Zitzewitz, D. W. Allan, and D. J. Glaze, "Measurement of the unperturbed hydrogen hyperfine transition frequency," *IEEE Trans. Instrum. Meas.*, vol. IM-19, pp. 200–209, Nov. 1970.
[17] J. Terrien, "Scientific metrology on the international plane and the Bureau International des Poids et Mesures," *Metrologia*, vol. 1, pp. 15–26, Jan. 1965.
[18] P. Giacomo, "Raccordement de l'étalon de fréquence à CH_4 et de la longueur d'onde étalon de la définition du mètre," presented at the 4th Int. Conf. on Atomic Masses and Fundamental Constants, Nat. Phys. Lab., Teddington, England, Sept. 1971.
[19] A. G. McNish, "The basis of our measuring system," *Proc. IRE*, vol. 47, pp. 636–643, May 1959.
[20] G. S. Simkin, *Izmer. Tekh.*, no. 10, pp. 6–10, Oct. 1968 (Transl.: "Establishment of a single time and length standard," *Meas. Tech.*, no. 10, pp. 1308–1314, Oct. 1968).
[21] Z. Bay, "The constancy of the velocity of light and prospects for a unified standardization of time, frequency and length," presented at the 4th Int. Conf. on Atomic Masses and Fundamental Constants, Nat. Phys. Lab., Teddington, England, Sept. 1971.
[22] Z. Bay and J. A. White, "Frequency dependence of the speed of light in space," *Phys. Rev.*, vol. D5, Feb. 1972.
[23] T. S. Jaseja, A. Javan, J. Murray, and C. H. Townes, "Test of special relativity or of the isotropy of space by use of infrared masers," *Phys. Rev.*, vol. 133, pp. A1221–A1225, Mar. 1964.
[24] L. O. Hocker, A. Javan, D. Ramachandra Rao, L. Frenkel, and T. Sullivan, "Absolute frequency measurement and spectroscopy of gas laser transitions in the far infrared," *Appl. Phys. Lett.*, vol. 10, pp. 147–149, Mar. 1967.
[25] K. M. Evenson, G. W. Day, J. S. Wells, and L. O. Mullen, "Extension of absolute frequency measurements to the cw He–Ne laser at 88 THz (3.39 μ)," *Appl. Phys. Lett.*, vol. 20, pp. 133–134, Feb. 1972.
[26] H. Hellwig, H. E. Bell, P. Kartaschoff, and J. C. Bergquist, "Frequency stability of methane-stabilized He–Ne lasers," *J. Appl. Phys.*, vol. 43, pp. 450–452, Feb. 1972.
[27] H. A. Gebbie, N. W. B. Stone, and F. D. Findlay, "A stimulated emission source at 0.34 millimetre wavelength," *Nature*, vol. 202, p. 685, May 1964.
[28] K. M. Evenson, J. S. Wells, L. M. Matarrese, and L. B. Elwell, "Absolute frequency measurements of the 28- and 78-μm cw water vapor laser lines," *Appl. Phys. Lett.*, vol. 16, pp. 159–161, Feb. 1970.
[29] A. V. Astin, "Standards of measurement," *Sci. Amer.*, vol. 218, pp. 50–62, June 1968.
[30] "Brief history and use of the English and metric systems of measurement with a chart of the modernized metric system," *NBS Special Publication 304A*, 1968.
[31] J. Terrien, "News from the International Bureau of Weights and Measures," *Metrologia*, vol. 4, pp. 41–45, Jan. 1968.

Time Transfer Using Near-Synchronous Reception of Optical Pulsar Signals

Abstract—The concept of time transfer between two geographically separated locations by using nearly simultaneous reception times from a common transmission has been used very fruitfully, e.g., the TV line-10 time transfer system and Loran-C. Some germane aspects of the concept are discussed and use of a signal from the optical pulsar NP0532 as the common transmitter is considered.

Theoretical considerations suggest that time could be transferred using this mode to an accuracy of about 2 μs and with global coverage. Some data were made available from Lawrence Radiation Laboratory giving the dates of pulsar events received at their observatory and also at the Harvard Observatory. A precision of about 13 μs was inferred from the data analysis.

This optical pulsar time transfer system seems to be feasible and worthy of further consideration because of the high accuracy and precision (a few microseconds for both) potentially achievable. For this potential, the development costs appear to be favorably competitive.

Manuscript received February 15, 1972. Contribution of the National Bureau of Standards, not subject to copyright.

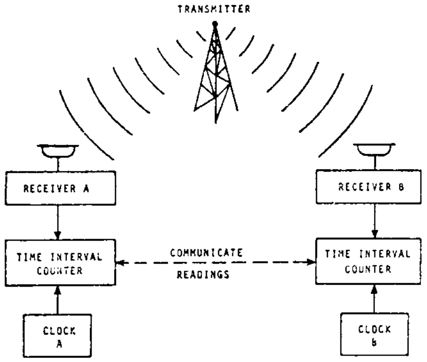

Fig. 1. Concept of precise time transfer using nearly simultaneous reception time of signals from a common transmitter.

Time synchronization or comparison of remote clocks is a common but often difficult to achieve need among the users of precise time signals. For example, the clocks at a satellite tracking station may need to be synchronized with respect to all other similar tracking stations around the globe to within a few microseconds. Many techniques have been developed and/or employed to satisfy the above needs, e.g., portable clocks, a multiplicity of satellite timing approaches, and the multimillion-dollar moon-bounce technique [1]–[10]. Though the cost for a single portable clock trip is not prohibitive, the accumulated investment for any of the above has been very large. This letter is an effort to present what may be a less expensive operational system for accurate time synchronization (or comparison) to within a few microseconds and with essentially global coverage.

From among the many methods that have been developed for time transfer or remote clock synchronization, one method will be discussed which has yielded some fruitful results during the past few years using TV signals [11]–[16]. Then the same method will be discussed with reference to its applicability to pulsar signals.

Fig. 1 illustrates this method in which time transfer or synchronization is accomplished by receiving signals at A and B at nearly the same time from a transmitter common to both receivers. In many cases, clocks A and B are much more stable and accurate than the transmitter clock; nevertheless, the transmitted signal as received can be used as a time transfer device. Under certain assumptions the instabilities of the transmitter and the propagation medium to first order contribute neither to the imprecision nor to the inaccuracy of the time transfer system.

As a more detailed analysis, suppose that at a time t_X an identifiable signal, e.g., a pulse or a zero crossing of a sinusoid, is emitted from the transmitter shown in Fig. 1. Let τ_{XA} and τ_{XB} be the propagation and equipment delay times from the transmitter to the time interval counters at A and B, respectively. If the readings of clocks A and B are t_A and t_B, respectively, then the difference in the readings of the time interval counters will be

$$[t_A - (t_X - \tau_{XA})] - [t_B - (t_X - \tau_{XB})] = t_A - t_B + \tau_D \quad (1)$$

where τ_D is the differential propagation delay $\tau_{XA} - \tau_{XB}$. If τ_D is calculable, then obviously the time difference between clock A and clock B can be accurately determined within the uncertainty of the calculated differential delay. If τ_D is not calculable, then it needs to be measured, e.g., with a portable clock. The stability of τ_D in either case will determine a limit for the precision with which the time difference $t_A - t_B$ can be measured by this system. If the propagation and equipment delay paths are similar, the differential delay τ_D may be extremely stable, e.g., for TV timing several nanosecond stabilities over several seconds have been achieved within a given transmitter locale [17].

Note that in this simple case the time of emission of the identifiable signal cancels in (1). However, in general, the identifiable signal will be repetitive, and A and B can receive events with different transmission times. All that needs to be added to (1) is the transmitter emission time difference Δt_X of the different events received, which can often be inferred from the repetitive nature of the signal, assuming the ambiguity can be resolved. In some cases ambiguity resolution may be difficult [15]. Measuring different events usually places very minimal constraints on the transmitter's stability and accuracy. That is, if δt represents the precision or accuracy desired of the time transfer system, then the stability or accuracy, respectively, of the transmitter need only be better than $\delta t / \Delta t_X$. For example, if time transfer is desired to a precision or accuracy of 1 μs, then Δt_X can be several hundred seconds and still require only 1 part in 10^9 stability or accuracy, respectively, of the transmitted signal.

There are several important time transfer users employing this near-synchronous reception mode. The International Atomic Time Scale maintained at the Bureau International de l'Heure, IAT (BIH), employs Loran-C and TV signals in this time transfer mode, and achieves precisions of a few tenths of a microsecond between seven international laboratories utilized in the scale [18]. The standard time and frequency radio station WWV is synchronized with respect to the Atomic Time Scale UTC (NBS) to a precision of about 30 ns using the TV line-10 time transfer system developed by the National Bureau of Standards [19]. Some satellite systems employ this mode for time transfer, and long baseline interferometry indirectly employs this mode as data are cross-correlated with impressive precisions in the picosecond region [20]. Though this letter is an effort to explore some of the capabilities of pulsar signals when used in the above time transfer mode, there are other interesting unexploited systems where this mode of time transfer is possible and perhaps useful. For example, the TV color subcarrier signal (3.58 MHz) appears to have stabilities in the nanosecond region over thousands of miles with, however, some difficulty in removing the ambiguity [15]; and even though the 60-Hz power-line system has very poor stability, the stability of the differential delay of this coherent power-line grid appears to be in the submillisecond region.

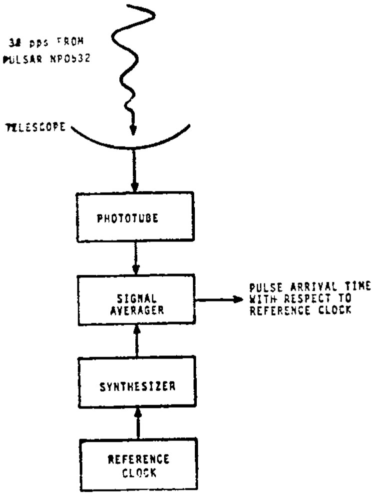

Fig. 2. Schematic of reception system for optical pulsar signals. The synthesizer causes the signal averager to scan the incoming signal from the phototube at an estimated pulsar rate.

A schematic diagram of a pulsar reception system is shown in Fig. 2. The signal averager determines the time interval between the arrival time of the pulsar signal and the local clock. This is accomplished by amplifying the pulsar signal in the phototube, then averaging several thousand of the pulses to improve the signal-to-noise ratio. The period of the Crab NP0532 pulsar signal is 33.107 ms. and the pulse width is about 2 ms. The rate of sampling in the signal averager as determined by the frequency synthesizer may be set from an extrapolation of previous pulsar data [21]. One of the present models for the slowing down of this pulsar signal is a "least-squares cubic fit (four parameters) to the phase as a function of time" [22]. Extrapolations based on such models provide longer averaging time to be better utilized in the signal averager except, however, when the pulsar signal makes an occasional jump in rate [23].

The cost of the equipment involved will be determined in large measure by the cost of the telescope, the size of which directly affects the signal-to-noise ratio and typically ranges from 24 in to 36 in (~60–90 cm). There are other less expensive ways of having a large receiver area such as the J. E. Faller multilensed receiver telescope [24]. Inexpensive phototubes can be obtained, but $1000 invested here is very well spent. The signal averager employed at Lawrence Radiation Laboratory (LRL) cost about $10 000 and the frequency synthesizer cost about $6000 [21]. Reference clocks that are fully adequate for the job can be purchased from about $8000 to $15 000.

A resolution of the pulsar signal to about 2 μs is believed achievable [21], [25] with about a 2-h sampling time and a telescope of about 24-in (61-cm) diameter. It is further believed that the precisions involved in determining the pulsar signal arrival time are primarily given by the statistics associated with particle (photon) detection and counting, and hence can be characterized as a white noise process; therefore, the uncertainty of the arrival time will be inversely proportional to the square root of the sampling interval. The total increase in delay due to the earth's atmosphere is only of the order of 10 ns, hence the differential delay associated with the atmosphere is totally negligible as well as calculable, assuming the pulsar signal is a plane wave as it arrives at the earth. The accuracy limitation for the differential time delay τ_D, due to the spinning earth, is also of minor consequence, i.e., one needs to know and can know earth position (given by the UT1 time scale) to better than 5 ms in order to have an uncertainty on τ_D of less than 8 ns. It is apparent that the reception equipment and the very weak pulsar signal are by far the largest contributors in the uncertainties of τ_D.

The data analyzed in this letter were made available through the kind cooperation of J. Nelson and J. Middleditch of LRL and are similar to the results published in [22]. The data analyzed gave the reception times at LRL and at Harvard University of the pulses from NP0532 (the Crab pulsar). The primary concern of these observers is to study the pulsar's behavior by measuring in an absolute sense the arrival times of the pulsar signals. Such a measurement requires reduction of the data to arrival times at the solar system barycenter by use of an accurate ephemeris for the earth—a nontrivial problem. Difficulties quickly arose when trying to compare the data of one observatory to another because each had a particular fourth-order polynomial to model the pulsar's behavior and an assumed best ephemeris for the earth's position. The assumption that the pulsar signal is a plane wave, which is a good one at the 1-μs uncertainty level regardless of where the earth is in its orbit, allows one to avoid these difficulties. Nelson and Middleditch supplied a data listing that used the Harvard polynomial fit and the LRL ephemeris for reducing the data as received at both observatories. Even then there appeared to be some difference in the method of properly identifying when the pulse occurred [22].

In order to evaluate the capability of the pulsar time transfer system an attempt was made to remove any bias due to the difference in method of pulse identification by taking the difference in the pulsar arrival times, Harvard minus LRL, on those nights when both made observations:

$$T_H(t) - T_L(t') \simeq \Delta T(t) \qquad (2)$$

where t and t' denote the local clock readings at Harvard and LRL, respectively. The LRL measurements were usually taken 3 to 4 h later than the Harvard measurements. Equation (2) assumes that both occurred at the same time t. This assumption requires that the instabilities of the pulsar be insignificant over this interval. This is probably a good assumption [25]. The local clocks at both sites were referenced to the same very stable time scale via a clock at Hewlett-Packard in Santa Clara and the Loran-C navigation chain on the East Coast.

In order to get an idea of the stability characteristics of the differential data, consider the following quantity:

$$\frac{\Delta T(t+\tau) - \Delta T(t)}{\tau} = \frac{\delta\nu}{\nu} \qquad (3)$$

where τ is the time interval between nights when the pulsar signal was commonly observed. Plotted in Fig. 3 are the absolute values of these differential fractional frequency deviations for all possible combinations of the $\Delta T(t)$. The dashed line in Fig. 3 is obviously an approximate model for the data and implies a precision capability of about

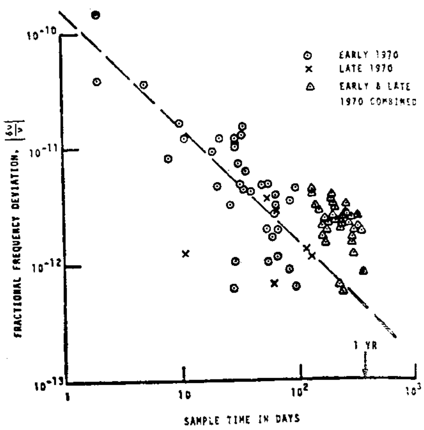

Fig. 3. Differential fractional frequency between the clocks at the Harvard and Lawrence Radiation Laboratory's observatories as deduced from the arrival time at both observatories of the optical pulsar signal NP0532. The dashed line implies an rms time error of about 13 μs and the slope is inversely proportional to the sample time, consistent with the assumption that the reception times are perturbed by a white noise.

13 μs. The slope of the dashed line is consistent with the assumption stated earlier that the uncertainty in the reception time is given by the statistics of particle (photon) counting —white noise. It should be noted that the triangles have a very high density above the line, and that these points are reduced from data belonging to two different sequences. The implication is that something changed which affected the biases after the first sequence and before the second sequence.

In conclusion, the analysis of the time difference or the comparison of data between two laboratories could be simplified considerably by correcting only for sidereal time, then afterward ascertaining the polynomial model for the pulsar signal and reference frame transfer to the solar system's barycenter. There is some further indication that a uniform method of determining the arrival time of the pulsar signal would be worthwhile. Perhaps the present differences in pulsar arrival time determination rest in equipment changes or in differences in equipment.

One would also conclude that the pulsar time transfer system has the potential for accurate time transfer on a global basis to within about 2 μs. The LRL group achieves uncertainties of this order on a regular basis [21]. The currently measured time transfer precision is about 13 μs. The drawbacks in this time transfer system are that measurements can be made only at night and cannot be made at all during the last part of May, all of June, and the first part of July. Cloud cover could also be a problem. The signal strength of the source at the earth and the expense of the receiver system to overcome the problem are significant considerations, since it appears that the precision and the accuracy of the proposed pulsar time transfer system are primarily limited in these areas. Overall, the optical pulsar time transfer system seems to be feasible and worthy of further consideration because of the high accuracy and precision potentially achievable as weighed against the investment in development and equipment costs.

Possibly in a similar hypothetical system not based upon pulsars, both the signal strength problem and the receiver cost problem could be overcome by outfitting a servoed synchronous earth satellite with a Q-switched laser having a beam large enough to cover the earth, and with the Q-switching being periodically triggered on command by an earth-based or on-board clock [26]. Such a system would appear to allow accurate global time synchronization in the subnanosecond region. In contrast the pulsar transmitter is free!

ACKNOWLEDGMENT

The author wishes to thank J. Nelson and J. Middleditch for supplying the data along with very interesting comments; P. Bender, H. Hellwig, and D. Halford for providing stimulating and worthwile suggestions; and H. Machlan and E. Helfrich for reduction and manuscript preparation, respectively.

DAVID W. ALLAN
Atomic Frequency and Time Standards Sect.
Nat. Bur. Stand.
Boulder, Colo. 80302

REFERENCES

[1] F. H. Reder and G. M. R. Winkler, "World-wide clock synchronization," *IRE Trans. Mil. Electron.*, vol. MIL-4, pp. 366-376, Apr.-July 1960.
[2] L. N. Bodily, "Correlating time from Europe to Asia with flying clocks," *Hewlett-Packard J.*, vol. 16, pp. 1-8, Apr. 1965.
[3] R. Easton, "The role of time/frequency in Navy navigation satellites," *Proc. IEEE*, this issue, pp. 557-563.
[4] E. Erhlich, "The role of time/frequency in satellite position determination systems," *Proc. IEEE*, this issue, pp. 564-571.
[5] J. McA. Steele, W. Markowitz, and C. A. Lidback, "Telstar time synchronization," *IEEE Trans. Instrum. Meas.*, vol. IM-13, pp. 164-170, Dec. 1964.
[6] J. L. Jespersen, G. Kamas, L. E. Gatterer, and P. F. MacDoran, "Satellite VHF transponder time synchronization," *Proc. IEEE*, vol. 56, pp. 1202-1206, July 1968.
[7] L. E. Gatterer, P. W. Bottone, and A. H. Morgan, "Worldwide clock synchronization using a synchronous satellite," *IEEE Trans. Instrum. Meas.*, vol. IM-17, pp. 372-378, Dec. 1968.
[8] D. W. Hanson and W. F. Hamilton, "One-way time synchronization via geostationary satellites at UHF," *IEEE Trans. Instrum. Meas.*, vol. IM-20, pp. 147-153, Aug. 1971.
[9] ——, "Clock synchronization from satellite tracking," *IEEE Trans. Aerosp. Electron. Syst.*, vol. AES-7, pp. 895-899, Sept. 1971.
[10] W. Higa, "Time synchroniziltion via lunar radar," *Proc. IEEE*, this issue, pp. 552-557.
[11] J. Tolman, V. Plácek, A. Soucek, and R. Stecher, "Microsecond clock comparison by means of TV synchronizing pulses," *IEEE Trans. Instrum. Meas.*, vol. IM-16, pp. 247-254, Sept. 1967.
[12] D. D. Davis, J. L. Jespersen, and G. Kamas, "The use of television signals for time and frequency dissemination," *Proc. IEEE* (Lett.), vol. 58, pp. 931-933, June 1970.
[13] J. D. Lavanceau and D. Carroll, "Real time synchronization via passive television transmission," in *Proc. 3rd Ann. Precise Time and Time Interval (PTTI) Strategic Planning Meeting* (Washington, D. C., Nov. 1971), vol. 1, 1972.
[14] D. D. Davis, B. E. Blair, and J. F. Barnaba, "Long-term continental U. S. timing system via television networks," *IEEE Spectrum*, vol. 8, pp. 41-52, Aug. 1971.
[15] J. Jespersen, B. Blair, and L. Gatterer, "Characterization and concepts of time-frequency dissemination," *Proc. IEEE*, this issue, pp. 502-521.
[16] D. W. Allan, B. E. Blair, D. D. Davis, and H. E. Machlan, "Precision and accuracy of remote synchronization via network television broadcasts, Loran-C, and portable clocks," *Metrologia*, vol. 8, Apr. 1972.
[17] D. D. Davis, private communication, 1969.
[18] B. Guinot, M. Feissel, and M. Granveaud, *Bureau International de l'Heure—Annual Report for 1970*. Paris, France: BIH, 1971.
[19] J. Milton, "Standard time and frequency: Its generation, control, and dissemination from the National Bureau of Standards Time and Frequency Division," NBS (USA) Tech. Note 379, Aug. 1969, pp. 21-25.
[20] W. Klemperer, "Long-baseline radio interferometry with independent frequency standards," *Proc. IEEE*, this issue, pp. 602-609.
[21] J. Middleditch, private communication, Dec. 1971.
[22] P. Horowitz *et al.*, "Optical time-of-arrival measurements from the Crab pulsar: Comparison of results from four observatories," *Astrophys. J.*, vol. 166, pp. L91-L93, June 1971.
[23] R. N. Manchester, "Pulsars: Observations and current interpretation," in *IEEE Int. Conv. Dig.* pp. 154-155, 1971.
[24] J. E. Faller, "The Apollo retroreflector arrays and a new multi-lensed receiver telescope," prepared for the Open Meeting of Working Group I of the Committee on Space Research (COSPAR), 14th Meeting, Seattle, Wash., June 1971.
[25] P. Bender, private communication, Feb. 1972.
[26] H. Hellwig and D. Halford, private communication, Feb. 1972.

Frequency Standard Work in Egypt

Abstract—The development of the National Physical Laboratory for metrology in Egypt is described. The Frequency Standards Department has been maintaining a cesium frequency standard since 1967. Reception of VLF transmissions is used for phase comparison with good results. Future goals include improving the reliability of the system and reception of Loran-C as well as investigating applications of standard frequencies for other measurements, such as new standards of length and voltage.

I. HISTORICAL

It became evident, by the late 1950's, that the establishment of a national laboratory for physical standards of measurement and values of physical constants is necessary for the calibration of the standards existing in the different laboratories and factories. A study was made to determine the best form in which the needs could be met.

An agreement between the Government and the U.N. Development programme was signed in 1963 for the establishment of a national physical laboratory for metrology, UNESCO being the executing agency.

The agreement provided the needed funds for paying experts, buying equipment, and a number of fellowships. The plan involved standards laboratories for mass, length, frequency, thermometry, photometry, radiology, and acoustics. These laboratories, together with some other laboratories, constitute the National Institute for Standards.

II. FREQUENCY STANDARD EQUIPMENT

The Frequency Standards Department was provided with the following equipment: one Hewlett Packard (HP) cesium-beam frequency standard (type 5060 A), a Tracor quartz crystal oscillator (type 2.5c), an Engineered Electronics Company (EECO) VLF receiver, a General Radio (GR) digital synchrometer, and a number of complementary instruments such as frequency synthesizers, oscilloscopes, counters, signal generators, etc. Some of the complementary instruments were provided by the Egyptian Government.

This equipment is minimal to what is desired in a frequency standards laboratory. It provides insufficient reliability and is inadequate for detailed research work. However, we were fortunate that the cesium frequency standard operated continuously without serious trouble from the winter of 1967 to late summer 1971.

III. FREQUENCY COMPARISONS AND PRESENT ACTIVITIES

Since December 1967, we have made continuous VLF phase comparisons with standard frequency transmissions and a local atomic frequency standard [1]. Initially, these measurements were made between the WWVL (20-kHz) signals from the National Bureau of Standards station at Fort Collins, Colo., USA, and the cesium-beam frequency standard of the National Institute of Standards (NIS), Cairo, Egypt. The relative phase difference between the received signal and the local standard is obtained in the form of strip chart records from a servo-type phase measuring receiver fitted with a shielded loop antenna and a tuned preamplifier (40-dB gain). (The received signal amplitude is also recorded.) Fig. 1 gives results of continuous phase recordings of WWVL signals received at Cairo from November 1967 to November 1968. This great-circle propagation path is 10 940 km in length and passes over Canada, South Greenland, and Germany. The phase data points of Fig. 1 are averages of two readings (two successive days) taken at 1500 UT. At this time the propagation path is wholly sunlit in all seasons, although the received signal is quite noisy. The slope of the fitted straight line through the Fig. 1 data represents the estimated frequency difference between the transmitted signal and the NIS atomic frequency standard. The VLF phase data indicate that the local standard was about eight parts in 10^{13} higher in frequency than that of the WWVL received signals over this 13-mo period. (The total phase difference over this period was $\sim 15\ \mu s$ [1], [2].) Fig. 2 shows the mean monthly phase values of WWVL signals as received in Cairo for each month of 1968. The mean monthly diurnal-phase changes show strong seasonal effects as noted by Brady *et al.* [3]; maximum values of 75 μs occur in Spring and Fall, while a minimum value of about 30 μs is estimated for midyear. (For a discussion of VLF diurnal phase effects see paper by Swanson and Kugel [4].)

Since January 1969, VLF phase comparisons have been made mainly with the improved GBR standard frequency transmissions from Rugby, England [National Physical Laboratory (NPL) broadcasts]. A shorter propagation path (3610 km), nearly southeast, affords improved phase comparisons through a more favorable SNR and a less variable diurnal phase change. During 1969, the monthly phase differences were no more than 5 μs for each of the first six months and within 10 μs for the following six-month period [5]. Typical diurnal phase-variation curves of the received GBR signals are given in Fig. 3. As with the WWVL received signals the GBR signals also show season-dependent day-to-night changes. These changes are about 9, 12, and 25 μs in midwinter, summer, and autumn, respectively.

Monthly phase comparison reports are issued and regularly sent to the BIH, Paris, France. (Failure of the cesium beam caused a temporary interruption of phase comparisons during the latter part of 1971.) The Frequency and Time Department is participating in renewing and updating the

Manuscript received February 22, 1972.