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The definition of the 'atomic' second

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Abstract
When the reference of a unit is changed, the task remains of expressing the new definition in the terms of the previous one. In two centuries, for instance, the definition of the metre was changed six times. Around 1955, the definitions of the second as the SI unit of time were changed from astronomical ones, based on the rotation (or revolution) of the Earth, to a definition stemming from a quantum phenomenon. The expression of the new atomic second in terms of the previous definitions required a number of actions and measurements. The aim of this paper is to review these actions, some of which, fifty years later, are being forgotten for a lack of adequate documentation.

1. Introduction

Metrology is based on respect for some firm rules, some of which are not explicitly defined nor immediately understandable or are unwritten, albeit they all are *per se* simple or obvious; one of these rules being the continuity of the numerical value of the unit when the physical definition giving that value is changed.

Throwing away the 'old' numerical value would have the consequence of not being able to use past results and negate the researches and struggles connected with the dedication of many past scientists.

The most recent and, probably, more accurate value should be equal to the old values as regards the most significant figures, but with an uncertainty that can change in time because of the improving technology of measurement. Following this approach, the past evaluations and calculations can be used safely using the same 'old' numerical results, but the user is warned that if the 'first'[1] figures in the numerical value are not changed, their accuracies are different.

One example is offered by the metre definition, which has changed six times in two centuries. The quantity remained the same and, consequently, the numerical values of the calculations, but the uncertainty has changed by six orders of magnitude, being presently limited to the accuracy of the assigned value of the velocity of light. Moreover, now the velocity of light is a fundamental quantity, it has, by definition, no error.

A second example is offered by the unit of time interval, the second. Half a century ago there was a huge step forward regarding this definition, moving from the astronomical definitions based on the motions of bodies in our solar system to an atomic definition; the 'length' of the second remained nominally the same. This case was more striking: the philosophies embedded in the old and new definitions were widely different as were the technologies of the instruments, the 'error' budgets, the traditions and mentality of the researchers involved, but wisely the rule of 'continuity' was preserved.

Proposals were made at the time to change the name of the 'second'; some people proposed to call the unit of time interval the *Essen*, others played with the idea of using different names for the unit of time interval as read on a clock versus the unit of time interval that defines frequency.

The adoption of the new atomic definition released a surge of other proposals, based on the total decimalization of time measurement. By the way, a decimal counting of time (as opposed to the conventional system of days, hours, minutes, seconds) is used in some technical systems. The widely used Modified Julian Date is a sort of decimal counting of days and decimal fractions of a day.

But apart from these and other, more or less fantastic proposals, a real problem had to be solved: what value was to be assigned to the frequency of the caesium resonance in terms of the current unit of the second; in other words, how to connect numerically the astronomical processes on which the previous definitions were based with the (natural) resonance frequency of the caesium atom that was to be the new standard.

This paper is devoted to the events that converged to or followed the construction in 1955 of the first caesium-beam frequency standard by Louis Essen at the National Physical Laboratory (United Kingdom), in order to attribute a value to the frequency of the atomic transition. This transition was assumed in the following years as the basis for the definition

[1] In this context 'first' means the first figures after the decimal point or, in general, the most significant ones.

of the 'second' of the Système International d'Unités (SI), by the CIPM (Comité International des Poids et Mesures).

On the basis of the above mentioned *continuity principle*, the new 'atomic second' had to be expressed in terms of the previous one, based on astronomical measurements. This activity was performed in Washington DC by William Markowitz, Director of the Time Section at the US Naval Observatory.

The second section of this report summarizes the last astronomical definition of the second, the third section lists the problems to be solved in order to arrive at the desired value and the cooperation between laboratories and individuals on national and international scales.

As will be seen in sections 3 and 4, this particular link between two widely different definitions required simultaneous research and practical activities in astronomy, microwave spectroscopy and radiotechnology. For the first two topics, the existing literature is adequate; however, for the third, even if it was performed at numerous institutions, available information is missing. As an attempt to fill this gap, this paper aims to provide some information on the radiotechnology involved. Not all these activities were purposely performed to find the frequency of the caesium transition; some of their outcomes, promoted by other missions, were at any rate instrumental in creating the culture and knowledge needed.

Section 5 gives details on how some of the problems that arose were solved, such as the difficulties of the transatlantic link between the UK and the USA and the coherent synthesis[2] of frequencies. Some conclusions are drawn in section 6.

An additional topic, to be outlined only, concerns the direct consequences that the new standard with the associate definition had for time and frequency metrology in the period 1955–1960.

2. Definitions of the second, as the SI unit of time interval

Interestingly, an 'official and old' definition of the second is not given in the literature.

By 'old' we mean a definition that emanated at least some centuries ago. It seems that a definition of the second as a fraction of the solar day was taken for granted and a formal statement was not felt to be needed or important.

One good reason was perhaps that the smallest time interval reckoned by the time-keeping devices of the moment (the resolution) was below such a small quantity. The first mechanical clocks that blossomed in Europe at the end of the 13th century[3], first with a verge-foliot mechanism as a regulator and later with a pendulum, had a daily rate of about a quarter of an hour, and the marks depicted on the dials were, at most, the hours.

Clocks with minute marks were introduced in the second half of the 17th century, while the marking of seconds appeared on the pendulum clocks used in the astronomical observatories and in maritime chronometers in the following century. The clocks used by Roemer (1644–1710) at the Paris Observatory to measure in 1676 the velocity of the light [1] had a resolution of a few seconds but were in a position to keep the time with errors of one or two minutes for periods of six months[4].

Possibly the first formal definition of the second as the 1/86 400th part of a solar day can be found in a complete treatise on the Metrology of Time, Length, Mass and Density, written by an Italian scholar in Poland in 1685[5,6].

In all the treatises of physics and astronomy that followed, the second has been assumed to be a consequence of the regular rotation of the Earth, and has continued to be taken for granted.

The first 'metrological', 'official' definitions given in 'modern' times can be found in the resolutions of the IXth General Assembly of the International Astronomical Union, held in Dublin in 1955. At that meeting, a rigid definition of the unit of time 'the second' was given for the first time; it was 1/31 556 696.975 of the tropical year for 1900. '*This unit has the great advantage of being invariable, unlike the mean solar second, which is subject to annual and other variations; but it has the disadvantage of being of difficult accessibility*'[7].

Also in the activities of the CGPM (Conférence Géneral des Poids et Mesures), the CIPM and the BIPM (Bureau International des Poids et Mesures), the second, as the unit of time interval, arrives at a later stage. Time-scale formation was, until 1988, the task of another international organization, the Bureau International de l'Heure (BIH), based at the Paris Observatory. It was at the moment of the closure of the BIH in 1988 that a time section was officially established at the BIPM. The CIPM formed, in 1956, a Consultative Committee for the Definition of the Second (CCDS), renamed in 1997 as Consultative Committee for Time and Frequency (CCTF). The first official definition of the atomic second in the SI dates from the year 1967–1968[8].

3. The problems that were solved by Essen, Markowitz, Pierce and many others

Comparing a frequency derived from astronomical observations to that obtained from an atomic transition is, in principle, a straightforward matter. Two clocks—at that time the best available were piezoelectric standards—were independently linked to the two phenomena and their output frequencies had to be subsequently compared.

Consequently, there were three basic problems to be solved:

(1) Astronomical observations were used to form a time scale by means of a frequency standard and observing

[2] Coherent synthesis will be dealt with in section 4.

[3] The first written citation seems to be from Galvano della Fiamma, a monk in Milano, saying that in 1309, in his church, San Eustorgio, was installed a 'horologium ferreum'; in the following years there were dozens of quotations in European languages.

[4] Details on the time measurements by Roemer can be found in the Proceedings of a meeting organized in 1976 by the French Conseil National Recherche Scientifique.

[5] Tito Livio Burattini: Il Metro Cattolico, Tipografia dei Padri Francescani, Vilnius, 1685.

[6] S Leschiutta: Tito Livio Burattini, metrologo dimenticato del '600, *Il giornale di Fisica* **21** 305–22 (1980).

[7] This last paragraph was taken from a paper of Essen [2], written a few months after the first experiments with the caesium device, still used as a resonator and not yet as the reference inside a servo-controlled loop.

[8] Resolution 1 of the 13th CGPM, SI unit of time (second) 1968 *Metrologia* **4** 43.

the transit of stars[9]; this was the task of Dr (later Prof.) William Markowitz, Director of the Time Division of the US Naval Observatory (USNO) in Washington DC (USA). An innovative astronomical instrument, the double-rate moon camera, invented by him was used. An important corollary was the availability of reliable clocks, by definition piezoelectric ones, to be used as a stable flywheel to drive a clock capable of maintaining a (nearly) constant rate for a few months.

(2) To perform spectroscopic measurements, linking the frequency of a frequency standard (a piezoelectric device) to an atomic transition, was the work of Louis Essen, senior researcher at the National Physical Laboratory (NPL), UK. He succeeded, in 1955, in creating an atomic frequency standard in which a crystal frequency standard based on an Essen ring[10] was used to excite the atomic resonance phase locked to the transition between some hyperfine states of a caesium-133 atom. Also in this case, the frequency standard had to be accurate and stable for two reasons:

– not to contaminate the measurement with its proper noise, and
– to act as a stable flywheel because the caesium beam was not operating continuously.

(3) To realize frequency and time comparisons between the two crystal frequency standards across the Atlantic Ocean with an accuracy of about 10^{-10}, via time signals on HF (MSF and WWV), on LF (MSF) and on VLF (GBR). This activity required the coordinated action of many individuals: the coordination of Essen and Markowitz plus Corke at the British Post Office and in the USA Pierce of the Cruft Laboratory in Cambridge, Winkler and the US Naval Research Laboratory (NRL). Other laboratories were directly or indirectly involved, via activities promoted by the International Union of Radio Science (URSI), of which Essen was an official, and later Chairman of Commission A—Electromagnetic metrology. Other discussions and agreements were reached in Commission 7—Standard Frequency and Time signals services of the Consultative Committee for Radiocommunications (CCIR), now the International Telecommunication Union Radiocommunications Sector (ITU-R).

As anticipated above, some of the technical activities leading to the ‘caesium frequency’ had been initiated or conducted for other reasons, but the dedication of researchers achieved useful synergies, combining results which would otherwise be scattered.

Moreover, the solutions for any of these problems had to be at the state-of-the-art, and this achievement had to be reached for a number of very different disciplines, such as observational astronomy, treatment of data, microwave technology, experimental physics, electronic technology[11] and circuits, frequency synthesis, ionospheric propagation, crystal frequency standards, LF and VLF[12] emissions and so on.

It must be noted that the solutions to the first two problems, the astronomical and the spectroscopic observations, are adequately covered in the existing literature, but news and details concerning the third problem, the link between the frequencies of some quartz clocks, one in Teddington, another in Rugby, UK and others in America, are lacking. Consequently, some of the technical solutions proposed to cope with the ‘transatlantic crossing’ will be outlined in section 4.

3.1. *The clocks used in the observatories, laboratories and transmitting stations*

The clocks used in the period 1935–1965 in astronomical observatories, metrological institutes and radio-transmitting stations were piezoelectric ones, in which electronic circuits had two tasks: to maintain in mechanical oscillation a piezoelectric resonator made of quartz, and to provide as an output a sinusoidal electrical signal having the same frequency as (or a convenient multiple of) the mechanical oscillation.

Piezoelectric clocks had to be kept in a thermally controlled environment but, being subject to ageing[13], they had to be periodically corrected using as a reference the transit of some selected stars at the meridian of the observatories.

To maintain the time signals on UT1 and to obtain ephemeris time (ET), three astronomical instruments were used: transit instruments, the photographic zenith tube (PZT) and the Markowitz double-rate moon camera, the last one being really instrumental in the caesium frequency measurement, the object of this paper. They are briefly described here:

Transit instrument. A ‘*transit*’ instrument is a simple telescope, with its trunnions resting in bearings oriented East–West. The telescope consequently spans the local meridian plane, and the crossing of this plane by some selected stars is to be detected. To help the astronomer in judging the instant of this event, the transit instrument is fitted with the so-called ‘*impersonal micrometer*’, a slide fitted with a number of lattices or reticules. The astronomer, by turning manually a knob, has the task of maintaining the moving star between two reticules; electrical contacts, activated directly by the slide, transmit to the recorder the transit time of the star. The same recorder kept the second pulses received by the local piezo or pendulum clock.

This kind of instrument was widespread, more than 25 were operated in observatories with the nickname of Bamberg or Askania, since many of them were made by these two German factories. The accuracy in timing one star was estimated between 12 ms and (20–30) ms.

Nearly 85% of all the time scales and the corrections to the astronomical clock and to the clocks in the metrological laboratories were obtained, until 1960, with this type of instrument. In the period 1935–1950 the seasonal variation in the Earth’s rotation was detected using these instruments.

[9] In practice the times of occultations of the stars by the moving disc of the Moon were considered.

[10] For the Essen ring, an annular quartz resonator was used, see point 5.3, and figure 3.

[11] Electron tube technology only was available.

[12] LF stands for low frequency, in international nomenclature the band 5 from $3 \times 10^{+4}$ Hz to $3 \times 10^{+5}$ Hz or kilometric waves; VLF stands for very low frequency, in international nomenclature the band 4 from $3 \times 10^{+3}$ Hz to $3 \times 10^{+4}$ Hz, or myriametric waves.

[13] Ageing is a systematic variation of the frequency with the running time, expressed as a daily fractional frequency variation, $(\Delta f/f)$/day. Research conducted in many laboratories and factories led to improved resonators, with the choice of the material, forms of resonators, treatment of surfaces, special temperature control and regulation of the exciting signal. These and other actions reduced, between 1955 and 1965, the ageing by nearly three orders of magnitude, from about 1×10^{-8} day^{-1} to some 10^{-11} day^{-1}.

Photographic zenith tube. About ten observatories in the world were routinely using a PZT, a vertically oriented instrument, in which the vertical direction is ensured using a pool of mercury as a horizontal mirror. The incoming light of the star, in its motion West to East, enters via a lens placed at the top of the tube, is reflected by the mercury pool, and at the crossing of the meridian is collected by a horizontal photographic plate placed at the top of the instrument and looking downwards. The carriage holding the plate was animated by suitable movements, controlled by a piezoelectric clock in such a way as to form in the same plate four images of the star. Simultaneously with the formation of the images on the plate, time markers coming from the clock were registered. The coordinates on the plate were read with a measuring machine, and in the transformation from plate-coordinates to sky-coordinates the registered times were entered in the calculations; the final solution gave the UT0 of the transit time of the star on the local meridian, the final accuracy being of the order of a few milliseconds, with suitable averaging. To be conservative, the daily noise of PZT measurement was <10 ms.

A comparison between these two instruments has been made by Thomson[14].

Double-rate moon camera. The US Naval Observatory in Washington was the only observatory using the Markowitz double-rate moon camera. This particular astronomical instrument was used since 1953 to time the transit of the stars. A similar instrument was installed in 1958 at the Royal Canadian Observatory.

The interest in determining time and longitude using the Moon instead of the stars, with the help of the Earth’s rotation, was recognized by ancient astronomers, who had in the past proposed no less than 20 different methods, using the coupling of the motion of stars and Moon: occultations or distances[15]. Amerigo Vespucci explains this point very well: ‘el moto più legger della Luna’[16], which is translated as ‘the Moon is very swift in her movements’. Its motion through the stars is indeed thirteen times faster than that of the Sun (0.55″ as opposed to 0.04″ in one second).

But reading the times of a star disappearing or reappearing from behind the Moon is a difficult task for the astronomer, owing to the glare of the Moon. In the dual-rate moon camera, a diaphragm-filter with the same angular dimension as the Moon was moved suitably inside the field of the telescope.

In figure 1, the two ‘rates’ of this peculiar camera are evident[17], one is given by the carriage holding the photographic plate in order to track the stars; the other, tilting a plane-parallel filter, keeps the Moon fixed on the plate. With the glare due to the Moon being consequently reduced to a large extent, the task of the astronomer becomes easier. The final accuracy in timing was estimated to be of the order of one millisecond when the observations were combined over a three-month period.

The frequency of the crystal clock driving the two synchronous motors was estimated within an accuracy of a few parts in 10^{-9} with protracted observations.

[14] Thomson M M 1958 The dual-rate moon-position camera *R. Astron. Soc. Can. J.* **53** (3).

[15] Leschiutta S and Tavella P: Reckoning Time, Longitude and the History of the Earth’s rotation using the moon, pp 225–36 in [3].

[16] Oberti E 1932 Amerigo Vespucci, Paravia, Torino.

[17] Figure 1 was taken from [4].

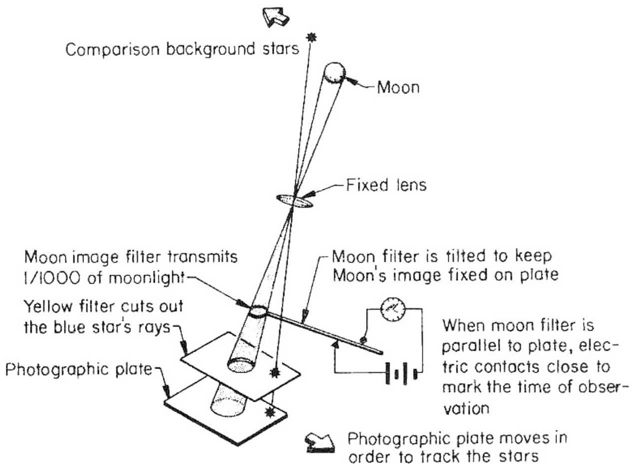

Figure 1. Principle of the double-rate moon camera.

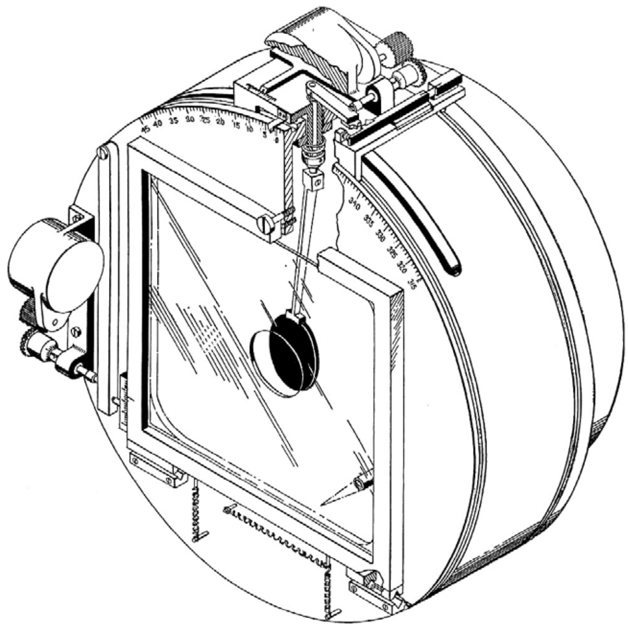

Figure 2. The double-rate camera used by Markowitz at the US Naval Observatory.

The double-rate camera, shown in figure 2[18], is the result of research undertaken by William Markowitz, between 1951 and 1953. It was attached to a 12 inch visual refractor of 180 inches focal length. The drawing and data are taken from a paper by Markowitz [5], printed in March 1954 in *The Astronomical Journal*.

The moon camera was designed to hold the Moon fixed against the background of stars for a 10 s to 20 s exposure, but usually 10 s were sufficient.

The ‘black’ circular filter intercepts the image of the Moon, reducing its brightness 1000-fold. The filter is made to tilt at a uniform speed by a synchronous motor mounted at the top of the camera, as shown in the drawing. The action of this plane-parallel field causes the image of the Moon to be displaced backwards by exactly the amount of its forward motion through the stars. In the finder, a plastic reticule was

[18] Figure 2 was taken from [5].

included marked with several concentric circles; when the Moon's bright limb was coincident with the proper circle, the driver-motor was turned on and the shutter was opened for the required exposure.

The axis of the filter can be rotated manually in order to place it at right angles to the apparent motion of the Moon. Timing is secured by an electrical contact attached to the tilting filter; the 'epoch' of the exposure is the instant at which the rotating filter is parallel to the emulsion, when there is no relative shift of the Moon. The contact, via a thyratron, was acting on a timing recorder.

In figure 2, the motor at the left is the synchronous motor used to drive the plate at uniform stellar speed; consequently the telescope's sidereal drive was not used. More details on the double-rate camera can be found in Markowitz's paper and in that by Thomson.

A conservative estimate of the daily noise of the double-rate camera is between 100 ms and 500 ms.

There is an oral tradition that Markowitz himself was reading and reducing the plates and, subsequently, making the calculations that led him to the value of (9192 631 770 $\pm$ 10) Hz as the frequency of the caesium resonance, with respect to second of ephemeris. This particular activity is not recorded in a recollection of his life that Markowitz dictated a few years before he passed away. The results obtained by Markowitz were confirmed some years later by the Greenwich Observatory.

As a personal remark, taking into account the capabilities of the timing emissions at the moment, of the frequency standards available, of the inevitable scatter of the moon camera, and some other factors, not least the widespread use and abuse in 'touching' the piezo-oscillator, it is almost impossible to explain the accuracy of the Markowitz determination. Similar events, i.e. results surpassing the capabilities of the moment, are not uncommon in the history of science that sometimes is prone to accepting the intervention of a serendipity principle. The other possible explanation calls for a first class understanding of physics, coupled with scientific integrity.

4. The measurement

4.1. General organization of the measurement

To help in understanding the various steps and equipment involved in the measurement, a general outline is presented here. Some of the steps are not adequately documented, but we hope to have reflected the substance of the events.

(1) At the NPL, a frequency standard was in operation from June 1955; it was used first as a resonator, and later as reference in a servo with a local oscillator locked to the caesium resonance. One crystal frequency standard of the Essen ring type was used as a flywheel.

(2) In Rugby, UK, the British Post Office was operating a number of transmitting stations. Among them, there were GBR, a powerful station at 16 kHz, active since the first radio telegraphic transmissions, and MSF at 60 kHz, still active and distributing standard time signals, time codes and standard frequency. Station MSF 60 entered into the history of radiocommunications in the 1920s because it was the first to establish radiotelephony across the Atlantic, via an agreement between the British Post Office and the American ATT.

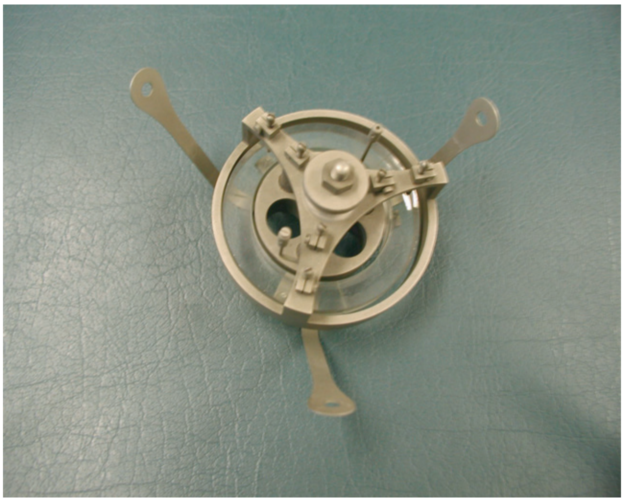

Figure 3. Essen ring quartz oscillator.
(This figure is in colour only in the electronic version)

The carrier for these stations was obtained via two synthesizers fed by an Essen ring quartz oscillator (figure 3 shows such a resonator). Corke, superintendent of the Post Office, responsible for the service, was most helpful in counselling the writer of this paper about the design of coherent synthesizers and other pieces of equipment and gave, back in 1962, permission to visit in Rugby the stations MSF, GBR and the Essen oscillators.

(3) At the NPL, some 120 km from Rugby, the GBR and MSF carriers were phase-compared using synthesizers, driven from the Essen ring that had been compared and later locked to the caesium resonance frequency. At the same NPL, the time signals coming from MSF, both on HF and on LF, were received and recorded along with those coming from WWV, the standard station of the NBS, kept in time from USNO, using PZT data.

(4) In Cambridge, Massachussets, USA, at the Cruft Laboratory, Harvard University, the carriers of MSF and later of GBR were compared, since 1954, using frequency synthesizers driven originally by a crystal frequency standard and later by an Atomichron[19].

(5) In Washington, at the US Naval Research Laboratory, a 10 kHz signal was obtained from a local hydrogen maser, to be sent via land lines to the USNO as a long-term reference.

(6) In Beltsville, Maryland, where the NBS station WWV was located, instructions coming from USNO were received via telephone calls, about the adjustments to be introduced in frequency and time. In this particular case, since Beltsville is near the USNO location, the resolution of the received signals was 0.1 ms.

(7) At the USNO, the audio frequency received from NRL was compared with a local piezoelectric standard driving the clock of the observatory and driving, also, the two synchronous motors of the dual-rate moon camera.

[19] Atomichron was a commercial atomic frequency standard, produced in 1956 in the USA by the National Company. See section 6.3.

The needed frequencies were all derived from the USNO master clock, a 2.5 MHz piezo-oscillator from Western Electric, with a fractional stability, from day to day, of around 10^{-10}. Its signal was compared with the hydrogen maser of the Naval Research Laboratory to obtain a long-term stable reference via an overland line carrying a 10 kHz signal. Moreover, a PZT was operated in order to know the difference between the UT1(WWV) and the UT1(observed), to be communicated to the WWV station.

4.2. Mechanization of the measurements

- At that time, there was no way of performing a direct measurement of Cs-ET as there was no available long-term stable reference, and Essen and Markowitz had to resort to the use of the astronomical UT as a reference.
- Astronomical UT was given by the time signals of WWV, MSF and GBR.
- The station WWV had to be kept on UT, by daily adjustments directed to them via telephone lines, on the basis of the last PZT observation.
- The noise of the HF and VLF time signals was about 1 ms.
- The very same time signals had to be used by Essen and by Markowitz.
- Essen was driving his clock and measurement system with the same Essen ring he was using to measure the caesium resonance.
- Essen had to estimate his caesium frequency with respect to the same time signals used at USNO.

All the time signals had resolutions that were too poor for estimating the caesium frequency with errors of less than 10^{-9} to 10^{-10}, because:

- HF and VLF time signals had a resolution of 1 ms on a daily basis; this means that a frequency could be appreciated only within 10^{-8},
- PZT has a noise on a daily basis of about 10 ms, and
- The double-rate moon camera needed to make measurements with respect to ET had a 'daily' error reaching 0.5 s.

This situation consequently compelled the scientists to make long-term averages; with a measurement lasting 100 days, the daily noises are in large part suppressed.

VLF phase comparisons helped in maintaining within close limits the frequency of the stations, not the time of their signals. The resolution on a daily basis of the frequency comparisons between two carriers, performed via relative phase measurements, can be 10^{-10} to 10^{-11}, with the measurement spanning one day, from noon to noon.

5. Solutions given to some additional problems

Along with the two main devices involved in the measurements—the dual-rate camera and the caesium frequency standard—other pieces of equipment were also instrumental; some were known previously but had to be improved, and others had to be developed. The synthesizers belong to the first category and the VLF receivers to the second.

5.1. Development and use of synthesizers

Manipulation of frequencies was necessary in all the operations described here. This meant altering their values while preserving the relative accuracy of the frequency of the driving signal. This operation was needed, for instance, to compare the stability and accuracy of frequency standards at different frequencies, to obtain a carrier of an emission at any frequency as derived from a frequency standard operating at another frequency, or, as a necessary ingredient to design a receiver able to make frequency measurements of a received signal.

The instrument performing these operations is called a '*synthesizer*', spelled also as 'synthetizer', a device having input and output frequencies with different values but with the same relative frequency error. A sinusoidal input signal of 100 kHz is converted, e.g., into a sinusoidal signal of 16 000 Hz with the output characterized by the same (modulus and sign) fractional or relative error characterizing the input. The instrument, also called a fractional-frequency generator, must have a number of requested characteristics. The most important of these are:

- the output wave, since it is obtained through a modulation process involving the input wave, will appear only[20] when the input signal is present[21] and then bear a fixed frequency ratio with respect to it. In the application envisaged during the transatlantic measurement, a given ratio of phases should be preserved between the two waves,
- the shape of the output wave is in practice a sinusoid and consequently can be used to drive a transmitter,
- by proper design, the amplitude of the output wave will approach a linear relation with that of the input wave,
- these principles are applicable to the whole frequency range in which it is possible to amplify and modulate,
- the actual values of the gains of the various stages are not important and
- the capability of the circuit to produce the proper fractional frequency is not affected by considerable distortion of the input wave, or extraneous frequencies, such as noise.

The technique of adding, subtracting and multiplying[22] frequencies had been known since the beginning of radiocommunications, but the possibility of dividing a sinusoidal frequency by an integer was revealed by Miller only in 1935[23].

Another circuit, based on a series of oscillators whose output frequency was locked to another signal[24], was discovered later, around 1940, but some of the requirements mentioned above were not fulfilled.

No single instrument in which these five operations could be combined (adding, subtracting, multiplying, dividing

[20] This wanted characteristic, in other words, is given by the disappearance of any output signal whenever the input signal is not available. Not all the synthesizers exhibit this behaviour, needed in time and frequency metrology.

[21] The reason is obvious: it is better not to have a signal than to have a signal with no proof of its integrity.

[22] Longo G 1934 Moltiplication d'une fréquence per simples facteurs fractionels *L'Onde Electrique* **13** 97–100.

[23] Miller R L 1939 Fractional-frequency generator utilizing regenerative modulation *Proc. IRE* (June) 446–57.

[24] This approach is called PLL (phase locked loop).

and PLL) was available until the period 1955–1960; the instrument is now called a decimal synthesizer. As an example, one instrument of this type, used in military applications, telecommunication and microwave spectroscopy, metrology and research on fundamental constants, has one standard frequency as input, and as many as 50 billion output frequencies, one at a time, ranging from 0.001 Hz to 49 999 999.999 Hz with steps of 0.001 Hz. A decimal synthesizer of this kind, developed by the Italian Navy during the war, was not revealed until 1945[25,26].

The consequences are that two different frequencies can be compared since it becomes possible to convert both to a unique value, where, for instance, an adequate measuring system is available, or to convert one frequency to the value of the other, thus enabling a direct comparison. Another advantage was to use a frequency standard as an input signal and have at the output the carrier of a transmitter. The radiated frequency had consequently the same fractional error as the frequency standard.

A *'coherent'* frequency synthesizer is a piece of equipment not only preserving the relative frequency error, but also maintaining a given ratio of integers between the phases of the input and output signals. Usual synthesizers do not preserve a given fixed ratio between the input/output phases, and each time the set is operated, the output phase assumes one of many possible values. Coherent frequency synthesizers assume one specific relation each time, and it is always the same.

In the measurement leading to the caesium frequency, frequency synthesizers derived from the Miller system were used to obtain the standard carrier frequencies for the transmitters used in Rugby (UK) for the stations GBR at 16 000 Hz and MSF at 60 kHz, in the receivers used at NPL to measure these two frequencies, and at the Cruft Laboratory and NRL in the USA, to compare the received carriers with local quartz frequency standards.

5.2. Piezoelectric 'flywheels'

If the final task was to compare the new atomic frequency standard with the ET given from the lunar observations, a large number of piezo-oscillators, as listed in section 4, entered in the measurement with the important role of a flywheel, offering the requested stability through many steps.

The generators used a number of different shapes as resonators: plates, bars, rings and diapasons kept in an oven to avoid temperature effects. The resonators were different, but usually the circuit of the oscillators was the same, inspired by a development made at the Bell Laboratories[27] and based on a Wheatstone bridge, with the resonator in one arm, and one simple amplifier for maintaining the oscillations. This circuit, called a bridge-stabilized oscillator, or Meacham bridge, presented a number of advantages and was used extensively for 20 to 30 years. The resonator element, controlling the frequency, was used as one arm of the bridge, kept in balance automatically by a thermally controlled arm; this oscillator provided constant output voltage, spectral purity and stabilization against fluctuations in power supply or changes in the circuit elements.

5.3. VLF receivers

In section 4 are listed a number of phase measurements on LF and VLF carriers, in England, the US and across the Atlantic; this technique had its first applications in the period 1955–1960. These measurements, in which two frequencies could be remotely compared with a resolution of 10^{-10} to 10^{-11} with measurements lasting about 10 h, were obtained with simple receiver–comparators.

Four types of receivers are described in a well-known and seminal paper[28] by Pierce of Harvard University. In such devices, the 'frequency divider' and 'frequency converter' stand for the frequency synthesizer, converting the frequency of the local standard usually at a 'round' value, such as 100 kHz or 2.5 MHz, to the nominal value of the radio frequency received. These devices were widely used in the period 1955–1975 by taking advantage of the astonishing stability of the propagation of VLF signals covering the globe.

In such devices for comparing the frequency of an incoming signal with a local oscillator, a radio frequency amplifier, tuned to the VLF station carrier, fed directly the intensity of the trace (Z axis of an oscilloscope); the horizontal trace was the internal time-base of the scope, triggered to any convenient rate by a signal coming, via a synthesizer, from the local frequency standard. The time-base period was regulated around the period of the incoming signal. With suitable settings, the luminosity was 'turning on' during the positive half-cycles of the incoming radio frequency signal. The trace on the scope was recorded by a camera in which the film was continuously and slowly moving (about 1 cm h^{-1}), the slope of the resulting figure giving directly the fractional frequency difference between the local standard and the received signal.

Another approach was to introduce a continuous and constant frequency offset in the local frequency standard that was subsequently brought to the nominal value of the receiver station. The two signals were fed to a phase detector, whose output was the beat between the local standard (that had been corrected to a known quantity) and the received one.

Other forms of receivers provided directly, in graphic or numerical form, the amplitude of the received signal and the phase. These receivers were adopting synthesizers of the coherent type.

The 'discovery' of the unexpected stability of the VLF propagation constituted a wonderful tool for propagation research, communication with submarines, detection of phenomena in the ionosphere, global navigation systems (such as the Omega) and global communication. The scientific impact was well reflected in the magazine *Radio Science*, printed under the auspices of the URSI American Committee, and in some books, the most widely used being *VLF Radio Engineering* by Wait.

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6. Final comments

6.1. The success of the measurement and the success of the definition

Looking at the problem in retrospect, the proposed aim of defining the caesium frequency with respect to the ET was achieved [12].

The definition adopted by the CGPM in 1967–1968 proved to be, at the same time, accurate, exhaustive and flexible. These three characteristics can be demonstrated considering that no additional rules (*mise en pratique*) had to be studied and agreed; that any physical laboratory could, in principle, design and build the standard, that the same 'recipe' was adequate for the first thermal beams, with magnetic state selection, or optical state selection or for completely different techniques, such as the so-called 'fountains'. The present definition was, moreover, used commercially with relevant success; it is estimated that more than one thousand caesium beam devices have been constructed.

In other words, the definition as it was drafted more than 40 years ago gave place to an increase in accuracy from 10^{-9} to 10^{-15}, with a gain in accuracy of more than one order of magnitude per decade.

The question about the mental and experimental paths taken by Markowitz that led him to write (9192 631 770 ± 10) Hz remains open, despite:

- using UT1 data with clocks corrected nearly every day, with a timing accuracy at the millisecond level at best, giving an accuracy in frequency of 1×10^{-8},
- taking data from the double-rate moon camera, having a resolution of around 0.5 s on ET and for UT from a PZT affected by a resolution of 10 ms,
- the need for a long chain of measurements and commands, composed of many laboratories belonging to different authorities, to be kept 'synchronized'.

6.2. The role of the crystal standards

The quartz oscillators in the measurements described here had a role similar to that of the hydrogen masers today, in the most accurate activities of time and frequency metrology.

The role is similar to that of stable flywheels in mechanical systems: piezo-oscillators are indeed used in the operation of caesium fountains, as the most stable reference available for the assessment of the frequency during the up-and-down flight of the ball of atoms. As in the past, nearly all the activities listed in section 4 required the presence of a stable crystal oscillator as a flywheel.

6.3. Status of time and frequency metrology between 1945 and 1955 and the first consequences of the new standard and definition in the period 1955–1960

It is not the aim of the present report to dwell on the status of time and frequency metrology for that period that was fascinating for the developments, applications, new results and brilliant personalities of some of the actors. A decision was taken to list some facts and developments without comments, but taking care to provide the interested reader with a dedicated bibliography.

At the end of hostilities, the International Administrative Conference held in Atlantic City, USA, in 1947, allocated some frequencies to the standard Frequency and Time Signals Services. One year later, in Stockholm, a session of the CCIR was held at which was decided the formal formation of Study Group 7, devoted to this topic. Bernard Decaux of France and Mario Boella of Italy were appointed Chairman and Vice Chairman, respectively.

The development of these activities can be followed in the CCIR documents and in some papers by Essen [13] and Essen and Steele [15]. In 1952, some atomic frequency devices were presented in the USA with an ammonia absorption cell, later also developed in other countries such as Italy and Japan. In 1955, the caesium frequency standard at the NPL [15] was announced, and its immediate application was made to the control of the standard stations and remote measurements using the VLF propagation [16, 17]. Figure 4 shows Louis Essen inspecting a vertical version of his time standard.

In 1956, commercial caesium standards developed by the National Company, USA became available. They were called Atomichrons: the first quantum electronic device and the first caesium tube produced commercially, representing an outgrowth of MIT work under Zacharias[29,30]. In 1958–1959, two Atomichrons were transported to the NPL, where they were left for an 18-month comparison with NPL caesium no 3 (table 1). These standards were widely used in national laboratories, as can be seen from table 1, taken from a paper by Essen and Steele [15].

The accuracy of the Atomichrons was of the order of 10^{-10}, thus paving the way for successful industrial developments. Three of those developments or consequences must be mentioned:

- the transportation by air of caesium standards for time synchronization between remote laboratories[31],
- the improvement in accuracy by four orders of magnitude; also by an automatic active control of many of the disturbances, and
- the existence of hundreds of similar devices in metrological laboratories around the world, which allowed the statistical construction of the International Atomic Time scale, TAI, entrusted to the Time section of BIPM.

In the five years immediately following 1955, i.e. until 1960, atomic frequency standards were developed in Canada [18], Italy [19, 20], Switzerland [21, 22] and the United States of America [23–28].

Acknowledgments

In preparing this paper, along with the existing documentation, substantial help was received from Dr C Costa for the drawings of the double-rate moon camera, and Dr Felicitas Arias

[29] A few years later, Zacharias attempted the construction of a caesium fountain, called *fallotron*.

[30] In 1992, MIT Press published a book concerning the life and activities of Zacharias, not only as a gifted researcher but also as a dedicated educator, *A Different Sort of Time: The Life of Jerrold R Zacharias—Scientist, Engineer, Educator* by Jack S Goldstein.

[31] This technique was the most accurate available for a few years.

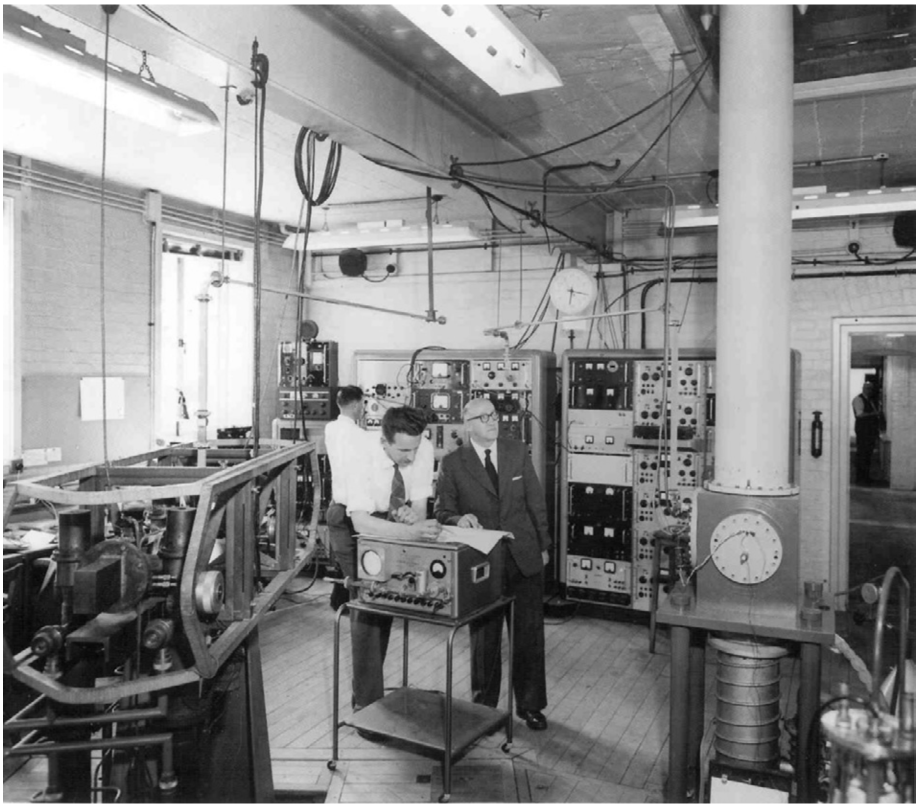

Figure 4. Louis Essen (wearing spectacles) inspecting a vertical version of his time standard (photograph reproduced by courtesy of the NPL, UK).

Table 1. Atomichrons used in metrological laboratories before June 1960.

Laboratory	Nation	Type of atomic standard
CNET Centre National d'Etudes des Telecommunications	France	Atomichron
CRUFT Lab.	USA	Atomichron
LSRH Laboratoire Suisse recherche Horlogère	Switzerland	Ammonia maser • $^{14}NH_3$ • $^{15}NH_3$
National Bureau of Standards	USA	Atomichron Caesium atomic beam
National Physical Laboratory	UK	Caesium atomic beam no 1 Caesium atomic beam no 3
National Research Council	Canada	Caesium atomic beam
US Naval Laboratory	USA	Atomichron

and Dr G M R Winkler for many observations, corrections, recollections and data regarding the links between lunar occultations and the measurements performed by Louis Essen and William Markowitz. In particular, the cooperation of Dr G M R Winkler must be recognized for the wealth of information concerning the events and the activities listed in section 4.

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