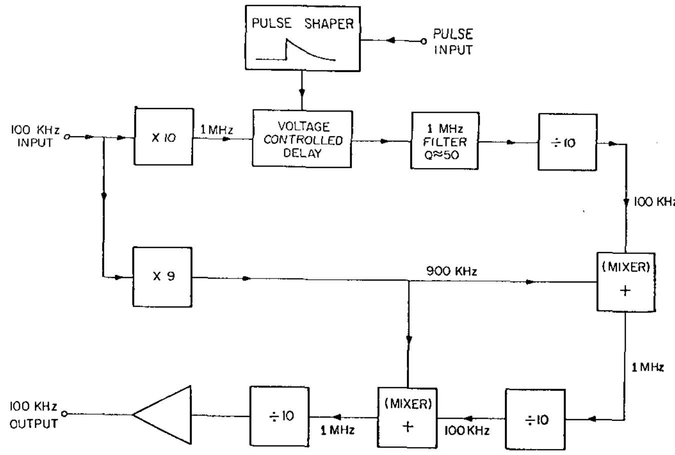
A Precision Pulse-Operated Electronic Phase Shifter and Frequency Translator

Since 1956, the definition of the unit of time (the second) has been in terms of the Ephemeris second, which must be determined by astronomical means. In October, 1964, the cesium beam was adopted internationally as an alternate standard to realize the unit of time. The frequency assigned to the appropriate atomic transition of cesium 133 was set at 9 192 631 770 Hz. However, all standard frequency and time transmissions, which are coordinated through the International Time Bureau (BIH) in Paris in accordance with CCIR regulations, do not presently broadcast the physical unit of time (the second).

Historically, this situation came about because one of the primary uses of precise time was in terrestrial (as opposed to space) navigation. In effect, what was needed could be more closely correlated with the Earth's angular position relative to the sun, rather than with an absolutely uniform time scale. Navigators (more specifically terrestrial navigators) had been accustomed to using a time scale called UT-2, which is essentially "mean solar time" corrected for a few known perturbations. To satisfy this need, the frequency of the "pendula" controlling the "time" markers of coordinated broadcasts has been slowed down to make the broadcast signals keep in approximate step with UT-2. Occasionally, steps of 0.1 second are also added when the UT-2 scale drifts outside of the predicted value. During 1965, the frequency offset of -150 parts in 10^{10} was incorporated in all coordinated broadcasts.[1] The value for 1966 is -300 parts in 10^{10}. According to CCIR regulations, these offsets are now restricted to an integral multiple of 50 parts in 10^{10}.

Thus, for a synchronous clock operating from an exact 100-kHz reference, the phase must be retarded at the rate of about one cycle per 5.5-minute interval for the -300×10^{-10} offset. Such slow phase shifts have normally been accomplished by electromechanical devices incorporating a resolver-type phase shifter. These devices being motor driven are notoriously wasteful of power and not nearly as reliable as solid-state electronics. Practically, one may realize a linearity with a resolver of about ±0.5 percent of one cycle or about ±50 ns for a 100-kHz signal. Because of these considerations, an all solid-state phase shifter was considered very desirable by the authors.

The heart of the phase shifters currently being used in the Atomic Frequency and Time Standards Section of the Radio Standards Laboratory of the National Bureau of Standards consists of a voltage variable delay line, a narrow-band filter, and a pulse shaper. The voltage variable delay line is a series of inductors, shunted to ground by a set of voltage variable capacitors (back-biased diodes work well) in a typical lumped-constant delay line fashion. A total of ten sections for the delay line has been used in the prototype models, which were designed to operate at 1 MHz.



$\Delta\phi=10$ ns/pulse

Fig. 1. Precision pulse operated phase shifter.

With a 1-MHz signal supplied to the delay line and the output signal fed to a narrow-band filter ($Q\approx50$), a voltage pulse is suddenly applied (risetime$\sim$0.1 μs) to the delay line. The amplitude of the pulse is so chosen that the delay is reduced by very nearly one microsecond. Due to propagation delays along the delay line for this pulse, the distortion in the output of the delay line persists for only about 1.5 μs for the prototype units. Since the duration of this perturbation is quite small relative to the reciprocal bandwidth of the filter, the output of the filter is essentially not disturbed by this process. Indeed, minimum variation in the amplitude of the 1-MHz signal from the filter is a reasonably sensitive criterion for pulse amplitude.

By now allowing the voltage on the delay line to slowly decay to its steady-state value, the frequency out of the delay line may be maintained within the bandpass of the filter, and thus exactly one cycle has been subtracted from the output signal in a smooth and continuous fashion relative to the input. In the prototype units constructed, the decay time of the pulse was set at 3 milliseconds, and thus the signal averages about 300 Hz off from the 1-MHz input during the decay time.

The generation of submultiples of this one cycle of phase is accomplished by using what amounts to a frequency error-multiplier run in reverse. First the 1-MHz signal out of the filter is divided to 100 kHz, which also divides the one cycle of phase shift by ten. That is, the steady-state phase shift of this 100 kHz is exactly $2\pi/10$ for each pulse supplied to the delay line. By mixing this 100-kHz signal with a 900-kHz signal derived from the input signal to the device, a new 1-MHz signal is obtained with phase shifts of exactly $2\pi/10$ or 0.1 μs for each pulse supplied to the delay line. Thus, by an iteration of frequency dividers and mixing with a signal that is phase coherent with the input, very precise submultiples of the one cycle of phase shift may be generated. A block diagram of an electronic phase shifter is shown in Fig. 1.

The limitations in accuracy of the phase shifts arise from the fact that there are several high "Q" circuits operating at essentially the same frequency, and hence "pick up" of a signal in a later stage can cause minor phase perturbations. By careful construction and shielding, it has been demonstrated at the National Bureau of Standards that a system similar to the one described here may be built such that accumulated phase perturbations are less than 0.01 percent of one cycle.

It remains now only to construct a pulsing circuit from a clock to pulse the phase shifter at the proper rate to generate the desired frequency offset.[2] Obviously, depending on the need, the granulations in this phase shifting process may be chosen for the particular application. The prototype units constructed at the Bureau generate ten nanosecond steps in the phase, and thus a series of pulses adjustable from 0 to 10 pulses in a two-second interval in steps of one pulse per two-second interval allows a wide choice of useful frequency offsets (0 to -500 parts in 10^{10} in steps of 50 parts in 10^{10}). While the output signal cannot be considered monochromatic, there are many applications where the granular nature of the phase is not significantly important (e.g., running a clock where precision of better than ten nanoseconds is not needed.

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[1] During the previous calendar years, the following offset frequencies have been used: 1959, -170×10^{-10}; 1960, -150×10^{-10}; 1961, -150×10^{-10}; 1962, -130×10^{-10}; 1963, -130×10^{-10}; 1964, -150×10^{-10}.

[2] R. C. Cumming, "Serrodyne frequency translator," *Proc. IRE*, vol. 45, pp. 175–186, February 1957.

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