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Naval Electronic Systems Command
NASA Goddard Space Flight Center
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Prepared by
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BANQUET SPEAKER

Humphrey M. Smith, OBE
Royal Greenwich Observatory
Subject: The History of Time

CALL TO SESSION

L. J. Rueger, APL

WELCOME ADDRESS

Captain Lionel M. Noel
Commanding Officer, Naval Research Laboratory

OPENING COMMENTS

Dr. Robert S. Cooper
Director, NASA Goddard Space Flight Center

OPENING COMMENTS

Captain Joseph C. Smith
Superintendent, U. S. Naval Observatory

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FOREWORD

The Proceedings contain the papers presented at the Eighth Annual Precise Time and Time Interval (PTTI) Applications and Planning Meeting. The edited record of the discussions following the papers and the panel discussions are also included.

This meeting provided a forum for the exchange of information on precise time and frequency technology among members of the scientific community and persons with program applications.

The 282 registered attendees came from various U. S. Government agencies, private industry, universities and a number of foreign countries were represented.

In this meeting, papers were presented that emphasized:

a) definitions and international regulations of precise time sources and users,

b) the scientific foundations of Hydrogen Maser standards, the current developments in this field and the application experience, and

c) how to measure the stability performance properties of precise standards.

As in the previous meetings, update and new papers were presented on system applications with past, present and future requirements identified.

On behalf of the Executive Committee, I want to thank all those who contributed to the success of this year's meeting. Special credit should go to the Technical Program Chairman and his committee, the Editorial Chairman and his committee, the Session Chairmen, Speakers and Authors.

Lauren J. Rueger
Lauren J. Rueger
General Chairman

CALL TO SESSION

L. J. Rueger
Applied Physics Laboratory

Good Morning. I am Lauren Rueger of the Johns Hopkins University Applied Physics Laboratory, and it is my pleasure to call to session, the 8th Annual Precise Time and Time Interval Applications and Planning Meeting.

A purpose of this meeting is the exchange of information that will enable us to make better use of existing and projected capabilities in the precision time and time interval technology.

I think that the technical program committee under Andy Chi has selected an excellent set of papers to initiate exchanges and information. We shall welcome participation from the attendees and the discussion periods that will be provided.

I must remind you that the sessions are being recorded for the purpose of preparing an accurate printing of the proceedings. You can help to keep the records correct by giving your name and affiliation, preceding any questions from the floor.

Last year, the attendees to this meeting were sent a questionnaire to help this year's committee being responsive to your interests. The results of this questionnaire indicate that you want predominantly short, technical papers. You want some flavor for the long-range needs and capabilities.

You want the discussions to be recorded in the proceedings. You want the meetings to continue on an annual basis, and you welcome the participation of the foreign countries and the United States industry to this meeting.

You will find the very gratifying response of papers has indeed required that the technical papers will be short. We hope the speakers will accordingly help us to keep the program on schedule.

The speakers are asked to see the session chairman prior to the scheduled sessions and to sit in seats reserved in the front rows here. There are a few late papers in the program that are listed on the last page. These will be given if time permits in the sessions that are indicated, but this will be at the discretion of the session chairman.

Again, this year we have a large foreign participation at this meeting. We apologize for any inconvenience to these people resulting from the security regulations of the Naval Research Laboratory, but we arc glad to have you here.

It is my pleasure to call upon representatives of the government sponsoring agencies for this meeting at this time. The first will be Captain Lionel Noel, the Commanding Officer of the Naval Research Laboratory.

WELCOME ADDRESS

Captain Lionel M. Noel
Commanding Officer, Naval Research Laboratory

CAPT. NOEL: On behalf of the Naval Research Laboratory, I would like to welcome you to the 8th Annual Precise Time and Time Interval Application and Planning Meeting. It is a pleasure to host this meeting.

I have noted that the PTTI meeting has grown in prestige each year. For the past several years and this year also, we have included foreign visitors and speakers.

As you know, the Navy has always had a vital interest in time; its close cousin, frequency; and the many and varied uses to which they are put.

Recently called to my attention was an article on the Naval Observatory in an old report, the year, 1864, to be exact. And I quote.

"For the purpose of giving correct time to the city, the staff has been placed on the top of the dome, and a large but light ball is hoisted 10 minutes before 12:00 o'clock of each day except Sunday.

"The pulley is connected with an electro-magnetic battery after the ball is up and the circuit is broken by the assistant in the chronometer room at the instant of noon."

Also, you may be interested in the state of the art in timekeeping at the end of the Civil War. Again, this is from the same old reference document. Measuring the hundredth part of a second.

As a matter of popular information for the benefit of those who read and wonder at the accounts of astronomical observations which record the movements of the heavenly bodies to the hundredth part of a second of time, we extract from a pamphlet issued by one of our colleges the following description of the instrument and method by which that wonder is performed.

The elegant instrument of Professor W. C. Bond, known as the magnetic register, or spring governor, is one by and upon which through the influence of electromagnetism the instant of time at which an observation takes place can be precisely recorded by means of very delicate machinery regulated by the spring governor, a contrivance at once peculiar and beautiful, a horizontal cylinder 13 inches long and 6 in diameter is made to revolve with great uniformity precisely once per minute of sidereal time.

NASA is especially dependent on what you people are doing. Over the years, we have worked hard with many of you in the precise time and frequency generation and measurement. The Goddard Center along with the Bureau of Standards pioneered the development of dual frequency VLF transmissions for frequency and time synchronization.

With the Coast Guard, we developed the use of omega radio navigation system for precise timing and presently use LORAN sea navigation system to achieve about plus or minus 25 microseconds of global clock synchronization at our network of tracking sites which are located at various places around the world.

We have evaluated the use of various satellite time transfer techniques using the GEOS and ATS-1 and 3 satellites, and more recently, have had the support of NRL in the satellite technology, Roger Easton's NTS-1.

Time synchronization plays an important role in long-based line interferometry in which Goddard is vitally interested for astrophysical and geodetic purposes. We are now in cooperation with the Applied Physics Laboratory and the Naval Surface Weapons Center developing NTS timing receivers for use in NASA laser network for satellite tracking.

When fully operational, the laser network will require about a microsecond of time synchronization worldwide. One of the NTS receivers is on display here today, and several papers this afternoon will review the NTS time transfer technique and the receiver design, operation and performance. I am sure that you will all be interested in that development.

Goddard continues to evaluate time transfer techniques, recognizing that submicrosecond timing will be required in the near future. We are looking at the possible use of our own tracking and data relay satellite system for timing which is being procured now for use during the early 1980s.

We are also studying the use of the Global Positioning System (GPS) for submicrosecond timing. This system will be well covered in papers presented today, and I believe is really one of the waves of the future.

I have a special interest in GPS because I was in the office of the Secretary of Defense in the Department of Defense before I came to Goddard, and was involved in getting the GPS system started and in working many of the problems associated with it.

GPS's unprecedented accuracy requirements will make it an excellent source of precise time and time interval information to any user with a simplified receiver anywhere on the surface of the earth.

Tomorrow, Goddard papers will discuss much of our activities in research on hydrogen maser frequency standards. I bring you some good news in this area. The design of our laboratory building at Goddard for frequency standards and measurements has been finalized and approved. Our primary hydrogen masers will be housed there. Construction is expected to start soon.

A low budget forced us to give up some of the conventional approaches for magnetically shielding the entire building. Also, we had to give up the idea of shielding the maser room alone. Instead, we will construct a shielded box which will drop down over each maser. This technique should achieve the same shielding factors, according to our tests, as the original goal.

Besides saving money, we will gain the freedom to move equipment and instruments around in the same room without affecting the masers. Even in adversity, ingenuity can sometimes cause benefits to be reaped. Be sure and keep that in mind when your next budget comes.

In our present hydrogen maser program, we are improving the shielding on our four field operable units so as to reduce the external magnetic sensitivity by a factor of five.

We are also developing new, second generation field operable masers based on the design of our NX series experimental masers.

Also, we are continuing our efforts on the development of variable volume masers with which we hope to achieve a part in 10 to the 14 accuracy. Using these variable volume masers as calibration standards, we should be able to determine the frequency stability and reproducibility of field masers at about 10 to the minus 14 level over long periods of time, perhaps as long as one to two years.

Further results on these developments will be given in NASA papers.

I am sure that you recognize that hydrogen masers are probably the clocks of the future. Our current time standards are based on cesium, largely, and the hydrogen masers are being brought along at a relatively rapid rate now due to expenditures that are being made by NASA and by the Air Force.

It is impressive that frequency standard technology has achieved parts in 10 to the 15 in frequency stability and parts in 10 to the 13 in accuracy, but future technology promises frequency standards with 10 to the minus 18 and 10 to the minus 16 in stability and accuracy respectively. This is something for all of you to work toward in your various laboratories.

OPENING COMMENTS

Captain Joseph C. Smith
Superintendent, U. S. Naval Observatory

CAPT. SMITH: Mr. Chairman, distinguished members and guests of the Eighth Annual Precise Time and Time Interval Applications and Planning Meeting, as one of the cosponsors representing the United States Naval Observatory, I am most honored to share this opportunity for reflective thinking with you.

Captain Noel mentioned how we used to drop the ball in time at the observatory. Dr. Strand, Dr. Winkler, the members of our time division, and I, hope we are still not doing that today.

The United States Naval Observatory since its inception has been deeply interested in and involved with time; for, as you are aware, time is integral to both fundamental and differential astronomy and, of course, in the precise location of any given point on this globe.

The United States Naval Observatory ties its Time Service Division, the Transit Circle Division, our Nautical Almanac Office, and our Exploratory Developmental staff closely together for exploitation of this basic truth.

Interaction between disciplines is always necessary if we are to progress in any given or collective field of endeavor. Specifically in the area of time, the mission of the United States Naval Observatory remains to derive, maintain and coordinate precise time and time interval, both astronomical and atomic, for the Department of Defense, and control distribution of and provide single management service and interservice support for precise time and time interval within the Department of Defense.

This mission area is supported by Navy and Department of Defense directives as well as deeply tied into public law. Our concern requires a time commitment improvement of our service. This requires feedback from users. We want to hear from you, and most specifically we want to hear from you about your timing problems.

We all know high-precision timing is expensive, and in today's climate this means that resources must be used optimally. This requires cooperation. The meeting today is a testimony that the timing community is interested and willing to cooperate, and this is very much appreciated by all of us at the observatory.

Our objective remains accomplishment of timing at minimum cost. We shall also take the necessary steps to assure worldwide continuity of precision. These goals would be incompatible without the support and cooperation which we receive from our friends throughout the services and other agencies, and overseas.

As I have examined the operations of the United States Naval Observatory during my short time on board, I am constantly reminded of the vastness of the unknown versus the known; of the continuing challenge to conquer, or at least reduce the size of this difference.

I am sure that the sessions and papers that will be presented here will be of significance in this endeavor. For "How much knowledge is enough?" The ancient sage told us, "Always just a little more."

I look forward to sharing this quest with you. Please continue to keep in contact with us on timing matters. We will make every effort to insure that the service we provide is as effective as we can make it.

My sincere thanks for joining us.

GUEST SPEAKER

THE HISTORY OF TIME

Humphry M. Smith. OBE
Royal Greenwich Observatory, Sussex, England

Speech delivered at Banquet of Eighth Annual Precise Time and Time Interval (PTTI) Applications and Planning Meeting, Wednesday 1 December 1976. Naval Research Laboratory, Washington DC, USA.

Note
This was prepared for verbal presentation on a social occasion; hence the dilettante style and the omission of acknowledgements and references.

The subject suggested to me for my talk this evening is "The History of Time". The almost limitless scope of this topic makes me very conscious of my inadequacy to deal with it competently. Even the erudite and outstanding scientist Sir Isaac Newton once remarked, "I seem to have been only a boy playing on the seashore, and diverting myself in now and then finding a smoother pebble or a prettier shell than ordinary, whilst the great ocean of truth lay all undiscovered before me". For a lesser mortal like myself, my immediate reaction to the challenge you have put before me is to re-echo the classic comment of Sam Goldwyn, - "In two words: im-possible".

Clearly within the limitations imposed by my oratorical stamina and by your capacity for endurance, it is impracticable to attempt a comprehensive dissertation or a detailed review of all aspects of this fascinating theme. I could concentrate on the dramatic history of clocks through the ages, but even in this restricted sphere of horology I recall that the late Prof Torrens had accumulated a library of some 5000 books on mechanical time keepers alone. Alternatively we might trace the development of philosophical concepts of time over the centuries, but here we should be fishing in murky waters. Plato said that "the feeling of wonder is the genuine mark of the philosopher for philosophy has its origin in wonder". One is tempted to add that the reader may experience a similar sensation of wonder, not far short of bewilderment. (Theaetetus 155 CD). A cursory examination of the material soon reveals a whole gamut of opinions, some blatently ridiculous, many abstruse, others facile and trite. As Cicero remarked, "there is nothing so absurd but some philosopher has said it". (De Divinatione, ii.58). But serendipity comes to our aid, and among the plethora of verbiage we find occasional gems of sagacity and perceptive and stimulating aphorisms. Another fruitful field of study is those practical applications of timekeeping which directly affect humanity, since particularly in recent years much research has been carried out on the interaction between timekeeping and social trends. As we come to the scientific manifestations of time in the contemporary scene, developments in precise measurement have made it necessary to take into account hitherto insignificant or even unsuspected complications, and have opened up entirely new fields of inter-disciplinary research.

In endeavouring to limit the scope of this review, and thus to avoid the Scylla of superficiality and the Charybdis of prolixity, I am encouraged by Derek de Solla Price to skip lightly over the superabundance of information so diligently compiled by assiduous but apparently gullible students of antiquarian horology, since he has concluded, and I quote "... from the history of astronomy and from the known development of sundials and other such devices that virtually all of the evidence for shadow- and water-clocks being used as timekeepers before about the fourth century BC is fictional". He claims that "A great deal of damage and impediment to clear scholarship has been caused by the widespread and facile idea that man has always 'kept time' by primitive astronomical means". What then is his explanation of the well-established existence of such devices dating from the early days of civilisation? He proffers the speculation that there was a strong development of astronomy, long before time was used as a concept, in the context of special omen events which occurred in the heavens and which were reflected by happenings on Earth. He claims that Magalithic monuments like Stonehenge and other ancient stone circles, the water-clocks of ancient Egypt, all the early sundials and sand-clocks, were conceived primarily for the fixing of heliacal risings and settings, new moons, equinoxes and solstices. It was only much later, shortly before the time of Christ, that there was a new movement, almost synchronously in China and in Greece, which established a new trend leading to the modern practice. Man was able to use existing sophisticated techniques of technological brilliance to give him the possibility of doing something he had not wanted before it was readily available. This product, timekeeping, caught on, and by a process of evolution time became the matter of deep philosophical and scientific importance which it assumed in the classical and middle ages, and which it is today.

A significant contribution to our understanding of the concept of time was by the Athenian philosopher Plato (427-347 BC) who stands with Socrates and Aristotle as one of the founders of the intellectual ethos of Europe. Many of his ideas on time are contained in the "Timaeus", the sequel to his more familiar "Republic". He postulated a creator as a living being with the attribute of being eternal, and concluded that it was not possible for him to bestow this characteristic of immortality on the created universe. Plato explains:- "For before the heavens came into being, there were no days or nights or months or years... Time came into being with the heavens in order that, having come into being together, they would be dissolved together if ever they are dissolved. As a result of this plan and purpose of God for the birth of time, the Sun and Moon and five planets... came into being to define and preserve the measures of time".

Similar views have been reiterated in differing forms. A Buddhist priest, Nagasena, in the latter part of the second century BC, stated:-"For those who have entered nirvana, there is no time". In his Journal Intime, Amiel (1821-1881) says:- "Time is the supreme illusion. For the supreme intelligence there is no time; Time and space are fragments of the Infinite for the use of finite creatures". Such thinking is in general accord with the mainstream of Christian doctrine: in Paul's first letter to Timothy he says of Christ "the only Sovereign, the King of kings and Lord of lords" that He "alone has immortality". The well-known theologian, I A Dorner, says:- "We must not make Kronos (time) and Uranos (space) earlier divinities before God." To round off these quotations, we add the apocryphal response popularly attributed to Augustine. While discussing concepts of temporal sequence, a persistent questioner asked what God was doing before He created the world, and allegedly received the response "He was making a hell for the persons who ask that kind of question". *

Although in many areas Aristotle was in substantial agreement with Plato, he is usually regarded as having been more confident in tone and more positive in character. As a result his authority became, throughout the middle ages, despotic and well-nigh sacrosanct. He regarded the Platonic unqualified identification of time with the cyclic movements of the heavenly bodies as untenable, but accepted the existence of an inter-relation between them. "Not only do we measure the movement by the time, but also the time by the movement, because they define each other". Thus he rejected the possibility of continuous rectilinear motion, since this would imply motion in an infinite straight line, a concept which he found unacceptable. For Aristotle therefore time was a circle, measured by the cyclic movements in the heavens. We are reminded of the poetic insight of Henry Vaughan (1619-1645):-

"I saw Eternity the other night,
Like a great ring of pure and endless light,
And calm as it was bright; and round beneath it
Time in hours, days, years
Driven by the spheres,
Like a vast shadow moved, in which the world
And all her train were hurled".

Dissatisfied with Aristotle's close association of time and motion, Augustine adopted a more subjective attitude, and proclaimed:- "It is in thee, my mind, that I measure times". Unfortunately we cannot pursue the many ramifications of philosophical thought on this controversial question. So let us conclude by accepting a duality in time. At one extreme we have Newton who, at the beginning of his Principia makes a statement which has been one of the most criticized, and justly so, of all his postulates. "Hitherto I have laid down the definition of such words as are less known, and explained the sense in which I would have them understood in the following discourse. I do not define time, space, place and motion, as being well known to all. Only I must observe, that the vulgar conceive these quantities under no other notions but from the relation they bear

* In fact Augustine said: "My answer to those who ask 'what was God doing before he made heaven and earth?' is not 'He was preparing Hell for people who pry into mysteries'..... I shall refrain from giving this reply". (Confessions XI 12)

to sensible objects. And thence arise certain prejudices, for the removing of which it will be convenient to distinguish them into absolute and relative, true and apparent, mathematical and common.

Absolute, true and mathematical time, of itself, flows equably without regard to anything external, and by another name is called duration; relative, apparent, and common time is some sensible and external (whether accurate or unequable) measure of duration by the means of motion, which is commonly used instead of true time; such as an hour, a day, a month, a year." (Andrew Motte translation).

On the other hand, we cannot disregard the subjective consciousness of time. It is a common experience that, depending upon psychological factors, the passage of time can be fast or slow. When we talk of a long period of time having passed quickly or slowly, we speak not of the time but of our mode of remembering it. A person of rapid recapitulation always says the time has passed quickly, another of a contrary habit, the contrary; and this whether the rapidity is a consequence of quickness of ideas, or of having little to recall. The poet Henry Twells (1823-1900) wrote the following words which appear on a clock in Chester Cathedral:-

When I was a child I laughed and wept, Time crept
When as a youth I waxed more bold, Time strolled
When I became a full-grown man, Time ran
When older still I daily grew, Time flew
Soon I shall find, in passing on, Time gone
O Christ! wilt Thou have saved me then? Amen.

No doubt we have all experienced the sensation epitomized in the succinct definition "Time is how long we have to wait". We can sympathize with the refugee, living under the borrowed name Schwartz, who in his agonizing experiences as recorded by Erich Maria Remarque in "The Night in Lisbon", said "Time - you know that - is diluted death, a poison administered slowly, in harmless doses". He looks back with nostalgia on happier interludes in Paris with his wife, Helen. "When your world is brimful of feeling, there's no room for time. You're on another shore, beyond time". As Oliver Herford said, 'There is no time like the pleasant'.

But let us leave the ruminations of the philosophers with an extract from the pen of Ralph Waldo Emerson. "Tobacco, coffee, alcohol, hashish, prussic acid, strychnine, are weak dilutions; the surest is time. This cup which nature puts to our lips, has a wonderful virtue, surpassing that of any other draught. It opens the senses, adds power, fills us with exalted dreams which we call hope, love, ambition, science; especially it creates a craving for larger draughts of itself"; and, in a more optimistic mood:- "God has infinite time to give us; but how did He give it? In one immense tract of lazy milleniums? No, He cut it up into a neat succession of new mornings".

This surely is the key to a full life, entering expectantly each new day with all its potential for service, for challenge, for exercise of mind and body, for fellowship, for enjoyment, for achievement, and ultimately, for the contentment and rest which comes from a sense of fulfilment. Consider the cautionary tale of Methuselah. He lived for nine centuries, but according to the records, he never did, thought, or wrote anything to make such longevity worthwhile.

Aristotle said in his Metaphysics "But as more arts were invented, and some were directed to the necessities of life, others to recreation, the inventors of the latter were naturally always regarded as wiser than the inventors of the former, because their branches of knowledge did not aim at utility". Even in this present-day technological age, the theoretician and abstract intellectual whose lofty deliberations make no beneficial contributions to the creature comforts of the human race is accorded a higher status, and regards contemptuously, with a confident air of superiority, the most brilliant scientist and engineer who provides in greater abundance for his material needs and added luxuries. Nevertheless we must now turn our attention from the visionary speculations of the ideologue to the banausic level of the scientist, the engineer and the artificer.

Alexandria is a convenient place from which to commence our casual meander through the enthralling story of the development of timekeepers. The conquests of Alexander disseminated the Hellenistic civilisation, and created a new intellectual centre which soon also became established as the Western nucleus of technology. The early history of mechanical gearing is still enigmatic but a subject of avid investigation. It is known that Archimedes in about 250 BC used a gearwheel meshed with a worm, and a simple planetarium is also ascribed to him. Ctesibius of Alexandria, in the second century BC, constructed a striking water clock in which an anaphoric drive (so called because it displayed the successive rising, "anaphora", of constellations above the Eastern horizon during the night) was combined with gear wheels, mainly used for jack work. (Jack is the general term used for mechanically-activated figures, so named after Jaccomarchiadus, or Jacques Marck, a clock-and lock-maker of Lille, France).

Vetruvius also made an anaphoric clepsydra in about 30 BC. A float was attached to a cord wound round a drum and fastened to a counterweight. The drum was mounted on a horizontal axis which also carried a planispheric disc. Clocks of similar design were still in use as late as the end of the 17th century, but in later models the time dial was stationary and the pointer travelled over it. Historians distinguish three types of clepsydra. One as employed by Vetruvius, another using a tipping bucket or a syphon to give intermittent motion, and a third which achieved the same effect by using a continuous flow and a trip lever. Heron of Alexandria in 62 AD makes a reference in his Pneumatica to a device which may have been driven by pneumatic or hydraulic power.

Within the time at our disposal we cannot trace the history of the independent developments which took place in China. An acknowledged authority on Chinese horology does however remark:- "There is no doubt that the Greeks were the more successful theorists, but equally none that the Chinese, on the whole, were the better practical instrument makers".

The Romans used three words to designate their timekeeping devices. Seneca in the first century AD used the Greek name "Clepsydra" for water clocks of varying degrees of complexity. The sundial was known as Solarium, and the same name was used for the smaller pocket sundials, such as the one only 3 cm in diameter, which was found in the Adriatic city of Aquileia. Another Graeco-Latin name frequently employed was horolgium, or "hour-counter". In fact the Romans were slow in acquiring their first time-keepers: the Sicilians in Syracuse had many and according to Pliny the Elder in his history of the first Punic War, the consul Marcus Valerius Messala brought a sundial back from Catana to Rome in 236 BC, where it was installed and continued to indicate the incorrect time for 99 years: no-one had realised that a sundial must be designed for the latitude in which it is to be used, and Rome was 4°23' north of Catana. Pliny lamented this deception of his unsuspecting fellow citizens, but the first sundial designed and constructed for the latitude of Rome was not installed until 164 BC. The number of dials increased rapidly. Cicero, who lived from 106 to 130 BC records that domestic clepsydra and sundials were common, and Juvenal, 60 to 130 BC, tells us that in empire days the upper classes not only possessed clocks but also had slaves who read the devices and announced the hours to their wealthy masters. Petronius, in "The Satiricon" tells of an invitation to dinner:- "Here, don't you know your host today? It's Trimalchio - he's terribly elegant... He has a clock in his dining room".

In general, however, the timekeepers, though much admired, were notoriously inaccurate. Lucius Seneca in his Apocolocyntosis (II, 2-3) confesses that although he can specify the date, he cannot give the time with any certainty, since it is easier to reach agreement between philosophers than between clocks, a truly devastating admission. (facilius inter philosophos quam inter horologia conveniet). A new class of technicians appeared during the reign of the Emperor Trajan 53-117 AD, and clocks became more attractive and more accurate. It is an interesting glimpse into Roman thinking that when Julius Caesar invaded the British Isles in 55 and 54 BC, he was very surprised to discover that the supposedly primitive Britons already had sundials.

One feature of Roman horologia still persists today in the use of Roman numerals to mark the hours. In order to achieve symmetry, it was customary to mark the four as IIII instead of the correct IV, since this balances the eight, VIII. A notable exception is the Westminster clock, with its famous "Big Ben" bell in the tower of the Palace of Westminster at the British Houses of Parliament.

Bells played a prominent part in the life of medieval towns, telling the hours, warning of impending dangers, summoning the populace for assemblies and announcing good news. It is little wonder that skilled and enterprising craftsmen experimented with various mechanisms for controlling them and ringing them effectively. There was also a demand from astronomers and astrologers for instruments that would imitate the movements of the stars and planets. There is a continuity and gradualness in technological change, and the techniques being developed by craftsmen were moving towards the construction of mechanical clocks; but rarely there are radical advances by which progress takes a leap forward. Such an event was the invention, by an unidentified person, at a date that cannot be established with certainty, of the verge escapement. The general consensus of opinion tends to place the inception of the device in the second half of the thirteenth century, but the verge escapement with foliot introduced a new era in timekeepers, and the unknown inventor must have been a mechanical genius. The suggestion that this European development had its origins in a complicated Chinese mechanism built at the end of the eleventh century does not now appear tenable.

There are well-documented accounts of many mechanical clocks constructed and installed in Europe during the fourteenth century, but in many instances the indications of the hours were by the ringing of bells, and not by the movement of dials or hands. In fact the word "clock" derives from the medieval Latin "clocca", a bell.

I will depart for a moment from the chronological sequence to recount a brief story: It is the story of a factory owner who complained that his workers arrived back late after the dinner-break, which was scheduled to end at 1 o'clock. Their excuse was that they sometimes missed hearing the single stroke of the bell. He overcame the difficulty by arranging for the clock to strike thirteen. Which brings to mind another story told in Punch 60 years ago by A P Herbert, in which the Lord Chief Justice in the Court of Criminal Appeal felt unable to rely upon a statement that had been made. He said "it is like the 13th stroke of a crazy clock which not only is itself discredited but casts a shade of doubt over all previous assertions".

But to return to our narrative. An outstanding example of the complex astronomical clocks which characterized this stage of development was made in 1350 by Giovanni de 'Dondi, probably with the help of his father, Jacopo. It reproduced mechanically the movements of the Sun, Moon and five planets, and incorporated a perpetual calendar. After the death of its maker, no one could be found to take care of it, and it finally disintegrated. Accurate details were recorded, and we have complete infomation on the design.

In 1370 Charles V of France installed a clock that struck the hours on one of the towers of the royal palace. He was delighted and had two similar clocks erected in other parts of the town. Being concerned that the bells could not be heard by all the citizens, he ordered all the churches in Paris to ring their bells (par pointez à maniere d'orologe) when the royal clocks struck. Thus everyone should know the time "whether the Sun is shining or not" (luise le soleil ou non).

A big clock, especially a public clock, was very expensive in those days. It was expensive to build: the mechanism of a public clock at Montpellier constructed in 1410 weighed about 2 000 pounds, and the bell a like amount. In addition there was a striking figure and other paraphernalia. The estimated cost was 200 "escuts", an obsolete gold coin roughly equivalent to the more recent "ecu" which was replaced with the franc. Before the days of currency-juggling and devaluation, the "escut" might be thought of as a genuine original dollar. In addition, the supplier required "deux muids de vin" and "deux molons de ble"; say two barrels of wine and two heaps of grain. But apart from the capital cost, there was a commitment to the regular wage of a specially-appointed governor. This was no sinecure. Often the governor had to wind the clock twice a day, and he had therefore to climb twice a day to the top of the clock tower; he had very frequently to grease the machine and set or reset the hand because the clock lost or gained much time in the course of half a day. Despite the drain on local finances, civic pride, utilitarianism and mechanical interest fostered the installation of a growing number of clocks. Throughout the 14th and 15th centuries many complex and elaborate clocks embodied a strange combination of brilliance in conception with a deficient technique of construction. If and when they worked, they gained or lost much time in a day. Generally it was not considered necessary to provide a minute hand. Even the famous palace clock of Charles V was said by Parisians "to go as it pleased" (l'horloge du palais, elle vas comme il lui plait).

Until about the middle of the 15th century, there were only public clocks or those in the possession of the very wealthy. Moreover since weights provided the only motive power, clocks were not easily portable. It seems likely that the first spring-driven clocks were made in Italy about 1410, possibly by Filippo Brunelleschi. There is little doubt that portable spring-driven clocks were becoming more numerous by 1450, and that an ingenious device, the fusee, had been invented to minimise the deleterious effect of the slowly diminishing driving power of the spring. (An earlier mechanism, the stackfreed, had been designed for the same purpose, but although its use persisted until the beginning of the 17th century, its performance fell far short of that of the fusee). Pocket timekeepers made their appearance towards the end of the 15th century and at the beginning of the 16th. More craftsmen acquired the skills of the trade, and during the 16th and 17th centuries in Europe, there was a growing market among the middle classes, merchants, lawyers, doctors, and apothecaries, who could afford to buy better houses, good clothes, and such amenities of life as domestic clocks.

While the performance of clocks was irregular, a minute hand was superfluous. No exact date can be given for the introduction of this refinement, but in the Ilbert collection in the British Museum there is a two-handed clock made by Nicholas Vallin in 1598. The inner hand rotates once per hour, but the only markings are the quarters. The clock chimes on thirteen bells. It was only with the invention of the pendulum which significantly improved the timekeeping accuracy, that the general use of a minute hand became justifiable. As is well-known, the isochronous property of the pendulum was discovered, or some authorities say "re-discovered" (see Note below) by the famous Italian astronomer, Galileo Galilei who also invented the thermometer, and the telescope, and was the founder of the science of dynamics. The application of the pendulum to a clock was due to Christiaan Huygens, the eminent Dutch astronomer and mathematician. In 1657 he assigned his invention to Saloman Coster, a master clockmaker at The Hague. On September 3, 1657, Coster made an agreement with John Fromanteel, a younger member of a family of clock-makers of Dutch descent living in London. Fromanteel agreed to pay Coster a royalty of 20 Carolus gulden for each clock he made, on condition he worked with his own steel and brass; if Coster supplied the material, he was to receive 18½ gulden per clock. A pendulum clock made by Coster himself in 1657 had a chapter ring, outside the hour ring, to indicate the minutes.

As this is an informal social occasion, and not confined to serious scientific dissertations, may I depart from the strict limitations of my assignment and turn to one of the lighter aspects of time which may be culled from the pages of the famous book by Laurence Stern, "The Life and Opinions of Tristram Shandy"?

Tristram tells us that he was "begot in the night betwixt the first Sunday and the first Monday in the month of March, in the year of our Lord 1718. I am positive I was". He goes on to explain why he can be so certain. "My father.... was, I believe, one of the most regular men in everything he did, whether t'was matter of business, or matter of amusement, that ever lived. As a small specimen of this extreme exactness of his, to which he was in truth a slave, - he had made it a rule for many years of his life, - on the first Sunday night of each month throughout the whole year, - as certain as ever the Sunday night came, - to wind up a large house-clock, which we had standing upon the backstairs head, with his own hands:- and being somewhere between fifty and sixty years of age, at the time I have been speaking of, - he had likewise gradually brought some other little family concernments to the same period, in order, as he would often say to my uncle Toby, to get them all out of the way at one time, and be no more plagued and pestered with them the rest of the month".

The euphemism, winding the clock, became quite common, and has even re-appeared in the recent craze for resuscitating folk songs with a modern

Note: The dubious attribution to Leonardo da Vinci depends upon the exercise of unnecessary ingenuity by a translator: "fa che unora sia duj sa in 3 000 partj e equesto faraj collorīolo allegerēdo o agravàdo il cōtrapeso" which, as pointed out in Baillie Clutton and Ilbert's revised Britten 'Old Clocks and Watches and Their Makers', is precisely the way of regulating a verge and foliot escapement.

musical setting. Those who are familiar with this trend may have come across the ditty with the chorus:-

> Take your time, me lovely old lad
> There aint no reason to hurry,
> For so long as you're able to wind up me clock
> Then I'll have no need for to worry

At this point it is interesting to recount the increasing influence of the Livery Companies. In London it had been the custom for various trades or crafts to group themselves together in particular precincts of the City. Signs of supervision of the crafts and trades by their respective guilds appear as early as the twelfth century, regulating prices, instituting technical education through apprenticeship, inspection of products, and a form of quality control. Each guild limited the number of apprentices, and forbad the conduct of its trade to any other than those who had been admitted to its freedom. In the 17th century the Freemen Clockmakers had obtained the right to practice their craft through the Blacksmiths' Company, and no doubt only the simplicity of the medieval iron clock allowed a specialist blacksmith to make one. (It must be made clear that the term "Blacksmith" implied an artist in iron; the role of shoeing horses was the province of the Farrier). After a number of attempts, which were opposed by the Blacksmiths, the Clockmakers eventually succeeded in obtaining their own Charter from King Charles 1 on 22 August 1631. The Worshipful Company of Clockmakers controlled the horological trade in the City of London and within ten miles thereof, and was governed by a Master, three Wardens, and a Court of Assistants. The executive officer is the Clerk, who is assisted on ceremonial occasions by his Beadle. I have the honour to be a liveryman of this distinguished Company which has numbered among its members many famous clockmakers, and which continues to cherish its traditions and to play an active role in contemporary horology.

But no history of timekeeping, however cursory, can fail to make some reference to the sociological changes which influenced,and were influenced by, the increasing infiltration of time in daily life. Jaques le Goff remarks:- "Perhaps the most important way the urban bourgeoisie spread its culture was the revolution it effected in the mental categories of medieval man. The most spectacular of these revolutions, without a doubt, was the one concerned with the concept and measurement of time". He examined in detail the gradual transition, in the middle ages of urban organization from Ecclesiastical to merchants' time. The practical time of the Church derived from antiquity, and the bells which announced the canonical hours, - Matins, Lauds, Prime, Terce, Sext, None and Vespers - continued to regulate the religious life of the community. But often the church clocks were imprecise and variable, and shopkeepers and workmen required a more exact time-keeping geared to worldly and secular needs. Goff says (and I give a free translation) "The public clock is an instrument of economic, social and political domination, belonging to the tradesmen who rule the community: and for this purpose the necessity of strict timekeeping becomes apparent, for in the textile industry it is advisable that the day-workers, the labourers of the industry, should come to and leave work at fixed times". It is evident that while cottage industry and agriculture were the backbone of rural life, even the church clock was almost superfluous; but as work became centred in the towns, and factories and mills were established, uniformity of time, within the locality, became of increasing importance. Thus to quote Goff again:- "This is the great revolution of the community movement in time regulation; these clocks set up everywhere are in competition with the church bells".

It may be convenient here to depart again from our chronological sequence and follow the subsequent developments of unification in time keeping. The need for local time developed from the industrial revolution, but by the mid-17th century, facilities for travel, hitherto the privilege of the aristocracy and prosperous merchants, began to become available to an increasing number of the populace. The stage-coach service, established in England in 1784, led to the spread of London time, determined at Greenwich Observatory, throughout the length and breadth of the country. Early in the 19th century, the railway system began to extend its tracks from the capital to the provinces, and the network of telegraph cables enabled all the major towns to conform to a unified system. In 1851 the Great Exhibition in Hyde Park, London, resulted in travel on an unprecedented scale. In a paper presented at the symposium last year to celebrate the Tercentenary of the Royal Observatory, I quoted Aldous Huxley's comment:- "In inventing the locomotive, Watt and Stevenson were part inventors of time". When Greenwich Mean Time was adopted as the legal time for England, Scotland and Wales in 1880, the law was endorsing an already existing situation.

Another aspect of timekeeping which cannot be omitted on this occasion concerns navigation. Many of you will be familiar with the problem facing the maritime nations in finding a solution to the determination of longitude at sea. In A Short History of Navigation, Branch and Brook-Williams recount the difficulties encountered by Columbus, which it is surely appropriate to quote in the country he is generally credited or blamed for having discovered:- "Columbus in his voyages used a simple needle supporting a paper compass rose and pivoted on a steel point. His ships were wooden and non-magnetic, but they were also small with consequent large motions in a seaway. Steering by that compass and other similar types must have done a great deal to enrich our language!" But such calamities as the wreck of Vice-Admiral Sir Cloudesley Shovell's fleet off the Isles of Scilly in 1707 after a twelve-day voyage from Gibraltar under cloudy skies, with the loss of 2 000 seamen was an outstanding and tragic occurrence which emphasized the hazards of navigational uncertainty, and which led the British Government in 1714 to offer an award of £20 000 to any person who could devise a method of finding the longitude of a ship at sea within an accuracy of 1° (or 60 nautical miles) at the end of a voyage from Britain to the West Indies. The use of a timekeeper on a ship for this purpose had been proposed as long ago as 1530 by Gemma

Frisius, but the first attempt to make a sea-going clock by Huygens in 1659 was unsuccessful. The reward was eventually won by a Yorkshire carpenter, John Harrison. Tests at sea had to be postponed, as Britain was then at war with Spain, and it was feared that the instrument might be captured. Preliminary trials were conducted on a barge in the Humber. It was in 1761 that Harrison's fourth timekeeper was taken to Jamaica and back in HMS Deptford. It was supervised on the journey by Harrison's son, William. On arrival in Jamaica it was found to be in error by no more than five seconds. The long and frustrating story of Harrison's battle to receive his reward is well-documented; suffice to say, he was eighty years of age before payment was made in full.

The need now became apparent for an international agreement on a standard meridian from which time and longitude could be reckoned. Many pamphlets were written, proposing various solutions, but a conference in Rome in 1883 strongly advocated the adoption of a single reference meridian, that of Greenwich.

If we are to pick out one name as that of the man chiefly responsible for the system of time zones based on Greenwich, that man must surely be Charles F Dowd, Principal of Temple Grove Ladies Seminary at Saratoga Springs. He received strong support from W F Allen, Secretary of the U S General Railway Time Convention, and fellowcountrymen Cleveland Abbe and President Barnard of Columbia University. Independently, Sandford Fleming, the Scottish-Canadian Engineer-in-Chief of the Canadian Pacific Railway, wrote copiously in favour and enlisted the interest of the British Government, despite the unenthusiastic, and at times hostile, attitude of such personalities as the Astronomer Royal and the Superintendent of the U S Nautical Almanac Office. Sir George Airy said:- ".. as to the need of a prime meridian, no practical man ever wants such a thing" while Professor Simon Newcome roundly condemned the whole idea, saying:- "A capital plan for use during the millenium. Too perfect for the present state of humanity. See no more reason for considering Europe in the matter than for considering the inhabitants of the planet Mars. No; we don't care for other nations, can't help them, and they can't help us".

At the formal conference in Washington in 1884 the various arguments were restated until eventually there was an unexpected measure of agreement. The British repressed their congenital leaning towards tradition, and the French relaxed their characteristic preference for logic. Practical considerations carried the day. The system of time zones related to the Greenwich meridian, and the adoption of Greenwich Mean Time, were duly approved. Various points of detail remained. It was not until 1925 that the almanacs employed GMT reckoned from midnight. The designation Universal Time was introduced to replace GMT, but has only been implemented in astronomical and some related contexts. But in these matters it is the users and the general public who seem to prefer the more meaningful term GMT with its obvious link with longitudes. The Radio Regulations of the International Telecommunications Union still retain GMT in their documents as the authorized designation of time in the radio and communications field, and the fourth annual Navigation symposium, meeting in Washington last year, unrepentantly demanded "that the terminology Greenwich Mean Time be continued in its present sense in the practice of navigation".

But let us return for a few moments to our consideration of clocks. Pendulum clocks were the subject of progressive improvement. Temperature compensated pendulums, dead-beat escapements, magnetic correction for variations in barometric pressure and in 1921, the free-pendulum clock. W H Shortt, a railway engineer, was investigating the causes of excessive wear on the track, especially on curves, and came to the reluctant conclusion that perhaps some drivers were not adhering strictly to the permitted speed limits. He decided to carry out some tests, which involved checking the speed of trains over short distances, and thus demanded accurate timing. His interest having been aroused, he employed his engineering skills in the construction of a clock to his own original designs. The first Shortt free pendulum and slave were tested at the Royal Observatory, Edinburgh, in 1921-1924 by Prof Sampson. In collaboration with F Hope-Jones of the Synchronome Company, Shortt clocks were made and brought into service at many of the major timekeeping observatories throughout the world, and ushered in a new standard of accuracy.

Incidentally, I found very puzzling a letter to the Times of 15 November 1976 (from Nikolai Tolstoy) who claimed that 50 years ago the Soviet Government executed Nikolai von Meck of the Peoples Commissariat of Railways for the crime of causing the trains to attend with diobolical precision to their timetables: the prosecution was able to prove that his intention was to cause speeding trains to wear out their tracks, thus leaving the USSR helpless in the event of war.

It was during the first year of my service as Head of the Time Department at Greenwich that we installed our first quartz clock. Almost immediately we were committed to a programme of extensive replacement of all the ancillary equipment. The old radio receivers, with their externally-mounted variable-reaction coils ceded place to newer designs which incorporated multi-electrode valves. To the best of my knowledge, the Greenwich Time Department was the first to make all routine measures of clock comparisons with electronic counters.

Radio time signals were measured using a visual cathode ray tube display with phaseable clock markers. The 1939-1945 war initially delayed some plans, particularly as we had to set up two emergency stations, Abinger and Edinburgh, for the control of the Rugby radio time signals, together with the short-wave emissions which we had also inaugurated. On the other hand, we were presented with a requirement, arising from the rapid developments in radar, to achieve a ten-fold increase in the accuracy of the radio time signals. With the assistance and ready co-operation of colleagues, both within the observatory and in other establishments, the target was attained. A major contribution was the provision, by the Post Office, of daily information on the quartz clocks at Dollis Hill Radio

Research Laboratories, who later supplied us with a number of clocks for use at our two time service stations. At Abinger an electronics laboratory was set up, and proved of immense value.

Probably the most outstanding advance in recent years was the realisation of atomic standards for time and frequency. We enjoyed the co-operation of the National Physical Laboratory, when in 1955 data from the caesium beam frequency standard of Essen and Parry became available for the absolute calibration of our quartz clocks. This continued until we were able to acquire commercial atomic clocks and to maintain an independent atomic time scale, and thus to take our place as one of the seven establishments contributing to the formation of the BIH scale of atomic time. Nevertheless, not everyone is greatly impressed. H Notwotny writes: "Today, as befits an age dominated by scientific thinking, precision and unambiguity, we have agreed to the definition of a standard second in terms of a spectroscopic frequency. The impact of this uncritical quest for physical precision is evident in many facets of our daily lives". Notice the sly dig "this uncritical quest".

One of the major tasks of a timekeeping observatory is the determination of astronomical time. The Airy transit circle, which defines the zero meridian, was superseded for time observations by small reversible transit instruments in 1926, and various improvements in instrumentation and in procedures met with some success. Around 1940 the photographic zenith tube, which had been adapted for time and latitude work at the US Naval Observatory, began to engage our attention. By courtesy of the USNO, full working drawings were made available to us, but after careful consideration we decided to embark on a new design. A small instrumentation laboratory was formed, and D S Perfect, working closely with Grubb Parsons of Newcastle, designed the instrument which, with a number of later modifications, is still in use today, and giving results of the highest quality. The decision of the Canadian authorities to instal a PZT on the same latitude has proved outstandingly successful.

I must apologize for straying from my original brief, the History of Time, to reminiscences of events during my forty years at the Royal Observatory. May I draw this discursive narrative to a close by referring briefly to three examples of the close collaboration which has been built up between the Royal Greenwich Observatory and our colleagues here in the United States.

It may not be generally known that the present co-ordinated system for radio time signals came into being following the success of an experimental exercise initiated by the USA and UK. The preliminary informal agreement was reached at a meeting in the garden of my house in Bexhill on a sunny afternoon on 19th July 1959. For the record, those present were H Barrell of the NPL and Chairman of the International Committee of Weights and Measures, R L Corke of the British Post Office Radio Branch Laboratories, L Essen (NPL), W Markowitz, Director of the Time Service at the USNO, and D H Sadler, C A Murray, N P J O'Hora and myself from the RGO. My wife provided tea. A more formal meeting at the USNO on 26 and 27 May 1960 endorsed the arrangements. Markowitz was in the Chair: other participants were Andrews, Hastings and McNish (USA), Corke, Essen and Smith (UK) and, as an observer, Kalra from Canada. The principles were unanimously agreed, but the details left fluid. Markowitz and I were to develop the scheme as circumstances required. Despite the fact that the method, as you all know, depends upon the introduction of time steps (now leap seconds), neither of us has so far experienced the fate of the legendary Chinese astronomers Hsi and Hso who in the reign of Chung Kang, 7th or 8th century BC, were guilty of transgressing the "inviolable laws" by which "astronomers who advance or set back the time shall implacably (or, without pardon) be punished with death".

The second example I choose is the close liaison which has been achieved in the use of Loran-C. In the early stages problems were legion, but together with the USNO and the US Coastguards, a firm and accurate link has been established.

My last example is still in the development stage. Using equipment loaned by the Naval Research Laboratory, we made a series of comparisons using the previous Timation satellite. We are now securing better data with the present NTS-1 satellite. There have been many interesting problems to solve, but useful experience is being built up. In this enterprise, as in the many others which have preceded it, an outstanding feature has been the happy and amicable spirit of co-operation which has developed spontaneously between the USA and UK partners in our technical and social contacts. I personally view the present satellite programme as one with a great future. Perhaps once again we are blazing a trail that others will follow. Another chapter in the History of Time is in the making.