Synchronization of Two Remote Atomic Time Scales*

Any time scale in use at present is generated from the combination of two basic functions. First is provision of some periodic phenomenon (frequency standard) to serve as the prototype for the unit length of time. Second is the addition of a means for counting the number of cycles (cycle accumulation) executed by this periodic phenomenon. Before the appearance of crystal oscillators and atomic clocks, these elements commonly took the form of 1) the pendulum, and 2) the escapement driving the hands. An atomic clock requires the same elements but they appear in different form: 1) a quartz crystal oscillator whose frequency of oscillation is controlled by an atomic transition, and 2) various electronic dividers and comparison circuitry.

Since October 9, 1957, the National Bureau of Standards has maintained an atomic time scale (NBS-A) in which the atomic transition is that of the United States Frequency Standard (USFS) at the Boulder Laboratories of the NBS. From October 9, 1957, until April 24, 1963, time accumulation for NBS-A was performed near Washington, D. C., by the same quartz crystal oscillator and electronic dividers which produce time pulses for the broadcasts of radio station WWV. As described previously,[1] atomic times were assigned to WWV pulses on a daily basis. The atomically-controlled WWV broadcast is set to agree closely with Universal Time, which is presently falling behind atomic time at the rate of 130×10^{-10} sec/sec. Therefore, during this time, NBS-A consists of a record of the lateness of WWV time pulses relative to an ideal clock referenced to the cesium frequency taken as 9,192,631,770.00 · · · cps. NBS-A was set to be coincident with the A.1 time scale[2] of the United States Naval Observatory, Washington, D. C., on January 1, 1958.

In July, 1962, a time-accumulation system composed of quartz crystal oscillators, dividers and synchronous clocks was put into operation in a laboratory adjacent to the USFS in the Boulder Laboratories of the NBS. Since the oscillators are controlled by the USFS, this system provides an improved method of maintaining atomic time, as well as bringing both elements of the clock to the same location. The entire system has proved capable of operation without interruption since its beginning and should be capable of continuous operation indefinitely. Since high-frequency radio propagation introduces uncertainties of an appreciable fraction of a millisecond in comparison between the time pulses from WWV and those from the Boulder atomic time scale, a more precise method was used to synchronize the two scales. This was done on April 24, 1963, by transporting a high-precision quartz clock from Boulder, Colo., to the WWV transmitter at Greenbelt, Md. (near Washington, D. C.), and returning it to Boulder in order to observe directly the time difference between the two time scales.

TABLE I

Transmitter and Location	Receiver Location	Propagation plus receiver delay measured by portable clock	Theoretical delay*
Loran C Cape Fear, N. C.	U. S. Naval Observatory	1839±5 μsec	1840 μsec†
Loran C Cape Fear, N. C.	NBS, Boulder, Colorado‡	8489±10μ sec	8492 μsec‖
Loran C Cape Fear, N. C.	WWV Greenbelt, Md.	——	1855 μsec ‖
WWV Greenbelt, Md.	U. S. Naval Observatory	316±50 μsec	——
WWV Greenbelt, Md.	NBS, Boulder, Colorado	9008±50 μsec	9.23 msec§

* These delays include the measured receiver delays involved in the total delay.
† Adopted by the U. S. Naval Observatory.
‡ This includes a microwave link from the receiver at Table Mesa to the NBS Boulder Laboratories.
‖ Secondary phase factors based on National Bureau of Standards Circular No. 573.
§ NBS Tech. Note No. 22.

Measurement of the time of occurrence of the Boulder time scale pulses before and after the trip agreed to within 5 μsec. It may then be concluded that on April 24, 1963, the Boulder time scale was brought into synchronism with the Washington time scale within these limits. Since this date the Boulder clock is taken as the clock of the National Bureau of Standards which maintains the atomic time scale NBS-A. The Washington time scale will assume a subordinate position, relatable to the one at Boulder by future clock carrying or observation of various pulse reception times.

Another type of time signal broadcast, with microsecond timing capabilities in the ground wave propagation region, is the East Coast Loran C system with a master station near Cape Fear, N. C., whose time signals are controlled by the U. S. Naval Observatory. In order to make additional checks of the WWV time pulses relative to the NBS-A time scale, and to make propagation and receiver delay measurements using Loran C signals, the portable clock was also taken to the U. S. Naval Observatory and to the master Loran C transmitter. Since there is no Loran C receiver as yet at the WWV transmitter, the propagation delay of the Loran C signals at the WWV transmitter could not be measured. The results of the clock-carrying experiment are summarized in Table I. The uncertainties shown for the measured values are due to the uncertainties in the portable clock (±5 μsec) and fluctuations (primarily due to propagation) in the time pulses as received. In addition to measuring some propagation and receiver delays of the Loran C signals, it was determined that the emission of the Loran C signal was 1247±5 μsec after the emission of the WWV seconds pulse on April 24, 1963.

Since the Loran C signals are received both at Boulder and the U. S. Naval Observatory, it is now possible to tabulate rather precisely an absolute time difference between the two atomic time scales, A.1 and NBS-A, by noting the arrival times on the respective time scales available at each place, and correcting for the receiver and propagation delays.

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[1] J. Newman, L. Fey, and W. R. Atkinson, "A comparison of two independent atomic time scales," Proc. IEEE (*Correspondence*), vol. 51, pp. 498–499; March, 1963.
[2] W. Markowitz, "Time measurement techniques in the microsecond region," *Engineers Digest*, pp. 9–18; July–August, 1962.

Power Output of the 6328 Å Helium-Neon Maser as a Function of the Resonant Cavity Length*

The mode density in a gaseous optical maser employing spherical mirrors is proportional to the mirror separation and to the effective beam cross-sectional area. At high mode density (*i.e.*, large mirror separations and/or large tube diameters) where the mode spacing is presumably smaller than the natural linewidth of the maser transition, competition exists among the modes for the same inverted population. In this situation, the gain of the medium is uniformly saturated, and one expects the total power output to be independent of the mirror separation.

In the case of a short maser operating in the lowest order transverse mode, the separation between longitudinal oscillating modes may be large compared to the natural linewidth of the maser transition; thus, an increase in mirror separation would be accompanied by an increase in power output until uniform gain saturation occurs when the mode spacing approaches the transition linewidth.

In order to study the dependence of power output on mirror separation, a 46-cm long, 6-mm ID 6328 Å maser tube provided with movable external mirrors of 10-meter radii was constructed.

Two sets of measurements were made. In the first set, the total power of all transverse

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