Time and Frequency Control

A new time and frequency monitor and control system for shipboard use is now under development by the Bureau of Ships. The accuracy of time and frequency required by the Fleet has increased steadily, and the need for more efficient and reliable use of the radio spectrum has resulted in communication systems requiring close frequency control. The advent of supersonic aircraft, missiles and space vehicles has made time and frequency synchronization essential, both for position determination and speed of communication.

For many years, the Navy has been involved in developing precise techniques and devices for accurately generating and determining frequency and time. Since the 1830's, the Naval Observatory has been responsible for determining time for the United States. Time signals were first broadcast from Boston Navy Yard in 1904, and the U. S. Naval Radio Station, Arlington, Virginia, began the first regular time broadcast in 1913.

The Naval Research Laboratory has collaborated with the Naval Observatory in developing electronic instrumentation and techniques for precise frequency control and millisecond timing. In the late 1920's the Naval Research Laboratory conducted studies of the international transmission of precision frequency signals at 20 mc. For approximately 40 years, the laboratory has been developing new techniques for measuring and producing electrical waves of accurate and constant frequency

Through close cooperation between the Naval Research Laboratory and the Bureau of Ships, the crystal oscillator has been developed to the point where naval applications for highly precise frequency determination and control are feasible. By applying precise quartz oscillators of advanced design, disciplined by invariant atomic resonance frequency standards, the existing VLF transmitters can be stabilized to provide extremely accurate frequency and time information to U. S. Navy units around the world.

Naval Observatory Time

The Naval Observatory determines three basic kinds of time: universal time (Greenwich mean time) from the rotation of the earth on its axis, ephemeris time from the revolution of the moon around the earth, and atomic time from the operation of atomic clocks. Universal time is divided into three types--UTO, UT1 and UT2. The type transmitted is UT2 from which standard time is derived. Standard time differs from UT2 by an integral number of hours. Sidereal time, determined from the position of stars, is related to universal time and occurs in two forms --true and mean sidereal. Thus, the Naval Observatory publishes data for determining seven different types of time.

Because of variations in the speed of the earth's rotation, universal time is not uniform as judged by atomic time. However, universal time is required when the rotational position of the earth on its axis must be known, as in celestial navigation, geodetic surveying, and tracking of satellites.

Time and Frequency Determination

Time determination must provide a reference moment, or epoch, to which the beginning of a time measurement can be referred, and which must be definable in terms of a natural phenomenon common to all observers; for instance, a particular date; and in terms of a basic unit of time interval in which elapsed time can be expressed; for instance, the second.

Frequency, by definition, is dependent upon time. Conversely, generators of constant frequency can be used to define periods for short time measurements and to drive time integrators or clocks for long time measurements. With the advent of the atomic resonator, constant or invariant frequency can be produced for measuring elapsed time in terms of a basic physical phenomenon.

Atomic time (A.1 system) is based on the resonance frequency of cesium. The cesium beam atomic resonator was developed at the National Physical Laboratory (NPL) in England in June 1955. A joint experiment was started with the U. S. Naval Observatory to determine the frequency of cesium in terms of the second of ephemeris time, which is provided by the dual rate moon camera.

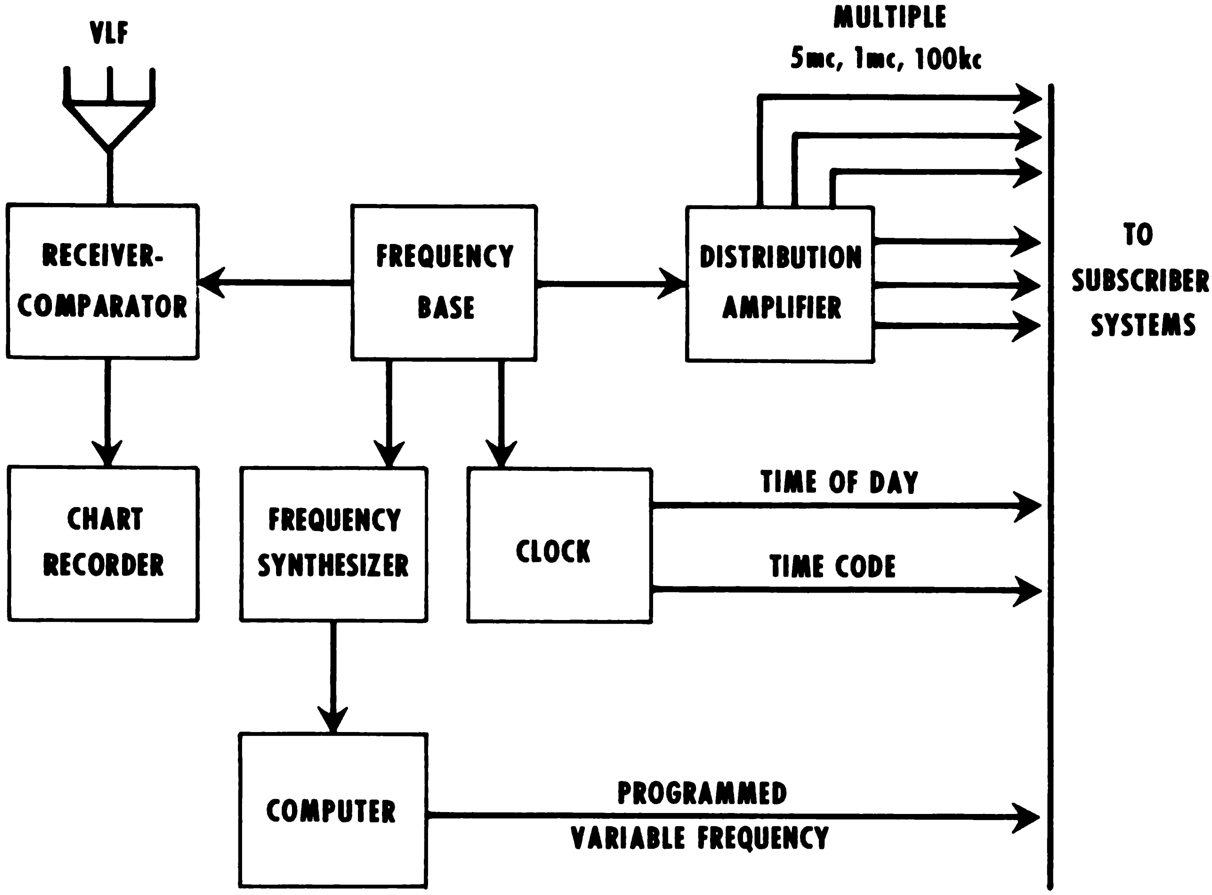

Figure 1. Block diagram of proposed time and frequency monitor and control system.

The fundamental unit of time, the second, was redefined in October 1956 by the International Committee of Weights and Measures to equal the second of ephemeris time. Until then, the second of mean solar time had been the fundamental unit of time. Dr. L. Essen of NPL determined the frequency of the cesium beam unit to be 9,192,631,830 ± 10 cps in terms of the 1955 second of universal time (UT2) known as Greenwich mean time. Subsequent data taken at the U. S. Naval Observatory indicate the frequency is 9,192,631,770 ± 20 cps in terms of the second of ephemeris time (ET). This frequency study is continuing.

A cesium beam atomic resonator controls the rate, or frequency, of the Naval Observatory master clock. The frequency is stable over several months to about ± 1 part in 10^{10}. It is stable from day to day within a month to about ± 1 part in 10^{11}.

The master clock is a combination of atomic resonator, quartz crystal oscillator and clock movement. It is an atomic clock in the sense that time is shown in hours, minutes, seconds and fractions, and the rate is governed by oscillations produced by the cesium atom.

Cesium beam resonators of various types have been placed in operation in several countries. The frequencies have been found to be the same to about ± 1 part in 10^{10}. To increase the precision of the A.1 system, the Naval Observatory receives reports on nine cesium resonators at various locations here and abroad. Frequencies are compared by monitoring the phase of VLF transmissions. The rate of the master clock is thus based on the operation of nine cesium beam atomic resonators.

The seconds pulses serve as the precise reference for all time service measurements. The master clock is compared with the results of observations for universal time made on each clear night with the photographic zenith tubes at the Naval Observatory in Washington and at its substation in Richmond, Florida. The atomic resonator is not operated continuously because it is a complex device. However, the quartz crystal oscillator and clock are operated continuously and may run for years without stopping. The oscillator and clock are driven by batteries which are continually recharged, so that a temporary power failure does not affect their operation.

The frequency of the quartz crystal oscillator is offset from the atomic frequency so that the time generated by the master clock is close to that of UT2. Moon observations are being continued to obtain the absolute frequency of atomic clocks with increased accuracy.

Synchronization of Frequency and Time

The Navy has long been aware of the need for rating and synchronizing frequency and time at remote points. Today microsecond time pulses are used in radar, in precision navigation systems, in velocity measurement and guidance of fast-moving aircraft and missiles, and in the rating of ship and shore frequency standards. Microsecond synchronization of clocks for periods of 24 hours or more at a number of range stations is desirable, for instance, to determine accurately the velocity of a missile along its trajectory. The standard frequency oscillators controlling the clocks at the various remote points must not vary by more than one cycle in one hundred billion cycles (1 part in 10^{11}) per day.

Similarly, precision frequency standards ashore and aboard ship must be accurately synchronized for successful operation of suppressed carrier-type, single-sideband communication systems. To assure the necessary minimum allowable accuracy of one cycle in 10 million of transmitter emission and receiver tuning, the standard oscillator used for reference or control in each installation must not deviate from that of any other ship or shore station by more than one part in 10^8 over a period of 60 days. This requirement is based on the assumption that each station will have an opportunity to check and correct its reference oscillator at least once every 60 days against reference standards available on a nationwide or worldwide basis, and that the individual standard reference oscillators do not drift at an average rate of much more than 1.5 part in 10^{10} per day.

One millisecond change in 24 hours represents approximately one part in 10^8. Where a difference of 0.1 millisecond in 24 hours can be observed accurately, frequency can be checked to one part in 10^9 per day. The resolution can be increased by developing the capability of observing smaller time changes accurately or by making measurements over a longer period. The average accuracy of frequency determination increases directly with the increase in ability to resolve smaller increments of time difference.

Present frequency standards for Fleet use have drift rates of less than one part in 10^9 per week. However, to prevent intolerable accumulated error, the frequency of the standards must be corrected periodically. The two methods normally used for correction through reception of radio transmission are:

- Time pulse method. The transmitted time pulses are derived from a clock which is controlled by a frequency standard. The received pulses are compared to pulses similarly derived from a local frequency standard. The gain or loss of time between the received and the local pulses over a period of time is directly related to the difference in frequency between the driving standards. One msec difference in 100,000 seconds (approximately one day) represents a frequency difference of one part in 10^8. If higher accuracies are required, either greater reading accuracy or longer observation time is necessary.
- Direct comparison of transmitted carrier frequency and local standard. Above 100 kc., the accuracy of comparison is limited by Doppler shifts caused by ionosphere variations. In general, one part in 10^7 or 10^8 is the best that can be expected. However, in the VLF range (10 to 30 kc.), the reflecting layers in the ionosphere are quite constant through large portions of the day, permitting comparison to a few parts in 10^{10} by observing the phase relation between the transmitted carrier and the local standard.

Time Signal Transmission

Most time transmissions are on high frequencies from about 2 to 25 megacycles per second. Continuous transmissions from WWV, Beltsville, Maryland, and WWVH, Hawaii, of the National Bureau of Standards, provide precise time and frequency on 2.5, 5, 10, 15, 20 and 25 megacycles per second and on 5, 10, and 15 megacycles per second, respectively. Similar transmissions are provided by other countries.

VLF has recently come into increased use for transmitting time signals. The phase of the carrier is very stable and it is little affected from day to day by variations in the reflection from the ionosphere. The first station to control VLF transmissions with high stability was GBR, Rugby, England, beginning about 1926.

The Navy operates several VLF high-power communication transmitters with worldwide coverage. The emission frequency and pulse keying of these transmitters can be stabilized at low expense to provide highly accurate frequency and time synchronization. The VLF transmitter of NBA at Summit, Canal Zone, was the first to be stabilized. The station is approximately 9° north of the equator, and its VLF coverage includes the entire United States and both the Atlantic and Pacific Missile Ranges. Its field strength at Washington, D. C. is about 600 microvolts per meter. The transmitter is a model TAW rated at 300 kw and operating at present on 18 kc.

Other Navy radio VLF stations which have been stabilized in frequency are: NAA, Cutler, Maine, 14.7 kc; NPG/NLK, Jim Creek, Washington, 18.6 kc; NPM, Lualualei, Hawaii, 19.8 kc; and NSS, Annapolis, Maryland, 22.3 kc. The Navy transmissions were stabilized by the Naval Research Laboratory, which has provided much of the electronic instrumentation for the Naval Observatory.

The VLF transmission of NBA and GBR may be monitored in phase about the world, enabling atomic resonators in various countries to be intercompared with high precision. The phase of a VLF carrier wave exhibits a daily variation of the order of 40 microseconds because of propagation variations, but returns to the same value to within about one microsecond in 24 hours. The precision of a frequency comparison, with respect to the oscillator at the transmitter, is about two parts in 10^{11} in 24 hours.

The precision oscillator at NBA employs an AT cut 2.5-mc crystal, which has a short-time drift rate of about two parts in 10^{10} per week. The 18-kc signal that drives the transmitter and the 1-kc that drives the local clock are synthesized from the 2.5-mc master oscillator. Regenerative dividers derive these frequencies because of their fail-safe nature; a break in the driving signal will stop the dividers. The transmitter is driven by its own variable frequency oscillator. For stabilized operation, this oscillator stage has been converted to function as a neutralized amplifier. The transmitter is keyed at its intermediate amplifier by the time pulses. The local clock gates the 1-kc source once each second for 0.3 second to generate the pulses that actuate the electronic keyer. Once each 15 minutes, the station call letters are inserted in Morse code and the information on fractional frequency offset (in parts in 10^{10}), which corrects the transmission from A.1 to UT2 time.

The delay through the keying and transmitter circuit is about 2.5 msec. A time comparison system is provided for monitoring the keyed output of the transmitter; the clock is then set ahead to compensate for the delay. The time ticks from the VLF transmitter and the HF transmitters are synchronized at the time of transmission.

The one major disadvantage of VLF for time pulse transmission is the inherent slow rise time of the VLF pulses. Although large transmitting antennas are used, they are still only a small part of a wavelength long at the transmitted frequency. The Q of these antennas is high and introduces a large time delay. (The wavelength of 18-kc is about 55,000 feet or 10 miles.) The antenna at NBA consists of six towers, 600 feet high, spaced to provide a flat top width of 1200 feet and length of 2400 feet. The approximate Q of the antenna is 700 and the pulse rise time is about 15 msec.

VLF Phase Comparison

A receiving system has been developed to provide VLF phase comparison. Its primary function is to measure relative phase between the transmitted VLF carrier frequency and a locally generated frequency, even if the received signal is below the noise level. Its secondary function is to provide time pulse monitoring facilities. The equipment consists of the following basic elements:

- A fixed tuned receiver.
- A synthesizer for producing a local reference frequency.
- A phase detector.
- A servo system and continuously variable phase shifter.
- A means for recording relative phase continuously.
- An audio output for monitoring time pulses.

Navigational Satellites

The transit navigational satellites 4A and 4B utilize Doppler shifts and contain clocks and radio transmitters, which are carried rapidly from one continent to another, transferring time about the world with high accuracy. Experiments are being initiated for synchronizing clocks between the United States and England. The accuracy should be about 100 microseconds initially; an accuracy of 10 microseconds may be obtained later.

Worldwide tracking of satellites requires close coordination of time signals around the world. Time signals transmitted by stations in England, Argen-

718-423 O-64—3

tina, Canada, Japan, South Africa and Switzerland are synchronized to about 1 msec, and the basic frequencies of the control oscillators are the same to about one part in 10^{10}.

Shipboard Frequency Standards

Communications art has advanced to the point where VLF transmitters are controlled in frequency and keyed to transmit very accurate time pulses. These VLF pulses can be received aboard ship and used as standards for controlling oscillator frequencies and time monitoring. The optimum system used today for maintaining accurate time and frequency control aboard Navy ships is a combination of a stable quartz crystal oscillator on the ship and a means of periodic correction from atomic frequency standards ashore via VLF radio pulses. However, as work progresses and the reliability of atomic resonant standards improves, these standards may supplement the crystal oscillators on ships. The cesium beam frequency standard currently available is not suited for shipboard use because of its poor reliability, complexity and cost.

Figure 1 is a simplified block diagram of a time and frequency monitor and control system. It will provide the necessary functions of time and frequency control and may be constructed from units now available.

The frequency base specified in the diagram contains three AN/URQ-10's, which are highly stable, multipurpose frequency standards designed for continuous duty use. They can be used for laboratory frequency measurements and for driving precision timing devices. Each provides three output frequencies of 5 mc, 1 mc and 100 kc and has a frequency drift of less than one part in 10^8 over 60 days. These frequencies are fed into a synthesizer that can multiply, add or divide them to provide any output frequency. The synthesizer output can be varied to produce as many frequencies as required, with the same stability as the frequency base.

The clock provides time of day information and coded time information for various processing requirements.

The 100-kc from the AN/URQ-10 is synthesized in VLF receiver to the desired VLF station signal frequency. These two signals are compared and the phase difference is plotted on the strip chart recorder. The strip chart record shows the relative time and frequency drift of the AN/URQ-10 as compared to that of the VLF transmitting station. The AN/URQ-10 can be adjusted to maintain accurate frequency through appropriate interpretation of the strip chart record. The clock can be synchronized with transmitted time information.

Portions of the time and frequency monitor and control system are now in various stages of development, ranging from breadboard models to off-the-shelf models. The system eventually installed in ships will probably adhere closely to the technical approach outlined in figure 1. Therefore, the basic operation and maintenance of the system can be predicted from a study of the equipment now available.

BuShips Management Office, Western Pacific

By Cdr. David M. Brooks, USN
and
Mr. Vincent F. Oliver
Bureau of Ships Management Office
Western Pacific Area

The Seventh Fleet is a powerful arm of the United States Navy and an important instrument of United States foreign policy. Behind the Seventh Fleet, and ever ready to fulfill its every need, is a substantial logistics support complex. The principal ports of this complex are Yokosuka and Sasebo, Japan; Subic Bay, Philippines; and Guam. Some fourteen activities in these ports, including the Ship Repair Facilities, are under the management control of the Bureau of Ships.

Prior to 1954, these activities were under the sole command of the Operating Forces of the Navy; the only connection of the Bureau of Ships with them was financial responsibility. In April of 1954, the Secretary of the Navy declared that shore activities of the Operating Forces would be assigned to the appropriate commands of the Operating Forces for military command, and to the appropriate Bureaus or Offices for management control. The purpose of this order was to free the Operating Forces of management control problems, for which they were neither organized nor staffed. The Ship Repair Facilities, Fleet Activities, and Naval Stations were assigned to the Bureau of Ships for management control.