NATIONAL BUREAU OF STANDARDS REPORT

NBS PROJECT

91:20-12-91124 January 2, 1963

NBS REPORT

7638

FREQUENCY AND TIME CALIBRATION SERVICES AT THE BOULDER LABORATORIES OF THE NATIONAL BUREAU OF STANDARDS

A. H. Morgan

NBS

U. S. DEPARTMENT OF COMMERCE
NATIONAL BUREAU OF STANDARDS
BOULDER LABORATORIES
Boulder, Colorado

FREQUENCY AND TIME CALIBRATION SERVICES AT THE BOULDER LABORATORIES OF THE NATIONAL BUREAU OF STANDARDS

A. H. Morgan

1. INTRODUCTION

Until rather recently the standard high frequency (HF) and time signal broadcasts of WWV and WWVH [NBS, 1960] have provided frequency and time calibration facilities, for the U. S. (and much of the rest of the world) of sufficient accuracy to meet practically all of the needs in this area. However, the recent rapid advances in many fields of science have made demands for increased accuracies that are not possible to achieve with the HF broadcasts. This situation was foreseen as early as 1956 when the standard radio broadcasts were begun by the NBS in the low frequency (LF) band at 60 kc/s (using the call letters KK2XEI, later changed to WWVB) and located near Boulder, Colorado.

In response to many requirements involving means for synchronizing widely separated clocks [Morgan, 1959] and providing accurate time signals worldwide, [Watt, Plush, Brown and Morgan, 1961] a study was undertaken at NBS which indicated that an optimum frequency [Watt and Plush, 1959] for this purpose was in the VLF band at about 20 kc/s. Accordingly, in April 1960, standard radio station WWVL, near Sunset, Colorado, was put into operation at 20 kc/s.

The signals of stations WWVL and WWVB have been received in nearly all parts of the Continental U. S. and in Canada, and the 20 kc/s signal has been received as far away as New Zealand, [Crombie, 1960] using a phase-lock receiving system. The carrier frequencies of these stations are controlled by the U. S. Working Frequency Standard (USWFS) and are stable to about ± three parts in 10^{11}; WWVB is directly controlled while WWVL is phase-locked [Fey, Milton and Morgan, 1962] by means of a 50 Mc/s radio link, which was put into operation in October 1961. This is a first in this field.

In addition to the standard radio broadcasts, there are some special measurements that may be made at the Boulder Laboratories that require facilities not available to many Standards Laboratories. This includes measurements of highly stable frequency sources, such as quartz oscillators, rubidium (Rb) gas cells, cesium beam standards (C_s), etc. and measurements of the power spectra of frequency sources.

2. FREQUENCY AND TIME STANDARDS

The present standard of time [Comité International des Poids et Mesures, 1957] is the Ephemeris Second and it is defined as the fraction $\frac{1}{31,556,925.9747}$ of the tropical year for January 0, 1900 at 1200 hours, Ephemeris Time (ET). It is determined by astronomical means to an uncertainty of a few parts in 10^9 in a period of a few years. Because time and frequency are inversely related by definition, standards of frequency and time are fundamentally the same. To make the standard quickly available, a relationship between the atomic transition frequency of cesium (C_s) and ET was found to be desirable. This was done [Markowitz, Hall, Essen and Parry, 1958] in 1958 and the value given, which is the only one available, is that there are 9, 192, 636, 770 ± 20 cycles of C_s per Ephemeris Second. The uncertainty of about two parts (pp.) in 10^9 in this value should, in the strictest sense, be transferred to the frequency derived from it. However, for all but perhaps the "purists", this is generally not a necessity and, for most high precision frequency measurements, not desirable. This is because it then is possible to take full advantages of the remarkable stability and accuracy of the C_s standards, [Mockler, Beehler and Snider, 1960] where accuracy refers to the closeness with which the ideal transition frequency of C_s is realized; which is one to three pp. in 10^{11}. It is quite generally agreed now that astronomical time will never match atomic time in regard to stability, accuracy and availability.

The Consultative Committee [Comité Consultatif pour la Definition de la Seconde, 1961] for the Definition of the Second of the International Committee on Weights and Measures (ICWM) met in Paris in April 1961 to consider the question of defining time in terms of an atomic standard. It seems quite probable that this may be done when the ICWM meets again in 1966.

3. FREQUENCY AND TIME STANDARDS AT NBS

3.1 Uniqueness of Frequency and Time Standards

There are at least three ways in which frequency and time standards are unique. They: (1) are not permanent (such as a meter bar which constitutes the standard of length) but must be continuously reconstructed and checked: (2) can be measured with higher precision than any other physical or electrical quantity, and (3) can be made widely available by means of radio signals.

3.2 U. S. Frequency Standard

The NBS has developed and maintains for the United States [NBS, 1960] and its outlying bases, accurate and precise cesium beam frequency standards [Mockler, Beehler and Snider, 1960] that constitute the U. S. Frequency Standard (USFS). They are among the most accurate, stable and reproducible atomic frequency standards in the world.

In addition, an ammonia beam Maser [Barnes, Allan and Wainwright, 1962] has been recently developed at NBS that is quite competitive with the C_s standards. Moreover, it has three properties that make it quite unique as a spectrum analyzer, [Barnes and Heim, 1961]: (1) it has a natural line width of the transition frequency that indicates a Q factor of about 10^7, which is about two or three times that of the best quartz crystals at room temperature or above: (2) the oscillation frequency is at K band without frequency multiplication, and (3) it is inherently a very low noise device.

3.3 U. S. Working Frequency Standards

In addition to these high quality standards, the U. S. Working Frequency Standards (USWFS) are maintained and periodically calibrated in terms of the USFS. The former, consisting of several highly stable and precise commerical quartz and atomic standards, generates output frequencies which are in general constant to about three parts (pp.) in 10^{11}, and are used to: (1) control or steer all of the NBS standard radio broadcasts (WWV, WWVH, WWVB, and WWVL): (2) distribute standard signals throughout the Boulder Laboratory: (3) control the microwave (MW) frequency standard in the Electronic Calibration Center: (4) calibrate equipment sent to Boulder Laboratory, and (5) control precise clocks.

4. STANDARD RADIO BROADCASTS

4.1 High Frequency Broadcasts of WWV and WWVH

The NBS maintains standard frequency and time signal broadcasts [NBS Miscellaneous Publication 236, 1960] at HF using stations WWV, Beltsville, Maryland, and WWVH, Maui, Hawaii. Both stations provide the following technical services: (1) standard radio frequencies: (2) standard audio frequencies: (3) standard time intervals: (4) standard musical pitch, and (5) time signals. All of these signals at each station are derived from a common master oscillator whose frequency is based on the USFS and whose daily stability is better than ± five pp. in 10^{11} at WWV and one pp. in 10^{10} at WWVH.

4.11 Frequency Offset from USFS

Beginning in January 1960 the master oscillators at WWV and WWVH have been intentionally offset from the USFS by a small, but precisely known, amount in order to reduce the departure of the time signals broadcast from UT2 time. In 1962 the offset was -130 pp. in 10^{10} and will be the same in 1963. From January 1960 to January 1962 it was -150 pp. in 10^{10}. It is expected that the offset may be left unchanged throughout the calendar year even though UT2 time is subject to unpredictable changes that are easily detected at the level of precisions involved.

4.12 Corrections to Carrier Frequencies Broadcast

For these reasons, corrections to the carrier frequencies as broadcast are determined by the NBS with respect to the USFS by means of the NBS standard low frequency (LF) and very low frequency (VLF) radio broadcasts, which are described below. These values are published monthly [WWV Standard Frequency Transmissions, 1958] in the Proc. IRE and are available in back issues to May 1958 with the data extending back to December 1, 1957. The data are given to one pp. in 10^{11} with an uncertainty of five pp. in 10^{11}.

4.13 Standard Time Intervals and Time Signals

Highly precise time interval and time marking signals, consisting of five cycles of 1,000 c/s at WWV and six cycles of 1,200 c/s at WWVH, are broadcast as a pulse at intervals of precisely one second. At the 59 second of each minute the pulse is omitted but two pulses separated by 0.1 second are emitted on the 60 second. To precisely mark the beginning of each five minute period beginning on the hour, an audio frequency modulation of 600 c/s is keyed on at both stations and continues for three minutes at WWVH and two minutes at WWV. The rest of the first five minute period at WWVH is silent except for the time pulses and the International Morse code time announcements occurring during the first half of the last minute. At WWV, the third minute has a time code modulation, the fourth and fifth has only the time pulses except for the time announcements made during the last half of the fifth minute. The next five minute period starts with a 440 c/s tone modulation but is identical otherwise with the first. These five minute periods alternate during each hour, except for the scheduled silent periods. At WWVH this is from 15 to 19 minutes past each hour, and at WWV it is from 45 to 49 minutes past each hour. Also, WWVH has a scheduled silent period from 1900 to 1930 UT, daily.

4.14 Step Adjustments of Time Interval and Time Signals

The time signals and time intervals are kept in close agreement with UT2 time [Markowitz, Unpublished] by making step adjustments, of precisely known amounts when necessary. Since 1959 the step adjustments were made as follows; at 0000 UT on date given:

(1) December 16, 1959, retarded by 20 milliseconds (ms)

(2) January 1, 1961, retarded by 5 milliseconds (ms)

(3) August 1, 1961, retarded by 50 milliseconds (ms)

Future adjustments will be made when necessary in steps of precisely 50 ms on the first day of the month following the one in which the transmitted time departs from UT2 time by more than 50 ms.

4.15 Coordination of Time Signals with Other Nations

See Appendix III for details on this.

4.16 Time Code on WWV

See Appendix IV for details on this.

4.2 LF and VLF Standard Broadcasts of WWVB and WWVL

NBS provides standard frequency broadcasts in the LF band (WWVB at 60 kc/s) and in the VLF band (WWVL at 20 kc/s). The former (with call sign KK2XEI) was begun in June 1956 and the latter in April 1960. Both have been received over the Continental U. S. using phase-lock receivers, and WWVL as far away as New Zealand [Crombie, 1960]. Both carrier frequencies are continuously maintained and are controlled by the USWFS; WWVB is directly controlled and WWVL by a very unique and the first of its kind, remote phase-control system [Fey, Milton and Morgan, 1962]. This corrects for the frequency and phase changes due either to the controlling oscillator, the transmitter or the antenna system, so that the transmitted carrier frequency at 20 kc/s is essentially as stable as that of the USWFS (± three pp. in 10^{11}).

4.21 Frequency Offset

The carrier frequencies of WWVB and WWVL, as transmitted, are also offset from the USFS by the same amount as those of WWV and WWVH so: (1) that when precise time signals are added to them, they will be in step with those of the other nations, as described above, and, (2) to minimize the inconvenience to the users of UT2 time.

5. MEASUREMENTS ON STABLE FREQUENCY SOURCES

5.1 General

No known radio frequency source is truly monochromatic regardless of how stable it may appear when measured over a given time interval. In the strictest sense, then, a source does not have a single frequency but a spectrum of frequencies, the latter depending on the manner in which the source is modulated and the characteristics of the unwanted modulating signals. Unfortunately, there is at present no single quantitative way of completely describing [Strandberg, 1960] a frequency source and so several measurements are necessary to completely determine its performance characteristics. These include stability measurements taken over various periods of time from milliseconds (ms) to hours, and up to several days; also, power spectrum measurements may often be necessary or useful.

5.2 Frequency Stability Measurements

For intervals of time shorter than about one day, the stability of a quartz oscillator is determined by effects other than the aging of the crystals. This includes unwanted modulation, noise and temperature effects, component instabilities, effects of voltage variations, etc., whose individual or combined effects are not predictable to any useful degree. Thus, it is necessary to make stability measurements over the time intervals of interest in terms of a source whose stability is better than the unknown. Usually, at BL this is either a commercial rubidium (Rb) gas cell standard or one of the NBS ammonia Masers, the choice depending on the period over which the source is measured. For intervals shorter than a few seconds the Maser is used, as is also true in the spectrum measurements described below. For long term stability measurements, a Rb standard is used but it is calibrated periodically in terms of the USFS.

5.3 Power Spectrum Measurements

To make use of some of the unique properties of the ammonia Maser, a spectrum analyzer system [Barnes and Heim, 1961] was developed. The source to be measured is multiplied in frequency to a value near that of the Maser frequency (23.870 Gc/s), mixed with that of the Maser, and the resulting beat note is analyzed with a narrow-band (3 c/s) crystal filter to obtain the power spectrum. The latter shows the relative energy distribution of the various frequency components of the source and is thus a measure of the spectral purity of the signal.

The process of frequency multiplication, as is well known and used in the Armstrong FM system, has certain definite effects on the power spectrum of the signal. All stable frequency sources have very little, if any, residual AM due to their inherently high amplitude stability, but do contain FM signals of varying degree. The multiplication in frequency of such sources also multiplies the basic FM modulation index (β) by the factor of multiplication. This means the sidebands at the carrier frequency are increased in amplitude by the frequency multiplication process with the usual reduction in the amplitude of the carrier caused by the increased β, where β is defined as the ratio of the modulating frequency to the maximum frequency deviation of the carrier.

In this system, the FM modulation index is less than one and the large multiplication factor enhances the FM sidebands by about 73 db. This greatly facilitates the spectral measurements of the relatively "purer" sources. Further details are given in Barnes and Heim 1961.

6. FUTURE PLANS FOR IMPROVING AND EXTENDING THE SERVICES

6.1 Improved Signals at 60 kc and 20 kc

Construction is underway on a new LF and VLF station, at Ft. Collins, Colorado, so as to provide early in 1963 improved services by these broadcasts. Station WWVB (60 kc/s) will radiate a carrier frequency of about seven kilowatts and will also have precise time signals consisting of five cycles of 1,000 c/s, transmitted once per second. They will be kept in agreement with the WWV/WWVH time signals, as transmitted, to within ± one ms, initially, with plans to increase this to less than 10 microseconds at a later date. These signals should be generally useful over much of the Continental U. S. and, by use of coherent pulse reception or similar techniques [under development at NBSBL), at much longer distances.

Station WWVL (20 kc/s) will provide a carrier frequency suitable for frequency calibrations, using phase-lock receiving techniques, over most of the world. The radiated power will be about one kilowatt. It will also be an experimental facility for testing methods [Watt, Plush, Brown and Morgan, 1961] of providing precise time signals, for world-wide clock synchronization from a single station.

6.2 Portable Clocks

In order to use the time signals from a radio station to accurately synchronize remote clocks to the master clock at the station, it is necessary to know the group delay times of the signals. For microsecond timing, the calculation of delay times over long radio paths is not of sufficient accuracy because of the uncertainty with which the parameters effecting the propagation velocity are known. This is true even for signals propagated by the ground wave over distances exceeding a few hundred miles. Therefore, it is necessary to measure the delay time over each radio path. The easiest and most accurate way to do this, and the initial accurate synchronization of clocks, [Morgan, 1959], is by means of highly stable and accurate portable clocks [method under development at NBSBL].

It is planned to measure delay times of certain special radio paths and synchronize the clocks with those at stations WWVB and WWVL. Also, to provide very accurate synchronization of the latter stations with WWV and WWVH.

REFERENCES

Barnes, J. A., and L. E. Heim, "A High Resolution Ammonia-Maser Spectrum Analyzer", IRE Trans. on Instr., 1-10, 4-8 (June 1961).

Barnes, J. A., D. W. Allan and A. E. Wainwright, "The Ammonia Beam Maser as a Standard of Frequency", IRE Trans. on Instr., 1-11, No. 1, 26-30 (June 1962).

Comité International des Poids et Mesures, Proces-Berbaux des Seances, 1956 Session, Ser. 12, 25, Gauthier-Villars, Paris (1957).

Comité Consultatif pour la Definition de la Seconde, 2^e Session, Proc. (April 1961).

Crombie, D. D., Private communication (1960).

Fey, R L., J. B. Milton and A. H. Morgan, "Remote Phase Control of Radio Station WWVL", Nature, 193, No. 4820, 1063-1064 (March 17, 1962).

Markowitz, Wm., R. G. Hall, L. Essen and J. V. L. Parry, Phys. Rev. Letters, 1, 105-106 (August 1958).

Markowitz, Wm., "Astronomical and Atomic Times", U. S. Naval Observatory, Washington, D. C. (Unpublished).

Method under development at NBSBL.

Mockler, R. C., R. E. Beehler and C. S. Snider, "Atomic Beam Frequency Standards", IRE Trans. on Instr., 1-9, 2, 120-131 (September 1960).

Morgan, A. H., "Precise Time Synchronization of Widely Separated Clocks", NBS Technical Note 22, (1959).

Morgan, A. H., J. A. Barnes, "Short Time Stability of a Quartz Crystal Oscillator as measured with an Ammonia Maser", Proc. IRE, 47, No. 10, 1782 (October 1959).

NBS Miscellaneous Publication 236, "Standard Frequency and Time Signals from WWV and WWVH", (Revised, July 1, 1960).

NBS, "National Standards of Time and Frequency in the U. S.", Proc. IRE, 48, No. 1, 105 (January 1960).

Strandberg, M. W. P., "Precise Specifications of a Frequency", The Microwave Journal, 3, No. 8, 45-50 (August 1960).

Under development at NBSBL.

U. S. Naval Observatory Bulletin 195, March 15, 1962 (Unpublished).

Watt, A. D. and R. W. Plush, "Power Requirements and choice of an Optimum Frequency for a Worldwide Standard Frequency Broadcasting Station", Journal of Research of the NBS, Vol. 63D, 1, 35-43 (July-August 1959).

Watt, A. D., R. W. Plush, W. W. Brown and A. H. Morgan, "Worldwide VLF Standard Frequency and Time Signal Broadcasting", Journal of Research of the NBS, Vol. 63D, 6, 617-627 (November-December 1961).

WWV Standard Frequency Transmissions, Proc. IRE, 46, 91 (1958), and subsequent issues.

APPENDIX I

NBS Standard Frequency and Time Broadcasting Stations

Station	WWV	WWVH	WWVB	WWVL
Place	Beltsville, Md.	Maui, Hawaii	Boulder, Colo.	Sunset, Colo.
Latitude	38° 59' 33" N.	20° 46' 02" N.	39° 59' N.	40° 2' N.
Longitude	76° 50' 52" W.	156° 27' 42" W.	105° 16' W.	105° 27' W.
Frequency 1/	2.5, 5, 10, 15, 20, 25 Mc/s	5, 10, 15 Mc/s	60 Kc/s	20 Kc/s
Offset 1/	-130 pp. in 10^{10}	-130 pp. in 10^{10}	-130 pp. in 10^{10}	-130 pp. in 10^{10}
Stability 2/	5 pp. in 10^{11}	1 pp. in 10^{10}	2 pp. in 10^{11}	2 pp. in 10^{11}
Time Sig. 3/	UT2	UT2	None	None
Step Adj. 3/	50 ms	50 ms	None	None
Time Code 4/	3rd min. of each 5	None	None	None
Schedule 4/				
Operation	continuous	continuous	continuous	continuous
Off Time	45-49 min. past hr.	15-19 min. past hr. 1900-1930 UT	None	None
Audio Freq. 5/ Modulation	440/600 c/s	440/600 c/s	None	None
Schedule	2 min. of each 5	3 min. of each 5	None	None

Antennas	Vert. Omnidir.	Vert. Omnidir.	Vert. Omnidir.	Vert. Omnidir.
Type	$\lambda/4$ at 2.5 Mc	$\lambda/4$ at 5 Mc	top loaded	top loaded
	$\lambda/2$ at other freq.	$\lambda/2$ at other freq.	tuned	tuned
Power Radiated	2.5, 20 Mc-1 kw	5, 10, 15 Mc-2 kw	2 watts	15 watts
	5, 10, 15 Mc-10 kw			
	25 Mc-100 w			

Notes:

1/ The carrier frequencies of WWV and WWVH were offset -150×10^{-10} from the United States Frequency Standard beginning January 1960; WWVL in April 1960, and WWVB in July 1960. During 1962 the offset will be -130 parts in 10^{10}. This offset enables the time signals, which are locked to the carrier frequency, to maintain close agreement with UT2 time. Corrections to the carrier frequencies as broadcast are available on a weekly basis from National Bureau of Standards, Boulder, Colorado, upon request. Corrections for WWV are also published monthly in the Proceedings of the Institute of Radio Engineers.

2/ Frequency Adjustments:

WWV

As necessary, adjustments of frequency not exceeding one part in 10^{10} are made at 1900 UT. The carrier frequencies are interrupted from 45 to 49 minutes past each hour.

WWVH

As necessary, adjustments of frequency not exceeding one part in 10^{9} are made at 1900 UT. The carrier frequencies are interrupted 15 to 19 minutes past each hour.

3/ Time and Time Interval Adjustments:

Adjustments at WWV of precisely 50 milliseconds may be made in the time signals (second pulses) at the transmitters at 1900 UT when necessary. Such adjustment will be made on the first of the month following the month in which the transmitted time departs from UT2 by more than 50 milliseconds.

WWVH time signals (one second pulses) are adjusted, if necessary, each day during the interval 1900 to 1935 UT to be emitted simultaneously with WWV time pulses within ± 1/2 millisecond.

4/ See Appendix IV for details regarding the time code.

5/ Audio frequency modulations:

The audio frequencies, *440 and 600 c/s, on WWV are transmitted by means of a single upper sideband with full carrier, except on 25 Mc/s. Power output from the sideband transmitter is about 1/3 of the carrier power.

Percent amplitude modulation, double sideband: *440 and 600 c/s signals is 75%; voice and sounds pulses, peak is 100% at both stations.

Standard Audio Frequencies are broadcast alternately from both WWV and WWVH during two or three minutes of each five minute interval.

* Standard Musical Pitch-A above middle C.

APPENDIX II

STANDARD TIME INTERVALS

WWV time intervals, as transmitted, have the same accuracy as the carrier ± one microsecond. The frequency offset mentioned above, under Standard Radio Frequencies, applies. Pulses are transmitted at one second intervals. Received pulses have random phase shifts or jitter due to changes in the propagation medium. The magnitude of these changes range from practically zero for the direct ground wave to about 1,000 microseconds when received via a changing ionosphere.

TIME SIGNALS

Signal schedule: Standard audio frequencies are interrupted at precisely three minutes before each hour at WWV, and two minutes before each hour at WWVH. They are resumed exactly on the hour. Except for scheduled silent periods seconds pulses are broadcast continuously except for the 59th pulse of each minute which is omitted. The beginning of a minute is identified by a double pulse consisting of two regular five millisecond pulses spaced by 100 milliseconds. International Morse code announcements of Universal Time (referenced to the zero meridian) are made each five minutes from WWV and WWVH. Voice announcements of Eastern Standard Time are made each five minutes from WWV.

Adjustments of precisely 50 milliseconds may be made in the time pulses when necessary to maintain close agreement with UT2 (see note under Time Intervals).

Corrections, in terms of UT2, of the time signals as finally determined by the U. S. Naval Observatory are published periodically by them.

RADIO PROPAGATION FORECASTS

A forecast of radio propagation conditions is broadcast in International Morse code from WWV at 19.5 and 49.5 minutes after each hour and from WWVH at 9.4 and 39.4 minutes after each hour. WWV broadcasts information relating to the North Atlantic radio path and WWVH broadcasts information relating to the North Pacific radio path. Quality is graded in steps ranging from W-1 to N-9 as follows:

W-1 Useless	U-5 Fair	N-6 Fair-to-Good
W-2 Very Poor		N-7 Good
W-3 Poor		N-8 Very Good
W-4 Poor-to-Fair		N-9 Excellent

INTERNATIONAL WORLD DAY SERVICE

A symbol indicating the geophysical "state of warning", as declared under the international program of the International Council of Scientific Unions, is broadcast in International Morse Code from WWV at 4.5 and 34.5 minutes after each hour and from WWVH at 14.4 and 44.4 minutes after each hour.

The following symbols are broadcast to indicate the geophysical conditions:

SYMBOL	CONDITION	REMARKS
AGI AAAA	Alert	Magnetic Storm with K-index over 5 Outstanding Auroral Display Outstanding increase in Cosmic Ray flux
AGI ———	Special World Interval in Progress	Geophysical activity of sufficient interest to warrant attention of experimenters throughout the world.
AGI EEEEE	No significant Geophysical events	

APPENDIX III

INTERNATIONAL COORDINATION OF TIME AND FREQUENCY TRANSMISSIONS

The United Kingdom and the United States began coordinating their time and frequency transmissions early in 1960. This coordination is the result of an agreement announced by Dr. James H. Wakelin, Jr., Assistant Secretary of the Navy (Research and Development), Dr. Allen V. Astin, Director of the U. S. National Bureau of Standards, and in the United Kingdom by the Astronomer Royal, Royal Greenwich Observatory, and the Director of the National Physical Laboratory.

Coordination was begun to help provide a more uniform system of time and frequency transmissions throughout the world, needed in the solution of many scientific and technical problems in such fields as radio communications, geodesy, and the tracking of artificial satellites.

Participating in the project are the Royal Greenwich Observatory, the National Physical Laboratory, and the Post Office Engineering Department in the United Kingdom, and, in the United States, the U. S. Naval Observatory, the Naval Research Laboratory, and the National Bureau of Standards. This program follows previous cooperative efforts of these agencies to achieve uniformity and simplification in procedures.

The transmitting stations which are included in the coordination plan are GBR and MSF at Rugby, England; NBA, Canal Zone; WWV, Beltsville, Maryland; and WWVH, Maui, Hawaii.

APPENDIX IV

TIME CODE ON WWV

The timing code provides a standardizing timing basis for use when scientific observations are made simultaneously at widely separated locations. It can be used for example, where signals telemetered from a satellite are recorded along with these pulse-coded time signals; subsequent analysis of the data is then aided by having unambiguous time markers accurate to a thousandth of a second. Astronomical observations may also benefit by the increased timing potential provided by the pulse-coded signals.

This 36-bit, 100-pulse/sec. time code, carried on 1,000-c/s modulation, is being broadcast from radio station WWV (2.5, 5, 10, 15, 20, and 25 Mc/s). Starting date was January 1, 1961.

1. The code is broadcast for 1-min. intervals and 10 times per hour. Except at the beginning of each hour, it immediately follows the standard audio frequencies of 440 c/s and 600 c/s.

2. The code contains time-of-year information (Universal Time) in seconds, minutes, hours, and day of year. It is locked in phase with the frequency and time signals.

3. The code is binary coded decimal (BCD) consisting of nine binary groups each second in the following order: two groups for seconds, two groups for minutes, two groups for hours, and three groups for day of year. Code digit weighting is 1-21418 for each BCD group multiplied by 1, 10, or 100 as the case may be.

4. A complete time frame is one second.

5. The least significant binary group and the least significant binary digit in each group occur first. The binary groups follow the 1-sec. reference marker.

6. "On time" occurs at the leading edge of all pulses.

7. The code contains 100-per-second clocking rate, 10-per-second index markers, and 1-per-second reference marker. The 1,000 c/s is locked to the code pulses so that millisecond resolution is easily obtained.

8. The 10-per-second index markers consist of "1" pulses preceding each code group except at the beginning of the second where it is a "0" pulse.

9. The 1-sec. reference marker is made up of five "1" pulses followed by a "0" pulse. The second begins at the leading edge of the "0" pulse.

10. The code is a spaced code format; that is, a binary group (BCD) follows each of the 10-per-second index markers. The last index marker is followed by an unused 4-bit group of "0" pulses just preceding the 1-0 second reference marker.