TEST OF ONE-WAY VELOCITY OF LIGHT AND RELATIVITY OF SIMULTANEITY

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TEST OF ONE-WAY VELOCITY OF LIGHT AND RELATIVITY OF SIMULTANEITY

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Abstract

Based on recent developments in femtosecond pulse technology[1,2] a laboratory experiment to measure the one-way velocity of light is proposed. The exposition contains a discussion of the theoretical significance of the experiment as well as a brief description of how it may be performed.

All laboratory measurements of the velocity of light so far performed yield only the average of "to" and "fro" velocities between two points A and B, and not the one-way velocities A to B and B to A separately. Let the A to B and B to A velocities be c_1 and c_2. We may write

$$c = \frac{c_1 + c_2}{2} \quad , \quad V = \frac{c_1 - c_2}{2} \tag{1}$$

where c is the average velocity and V is the deviation from this average velocity. On heas

$$c_1 = c + V \quad , \quad c_2 = c - V \tag{2}$$

Our aim is to measure, in any given inertial frame, the two velocities c_1 and c_2 or, equivalently, c and V.

Note that to measure c_1 and c_2 or c and V one does not have to consider the laboratory moving, nor any frame moving relative to it; c_1 and c_2 are definable in a single frame. The measurement here is concerned only whether $c_1 = c_2$ in all directions (isotropy of the propagation of light) or $c_1 \neq c_2$ (non-isotropy of the velocity of light).†

Of course one will want to know whether c_1 and c_2 are the same when a frame is moving with a velocity v (relative velocity) with respect to the original frame. For example, the theory of relativity says that $c_1 = c_2 = c$ that is $V = 0$ in both the original and in the moving frame independently of v. It is conceivable that the velocity of light is anisotropic in both the original and in the moving frame independently of v. The experiment we propose is capable of deciding whether the propagation of light is isotropic in such frames. If $c_1 = c_2 = c$, $V = 0$ the experiment would be said to agree with the second postulate (constancy of the propagation of light) of the special theory of relativity. To ascertain the second postualte, we need not worry about any frame moving relative to the one on which the experiment is performed, although we need to set this frame to motion relative to its original state (for example we need to measure c_1 and c_2 now and six months later on the earth when earth's orbital motion is directed opposite).††

Consider the experimental arrangement Figure 1 below: Two colliding beam femtosecond pulse lasers of equal pulse repetition frequency[2] are connected to an acoustic bar. The two lasers are completely independent except that two signals split (one from each) by semi-transparent mirrors are locally amplified and used to phase-couple with the acoustic bar. The propagation of sound waves in the bar are assumed isotropic with respect to the bar. This assumption is quite safe since the bar is a mechanical system. If the bar is brought to resonance by the applied pulses at its two free ends (support in dicated) we can safely assume that its two ends define simultaneous oscillations in the frame at rest relative to the bar (laboratory). If now the two laser beams are brough together by a right angled mirror as shown, the pulses will completely or partially overlap depending on whether c_1 and c_2 are equal or not equal.[3] One has the relation

$$\delta t = 2\ell \frac{V}{c^2} \tag{3}$$

Thus if $\ell = 25$ cm, and if $\delta t = 30$ fs shift is detectable in a statistical (correlation measurements) sense, one would be able to set an upper bound $|V| < 6$ km/s. It seems that with the present sub-picosecond pulse technology of 100 fs and lower,[1,2] one might be able to achieve a precision of this order of magnitude. Of course, in the actual experiment the right angled mirror does not have to be exactly at the center as long as the whole apparatus can be rotated around the vertical. Also one could have a gate which permit measurements to be taken only <u>when</u> the acoustic bar is in high resonance so that the quality of the statistics is not diluted. Existing colliding pulse lasers have pulse widths of 100 fs and a stable pulse repetition frequency suitable for large statistics.

A conceptually simpler experiment may be to replace the function of the acoustic waves with electrons. In Figure 2 the two points A and B can be made to emit electrons by shining the two laser beams on them. The emitted electrons (pulses with the repetition frequency) can be collected at the middle by applying a voltage difference between the middle and the two ends. If the pulses are simultaneous the electrons will arrive simultaneously. This can be ascertained with a streak camers.[4] The assumption here is that electrons are mechanical systems hence will come to the middle simultaneously if they are emitted simultaneously. Thus <u>while</u> electrons are arriving simultaneously (can be arranged with a delay at the trigger line) the previous arrangement with right angled mirror can check whether the light pulses also arrive simultaneously. Systematic deviations (if any) from the exact coincidence could then be measured. Again the relation between δt and V leads to an upper limit for V. However, rapid operation may permit large amounts (due to regularity in repetition frequency) of statistics to be collected, leading to a sufficiently interesting upper bound. Again, the design can be simplified by making the device rotatable, in which case the detection device does not have to be at the center, etc.

One may want to discuss the relative merits of the acoustic or electronic arrangements from the point of view of basic theory. They are here used in the sense of providing a mechanical synchronization (of the clocks) at A and B so that optical velocities can acquire operational meaning. If this synchronization itself is done via light propagation one can only measure the average velocity c. Thus the function of the acoustic waves and/or electronic pulses is to provide a synchronization independent of the optical waves. One may worry about whether acoustic waves or electronic motion are really independent of electromagnetic waves. We believe they are as the rest masses of the atomic nuclei or of free electrons are not wholly of electromagnetic origin. In any case it does not matter because from a relativistic point of view we are really inquiring whether these velocities satisfy the relativistic composition law.

The above considerations concern the second postulate of special relativity but not necessarily the first postulate (the principle of relativity). This is evident if we write[5]

$$dx' = A(dx+vdt) \qquad dx = B(dx' - vdt')$$
$$dt' = A(dt + \frac{v}{c^2}dx) \qquad dt = B(dt' - \frac{v}{c^2}dx') \tag{4}$$

where $AB = 1/(1-v^2/c^2)$. One can easily show that, in each frame, the velocity of light is c in both directions, and $v' = dx'/dt' = (u+v)/(1+uv/c^2)$, etc., but nevertheless $ds^2 = c^2dt^2 - dx^2$ and $ds'^2 = c^2dt'^2 - dx'^2$ are <u>not</u> necessarily equal. One has

$$Ads^2 = Bds'^2 \tag{5}$$

The first postulate, on the other hand, states that the two frames are in every respect equivalent, namely, $A = B = 1/\sqrt{(1-v^2/c^2)}$. Evidently this cannot be ascertained if every measurement is made with the light rays since we would then have $ds^2 = 0$, $ds'^2 = 0$. To ascertain $ds'^2 = Kds^2$, $K = A/B = 1$ one must have measurements on objects which do not lead to $ds^2 = 0$, $ds'^2 = 0$ and this is primarily the function of the acoustic waves and/or electronic pulses. For them $ds^2 \neq 0$, $ds'^2 \neq 0$ so that $A = B$ can be ascertained.

From these considerations it may be inferred that the successful performance of the above experiment embodies within itself the complete logico-empirical foundation of the special theory of relativity including one of its central assumptions, the relativity of simultaneity. The same cannot be said, for example, of the familiar Michelson Morley experiment, because there all measurements are made on light rays alone. Such cannot ascertain K = 1 hence Michelson-Morley experiment cannot provide the complete logical foundation of the special theory of relativity. That Michelson Morley experiment cannot be used to prove the logical completeness of the special theory of relativity is clear from the fact that Lorentz, Poincare and others were able to account for the result of this experiment without committing to the special theory of relativity.

Admittedly the experiment stipulated above is not easy to perform nor is it clear the accuracy hoped for can be reached in the very first time it is attemped. However, the basic significance of the experiment is so enticing that it must be tried even at considerable risk. Besides, the experiment sets a well-defined goal by which one may be able to advance the femtosecond pulse generation and detection technology to a point where they may be put to other uses such as high resolution studies of ultrafast phenomena.

Having exhibited the conceptual preliminaries of the experiment in terms of some simple arrangements, we may now go over briefly how the actual experiment may be performed. Consider Figure 3 where the two beams split from a single colliding pulse laser are reflected from two mirrors and led to two identical streak cameras. Each camera has its own monitor, storage and computer processing facility capable of averaging, normalizing, shifting, subtracting, etc., but both are triggered by a single trigger mechanism. At a given time and orientation of the instrument the averaged distributions are so normalized that they are identical. If the light rays are along the line where V is maximum, a 180^{o} rotation will yield a shift of the distributions given by

$$\delta t = \frac{4\ell V}{c^2}$$

where ℓ is the effective length of the electronic path in the streak camera (presently about 10 cm). The shift δt can be inferred by subtracting the two images, or their sums, from each other at different orientations of the instrument. In this arrangement the correlation measurements of Figure 1 using KDP is replaced by the electronic computer processing components. This change may cause a loss of accuracy but it presents a simpler situation since streak cameras can be operated in the synchroscan mode leading to large statistics.

To give an idea of what is possible with existing technology we remember that a commercial streak camera can have a resolution of 1 ps, a jitter of 10 ps (W. Knox and G. Mourou, Optics Communications. 37, 203, 1981; point out that jitter can be reduced to about 2 ps) and a temperature drift of 7.2 ps per degree centigrade*. Thus one needs about 30 ps display length

*The camera used in the preliminary set up had a resolution of about 1.6 ps and a jitter less than ±20 ps.

(to accomodate jitter). Since there are 256 scan lines, the line resolution is about 120 fs. Temperature drift is small enough during each averaging so that it is not a problem (24 fs/hour expected). If we assume that the velocity resolution is about one scan-line (it could actually be better if large averages are taken and the calculations are carried to sufficient digits) the corresponding velocity resolution will be

$$\Delta V = \pm 27 \text{ km/sec.}$$

or better. The rotation of the instrument can be a problem for reasons of mechanical and geomagnetic factors. However, the instrument may be fixed and advantage taken of the rotation of the earth.

It is, of course, expected that some unforeseen problems will tend to dilute the above estimate but it is also expected that streak cameras with higher resolution and lower jitter will be developed to counteract, or even substantially improve the estimate.

It is hoped that with improved techniques the result will be considerably better.

We emphasize that the experiment does not make use of the relation $\lambda\nu = c$ and it is not an interferometric experiment. It is a direct probe into the basic space-time structure and a clean test of special relativity <u>independent</u> of wave or particle conceptions of light.

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† More generally $c(\theta) = \Sigma\alpha_\ell P_\ell(\cos\theta)$ where $P_\ell(\cos\theta)$ are spherical harmonics, $P_0 = 1$, $P_1 = \cos\theta$, etc., with $\alpha_0 = c$, $\alpha_1 = V$ so that $c(\theta) = c + V\cos\theta$, etc.

†† Note that in principle V and v have nothing to do with each other. However, in the past the (hypothetical) "ether" assumption (in which V - 0) gave the false impression that, in a frame moving relative to the ether, V would be equal to -v (the relative velocity with respect to the supposed ether).

¶ Contrary to general belief the Michelson-Morley experiment cannot be used to prove the isotropy of the velocity of light because it does not, by itself, remove the possibility of clocks recording time differently in different directions. This applies also to arrangements of stabilized lasers with no connecting mechanical link. Mechanical components we introduce remove such a possibility.

¶¶ Compare with J.G. Small, 1976 "Conference on Precision Electromagnetic Experiments" Boulder Colorado, USA, IEEE 1976, p.184-5.

APPENDIX A

In the above arrangement the measurements are assumed to be made when V and the optical path are aligned. It is, however, clear that if the instrument is oriented differently the velocity is to be replaced by V cosθ. With this replacement the measurement procedure can be applied continuously for all orientations.

It is also to be noted that the relativity of simultaneity imbedded in the Lorentz transformations is here being tested although this is not intuitively obvious. To render this point more visible to intuition note that a vertical ray will appear to a moving vehicle on the earth as tilted by an angle α as

$$\sin\alpha = \frac{V}{c}$$

Since in a Lorentz invariant theory rays and wave-fronts are always perpendicular, the wave-fronts must now fall at a slant α which means that the simultaneity of the fall of a wave front in the original frame (for example, at two points A and B, $\Delta x = \overline{AB}$) has to lead to a time difference

$$\Delta t = \sin\alpha \frac{\Delta x}{c} = \frac{V}{c^2}\Delta x$$

which is precisely the formula (3) from which we have started. The factor of 2 in (3) is due to the use of two such intervals whose effects add.

Finally we may note that in these considerations we have not made use of any specific model of waves or particles. (The derivation of Δt above can also be made from special relativity independently of a wave model). Our model, if anything, is just the space-time kinematics determined by the two principles of special relativity.

It is, however, possible to discuss the experiment in terms of a Lagrangian model satisfying the two postulates of special relativity. Let a representation (not necessarily a classical wave) $\phi(x,y,z,t)$ of the Lorentz transformations be used to construct the Lagrangian as

$$L = \tfrac{1}{2}(\partial_\mu\phi)^2$$

One has the wave equation

$$\left(\frac{\partial^2}{\partial x^2} + \frac{\partial^2}{\partial y^2} + \frac{\partial^2}{\partial z^2} - \frac{1}{c^2}\frac{\partial^2}{\partial t^2}\right)\phi = 0$$

But this field can be quantized to obtain quanta which satisfy $k_\mu k^\mu = 0$.

Writing $m_0 \frac{dx_\mu}{ds} = \hbar k_\mu$ one finds

$$v_x^2 + v_y^2 + v_z^2 - c^2 = 0$$

In other words such quanta act as particles which move with the velocity of light. We conclude that the Lagrangian model with quantization leads to space-time relations independent of wave or particle models although, in some ways, compatible with both. Assuming our model of reality is such a quantized Lagrangian the experiment tests the basic space-time kinematics of special relativity independent of wave and particle character of light.

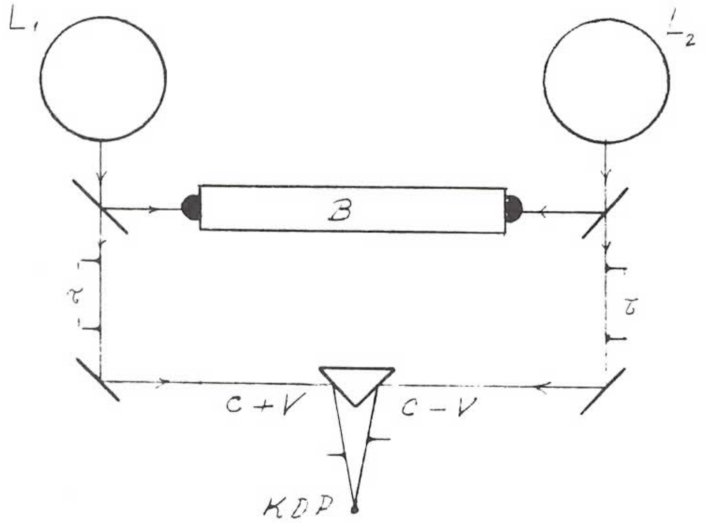

Figure 1. Two colliding-pulse ring lasers L_1 and L_2 send f's pulses of repetition frequency τ. When the acoustic bar is in high resonance correlation (KDP) measures the degree of overlap.

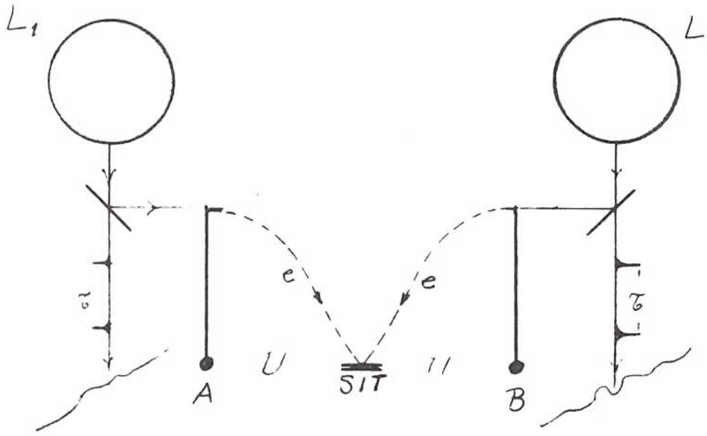

Figure 2. Same arrangement as in Figure 1 except that the acoustic bar is replaced by a photo-electronic detection system where a streak tube monitors simultaneity of arrivals.

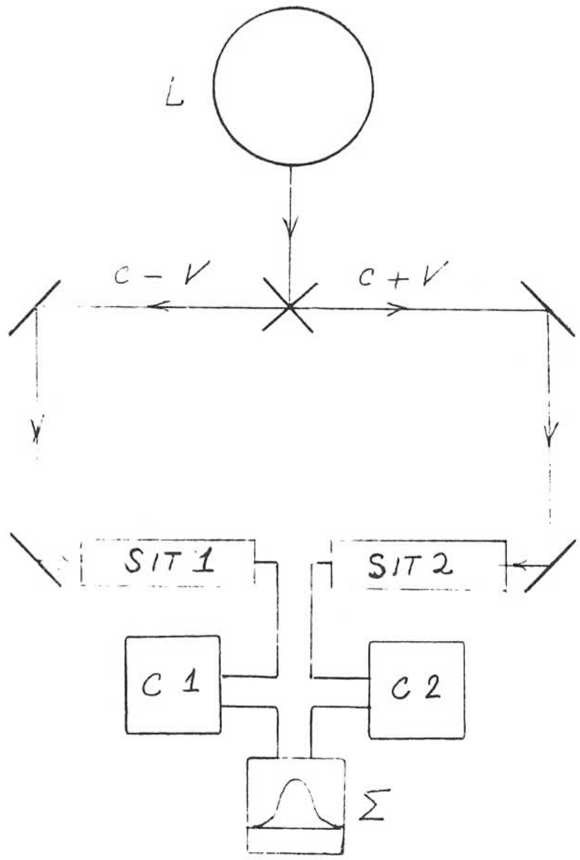

Figure 3. Outputs of streak cameras 1 and 2 are averaged, normalized, added and stored (Σ). The results at different orientations (e.g. at 180°) are subtracted to measure V, if any, via the widening of the distribution.

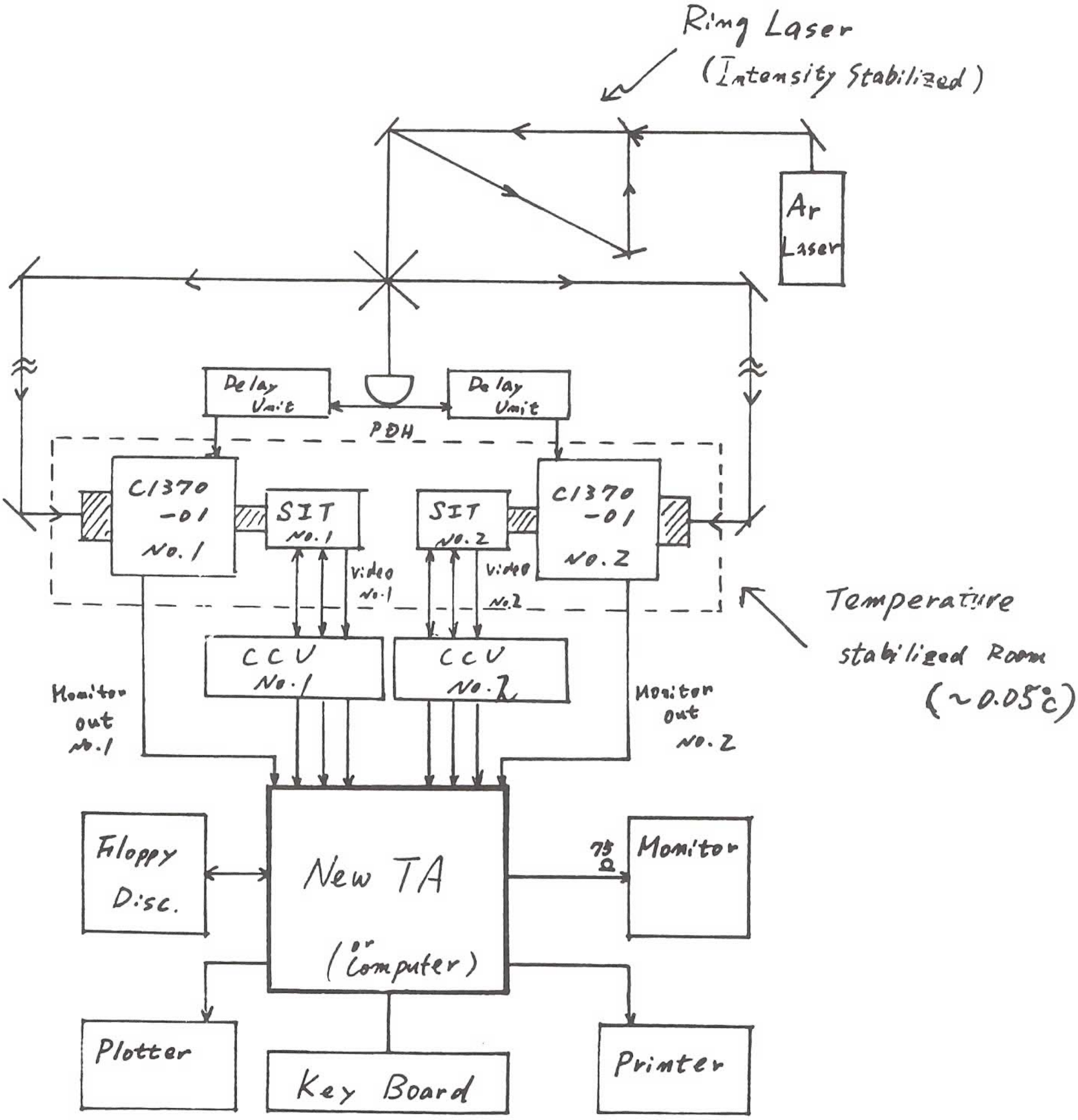

Figure 4. Block diagram of the experiment in progress. Components are to be replaced as more advanced ones become available.