FACILITIES AND SERVICES IN THE TIME DEPARTMENT OF THE ROYAL GREENWICH OBSERVATORY

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INTRODUCTION

The Royal Greenwich Observatory plays a unique role in timekeeping, having both national and international significance. When the Observatory was founded in 1675, two specially-designed clocks by Thomas Tompion were installed to enable the first Astronomer Royal to check on the regularity of the diurnal rotation of the Earth. In the nineteenth century distribution of time signals by electric telegraph became increasingly popular and by 1880 Greenwich Mean Time (GMT) was adopted as the standard time throughout England, Scotland and Wales. Following a meeting of scientific experts in Rome in 1883, the Washington Conference of 1884 recommended the use of the Greenwich meridian as the reference meridian for the worldwide measurement of time and longitude.[1] The designation GMT is still in very widespread use, but in many branches of scientific work it has, since 1928, been known as Universal Time (UT).[2]

CLOCKS

Quartz clocks came into use at Greenwich in about 1938, and by 1944 had completely replaced the former pendulum clocks.[3] From the middle of 1955 the rates of the Observatory clocks were checked in terms of the caesium beam frequency standard at the National Physical Laboratory, and in 1966 a commercial atomic clock (HP5060A) was installed at the new location of the Royal Greenwich Observatory at Herstmonceux in Sussex. The time department now operates five caesium standards, which are housed in cellars at sub-basement level. Each standard has an independent earthing system, an individual emergency power supply, and the distribution of time and frequency is by buffered screened balanced lines. On initial installation, each standard is carefully set up according to the manufacturers recommended procedure, the C-field being adjusted to the optimum level. No subsequent frequency adjustment is made by off-setting the C-field. In these strictly controlled conditions, the standards are capable of a stability of mean rate over periods of weeks of better than 0.01 microseconds per day. (1 in 10^{13}). The rates of individual standards can differ by as much as 0.5 microseconds per day, and occasional inexplicable changes of rate of a few tenths of a microsecond per day can occur.

COMPARISON EQUIPMENT

In the twenty years up to around 1955, most of the equipment used in the time service was designed and made in the department [4, 5], but in more recent years many electronic instruments have become commerically available. The primary system of clock comparisons utilizes a 10 nanosecond time resolution counter, programmed by a digital clock, to compare the clocks in groups of three, giving both a printed and a punched tape record. These time comparisons are supplemented by continuous records of linear phase comparators with a full scale deflection of one microsecond.

International comparisons are normally effected by reception and measurement of the Loran-C emissions. At Herstmonceux routine measures are made on Ejdes (master) and Sylt (slave) of the Norwegian Sea Chain and on Estartit (slave), Mediterranean Chain, using Austron 2000 C receivers checked differentially and by a simulator. Supplementary comparisons are made using VLF emissions and Tracor 599 and 599T receivers.

CHECK COMPARISONS

The Royal Greenwich Observatory is indebted to the US Naval Observatory for carrying out periodic traveling clock trips, which serve as a valuable check on the routine linkages via Loran-C. The continuation and extension of this service is essential to the task of the Bureau International de l'Heure (BIH) in the formation of an international scale of atomic time.

Comparisons have also been made by the Office National d'Etudes et de Recherches Aerospatiales: a clock carried in an aircraft was compared with clocks on the ground while the aircraft was in flight[6]; and by the US Naval Research Laboratory using the clock carried in the Timation II satellite. [7]

INTERNATIONAL CO-ORDINATION

A significant feature of recent developments in timekeeping has been the acceptance of the need for full international co-ordination, and the Royal Greenwich Observatory has cooperated fully in these projects[8]. There are three major areas of co-ordination:

a. Astronomical—Corrections for the effects of polar variation (p. v.) on astronomical time determination have been applied to the RGO observations since 1948, and for the seasonal fluctuation in the rate of rotation of the Earth since 1950. [9] The "smoothed" scale of astronomical time thus achieved was designated Provisional Uniform Time (PUT) and was the forerunner of UT2 used internationally since 1956.

The observations made with the Herstmonceux PZT are of a very high standard of accuracy and an interesting development has been the establishment in Canada of a PZT at Calgary at the same latitude[10]. The two instruments employ the same stars, the same adopted star places and the same basic methods of reduction. Full co-ordination permits the separation of errors associated with a particular instrument and site from those common to both. These two instruments together make a valuable contribution to the work of the BIH in computing current values of UT and p.v., and to the work of the International Polar Motion Service (IPMS) in the calculation of the definitive polar motion. During periods when the BIH data are required with the minimum delay by the Jet Propulsion Laboratory for the navigation of space vehicles, the Herstmonceux observations are communicated daily to the BIH by Telex.

b. Time Signals—International co-ordination of radio time signal emissions was pioneered by the British and United States time services in 1961 under the joint direction of the USNO and RGO, using the "offset and jump" method introduced in the MSF emissions in 1958[11]. The obvious practical advantages of such a scheme led to the recommendation by the International Astronomical Union (IAU 1961) and the International Radio Consultative Committee (CCIR, 1962) of the extension of the system to worldwide co-ordination under the control of the BIH. This system was modified by the elimination of the offset in 1972, and is now universally adopted.

A CCIR Working Party (IWP 7/1), has the continuing task of studying the implementation of the system and its possible improvement.

c. Atomic Time—The Greenwich Atomic Time Scale GA was established in 1955, and an adjustment was made (GA2) in 1958 to bring it into step with other national and international scales. The international scale (IAT) formed by the BIH was adopted by the International Committee of Weights and Measures in 1972 and is proving to be indispensable. Until mid-1973 the IAT scale was formed from seven independent scales (of which GA2 was one): since that date it has been formed using the data from individual atomic standards. The data are made available to the BIH by using Loran-C comparisons. The UTC scale used in radio time signal emissions is based on IAT, and differs from it by an exact number of seconds. This has become the "de facto" civil time in most countries, and the implications of this are being studied by a working party set up by the Consultative Committee for the Definition of the Second (CCDS of the CIPM).

CURRENT WORK

The vital role of the Loran-C system in the formation of IAT and in the coordination of radio time signal emissions on the UTC system, has led to a review of the factors affecting the accuracy of Loran-C measurements. Differential measures can be made on a routine basis to an accuracy of 0.01 microsecond, but there is still some confusion regarding absolute measures. It is recommended by the USNO that calibration of a reception station should be performed using a whip aerial: most users are forced to employ frame aerials for their routine operational work. European reception sites suffer a high level of interference, and cycle identification is difficult. With the cooperation of the USNO, and of the US Coastguards (responsible for the Loran-C system) many tests have been made. Some adopted propagation times appear to be in need of revision. A puzzling feature is the apparent drift between the Loran-C comparisons and those made with a travelling clock (see Table 1).

Another point of interest concerns the IAT scale. This is formed almost entirely of commercial (Hewlett Packard) standards. The occasional measures made with long-beam laboratory standards (which have a range of the order of 1 in 10^{12} indicate a systematic departure of IAT from the SI definition of the second[12]. There is a considerable body of opinion in favour of preserving the uniformity of the IAT scale to the highest degree possible so as to form a continuous uniform scale even if this entails a gradual drift from the best contemporary determinations of the SI second. It is a matter for discussion whether the IAT scale should be re-assessed and, if so, how often.

The arguments in favour of changing from a mean of independent scales to a statistical mean of individual standards carried weight: the new system permits the use of more standards (including those of establishments having only one or two atomic clocks), eliminates the uncertainties as to the procedures used at independent establishments in the formation of their own scales, and makes it reasonable for the BIH to adopt objective statistical methods of weighting. Nevertheless, there is a feeling that the ideal method has still to be found.

A promising development is foreseen in the successful tests made, both in the U.K. and in Australia, using Timation II. With the improvements planned in subsequent satellites, there is a prospect of achieving an accuracy no less than that of Loran-C under favourable conditions, and with the possibility of a full worldwide coverage. Long-term parallel operation of Loran-C and Timation is necessary.

Table 1

Traveling Clock — Loran-C

unit : microsecond

Date	OP	Date	RGO	Date	PTB
1969 Feb. 24	-0.1	Feb. 25	0.0		
July 11	+0.2	July 10	+0.4	July 21	+0.4
Oct. 29	-0.3				
1970 Feb. 16	-0.5	Feb. 17	0.0		
June 22	0.0	June 22	-0.3		
Aug. 15	-0.6				
Sep. 10	-0.6	Sep. 14	-0.6		
		29	-0.4		
Oct. 20	-0.4			Oct. 13	-0.1
1971 May 16	-0.8				
Sep. 23	-0.3	Sep. 30	+0.1	Sep. 25	0.0
1972 Apr. 11	-0.6	Apr. 19	-1.8	Apr. 14	-0.3
Dec. 7	-1.0	Nov. 30	-1.5		
1973 May 7	-1.3	May 15	-2.2		
Sep. 26	-1.1	Sep. 17	-1.3		

Differences of UTC comparisons with USNO using traveling clock and Loran-C.

It will be evident that in the collation of data and in the operation of an international service, the BIH is fulfilling an even more important function. The existing and predictable demands for accuracy can only be met by combining worldwide observations to determine UT and by syncretizing atomic clocks to establish an international standard atomic clock time. If this essential service is to be maintained, and is to be developed, adequate financial provision is obligatory, but practical assistance in the loan of equipment and staff could also be of assistance.

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QUESTION AND ANSWER PERIOD

DR. WINKLER:

We are open for questions.

DR. REDER:

Mr. Smith, wouldn't it be good, if you do make this comparison which you showed in the last two slides, to have at least one of those equipments which are used in France brought to your place or the U. S. Naval Observatory for comparison to be sure it is not due to an equipment difference?

MR. SMITH:

I am sorry, but in the limited time at my disposal, I couldn't explain the experiment in detail. I should have said that the receivers and full measuring equipment from the United States Naval Observatory were taken both to Herstmonceux and to Paris.

The agreement between the onsite equipment at Herstmonceux and Paris with that which was brought from the USNO was absolutely first class, and therefore there was the common element which you so rightly point out is necessary to an experiment of this type.

DR. WINKLER:

Mr. Lavanceau?

MR. LAVANCEAU:

In regard to the Loran C measurements of 1973 on two different occasions in Europe (Paris, Royal Greenwich Observatory, Germany, and also in the Faeroe Island, near the master station of the Norwegian Loran C chain), extreme care was taken in taking the measurements, i.e., during the same week, using the very same equipment, including antenna cables. All measurements made in Paris, BIH, and the Royal Greenwich Observatory did agree very, very well. I think one should realize and recognize that Loran C is a marvelous transfer tool. When one wants to make relative time transfer measurements, extreme precision can be achieved, such as perhaps tenths of microseconds or better.

But, when one is trying to make absolute measurements, there are so many variations, so many variables which sometime cannot be controlled that the scatter of the data, which we have seen here, is actually not really very large.

In most cases, it is 0.5 microseconds, and if one realized that some of this linkage is built by using 5 or 6 different sources of data, like for instance, when one is trying to relate measurements made at the U. S. Naval Observatory to measurements made at the same time across the Atlantic.

You know, one may not appreciate the fact that any small errors which one will encounter at one of these locations will of course add in some statistical way, and perhaps create that scatter. The Loran C system is capable of achieving greater accuracy, but a considerable price may have to be paid for that. This may not be easy to cope with.

DR. WINKLER:

I would like to make a comment myself. There are really two issues here. Mr. Lavanceau mentioned the small (0.5 microseconds) scatter in the measurements across the North Atlantic.

The question which we are also debating is the difference between making absolute measurements and relative measurements which you calibrate by visiting portable clocks, and this is what we have done from the beginning of the use of Loran C in the international system of atomic time keeping.

The observatory, for that very reason, has sent portable clocks to various establishments about twice every year.

We have kept a check on the propagation delays. But when you talk about absolute time transfer, i.e., when you set up equipment at the new location, and compare the computed delays with your own calibrated delays including the equipment, what is then the error, in an absolute sense of your time transfer?

We are talking about a problem which is common to every synchronization system in existence. It is only the magnitude which is different for the various systems.

If you take a VLF timing system, the magnitude is ten times larger. The differences between computed delays and actually calibrated delays are as large as 10 microseconds.

In a satellite system you also have exactly the same situation that one must calibrate a path or location. I think we will hear more about that this afternoon.

Again, we have to understand that difference between an absolute and a relative measurement where you calibrate overall by bringing a portable clock to the point of use, from time to time, to check everything, to certify the operation, and that it is one operation which essentially will have to be done in every system of time transfer.

Now, the magnitude of the specific effects we are here concerned with is for me startlingly great. I would think that what we have to accomplish urgently is a standardization of methods.

We have found between the various stations which we have visited that if we do the same things, with the same equipment, everywhere, we find a very high degree of conformity and repeatability of results.

But the general problem arises, I think, in using equipment which has been calibrated in entirely different ways, and then, of course, you could expect such discrepancies as discussed before. The discrepancy, in fact, has been two and a half microseconds roughly.

I am afraid we will have to stop here, because time is pressing. I will have to defer any further discussion to the outside or after the break.