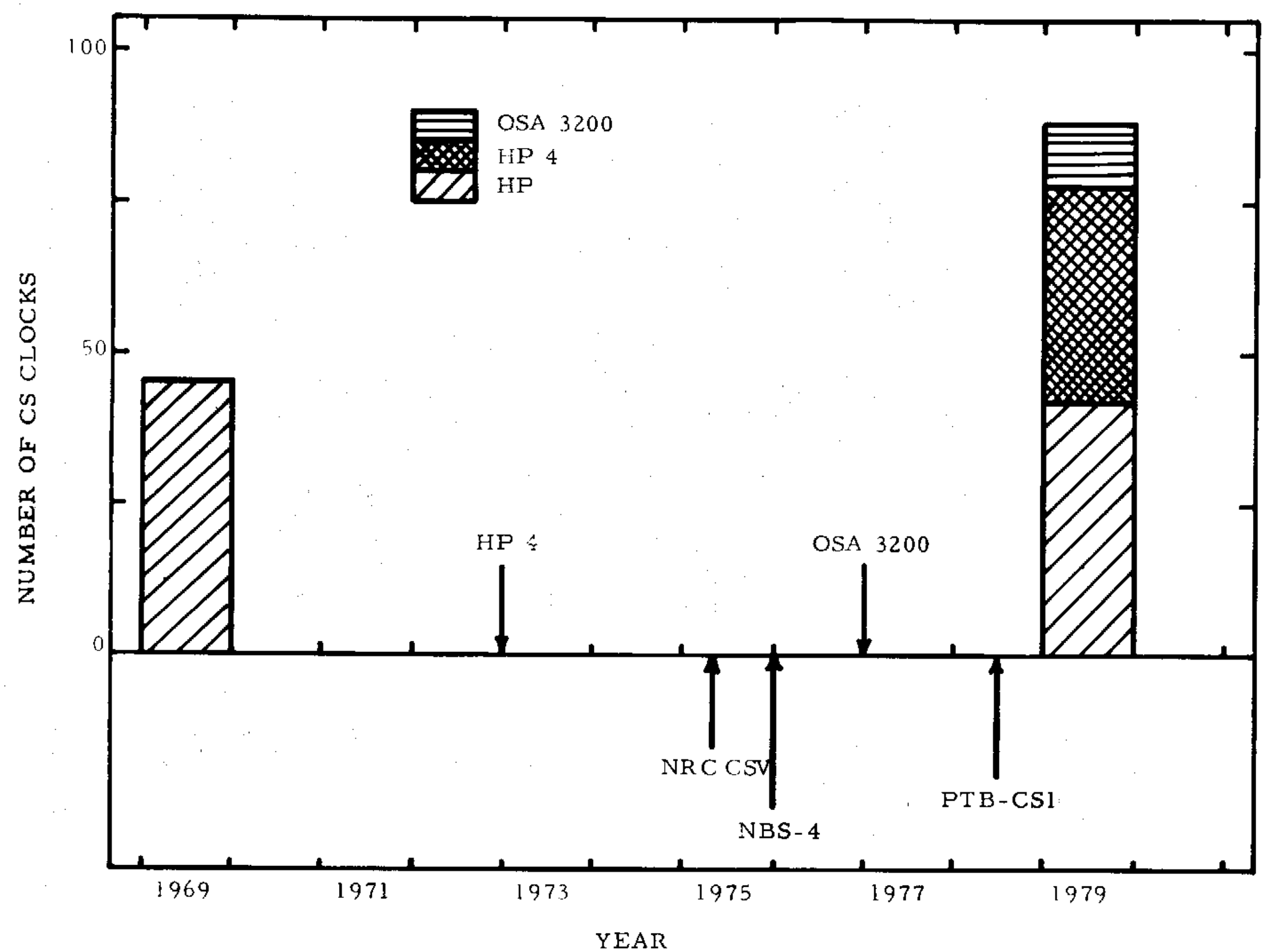

Figure 1. The Clock Ensembles of TAI in 1969 and 1979 are Shown and the Introduction of the New CS Clocks, Commercial and Laboratory. The Abbreviation HP 4 Means Hewlett–Packard Option 4 and OSA 3200 is the Oscilloquartz Model 3200.

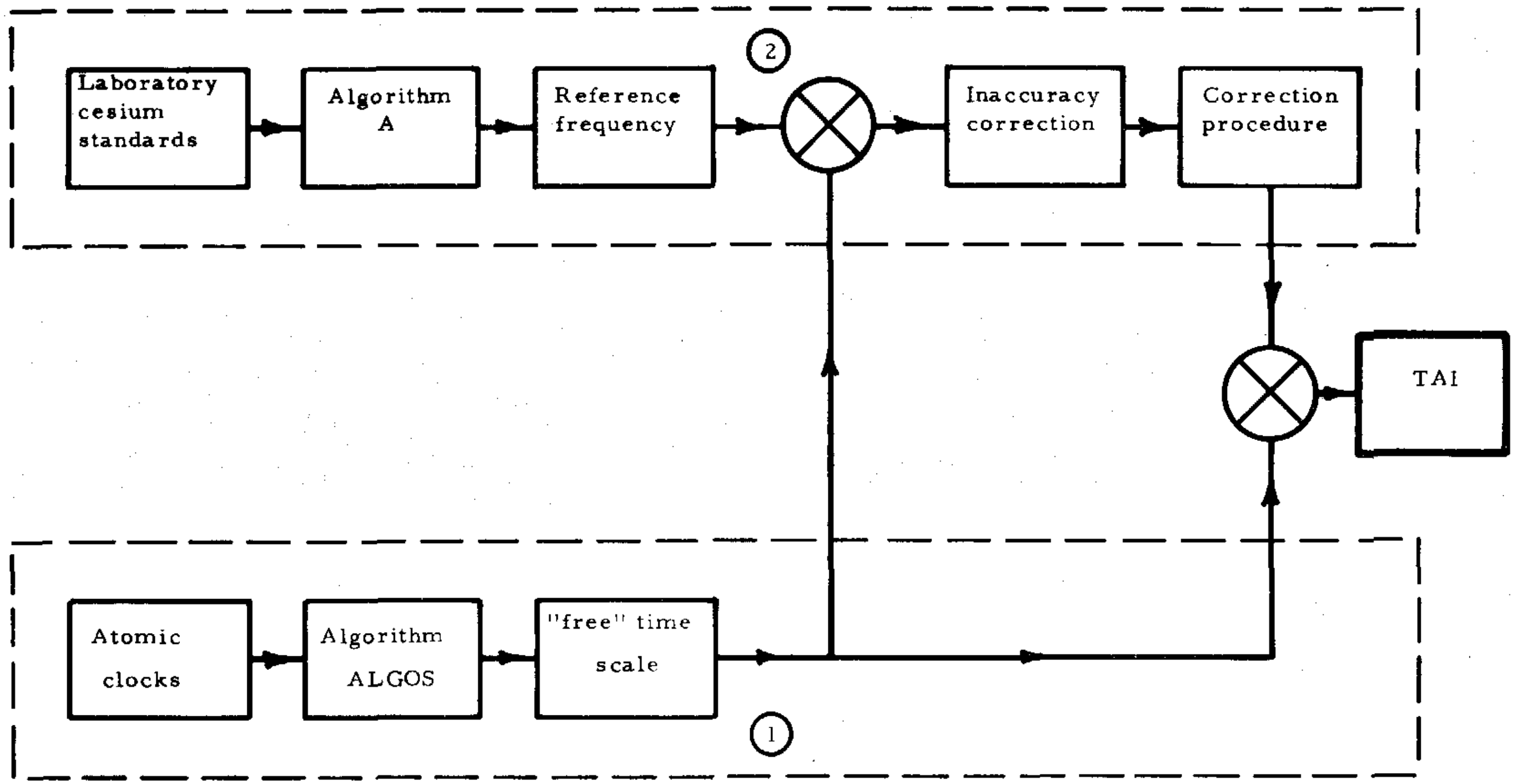

Figure 2. Schema of the TAI Computation in 1979. The Numbers 1 and 2 Refer to the Two Steps of the Computation

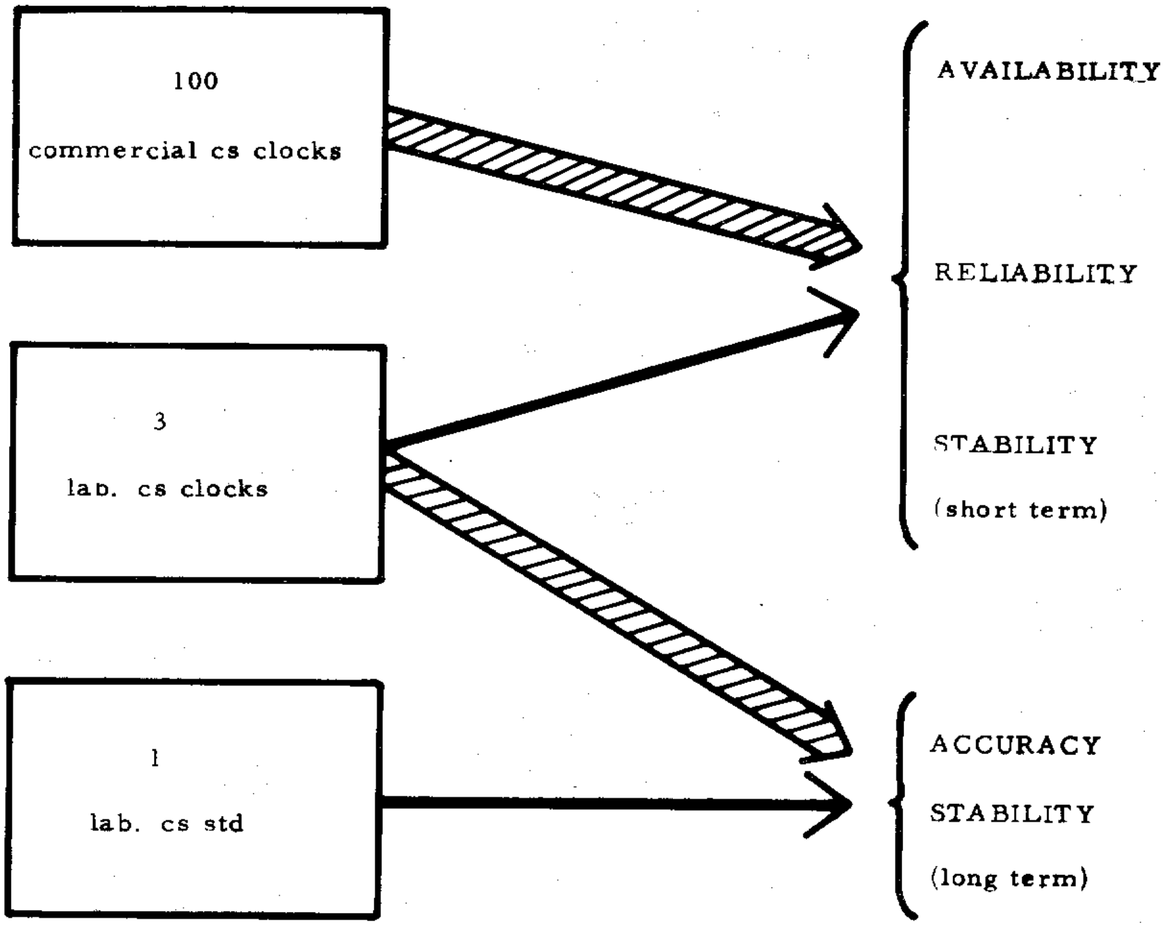

Figure 3. Current Computation of TAI. The Links Between the Available Devices and the Qualities Which are Looked for TAI are Shown. A Wide Line Indicates an Important Connection.

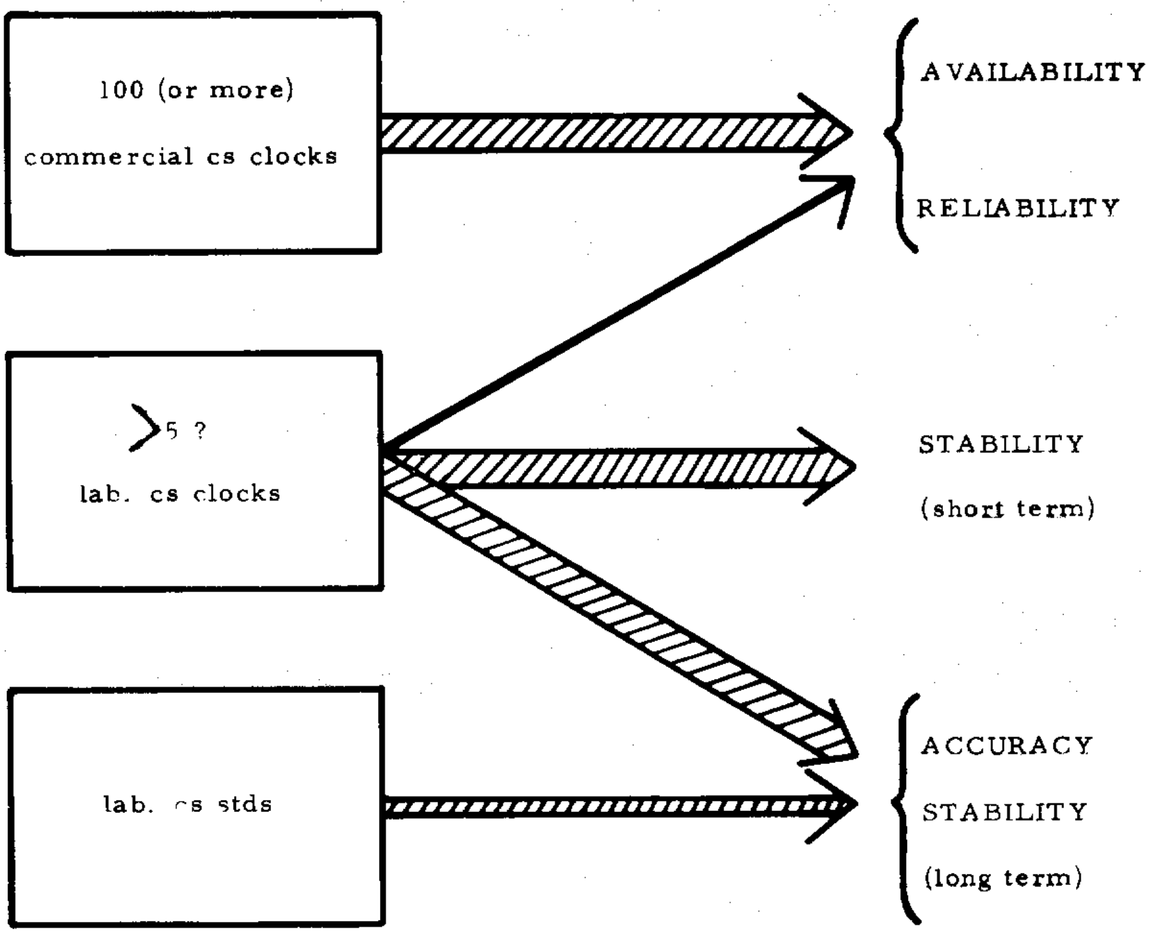

Figure 4. Foreseeable Computation of TAI. The Links Between the Available Devices and the Qualities Which are Looked for TAI are Shown. A Wide Line Indicates an Important Connection.

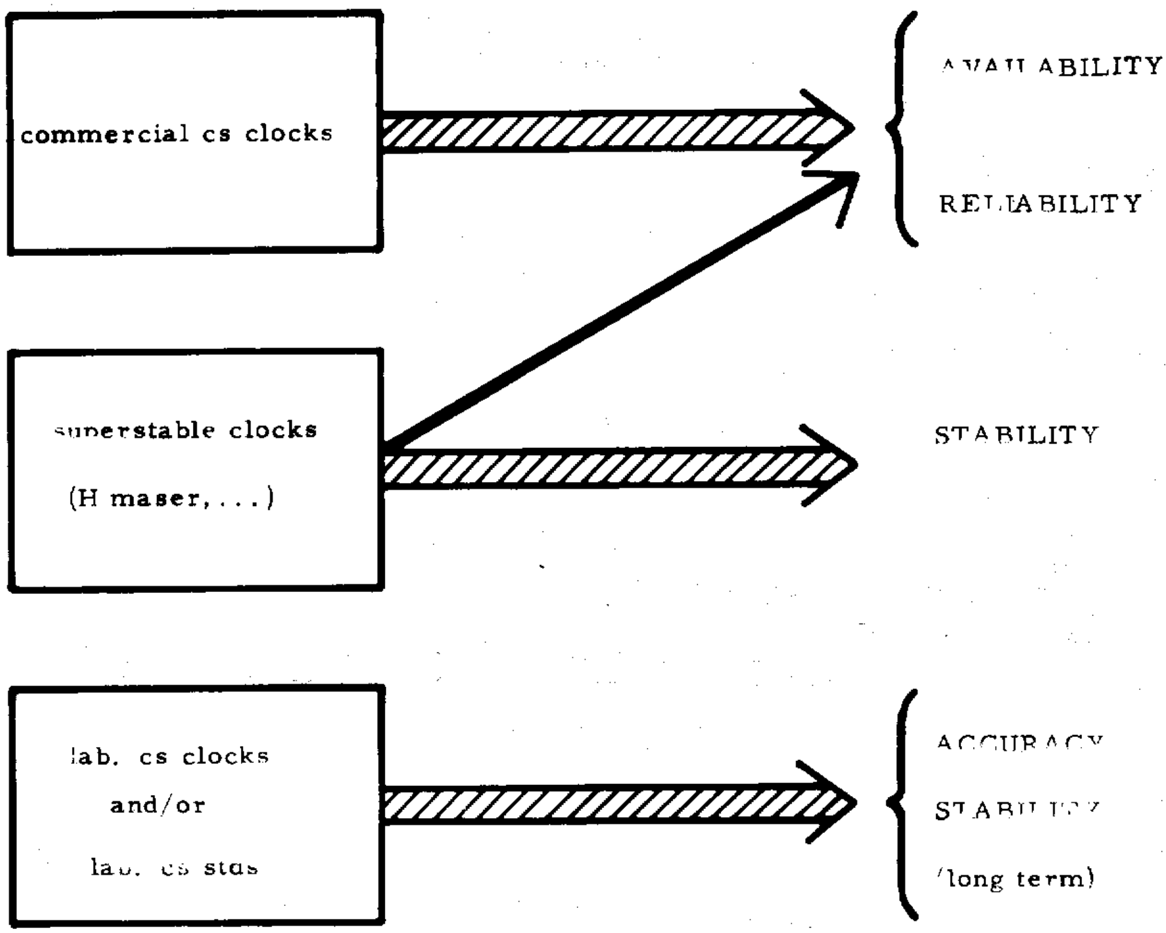

Figure 5. Potential Computation of TAI. The Links Between the Available Devices and the Qualities Which are Looked for TAI are Shown. A Wide Line Indicates an Important Connection.

QUESTIONS AND ANSWERS

DR. STEIN:

You made the distinction between, I think, what you called the laboratory cesium standard and, a laboratory cesium clock. Is that intended to represent the difference between a device which runs all of the time and a device which runs only a small fraction of the time?

DR. GRANVEAUD:

Yes.

DR. STEIN:

In that case I think it is probably important to add to your view of the future the fact that the kinds of developments that are going on right now in the cesium standard area will result in devices with full accuracy that is achieved without any interruption in the operation.

DR. GRANVEAUD:

Yes.