OPTICAL TECHNIQUES FOR TIME AND FREQUENCY TRANSFER

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Abstract

Light has been used as a mean for time synchronization for a long time. The flight time was supposed to be negligible.

The first scientific determination of the velocity of the light was done by measuring a round trip flight time on a given distance (France 1849). The well known flying clock experiment leading to Einstein General Relativity is another example (1905).

The advent of lasers, particularly short pulse and modulated ones, as well as the improvements of the timing equipments have led to new concepts for time and frequency transfer.

We describe in this paper some experiments using different techniques and configurations which have been proposed and tested in this field since the beginning of the space age. Added to that, we set out advantages, drawbacks and performances achieved in the different cases.

INTRODUCTION

The development of lasers and space techniques have again put into focus optical time and frequency transfer techniques. This area is so far one of the most advanced and has the best potential for very accurate time and frequency transfer.

The definition we have adopted in this paper is that the information about time and frequency transfer is carried by an optical beam which can be modulated. The most widely used method is intensity modulation (continuous wave or pulsed beam). It can also be frequency modulation or the rotation of the polarization.

Optical techniques already existed before lasers, but actually it is with their advent in the mid 50's that more and more precise experiments have been made. The advance of civilisation has led to the need for more and more precise dissemination and synchronization in the time and frequency domain. Accuracies reach the nanosecond level for day to day applications or the picosecond level for research.

Actually three different methods have evolved successively and have coexisted. This is still true nowadays where the three techniques and their application still coexist.

The method we call "one way" was the most intuitive. It was also the only possible method as long as we did not know how to modulate a signal. The first artificial modulations were also one way mode, until the modulation was fast enough to get evidence of the speed of the light, leading then to two way methods.

The need for time transfer at such distances that the two sites are not in direct view, has led to use of "relays" (satellites, etc..), because the transfer with "multiple steps" did not give the necessary precision. The double two way was adopted since then.

The improvement of techniques are such that we are far from reaching the limits of these three methods. The evolution in time and frequency transfer techniques leads into prediction that we will reach the subpicosecond domain in the next 10 or 20 years.

HISTORIC

For thousands of years optical observations were sufficient to regulate daily activities. When religions began to appear, it led to the need for calendars based on ephemeris:

- Solar ephemeris : Incas, Egyptians, Greeks, Romans
- Lunar ephemeris : Pre hellenic, Mesopotamian

Some religious events are still related to the motion of the Moon and the Sun:

- Easter, Passover, Ramadan, Civarâtri.

Navigation has required new methods for providing time, and these have endured until the coming of the "marine chronometer".

Knowing the direction of the sun is not enough to determine one's position on the surface of the Earth, it is also necessary know the time of a zero longitude. Therefore, the ephemerides for navigation were based on the movements of celestial bodies such as the Jupiter satellites, planetary eclipses and even lunar eclipses and occultations. The rapid advance of sea navigation, and the high number of accidents drew inventors to study other methods, for more precise and more accessible time than obtainable by astronomical methods.

One of the most successful and durable has been the time Ball. The time Ball is used to check one's chronometer for sea navigation. The inventor was Captain Wanchope of the Royal Navy. There was a Ball on a staff, and someone would raise it. Someone else was watching the clock, and at a particular time, he lowered the Ball. It was later done by direct telegraphic signals. The first time the Ball was dropped in England was at Greenwich Royal Observatory in 1833. The first North American one was also very early in the 1840 's. It was lowered at the Naval Observatory in Washington. The Time Ball was utilised up to the 1930's. Useage began to decrease when radio signals became important. If you can get time at sea, you are really no longer interested in getting time only when you are at seaport. The Time Ball has been also employed to give accurate time to railroad networks and cities.

Simultaneously military people in order to coordinate the attacks of their armies developed some other optical methods for synchronization such as fires, flares, etc...

All these methods presented above are what we define as "one way". These techniques have improved a lot with the advent of lasers. The modulation is being carried by other media then air (optic fibers, etc..). In particular, lasers have lead to better precision, to longer range, to diversification of the transit media, and to directivity assuring discretion of experiments.

ONE WAY TECHNIQUES (Fig.1)

In the development of this technique three steps could be considered :

A. PASSIVE MODE

1. Visible very distant object as a reference for direction. The modulation of the direction and/or the amplitude of the beam is made by the rotation of the earth (sunrise, sunset, sundials). It gives only the Local Time and is dependant on the position of the observer on the earth, thus it does not allow any navigation.
2. Very distant objects in the sky whose relative position and/or intensity is time dependant (movement of celestial bodies). It gives Ephemeris Time which is the same for the whole earth. The development in England of the first marine clocks decreased the interest in these two methods.

Let us mention here that the most recent developments in the study of optical quasars as frequency standards and frequency transfer could be linked to this family. The excellent stability of their frequencies make them more precise and accurate.. They have the advantage of being accessible. Therefore, they could be used in place of, or compete with hydrogen masers. Combining Local Time and Ephemeris Time makes navigation possible. In the two techniques presented here only the direction is important, thus they are independant of the travel time of the light between a beacon and an observer. The determination of the time is made in a passive mode which means that the observers use only natural phenomena.

B. ACTIVE MODE

The next one–way techniques are active ones, which means that the synchronizing event is short. A phenomena is considered as short when its value is small or equal to the accuracy expected. We will consider two groups of techniques, mainly created by man. Fires, flares, etc are part of this category.

1. The velocity of the light is considered as infinite.

   It means that the travel time is negligible. The accuracy ranges from minutes to seconds for distances up to a few hundred kilometers. The Time Ball concept was the last and most accurate development. In this case the accuracy reaches the limit of human reflexes (0.1s) for distances up to 3O kilometers. Even for such distances the travel time of 100 μs could be neglected in respect to the accuracy (0.1s). The advantages of this first method are the simplicity and the non–saturation (unlimited numbers of users could participate at the same time). The disadvantages are the consequences of the advantages, simplicity means a rather poor accuracy and non-saturation leads to the lack of discretion.

2. The velocity of light is considered as finite.

   Although electro–optical methods were able to modulate the light up to 100 MHz and pulses in the nanosecond range, it is only with the advent of lasers that light was used for more accurate time and frequency transfer, because of their coherent light beam (directivity and high peak powers). The signal was originally carried by air as in the older methods, but also through optical fiber developed industrially in parallel with the laser. The accuracy of measurements obtained with these methods is such that the velocity of the light has to be taken into account. The transit time between the two ends of the link could be determined by two different ways.

   a) It can be computed using a model knowing the distance and the meteorological parameters (pressure, temperature, and possibly relative humidity). The accuracy for time transfer could be then around 50 ps over short distances and the precision for frequency transfer about 10^{-17} over 100 s. This has been the method commonly used so far.

   b) A differential measurement of the travel time between two wavelengths could provide a better determination of the index of refraction correction.

      – The sensitivity of the process is greatly dependant on the choice of the two wavelengths which must be as far apart as possible. As an example, for air transmission and the two colors 532 nm and 698 nm the differential measurement has to be at the level of 1/40 of the expected accuracy for the time transfer. This figures would become 1/9 for the pair 532 nm and 355 nm.
      – The pair of wavelengths must cross the transiting medium with an attenuation as low as possible. This factor limits the transmission through air at wavelengths longer than 400 nm if the distance is longer than 20 kilometers.
      – The bandwidth of detectors must cover both wavelengths (for example a S20 photocatode is limited between 200 nm and 700 nm). This is particularly true when only one detector is used which is the case with a streak camera (picosecond resolution).

      This method promises accuracies up to 50 ps over very long distances and 10^{-18} for frequency transfer precision over 100 seconds or more. It means that we need a differential time measurement very accurate which is difficult to achieve, technically speaking.

TWO-WAY TECHNIQUES (Fig. 2)

In two way techniques, the flight time is not determined by a differential measurement but directly. The round trip flight time of the light between transmitter and receiver is measured. It is assumed that the only delay is half of that of the two way travel time. The concept for two way appeared as early as 1849 with Fizeau and his Tooth Wheel Experiment over a distance of 17.266 km.

Before the development of lasers, some range–finders based on round trip time determination were designed, opening the possibility for time and frequency transfer. But then the level of time keeping and the needs in time and frequency transfer were not at the level of such expensive, state of the art equipment. These needs appeared at the same time as the development of different laser sources (Gas Solid, Dye, Solid state). Soon some experiments were set up. Ranging and time transfer accuracy went from microseconds to nanoseconds almost immediately.

Several forms of light modulation appeared following the laser development:

- pulse modulation with pulse duration ranging from microseconds (free–running, 1960) to nanoseconds (Q Switched, 1964) to picoseconds (Mode Locked, 1970) and even to femto and atoseconds (mode locked and pulse compression).
- continuous waves (CW) where the modulation could be a sinusoidal variation of the intensity or a rotation of the plane of polarisation at constant speed.
- quasi CW often operating in a continuous mode–locked mode (series of equally time spaced picosecond pulses).

The first experiments were made in open air, optical fibers did not exist yet. It is obvious that the two paths of the light go through the same medium. The meteorological parameters are stable enough for round trips shorter than a few seconds.

With the growing use of optical fibers (OF), the control of the light propagation medium was greatly improved.

The advantages of optical fibers are :

- all weather operation
- very efficient energy budget link,this is due to the very low losses of optical fibers around 1.3 micrometers, the design of laser diode emitting at that wavelength, and the development of very fast and efficient detection diodes. These two diodes matched together. It has to be noted also that the coupling of the emitting and receiving devices to the OF is tight.

The parameters modifing the travel time are slowly changing, temperature, in particular. It should be controlled.

This is particularly important for frequency transfer. A "zero delay change" method could be designed where the one–way delay is maintained constant by a variation of the temperature of the optical fiber via a feedback loop taking into account the two way round trip delay. OF are often used in cables grouping several ones and it is possible to determine the round trip time using two different OF one for each travel direction. Only a very small differential error is possible as the thermal conditions of two fibers in the same cable are very close to each other. When time and frequency transfers are concerned the delay of the transmission from one point of the link to the other is measured "in situ". A two wavelength system is not necessary as long as the two way travel time is short enough to assume that the travel delay is the same for the two directions of flight.

For time and frequency transfer at very long distances, the atmosphere cannot be neglected. Then the travel delay is not the same for the two directions of flight (relativity experiment on circum solar spacecraft).

If not, the two way method used with two colors could provide the differences of the two directions of flight times, making a differential measurement at the two ends of the link. When the two way energy or power link budget is too difficult to achieve from one side, both equipments could be active. The target side could detect the signal and reemit it with an optical transponder with its known delay. The concept could be useful for solar or planetary probes.

DOUBLE TWO WAY TECHNIQUES

If the two points to be synchronized are not in direct access or view (distance, obstacle,..) a relay could be used. In this case a double two way link is set up. This could be done in several ways.

1. LASSO concept Fig. (3 A)

The two ground stations are laser ranging equipments measuring the travel time of the light from the station to the relay and back. The epochs of emissions are also recorded. The equipment of the relay consists in the retroreflector panel and a time intervalometer linked to a light detection device. The time differences of the on-board detected signals are transmitted by telemetry to the stations.

2. AJISAI concept Fig. (3 B)

The target (spacecraft) could be completely passive consisting of mirrors. Each station sends a signal to the target and reaches the other station by reflection. The travel times from one station to the other is the same in both direction and therefore cancel. The disadvantage of the method is its poor efficiency caused by the low probability of specular reflection from a station to the second one. This efficiency is somewhat improved by the very large number of mirrors on board the satellite.

As for the two way, the target could be equiped with optical transponders working in one of the two preceding modes.

FUTURE OF OPTICAL TIME AND FREQUENCY TRANSFER

The bandwidth accessible by an optical beam is tremendously wide. This allows very high frequency or modulation of very short pulses. Up to now the useful bandwidth was limited to some tens of gigahertz. At these bandwidths one must take into account the dispersive effect of the medium of transmission. As an example, a light pulse of 10 ps at the minimum bandwidth compatible with the Fourrier transform is widened by 10 ps if it travels through two 20 km paths of standard atmosphere. By convolution of the original pulsewidth and the broadening, one can see that the returning pulse has a 14 ps duration. By adding some extra hardware such as prisms or gratings the pulse could be recompressed to 10 ps. A minimal pulsewidth, for each travel distance through a dispersive medium, could be computed. If one wants to use shorter pulsewidth at higher frequency modulation, one has to take into account the difference between phase and group velocity. This remark is particularly true for time transfer and is far less important for frequency transfer with the new compression technologies developed for laser pulse generation; subpicosecond and even subfemtosecond measures could be conceived.

The optical time and frequency transfer is still at its infancy and improvement of the accuracy by two or three orders of magnitude could be predicted (Atosecond domain).

CONCLUSION

In the past, we have always acted, as if infinite air space, infinite radio space, infinite energy and raw materials exist. We rapidly come to the point when the infinite character of resource approximations are no longer valid, and we have heavy pressure to plan and organize. It is now the era when time and frequency technology will become one of man's most valuable and useful tools.

The quality of time and frequency information depends upon two things: the quality of the clocks that generate the information and the fidelity of the information channels that disseminate the information. The use of light in the techniques for time and frequency transfer, which was a new approach, is now maturing.

The intrinsic qualities of this new concept is a big step forward :

- the bandwidths of the optical beams can be very wide ;
- the sensitivity to ionospheric effects is small compare to the radio techniques;
- it is easy to obtain good link budget thanks to the high directivity of the optical or laser beams;
- finally it is difficult to detect an optical emission that is not directed to you (confidentiality)

Some problems still have to be overcome, some new applications still have to be studied and new experiments have still to be imagined. This should lead to a new level of scientific achievement in particular.

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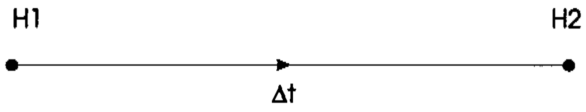
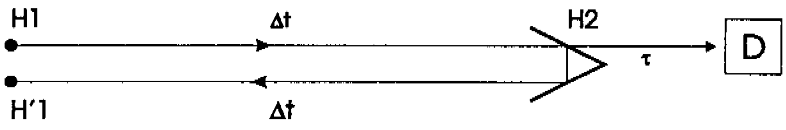
ONE WAY (Fig.1)



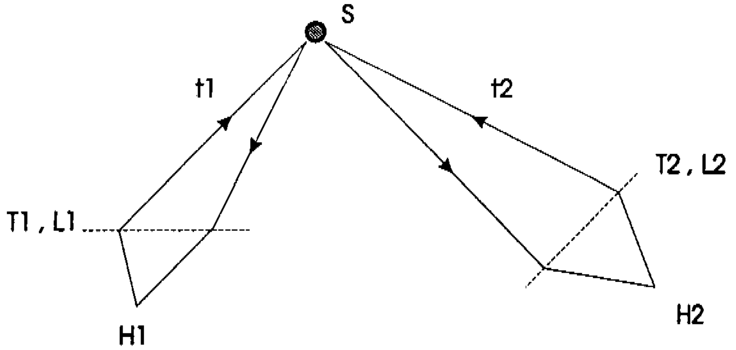
$H2 - H1 = \Delta t$

TWO WAY (Fig.2)



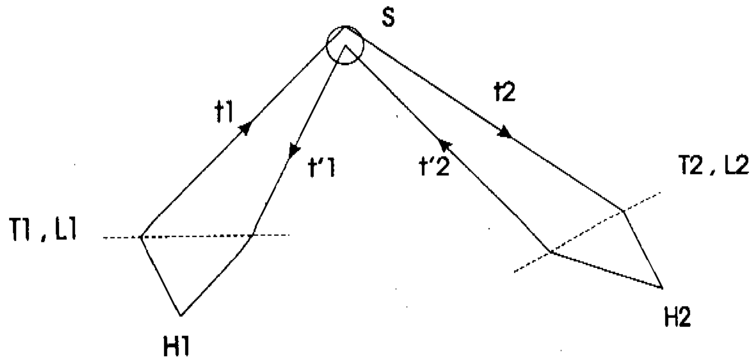
$2\Delta t = H1 - H'1 \qquad H2 - H1 = \Delta t + \tau$

DOUBLE TWO WAY (Fig.3a)
LASSO



$H2 - H1 = (TS1 - TS2) + (t2 - t1) + (T2 - T1)$

DOUBLE TWO WAY (Fig.3b)
AJISAI



$H2 - H1 = ((t1 + t2) - (t'1 + t'2)) / 2$

QUESTIONS AND ANSWERS

J. Levine, NIST: I just wanted to comment that the geological community for many, many years has been making measurements that are very similar to your measurements for the point of view of earthquake predictions. The measurements are made through the atmosphere; they typically measure baselines up to 30, 40 or 50 kilometers long, with an uncertainty of about 10 to the minus 7 or 10 to the minus 8. If you turned those measurements around and thought of them not as distance measurements but as time measurements, that results in time transfer of between one and ten ps. That is very, very old data. Some of the measurements use multiple wave lengths; some of the measurements use single wave lengths. There are one–way and two–way measurements. Now all of those techniques use not pulses, as you have discussed, but modulation on the laser beam itself; and there are a lot of technical advantages to that. And you might want to consider those kinds of schemes in the future for your measurements too.

Jean Gaignebet: I will just make a comment. When you want to make time transfer with a light, you need not know the index you are crossing because you are not correcting to the distance. You have directly the time of flight. We are going to more than one wave length for this reason.

The second problem is the kind of modulation. If the gain of your link is high enough, you could use modulated beams. If the gain is very low, and that is what we have when we range on long distance targets, the closed retro–diffusion is completely perturbing your phase measurement. So for long distances, you are driven to pulse systems.

J. Levine: The modulation is only from point to point on the ground.

Jean Gaignebet: Quite short distances.

J. Levine: Up to 50 kilometers perhaps.

Jean Gaignebet: Yes. I know that the system designed in France, and it uses the direction of the polarization of the beam which is rotating at 100 MHz. That is working up to 50 kilometers. Then the retro–reflector panels have to be so large in order to keep the gain that you cannot do it because the corner cubes are depolarizing your beam.

J. Levine: That is absolutely true. The comment that I was making was with respect to point–to–point measurements on the ground.

G. Thomas Becker, Air System Technologies, Inc.: This is a two–part question. Surely there is a very large path attenuation from ground to satellite and back. What is that, and would not the resulting received optical signal be so weak that there is a large integration time in the detector? How do you overcome that?

Jean Gaignebet: The figure in attenuation range is between ten to minus 16 to ten to minus 22, which means that we are often working in single–photon detection systems. Even for LASSO work, lunar laser ranging stations have physically a few photons per shot. So all the technology has to be developed to keep the accuracy at such low levels. We are working very fast in microchannel PM tubes, always in the geiger mode. One of the advantages is that often we have a very good ephemeris of the satellite. So we could have a very narrow range gate, and have almost no noise or very weak noise in this gate.