Measuring a One Way Light Speed

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Abstract A novel method of measuring measuring a one way light speed (OWLS) is proposed using standard equipment of frequency generators, laser pulse generators and oscilloscopes with periodic pulses going from A to B and also from B to A. The method can then inform B how long it has taken light pulses to reach B's laboratory from A and similarly A can establish how long the pulses have taken to come from B. The method is based on experimental work that actually used a very similar method to measure the relative speeds of photons and classical pulses. It is expected that with classical optical pulses, the method could measure the one way velocity to an accuracy better than 1 part in 10^6.

Introduction

It is generally accepted that the result of the Michelson Morley experiment relies on the two way speed of light being invariant. In current forms of this experiment the constancy can be measured with remarkable accuracy[1]. There are also sophisticated measurements of the one way light speed (OWLS) again with a remarkable accuracy and constancy [2, 3]. Never the less, there is still no universal agreement that the one way light speed is actually a fixed value of *c* because there are both theories and experiments that suggest that *c* can vary or appear to vary depending on the velocity of the frame of reference [4,5,6,7,8,9] There are also varying views about the measurement of OWLS [10,11,12,13]. Indeed the references here are but a small sample and it is not the intention to give a review in this short contribution. Here, the paper is limited to describing a novel way of measuring OWLS with relatively straightforward apparatus of stable frequency sources, oscilloscopes and pulse generators. A slightly different version of this system was used to measure the relative speed of photons and classical pulses propagating along optical fibres [14], but the system was not invented with any initial intention that it would measure OWLS. The experiment, described below, is a proposal but is based closely on these previous experiments that worked well

The Experimental Setup

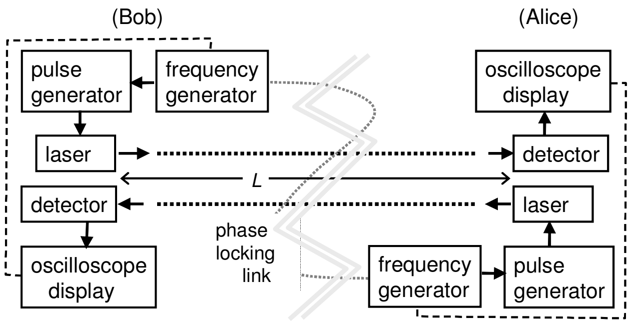

Figure 1
Schematic Layout of experiment . Bob & Alice both do the same experiment

The experiment to be described is to be carried out by the time honoured experimentalists, Bob and Alice. Figure 1 shows the apparatus schematically. Bob and Alice cannot agree on the relative settings of their clocks but they can agree that they always measure the same temporal intervals. So in their two laboratories they have set up identical optical sources and optical detectors which are known to be situated exactly *L* metres apart. They each have identical stable frequency generators combined with a phase locking loop between the two identical generators. Their first task is to establish that they can phase lock their signal generators at a series of frequencies F_N ranging say from F_{min} to $F_{max} \sim 4\ F_{min}$. If signal generators are identical then from symmetry one expects the phase at each end of the phase locking link to be identical. Each signal generator is sending out and receiving a round trip signal. Simultaneity with periodic signals means that they have the same phase.

We digress here because phase is important. Phase is invariant to translation to different frames of reference. For example zero is always zero, and a maximum always a maximum. One can view phase as the position of a vector rotating around the axis Oz of propagation or translation rather like one hand of a clock whose shaft is pointed along Oz. If the phase hand points to 0 on the 360^o clock face in one frame, then moving with a different velocity does not alter the phase pointer: it remains at 0. If symmetrical phase locking is achieved for the two signal generators then it is always symmetrical phase locking. We can check the symmetrical phase locking with the two signal generators close by and then move them far apart with confidence.

Figure 2 shows the phase locking process schematically on the extreme assumption that the phase velocities from A to B is not equal that from B to A. The symmetry and periodicity means that it is not possible to say that V_A lags V_B or that V_B lags V_A. So if we trigger an oscilloscope at the point when dV_A/dt is a maximum, it will with a periodic system be exactly the same phase as when dV_B/dt is a maximum. A trigger pulse will appear every period, i.e. every $1/F_N$ and each trigger pulse is as good as any other trigger pulse. This will be true for all the frequencies F_N where symmetrical phase locking is achieved. This is then a frame invariant form of simultaneity that is available only to periodic systems. We will deal with asymmetrical phase locking shortly.

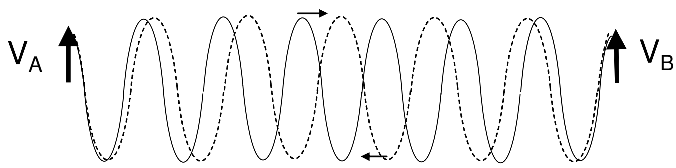

Figure 2
Schematic of symmetric phase locking with unequal propagation

Once Alice and Bob have established that they can find an appropriate set of phase locked frequencies $\{F_N\}$ they then set their signal generators to trigger their pulse generators and trigger their oscilloscopes so as to both send and receive periodic trains of optical pulses (say with pulse widths of a nanosecond or two << $1/F_{max}$) with the same periods $1/F_N$ as their phase locked frequency generators. We will concentrate on the measurements that Bob makes. Alice will simply duplicate these procedures in her own laboratory.

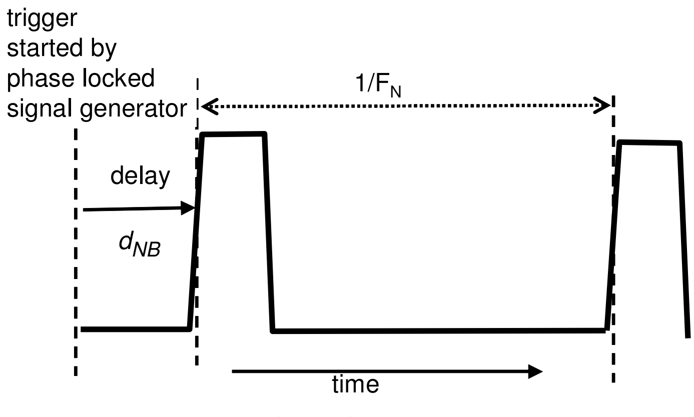

Figure 3
Display on the oscilloscope

Bob connects his optical pulse detector to his oscilloscope, triggered from the phase locked signal generator. Bob sees at least one pulse arriving regularly from Alice and reads off the time d_{NB} where the rising edge of the pulse is observed, the delay d_{NB} being measured from the trigger time of the scope. Figure 3 shows schematically what he observes. The repetition of the incoming pulses is cycled through the set of agreed frequencies F_N with Bob measuring the appropriate value of d_{NB} and recording the sequence of frequencies and delays $\{F_N, d_{NB}\}$. A useful set should typically have 20 to 50 frequencies spread over a range where $F_{\max}/F_{\min} \sim 4$. The duration $2T_p$ of the pulses (perhaps 1 or 2 ns) is not important so long as $2T_p < 1/F_{\max}$ but the rise times need to be independent of F_N and sharp enough to make reliable and precise (~ 100 ps) measurements of the pulse's arrival time.

Analysis of Data

The analysis of these results is as follows. It is known that there is some time of flight T_{AB} for the pulses to go from Alice's laser to Bob's detector over the distance L kilometres. Now, as we have seen, with a phase locked system where the trigger is always at one phase point in Alice's system, then it is at the same phase point in Bob's system. With the periodic signals it is not possible to tell the difference between the time of Alice's periodic trigger signal and the time of Bob's periodic trigger signal. For the duration of the experiment it is necessary that T_{AB} is known to be constant. It is also necessary that the periodic pulses have a stable period $1/F_N$. Now what Bob can observe is that the front edge of an optical pulse arrives some time d_{NB} after one of the periodic triggers. The time T_{AB} has to be an exact integral number of periods M_N *plus* the additional delay d_{NB} measured on the oscilloscope :

$$T_{AB} = M_N (1/F_N) + d_{NB} \tag{1}$$

Here M_N is known to be an integer although not known in its value. If one has chosen T_{AB} correctly one finds that integer

$$M_N = (T_{AB} - d_{NB})F_N \tag{2}$$

Of course neither T_{AB} nor M_N are known. However Alice and Bob know the round trip time for their pulse and can have a good guess that T_{AB} is somewhere around $T_{roundtrip}/2$. The following computer program is set up. An estimate or guess T_{est} is made of T_{AB}.

$$R_N = \text{round to nearest integer } \{(T_{est} - d_{NB})F_N\} \tag{3}$$

Again it is stressed that in an exactly periodic system the temporal reference point can be taken to be the start of any cycle. The start of any cycle is as good a time reference as any other cycle. At the first estimate, it is most unlikely that the estimate is right. The error in the estimate gives rise to an error quantity:

$$E_N = (T_{est} - d_{NB})F_N - R_N \tag{4}$$

We consider all the different frequencies but retain the same value T_{est}.

$$\text{Error}(T_{est}) = \Sigma_N \mid E_N \mid \tag{5}$$

Now plot "Error" against a whole set of values "T_{est}" and look for a minimum in "Error". If $T_{est} = T_{AB}$ then ideally with precise measurements one finds $\text{Error}(T_{AB}) = 0$. Of course the measurements are not infinitely precise so that one wishes to see what actually happens.

Figure.4 shows the results of a synthesized run for a time of flight for a value of T_{AB} of 100,103 ns or approximately 30 kilometres. Now for simplicity only ten frequencies have been chosen covering a range from 25 MHz to 100 MHz . The following synthesized data is created for a simulated measurement where d_{NB} is measured accurately to the nearest 100ps. In Figure 3 [C] random errors up to +/– 250 ps were included to demonstrate how robust the system is against random errors.

Table 1

F_N (MHz)	25.0	29.1	34.0	39.7	46.3	54.0	63.0	73.5	85.7	99.9
d_N (ns)	23	34.3	14.8	2.2	16.6	10.4	7.8	7.8	9.7	2.9

It can be seen from the examples of figure 3 that the correct time of flight shows up very clearly as a remarkably sharp dip in the minimum of “Error”. The better the estimate of the time of flight the more accurately can one pin-point its true value. The more measurements, with different frequencies, also makes for a greater potential accuracy of the measurement. Figure 4C shows the range of error that the system exhibits for +/– 0.25 ns errors in measuring the delays d_{NB}: demonstrating robustness.

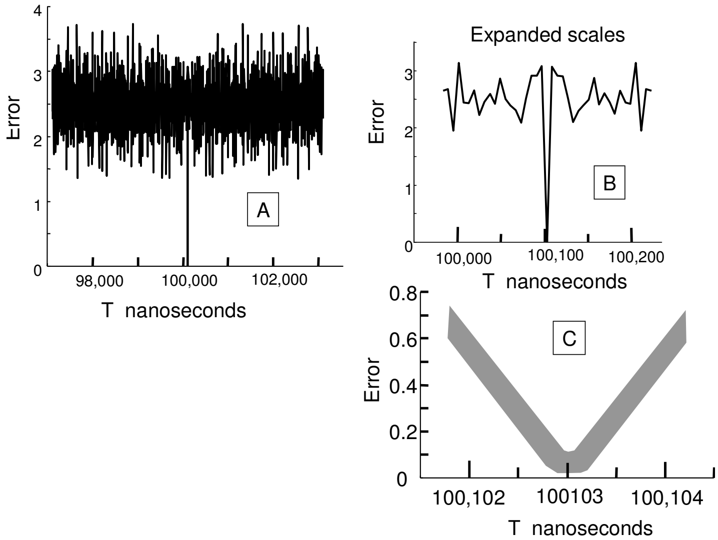

Figure 4 Example of a measurement showing ability to recover the time of flight.(synthesized data as in Table 1).

Now the elementary system was found experimentally not to work exactly in the way that is suggested by equation 1. Figure 5 shows a more full representation of the parameters. Because the oscilloscope triggers off a pulse edge and there is a centre of symmetry (C of S) and it is found that the effective temporal periodicity is not $1/F_N$ but $1/2F_N$.

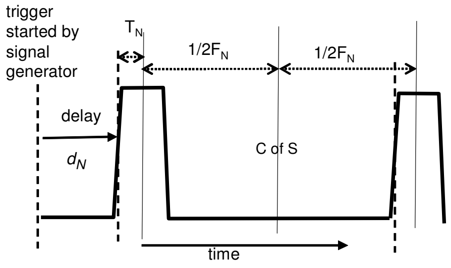

Figure 5
Illustrating the parameters that affect the detailed practical measurements

Similar arguments apply with phase locking. Figure 6 shows that one might have asymmetric mode locking so that there might be a phase difference of 180^0 between the trigger at Alice and the trigger at Bob. But all this is going to do is to make the effective periodicity $1/2F_N$ rather than $1/F_N$.

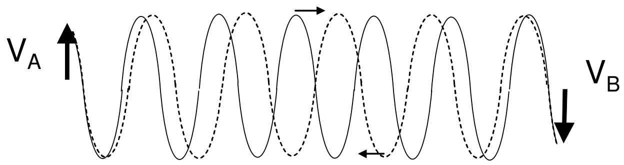

Figure 6
Asymmetric mode locking

One is now assured that the time of flight T_{AB}, less the delay d_{NB}, and less half the pulse width T_p has to be an integral number of 1/2 inter-pulse periods. The equations (1)-(3-4) have to be replaced by:

$$T_{AB} = \mathrm{M_N}[1/2F_N] + d_{NB} + T_p \tag{6}$$

$$\mathrm{R_N} = \text{round to nearest integer } \{(T_{est} - d_{NB} - T_p)2F_N\} \tag{7}$$

$$E_N = (T_{est} - d_{NB} - T_p)2F_N - \mathrm{R_N} \tag{8}$$

The final error remains as in equation (5) but using equations (7) and (8). Results obtained are very similar to those of Figure 3.

Back-Back Correction

There is one more correction to make to find the exact time of flight. The difficulty is that the time of flight through the electronics can be a significant number of nanoseconds and is hidden, at present, within the time of flight T_{AB}.

Because Bob has an exact replica of Alice's apparatus, he simply switches his system around to make a 'back-back' measurement as in Figure 7. Here the pulsed laser feeds 'directly' into the detector. If the detector is not to saturate, there may be some necessity for a neutral density filter (attenuator) that is sufficiently thin/short so as not to materially alter the time of flight. This new measurement will estimate the electronic time of flight which must then be subtracted from the original measurement T_{AB} to obtain the true time of flight over the distance.

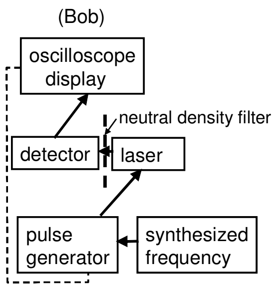

Figure 7
Back-Back measurements to eliminate time of flight through the electronic systems

However if all that one wishes to know is $T_{AB} - T_{BA}$ and Alice does exactly the same set of measurements as Bob, then back-back measurements need never be made. In fact the interesting result is that one finds the value:

$(T_{AB} - T_{BA})$ from processing the set $\{F_N, (d_{NB} - d_{NA})\}$

Here one only has to have a guess at the range of $\tau \sim (T_{AB} - T_{BA})$ that might be plausible and then τ is the extent of the search range for $(T_{AB} - T_{BA})_{\mathrm{est}}$.

Discussion

The most serious objection to this system is that the two frequency signal generators have to be phase locked in order that their two signals have a 'common' phase reference. This is a two way link. However it is accepted that the two way velocity is invariant so that the round trip phase change is invariant. Phase is an invariant under translation and the same phase is the signature of simultaneity for periodic systems . Phase locked periodic systems then by their construction have a common phase reference which for periodic systems means ‘simultaneity’.

It is of interest to record that this periodic system was invented to ensure that one could measure single photons and classical pulses in exactly the same way and demonstrate that single photons and classical pulses travelled with the same velocity along a fibre [14]. With that system there was of course only a single frequency generator (a synthesizer) and one pulse generator. There was no need for a phase locked loop. The data processing for both single photons and classical pulses was identical to the data processing given here. The same pulsed laser source was used for classical as well as for single photons so that the photons and classical particles came from the same spread of optical frequencies. The single photon regime was approximated by attenuating the light from the laser so as to ensure that on average there was no more than one photon per 20 pulses that were received. The probability of two photons in any one pulse was then negligible. For single photons the photo-detector and oscilloscope were replaced with a single photon avalanche detector together with an appropriate digital display. The back-back measurements were important because the ‘time of flight’ through the electronics for the single photon measurements was distinctly different, by several nanoseconds, from the ‘time of flight’ through the photo-detector and oscilloscope amplifiers. The system was able to achieve reliable and repeatable results of measuring times of flight to an accuracy of +/− 0.2ns in 30,000 ns. The error was substantially caused by an inability to measure sufficiently precise times of arrival, and the time of flight (i.e length of fibre) was limited by attenuation in the fibre. With purely classical pulses and optimised fibre, substantially longer distances could be envisaged with perhaps an accuracy of +/− 0.2ns in 100,000 ns.

Those who actually believe that there is evidence that the velocity of light changes { for example by factors ~ [1+/− (v/c)] dependent on the direction and velocity v of a travelling system} will note that the method, unless refined further, will probably require v to be larger than 1 km/s to falsify or confirm their theories. The actual experiments on photons and classical pulses were performed with coils of fibre so that there was never any intention to make an OWLS measurement. Such a measurement requires two remote laboratories, situated ideally on an east to west line, connected by a stretch of optical fibre, or a clear line of sight.

In conclusion it has been shown how two experimenters with identical equipment of stable frequency sources and pulse generators might make simultaneous OWLS measurements from A to B or from B to A which can then be compared. From experimental work done previously with stable frequency synthesizers and where arrival times of optical pulses could be measured to about 100ps accuracy then it is expected that one could measure the one way light speed to an accuracy that was around 1 part in 10^6. Improving on this accuracy requires sufficiently stable and precise frequency sources that can be phase locked and also an ability to measure arrival times of optical pulses to much better than 100 ps achieved previously.

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