NASA

Technical Memorandum 82053

A Proposed Method for Wind Velocity Measurement From Space

(NASA-TM-82053) A PROPOSED METHOD FOR WIND VELOCITY MEASUREMENT FROM SPACE (NASA) 37 p HC A03/MF A01 CSCL 04B

N81-15638

Unclas
G3/47 12801

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NOVEMBER 1980

National Aeronautics and
Space Administration

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ABSTRACT

An investigation has been made of the feasibility of making wind velocity measurements from space by monitoring the apparent change in the refractive index of the atmosphere induced by motion of the air. The physical principle is the same as that resulting in the phase changes measured in the Fizeau experiment. It is proposed that this phase change could be measured using, for example, a three cornered arrangement of satellite borne source and reflectors, around which two laser beams propagate in opposite directions. It is shown that even though the velocity of the satellites is much larger than the wind velocity, factors such as change in satellite position and Doppler shifts can be taken into account in a reasonable manner and the Fizeau phase measured. This phase measurement yields an average wind velocity along the ray path through the atmosphere. The method requires neither high accuracy for satellite position or velocity, nor precise knowledge of the rafractive index or its gradient in the atmosphere. However, the method intrinsically yields wind velocity integrated along the ray path; hence to obtain higher spatial resolution, inversion techniques will be required. This paper addresses the general principle of the technique and presents a particular system configuration as an example, to show that wind measurements are possible.

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INTRODUCTION

The present report is a study of the potential for measuring wind velocity using the phase change induced in two coherent laser beams traversing the atmosphere in opposite directions. It will be shown that a coherent measurement is feasible from space and can be accomplished in spite of the motion of the satellites. At a first glance this seems to be a formidable task. Satellites are moving at velocities of the order of 10km/sec, while wind velocities are of the order of 1 to 10m/sec, a difference of several orders of magnitude. In addition, the position of the satellites is not available to within an accuracy of an optical wavelength, which would seem to be important for a coherent experiment. However, it is shown below that these problems can be adequately resolved. This method does not require extraordinary accuracy of satellite position and velocity, in fact, resolution of the order of 1-10m is sufficient. Also, one does not need a detailed knowledge of the atmospheric refractivity and its gradient, beyond that available from existing models and data. On the other hand, we have assumed the availability in space of laser systems for remote sensing purposes. While this is still a thing of the future, there is a reasonable prospect that such systems will exist towards the end of the century.

In order to put the present study in the right perspective, it is worthwhile to quote from Gordon Little[1]: ". . . In general, the development of a remote sensing concept can be seen to follow a logical sequence. In Step A, the concept is identified, and preliminary first order estimates made of its feasibility. In Step B, the potential capabilities and limitations of the concept are analyzed theoretically in considerable detail. If the concept still appears attractive, the development of research equipment for the experimental evaluation of these capabilities and limitations takes place in Step C. Assuming that this quantitative experimental evaluation of the concept is successful, the next stage (Step D) is to build a development model (as opposed to a research model) which is thought of as a prototype of an operational unit which is to be capable of being used in the field by the research workers or technicians other than the original research group. If the concept continues to show promise, Step E involves working with industry to obtain commercially built units for field evaluation. Once this stage has been successfully completed, the final stage (Step F) requires that fully evaluated commercial units be routinely available for procurement." Obviously the present report is mainly concerned with Step A. At this stage we close our eyes to budgetary requirements, and important engineering problems such as detectability of signals by means of existing or projected optical instrumentation, the problem of tracking, and probably many others.

The method to be presented below possesses many features which make it attractive as complementary to other systems when they operate under adverse conditions. For example, some information about winds can be obtained by monitoring cloud motion. In contradistinction, the present method is suitable for clear skies. Other microwave radar and radiometry methods[2] correlate wind measurements and sea state. The present method will work equally well over sea and land and at arbitrary elevations. Unlike atmospheric radar or lidar, the present method does not depend on backscattering from irregularities and particles. Since it is based on forward propagation, a transparent line of sight will yield the best results. Other line of sight methods exist, see for example Ishimaru[3], relying on the presence of atmospheric inhomogeneities. These methods are particularly useful for measuring transverse winds, while the present method yields the wind component along the beam. It is also notable that the present method does not require exceptional imaging qualities, which would tend to make the optical equipment costly and heavy.

In the sections to follow, the theory of the Fizeau experiment is briefly reviewed and its applicability to the atmosphere considered. Then, typical configurations applicable to measuring winds are discussed. The Doppler effect is discussed in detail. This is relevant to the present method because of the change of frequency and direction of propagation, occuring during reflection from moving satellites. Next, an outline of the signal processing necessary to effect a measurement is presented, showing that in principle the Fizeau phase offsets are measurable in the presence of the various Doppler effects. Finally a brief discussion of the coherence problem is given. Clearly, if the present concept survives scrutiny by the scientific community, this and many other aspects of the system will have to be discussed in greater detail.

THE FIZEAU EXPERIMENT AND ITS APPLICABILITY TO ATMOSPHERIC MEASUREMENTS

The present method for wind velocity measurement is based on the measurement of the Fresnel convection coefficient in the Fizeau experiment[4]. One possible variant of the Fizeau experiment is depicted in Fig. 1. This is an interferometer in which two light beams, emanating from a common source, traverse a moving fluid in opposite directions. Experimentally one finds that the emerging waves differ in phase by an amount which is proportional to the velocity. The analysis of the Fizeau experiment is based on the Lorentz transformation for frequency and propagation vector, which to the first order in v/c takes the form[5]

$$\underset{\sim}{k}' = \underset{\sim}{k} + \omega \underset{\sim}{v}/c^2 ,$$

$$\omega' = \omega + \underset{\sim}{k} \cdot \underset{\sim}{v} , \tag{1}$$

where $\underset{\sim}{v}$ is the velocity of the fluid as observed in the laboratory frame of reference, $c = 3 \cdot 10^8$ m/sec is the speed of light in free space; $\underset{\sim}{k}$ and ω are the propagation vector and (angular) frequency, respectively, in the comoving frame of reference where the medium is observed to be at rest. The primes denote quantities measured in the laboratory reference frame, quantities in the comoving frame have no primes. In the comoving frame the refractive index is defined by

$$n = \frac{c}{\omega} \sqrt{\underset{\sim}{k} \cdot \underset{\sim}{k}} \tag{2}$$

and n is assumed to be independent of frequency (i.e., nondispersive). Hence in the laboratory frame one observes, to the first order in v/c:

$$n' = \frac{c}{\omega'} \sqrt{\underset{\sim}{k}' \cdot \underset{\sim}{k}'} = n - (n^2 - 1) \frac{\underset{\sim}{k} \cdot \underset{\sim}{v}}{|\underset{\sim}{k}| c} , \tag{3}$$

and when $\underset{\sim}{k}$ and $\underset{\sim}{v}$ are codirectional, this becomes

$$n' = n - (n^2 - 1) v/c , \tag{4}$$

where $n^2 - 1$ is the Fresnel convection coefficient. This shows that the refractive index is affected by the velocity of the moving fluid. It is this effect which provides a method for direct measurement of wind velocity in the atmosphere. The phase change accumulated by an electromagnetic wave along a trajectory (ray) is given by

$$\phi = \frac{\omega'}{c}\int_{P_1}^{P_2} n'\,dL \tag{5}$$

where the integration is along the ray from P_1 to P_2. Referring to Fig. 1, it is clear that the total phase difference between the rays is

$$\Delta\phi = \frac{4\pi L v}{\lambda c}\,(n^2 - 1). \tag{6}$$

For tenuous media like the atmosphere it is convenient to define a refractivity N by $N = (n - 1)\cdot 10^6$, hence (6) can be approximated by

$$\Delta\phi = 8\pi L v N\, 10^{-6}/(\lambda c). \tag{7}$$

In an inhomogeneous medium this would be replaced by

$$\Delta\phi = \frac{8\pi 10^{-6}}{\lambda c}\int_{path} vN\,dL\ . \tag{8}$$

where v is the component of the velocity parallel to the ray path. An average value for vNL for a given atmosphere may be defined by equating (7) and (8).

To get an idea of the numbers involved, consider light at $\lambda = 0.5\mu$ and a medium having $n = 1.3$ (e.g., water). Taking $v = 10$ m/sec and $L = 1$ m in (6) yields: $\Delta\phi = 0.58$ rad $= 33°$. Such a value is easily measurable in an interference experiment by observing the shift of the fringe pattern relative to its position for $v = 0$. In the case of the atmosphere, let 10 m/sec $\cong$ 20 mph serve as a typical value for the wind velocity. The atmospheric refractivity is on the order of $N = 300$ (e.g., see Bean and Dutton[6]). Consider a source in the IR band, with $\lambda = 10\mu$. In this region strong stable CO_2 lasers are available and a window exists for which the clear atmosphere is practically lossless. Setting the path length at $L = 100$ km yields in (7) the result $\Delta\phi = 2.5$ rad $= 144°$. This is an easily measurable phase. If we keep distances on a scale of $L = 100$ km and the wind velocity reduces to about 2 mph, then we still have $\Delta\phi = 14.4°$ which is not difficult to measure. However, if we now choose a source in the microwave region, for example with $\lambda = 10^{-2}$ m then $\Delta\phi$ will be smaller by a factor of 10^3. This would seem to completely rule out the use of microwaves for the terrestrial atmosphere. However, in planetary atmospheres one may encounter distances, velocities and refraction indices for which the use of microwaves may be of interest.

SATELLITE CONFIGURATION

To illustrate that a measurement of wind velocity might be possible using the Fizeau effect, we will consider a hypothetical satellite configuration. In principle two rays are needed, one traveling through the atmosphere downwind, and the other traversing the atmosphere in the upwind direction. Fig. 2 shows a potentially suitable satellite configuration. In this example M is a master station on which the laser source is located and on which the processing of the returned signals takes place. The slave satellites S_1 and S_2 serve only to reflect the rays in the desired direction. The ray paths are marked 1, 1', 1" and 2, 2', 2" in an obvious way. Configurations are also possible in which the earth (e.g., the ocean) is one of the reflectors. But the problem of maintaining beam coherence becomes critical for these configurations. Systems in which the master station or a reflector is located on the earth's surface, or on board an aircraft are also potentially feasible. The configuration illustrated in Fig. 2 will serve here to describe the principle.

Assume for the moment that all elements of Fig. 2 are at rest except for the atmosphere. Then the basic configuration consists of two laser beams which traverse the paths of equal length 1, 1', 1" and 2, 2', 2" in opposite directions. In principle, this geometry is identical to the Fizeau experiment, (Fig. 1) each beam will have experienced a phase shift which is due to two terms: the round trip distance and the contribution due to the motion of the medium. If the round trip distances are identical, then the only phase difference will be due to the motion of the medium, and since the beams traverse the moving medium in opposite directions with respect to the wind direction, the contributions to phase difference due to the Fizeau effect (8) will add. The net phase difference between the beams will then be given by (8) and can be measured by appropriately mixing the two beams at the master station. It is important to note that a knowledge of the total path length around the triangle is not necessary. Only the ray path through the medium and the value of N on it are needed. The necessary accuracy for these parameters is independent of wavelength, i.e., in (7) it is the relative errors $\Delta N/N$, $\Delta L/L$ that affect the result. To get an idea of the path length L through the atmosphere consider its effective height to be h = 5 km and let the radius of the earth be $a = 6360$ km. Then from Fig. 3 $L = 2a \, tg \, \alpha$ and $\cos \alpha = a/(a + h)$. Substituting for h and a yields $L \cong 500$ km. Thus, if N and L are each known to within say 1%, e.g., 5 km in a 500 km path and 3 N units for $N = 300$, then the error in computing the wind velocity will be on the order of 2%. Reasonable models for N and its gradient dN/dh are available[6], and satellite position . available to an accuracy of meters or better.

The preceding arguments apply only if all elements of the system are at rest. If the satellites M, S_1 and S_2 are allowed to move relative to each other and to the earth, as will be true in practice, then several important problems arise. First of all, changes will occur in the frequency of the laser pulses when they are reflected from the moving platforms S_1 and S_2. It will be shown that there is a net Doppler frequency shift between beams which travel around the triangle (MS_1S_2) in opposite directions. This net effect gives rise to a nonvanishing phase difference between the two returning signals. It will be shown below how this effect can be taken into account and a meaningful measurement of the Fizeau phase change made. A second problem encountered when the system moves is that the path length need not be the same for beams which traverse the triangle in opposite directions. The upwind and the downwind beams (Fig. 2) encounter the satellites S_1 and S_2 at different times for pulses leaving M simultaneously. If the satellites are moving, this means they are encountered at different positions. This change in position introduces a net path length difference between the two beams. This is a real problem, because a path difference on the order of one wavelength would completely obliterate the phase difference due to the Fizeau effect. However, it will be shown below that all motional effects can be properly taken into account in the computation of the wind velocity. The fact that the laser beams become nonplanar along the path because of beam spread and that the satellites do not move on straight lines (due to orbital motion) will also be discussed below.

ANALYSIS OF SATELLITE MOTIONAL EFFECTS

Generally speaking, relative motion of the components of a system introduces frequency, direction and amplitude shifts, in addition to affecting the positions of the various parts of the system. These manifestations of motion can influence the phase of the returning rays. Consequently a procedure must be devised for deriving the Fizeau phase change (8) in the presence of the spurious phase factors. In a proper relativistic treatment of electromagnetic plane waves in moving systems[5] there appears an amplitude effect of the first order in the velocity. This does not affect the phase and therefore, for purposes of this discussion, it can be neglected. Doppler shifts in wavelength and frequency are first order effects in v/c and since (7), (8) are already of the first order in v/c, these effects are of second order importance in the computation of the Fizeau effect. However, they have to be taken into account. For example, since we will be adding the returning waves in order to measure the Fizeau effect, any net frequency difference will cause the waves to beat in and out of phase, complicating the measurement of $\Delta\phi$. Consequently a careful relativistic treatment of the Doppler frequency shifts will be presented below to properly assess these effects.

Relativistic Doppler effect: Let two inertial systems of reference move at a relative velocity $\underset{\sim}{v}$. The 'laboratory' system of reference $\underset{\sim}{x}'$, t' is now attached to satellite M. The 'comoving' system $\underset{\sim}{x}$, t refers now to any other part of the configuration. Gravitational effects are neglected. For the special case where the origins $\underset{\sim}{x}' = 0$, $\underset{\sim}{x} = 0$ coincide at $t = t' = 0$, special relativity prescribes the transformation[7,8]

$$\underset{\sim}{x}' = \tilde{U} \cdot (\underset{\sim}{x} + \underset{\sim}{v} t) \quad , \qquad \underset{\sim}{x} = \tilde{U} \cdot (\underset{\sim}{x}' - \underset{\sim}{v} t') \quad ,$$

$$t' = \gamma (t + \underset{\sim}{v} \cdot \underset{\sim}{x}/c^2) \quad , \qquad t = \gamma (t' - \underset{\sim}{v} \cdot \underset{\sim}{x}'/c^2) \quad ,$$

$$\gamma = [1 - (v/c)^2]^{-1/2} \quad ,$$

$$\tilde{U} = \tilde{I} + (\gamma - 1) \hat{\underset{\sim}{v}} \hat{\underset{\sim}{v}} \quad , \qquad (9)$$

where $\tilde{I}$ is the idemfactor dyadic and $\hat{\underset{\sim}{v}}$ is a unit vector. In our case $\underset{\sim}{v}$ is the velocity of the comoving system as observed from the laboratory. In the laboratory system an incident plane electromagnetic wave is given by:

$$\underset{\sim}{E}_i{}' \, e^{i \underset{\sim}{k}_i{}' \cdot \underset{\sim}{\bar{x}}{}' - i\omega_i t'} \,, \tag{10}$$

where $\underset{\sim}{\bar{x}}{}' = \underset{\sim}{x}{}' + \underset{\sim}{a}{}'$, and $\underset{\sim}{a}{}'$ is an arbitrary constant. Thus in terms of $\underset{\sim}{x}{}'$, (10) becomes

$$\underset{\sim}{E}_i{}' \, e^{i \underset{\sim}{k}_i{}' \cdot \underset{\sim}{a}{}'} \, e^{i \underset{\sim}{k}_i{}' \cdot \underset{\sim}{x}{}' - i\omega_i{}' t'} \,, \tag{11}$$

and $e^{i \underset{\sim}{k}_i{}' \cdot \underset{\sim}{a}{}'}$ is a constant phase factor which must be carried along. In the comoving system we have a plane wave

$$\underset{\sim}{E}_i \, e^{i \underset{\sim}{k}_i{}' \cdot \underset{\sim}{a}{}'} \, e^{i \underset{\sim}{k}_i \cdot \underset{\sim}{x} - i\omega_i t} \,, \tag{12}$$

where the electric field $\underset{\sim}{E}_i$ is determined by the relativistic transformations for the fields. (This is not given here because only the phase is of importance. Details are to be found elsewhere[5]). According to the so called principle of the conservation of the phase, the exponents in (11), (12) must be equal. This prescribes

$$\underset{\sim}{k}{}' = \tilde{U} \cdot (\underset{\sim}{k} + \omega \underset{\sim}{v}/c^2) \,, \qquad \underset{\sim}{k} = \tilde{U} \cdot (\underset{\sim}{k}{}' - \omega' \underset{\sim}{v}/c^2)$$

$$\omega' = \gamma(\omega + \underset{\sim}{v} \cdot \underset{\sim}{k}) \,, \qquad \omega = \gamma(\omega' - \underset{\sim}{v} \cdot \underset{\sim}{k}{}') \,. \tag{13}$$

We are interested in the effect produced when an incident wave is reflected (e.g., from a plane mirror) to a new direction. The reflector is moving according to

$$\underset{\sim}{x}{}' = \underset{\sim}{v} \, t' \,, \tag{14}$$

and the local origin $\underset{\sim}{x}{}' = \underset{\sim}{x} = 0$ is chosen such that it is on the plane mirror at $t' = t = 0$. The reflected wave is given by

$$\underset{\sim}{E}_0 \, e^{i \underset{\sim}{k}{}' \cdot \underset{\sim}{a}{}'} \, e^{i \underset{\sim}{k}_0 \cdot \underset{\sim}{x} - i\omega_0 t} \,, \tag{15}$$

where on board the satellite the frequency is unchanged:

$$\omega_o = \omega_i \ , \tag{16}$$

and $\underset{\sim}{k}_o$, $\underset{\sim}{k}_i$ are related by Snell's law; $\underset{\sim}{E}_o$ is determined by the pertinent boundary conditions. Using the relativistic transformations once more, we obtain in the laboratory system of reference

$$\underset{\sim}{E}_o{}' \, e^{i \underset{\sim}{k}_i{}' \cdot \underset{\sim}{a}'} \, e^{i \underset{\sim}{k}_o{}' \cdot \underset{\sim}{x}' - i\omega_o' t'} \ , \tag{17}$$

where from (13):

$$\frac{\omega_o'}{\omega_i'} = \frac{|\underset{\sim}{k}_o'|}{|\underset{\sim}{k}_i|} = \frac{1 + \underset{\sim}{v} \cdot \hat{\underset{\sim}{k}}_o/c}{1 + \underset{\sim}{v} \cdot \hat{\underset{\sim}{k}}_i/c} = \frac{1 - \underset{\sim}{v} \cdot \hat{\underset{\sim}{k}}_i'/c}{1 - \underset{\sim}{v} \cdot \hat{\underset{\sim}{k}}_o'/c} \ . \tag{18}$$

Finally, the wave is transformed back to the original system $\bar{x}'$, yielding

$$\underset{\sim}{E}_o{}' \, e^{i(\underset{\sim}{k}_i' - \underset{\sim}{k}_o') \cdot \underset{\sim}{a}'} \, e^{i \underset{\sim}{k}_o{}' \cdot \bar{\underset{\sim}{x}}' - i\omega_o' t'} \tag{19}$$

Eq. (19) is the form taken by an arbitrary plane wave (10) after reflection from a plane surface moving at velocity $\underset{\sim}{v}$.

We now make a few observations. Eq. (18) explains the fact that there is no Doppler frequency shift in the Fizeau experiment as presented in Fig. 1. All parts of this system are at rest, except the moving fluid. But in the fluid only forward type propagation takes place, i.e., $\hat{k}_o' = \hat{\underset{\sim}{k}}_i'$, hence according to (18) $\omega_o' = \omega_i'$. Second, comparing (10) and (19) at $x' = 0$, $t' = 0$ we see that the exponential $e^{i(\underset{\sim}{k}_i' - \underset{\sim}{k}_o') \cdot \underset{\sim}{a}'}$ describes the round trip phase change due to the initial location and the motion of the reflector. Third, since $\underset{\sim}{k}_o'$ is Doppler shifted with respect to $\underset{\sim}{k}_i'$ this phase factor contains a first order velocity effect. In a velocity independent system, $\omega_o' = \omega_i'$, hence the time factors in (10), (19) are equal and the phase difference between the two waves is a constant, independent of time. But when $\underset{\sim}{v} \neq 0$, then $\omega_o' \neq \omega_i'$ and the phase difference depends on time. This is so because the change of phase takes into account the motion of the reflector (14) and vanishes only at $t' = 0$ when the reflector is at $\underset{\sim}{x}' = 0$.

In the configuration being considered here, we have waves travelling in both the up- and downwind directions around the triangle. Thus, one must consider the Doppler effect for waves propagating in opposite directions, as depicted in Fig. 2. Assuming S_1 to be in motion, the Doppler effect for rays 1, 1′ is given by (18). For 2′, 2″ the same formula applies, but the directions and frequencies will be denoted by bars,

$$\frac{\bar{\omega}_o'}{\bar{\omega}_i'} = \frac{1 + \underset{\sim}{v} \cdot \hat{\bar{\underset{\sim}{k}}}_o/c}{1 + \underset{\sim}{v} \cdot \hat{\bar{\underset{\sim}{k}}}_i/c} . \tag{20}$$

Now align the rays such that in the comoving system they are oppositely directed

$$\hat{\underset{\sim}{k}}_o = \hat{\bar{\underset{\sim}{k}}}_i , \quad \hat{\bar{\underset{\sim}{k}}}_o = \hat{\underset{\sim}{k}}_i . \tag{21}$$

Note that due to the relativistic formulas for the aberration phenomenon (13), there will be some difference in directions, either in the laboratory or in the comoving system of reference. The present choice simplifies the discussion. Using

$$\omega_i' = \bar{\omega}_i' \tag{22}$$

and substituting (18), (20), (21), we obtain

$$\frac{\bar{\omega}_o'}{\omega_o'} = \frac{1 - (\underset{\sim}{v} \cdot \hat{\underset{\sim}{k}}_i/c)^2}{1 - (\underset{\sim}{v} \cdot \hat{\underset{\sim}{k}}_o/c)^2} . \tag{23}$$

Thus, in this case, the reflected rays 1″ and 2′, Figs. 2, 3, do not have the same frequency, the difference being of the order $(v/c)^2 \cdot \omega_i'$. This is to say that reflection from a moving mirror is non-reciprocal, in the sense that a net frequency difference occurs when the roles of incident and reflected waves is reversed. Although this effect is of second order in v/c it can be significant because it introduces a time dependence into the problem. Moreover, if (21) is not satisfied, a first order effect will appear in (23). This can happen as a result of beam spread and orbital motion, discussed below.

Effects due to orbital motion and beam spread: For a finite reflector the above results may be still used provided edge diffraction effects are negligible. However, it must be noted that additional geometrical effects are present, which must be adequately taken into account. As the reflector moves, it intercepts different parts of the incident beam. Also the outgoing beam is laterally displaced as depicted in Fig. 4. However, as long as the reflector and the receiver are well within the beams, the above plane wave formulas are applicable. Pulses emitted simultaneously from M (in opposite directions around the triangle) will reach S_2 about 0.01 sec apart because of the different paths traversed. During this time the reflector S_1, say, moves a distance of the order of 100 m. This distance is small compared to the expected beam cross sections and therefore the plane wave formulas can be used, provided the directions of the rays are properly taken into consideration.

Due to the orbital motion of the satellites, the velocity does not remain constant, and the kinematic effects might affect the results of the measurement. For a satellite moving at a height of say 1000 km the absolute value of the velocity remains practically constant during a period on the order of a second. However, the direction of the velocity is changed on the order of 10^{-3} rad/sec. This will affect the Doppler shift (18) and constitutes a perturbation which must be taken into account in the signal processing (discussed in the next section).

The analysis of the Doppler effect given above is based on the assumption of plane wavefronts. Due to the spreading of laser beams, wavefronts become curved. In Fig. 5 it is assumed for sake of an illustration, that the wavefronts are spherical, having point a as the center of curvature. Fictitious rays and the fictitious extension of the reflector are shown in dashed lines. The moving reflector first engages rays 1, 1′, later it intercepts 2, reflecting it as 2′. By inspection of the fictitious rays 1, 1″ and 2, 2″ it becomes clear that the only effect on our analysis is again a change of direction, this time for the unit vectors $\hat{\underset{\sim}{k}}$ in (18). This effect is of the same magnitude as the above orbital motion effect.

Effect of relative motion on measurements: In general both satellite and atmosphere (wind) are in motion relative to an observer on the earth. Thus the question of what velocity will register in our measurements is of importance. To be specific, we first consider the Fizeau experiment of Fig. 1, assuming $v = 0$. The phase accumulated by the rays depends on the electrical length (i.e., the equivalent free space length) of each path. The phase difference provides the zero reference for our experiment. Now let us set the upper vessel (Fig. 1) in motion, at a relative motion v_R with respect to the laboratory. Because of the ensuing Doppler effect, the excitation frequency for the upper vessel is now different. This is tantamount to saying that the electrical length is modified. This will shift the zero reference, but will not otherwise affect the results of the Fizeau experiment. This is due to the fact that the Fizeau effect is already of first order in v/c, hence changes of frequency due to motional effects are negligible in (7), (8). A detailed discussion, pertinent to the configuration of Fig. 2 is given in the next section. An investigation of relative motion in the Fizeau effect has been conducted by Zeeman (e.g., see Jones[4] for reference to original papers, see also Zernike[9]).

SIGNAL PROCESSING

In order to extract the phase change due to the motion of the atmosphere, it will be necessary to compare the phase of the two laser beams which have propagated around the path (Fig. 2) in opposite directions. First, consider the case where the atmosphere is absent. To further simplify the analysis, it is temporarily assumed that orbital motion and beam spread effects are absent. These restrictions will be waived later on. To begin, consider the phase accumulated by a plane wave transmitted from the master station, M, and travelling around the path in the direction M, S_1, S_2, M. (From now on primes will be suppressed since only observations in the laboratory frame will be considered.) Assume that the wave transmitted from M is:

$$\underset{\sim}{E}_{M1} \, e^{i(\underset{\sim}{k}_{M1} \cdot \underset{\sim}{x}_M - \omega t)} \, , \tag{24}$$

where $\underset{\sim}{k}_{M1}$ is directed from the local origin $\underset{\sim}{x}_M = 0$ to the local origin $\underset{\sim}{x}_1 = 0$ of S_1. Consequently the phase factor $e^{i \underset{\sim}{k}_{M1} \cdot \underset{\sim}{a}_{M1}}$ is introduced in translating the wave to the local origin of S_1. Although the choice of $\underset{\sim}{x}_1 = 0$ is arbitrary, if we choose it on the actual reflector at $t = 0$ (and not its fictitious extension as in Fig. 5) then $\underset{\sim}{k}_{M1}$ and $\underset{\sim}{a}_{M1}$ are parallel and $\underset{\sim}{k}_{M1} \cdot \underset{\sim}{a}_{M1} = k_{M1} a_{M1}$. The wave reflected from S_1 is therefore given by

$$\underset{\sim}{E}_{12} \, e^{i k_{M1} a_{M1}} \, e^{i \underset{\sim}{k}_{12} \cdot \underset{\sim}{x}_1 - i \omega_{12} t} \, , \tag{25}$$

where $\underset{\sim}{k}_{12}$ is directed towards the local origin $\underset{\sim}{x}_2 = 0$ of S_2. The wave arriving at S_2 will have the additional phase factor $e^{i k_{12} a_{12}}$, where a_{12} is the distance from $\underset{\sim}{x}_1 = 0$ to $\underset{\sim}{x}_2 = 0$. Thus, the wave reflected by S_2 in the direction of M is given by

$$\underset{\sim}{E}_{2M} \, e^{i(k_{M1} a_{M1} + k_{12} a_{12})} \cdot e^{i \underset{\sim}{k}_{2M} \cdot \underset{\sim}{x}_2 - i \omega_{2M} t} \, , \tag{26}$$

where $\underset{\sim}{k}_{2M}$ is directed towards the local origin of M. Hence at M we receive at $\underset{\sim}{x}_M = 0$ a signal

$$\underset{\sim}{E}_M^{(a)} \, e^{i[k_{M1} a_{M1} + k_{12} a_{12} + k_{2M} a_{2M} - \omega_{2M} t]} \equiv \underset{\sim}{E}_M^{(a)} \, e^{i \psi_a} \, , \tag{27}$$

where $\underset{\sim}{E}_M^{(a)}$ is its amplitude. Similarly, for the round trip 2, 2′, 2″ we start with a wave emitted by M,

$$\underset{\sim}{E}_{M2}\; e^{i \underset{\sim}{k}_{M2}\cdot \underset{\sim}{x}_M - i\omega t} \ , \tag{28}$$

where by now the notation is obvious. The wave reflected by S_2 towards S_1 will be

$$\underset{\sim}{E}_{21}\; e^{i k_{M2} a_{M2}}\; e^{i \underset{\sim}{k}_{21}\cdot \underset{\sim}{x}_2 - i\omega_{21} t} \ . \tag{29}$$

There will be a similar reflection produced by S_1, and so finally the wave arriving at $\underset{\sim}{x}_M = 0$ is

$$\underset{\sim}{E}_M^{(b)}\; e^{i[k_{M2}a_{M2} + k_{21}a_{21} + k_{1M}a_{1M} - \omega_{1M}t]} \;\equiv\; \underset{\sim}{E}_M^{(b)}\; e^{i\psi_b} \ , \tag{30}$$

which will be compared to (27) in order to extract the phase difference due to the Fizeau effect. Notice that $k_{ij} \neq k_{ji}$ (e.g., $k_{M1} \neq k_{1M}$), since the Doppler frequency shifts are different in each case. Also note that the amplitudes $\underset{\sim}{E}_M^{(a)}$ and $\underset{\sim}{E}_M^{(b)}$ are unimportant for our problem and so no explicit expressions are included for them. Any boundary condition at the reflectors S_1 and S_2 would be identical for the two oppositely traveling waves and is already absorbed into the amplitudes $\underset{\sim}{E}_M^{(a)}$ and $\underset{\sim}{E}_M^{(b)}$.

In view of (18) all k_{ij} and ω_{ij} in (27), (30) are proportional to the source frequency ω. Hence ψ_a, (27), and ψ_b, (30) can be recast in the form

$$\begin{aligned} \psi_a &= \omega(\alpha + \beta t) \ , \\ \psi_b &= \omega(\hat{\alpha} + \hat{\beta} t) \ . \end{aligned} \tag{31}$$

Now suppose that the two beams a and b are coherently detected and the phase difference $\Delta\psi = \psi_a - \psi_b$ measured, yielding:

$$\Delta\psi = \omega\,[(\alpha - \hat{\alpha}) + (\beta - \hat{\beta})t] \ . \tag{32}$$

Taking $\lambda = 10\mu$, and $v_s = 10$ km/sec for the satellites, to be representative values, according to (23) we find the difference frequency $\omega_{1M} - \omega_{2M} = \omega(\beta - \hat{\beta})$ to be on the order of $\omega(v_s/c)^2 \simeq$ 100 kHz. Next we consider the values of $\omega(\alpha - \hat{\alpha})$, (32). For an observer on the ground we have, to the first order in the velocity (Fig. 2):

$$
\begin{aligned}
k_{M1} &= k\,(1 + \underset{\sim}{v}_M \cdot \hat{\underset{\sim}{k}}_{M1}/c) = k\,(1 + \sigma_{M1}) \,, \\
k_{M2} &= k\,(1 + \underset{\sim}{v}_M \cdot \hat{k}_{M2}/c) = k\,(1 + \sigma_{M2}) \,, \\
k_{12} &= k_{M1}\,(1 - \underset{\sim}{v}_1 \cdot \hat{\underset{\sim}{k}}_{M1}/c + \hat{\underset{\sim}{k}}_{12} \cdot \underset{\sim}{v}_1/c) = k_{M1}(1 + \sigma_1), \\
k_{2M} &= k_{12}\,(1 - \underset{\sim}{v}_2 \cdot \hat{k}_{12}/c + \underset{\sim}{v}_2 \cdot \hat{\underset{\sim}{k}}_{2M}/c) = k_{12}\,(1 + \sigma_2) \,, \\
k_{21} &= k_{M2}\,(1 - \underset{\sim}{v}_2 \cdot \hat{\underset{\sim}{k}}_{M2}/c + \underset{\sim}{v}_2 \cdot \hat{\underset{\sim}{k}}_{21}/c) = k_{M2}\,(1 + \sigma_2), \\
k_{1M} &= k_{21}\,(1 - \underset{\sim}{v}_1 \cdot \hat{\underset{\sim}{k}}_{21}/c + \underset{\sim}{v}_1 \cdot \hat{\underset{\sim}{k}}_{1M}/c) = k_{21}(1 + \sigma_1) \,, \qquad (33)
\end{aligned}
$$

and for $a_{ij} = a_{ji}$ (e.g., $a_{M1} = a_{1M}$) this yields

$$
\begin{aligned}
\omega\,(\alpha - \hat{\alpha}) = \; & k\,[a_{M1}\,(\sigma_{M1} - \sigma_{M2} - \sigma_2 - \sigma_1) + a_{M2}\,(\sigma_{M1} + \sigma_1 + \sigma_2 - \sigma_{M2}) \\
& + a_{12}\,(\sigma_{M1} + \sigma_1 - \sigma_{M2} - \sigma_2)] \,, \; k = \omega/c. \qquad (34)
\end{aligned}
$$

Taking a_{ij} on the order of 10^4 km, it turns out that $\omega\,(\alpha - \hat{\alpha})$ is on the order of $2\pi \cdot 10^7$ rad. Since $\omega\,(\alpha - \hat{\alpha})$ is much larger than $\Delta\phi$ which we are trying to measure, a method must be found to calibrate the system for $\omega\,(\alpha - \hat{\alpha})$ prior to measurement, and to account for its variation during the measurement. This will be discussed subsequently.

There exist a variety of effects changing $\omega\,(\alpha - \hat{\alpha})$ and $\omega\,(\beta - \hat{\beta})$ from the values obtained above. Note that signals simultaneously emanating from M do not reach S_1 (or S_2) at the same time since the paths that they follow are of different length (e.g., MS_1S_2 compared to MS_2). The time difference is on the order of 10^{-3} to 10^{-2} seconds. As a result the σ_1 in (33) associated with k_{12} and k_{1M} are not the same, nor are the σ_2 associated with k_{21} and k_{2M} identical. Taking this effect into account only slightly changes the magnitude of $\omega\,(\alpha - \hat{\alpha})$ in (34). The most important effects are the changes that occur in satellite velocity with time as the satellites move in their orbits around the earth (orbital motion), and the fact that the laser beams are not truly plane waves (beam spread).

These two effects can introduce a time dependence in $\sigma_{1M}, \sigma_{2M}, \sigma_1, \sigma_2$. To study the effect of orbital motion, let us represent (34) by $2\pi \cdot 10^7 \cos\theta$, where θ is the angle understood in the scalar products in (33). Due to orbital motion θ is time dependent and therefore a representative for (34) can be written in the form

$$2\pi \cdot 10^7 \cos\left(\theta_0 + \frac{v_s}{r}\tau\right), \tag{35}$$

where r is the distance of the satellite from the earth's center and v_s is its velocity, and θ_0 refers to the time $\tau = 0$ which is arbitrarily chosen. Thus during one second $\hat{\underset{\sim}{v}}_s$ changes by an angle on the order of $v_s/r \approx 10^{-3}$ rad. For worst case analysis take $|\theta_0| = \pi/2$, hence near $\tau = 0$ (35) behaves as $2\pi \cdot 10^4\tau$, corresponding to a frequency on the order of 10 kHz. The time dependence introduced by beam spread is of the same nature and magnitude, with $r = 10^4$ km in (35) standing for a typical distance between satellites. The effect on $\omega(\beta - \hat{\beta})$ is even larger, since $\beta - \hat{\beta}$ corresponds to a small difference between large numbers. Here the time delay for simultaneously emitted signals arriving at a reflector introduces a change of direction which perturbs (21). Hence (23) contains first order effects which must be carefully evaluated. For $v_s \approx 10$ km/sec, a distance 10^4 km between satellites and delay time on the order of 10^{-2} seconds, the angle subtended by the oppositely propagating beams is on the order of 10^{-5} rad. This number is on the order of v/c hence the frequency difference is on the order of $(v/c)^2$ as in (23); i.e., $\omega(\beta - \hat{\beta})$ is still considered to be in the 100 kHz band. Depending on the parameters chosen in Fig. 2, $\omega(\beta - \hat{\beta})$ on the order of 1 MHz can also be considered realistic. In any case, for a short period of observation, on the order of 1 – 10 seconds, it can be assumed that the time dependent effects combine to yield in (32) a fixed value $\omega(\alpha - \hat{\alpha})_{\tau=0}$ and a slightly modified frequency $\omega(\beta - \hat{\beta})$. Of course, we cannot hope to compute these values from the formulas given above with sufficient accuracy allowing for measurement of the Fizeau effect, however $\omega(\beta - \hat{\beta})$ is amenable to very high precision measurement, and for $\omega(\alpha - \hat{\alpha})_{\tau=0}$ only its deviation from an integral number of 2π is relevant (i.e., $\omega(\alpha - \hat{\alpha})_{\tau=0}$ modulo 2π). Commercially available counters are capable of time measurement with an error on the order of 10^{-10}, which will also be the error in frequency for a one second measurement (atomic clocks are several orders of magnitude more accurate). This suggests a method for calibrating the system. Thus if we measure the frequency $\omega(\beta - \hat{\beta})$ and make a phase measurement at some time $\tau = 0$ (prior to the time when the line of sight penetrates the atmosphere), then we can safely assume that $\omega(\alpha - \hat{\alpha})_{\tau=0} + \omega(\beta - \hat{\beta})\tau$ is known for a period on the order of 1 – 10 seconds.

This brings us to the point where we wish to consider the effects of the atmosphere on our system. There are three effects taking place simultaneously, and since the Fizeau phase (7), (8) is the one we want to measure, the other two must be computed, using independent data. The first of these two effects is the relative motion in the system, which produces different excitation frequencies for the oppositely moving rays. In ψ_a (27) we have to subtract the free space phase $k_{M1} L$ and add the effect of the refractive medium as $k_{M1} L n$. Similarly $k_{1M}(n-1)L$ is added to ψ_b (30). The difference is given by

$$\Delta\psi_R = k(\sigma_{M1} - \sigma_{1M}) LN \cdot 10^{-6} \quad . \tag{36}$$

which takes into account the relative velocities, as explained in the previous section. In (36) the same effective value LN is assumed for the two oppositely going waves. Comparing (36) and (7), it is seen that the Fizeau phase is three or four orders of magnitude smaller, because of the ratio of the wind velocity to satellite velocity. However, satellite velocity can be accurately measured by monitoring the motion. It can also be inferred from the satellite's height, assuming a circular orbit. For example, if the positioning error is 10 m, we use $v_s^2 = rg$, where $g \approx 10\ \mathrm{m/sec^2}$ is the gravitational constant relevant to the distance r from the earth's center, obtaining $\Delta v_s / v_s \approx 10^{-6}$. To compute (36) we need the directions $\hat{\underset{\sim}{k}}_{M1}$, $\hat{\underset{\sim}{k}}_{1M}$. With a positioning error 10 m and distance between satellites on the order of 10,000 km, the error is on the order of 10^{-6}. Satellite positioning is continuously improved, and with the advent of the Global Positioning System project one or two orders of magnitude improvement can be expected. Hence in computing (36) we still have enough precision left for determining the Fizeau phase (7), (8). The second effect which must be computed independently is the change in path length and direction of propagation of the line of sight due to ray bending in the atmosphere. In order to assess this effect we assume that on a path length of 100 km in the lower atmosphere the ray bending will be significant. Using the (4/3)a effective earth radius model[6], this means that the radius of curvature of the ray will be 4a. This will bend the ray through an angle on the order of 10^{-3} rad at the extreme level of penetration into the atmosphere, when the line of sight is close to occultation. The effect on the path length is on the order of $1 - \cos 10^{-3} \approx 10^{-5}$ hence with $\omega(\alpha - \hat{\alpha}) \approx 2\pi \cdot 10^7$ we have to compute a phase on the order of 20π which is much smaller compared to $\Delta\psi_R$. On the other hand, the change of direction on the order of 10^{-3} rad implies a change in the Doppler effect factors $\hat{\underset{\sim}{k}} \cdot \underset{\sim}{v}/c$. The effect on $\omega(\beta - \hat{\beta})$ is negligible, because $\beta, \hat{\beta}$ are affected in the same way, leaving the difference $\beta - \hat{\beta}$ practically unaltered. However, the factors σ in (33) are changed, implying a phase on the order $\Delta\psi_B = 2\pi \cdot 10^4$ which is larger than $\Delta\psi_R$. It is therefore expected that the minimum altitude for measurement of wind speed will be limited by the accuracy with which $\Delta\psi_B$ can be determined.

Prior to the line of sight penetrating the atmosphere $\Delta\psi$ is measured and its value during the measurement can be projected by knowing the frequency, as explained above. While the remote sensing measurement of the wind velocity is taking place, a different phase $\Delta\psi_A$ is recorded. The difference, including the correction factors $\Delta\psi_R$, $\Delta\psi_B$ discussed above finally yields the Fizeau phase $\Delta\phi$, according to

$$\Delta\phi = \Delta\psi_A - (\Delta\psi + \Delta\psi_R + \Delta\psi_B). \tag{37}$$

From this the wind velocity is obtained as an average value over the path, for various altitudes.

We have considered the various effects separately; the combined error in measuring the wind velocity is expected to be larger. On the other hand, worst case parameters have been chosen most of the time, and some effects will tend to mutually cancel. A better understanding of the interaction of the various effects calls for a computer modelling of the entire problem.

COHERENCE CONSIDERATIONS

Since the proposed procedure for measuring wind velocity depends on making phase measurements, the coherence of the laser beams as they traverse the system must be examined. The problem will be discussed below in a preliminary way. Clearly, better understanding of this aspect of the problem is needed.

First, the coherence time of the source must be examined. In the configuration of Fig. 2 ray 1 reaches S_1 before 2′. Assuming the distance difference to be 3000 km, this amounts to a delay time of 0.01 sec. During this time S_1 was moving at a velocity of 10 km/sec, say, covering a distance of 100 m. It follows that the time difference between rays 1″, 2″ returning to M, Fig. 2, is of the order of 1 μsec. Such a coherence time is of course amply supplied by a laser.

Next, the randomness of the atmosphere must be taken into account. Over the long paths planned here, it is expected that atmospheric turbulence and irregularities will degrade the phase information. What we shall argue here is, that this does not invalidate the fundamental ideas given above, and that there are ways of controlling the amount of incoherence encountered at the detector.

In order to understand the physics of the problem, consider a point source in a random medium like the atmosphere. Due to the random irregularities in the atmosphere, the wave will develop phase fluctuations, i.e., the wavefront away from the point source will not be spherical any more. The presence of a distorted wavefront also means that rays, perpendicular to wavefronts, will now travel in directions which are not strictly radial. At larger distances these rays will interfere, giving rise to the scintillation phenomenon. This problem has been studied extensively, both theoretically and experimentally. See Ishimaru[3], and Tatarski[10], who also cite many earlier references. Since the present problem is closely related to scintillation from point sources, ideas relevant to this subject will be used.

A discussion well suited for our problem is given by Lawrence[11]. He argues that the irregularities most effective in producing scintillation are of dimension of the first Fresnel zone. Hence, in order to use point source theory, at least the first Fresnel zone for $\lambda = 10\mu$ must be illuminated. For the present parameters where satellites are about 1000 km high above the ground and about 7500 km apart, the Fresnel zone is of the order of 4 m, midway between the satellites. Typical laser beam spread angles are of the order of λ/D, D being the aperture diameter of the transmitter. Taking D to be 0.1 m, we obtain an angle of 10^{-4} rad. This means that the radius of the beam's cross section will be hundreds of meters, containing many Fresnel zones. We are therefore justified in treating the radiation as originating from a point source. The diameter of the most effective irregularity, which is also the radius of the first Fresnel zone, is given by

$$d = \sqrt{\lambda g}\ , \quad g = z_1 z_2/(z_1 + z_2). \tag{38}$$

where z_1, z_2 are the distance to the source, the distance to the receiver, respectively. As a first approximation for our case, the atmosphere can be thought of as being lumped midway between the satellites, so that $z_1 = z_2$ and as mentioned above, $d \approx 4$ m. It is argued that in the presence of larger irregularities, the smaller ones predominate, much like the case of a ground glass plate put in front of a lens. On the other hand, the spectrum of atmospheric turbulence increases with irregularity size. It is therefore assumed that irregularities whose size is given by (38) are most effective. It is also known that the validity of the present model is limited[12]. Corresponding to the irregularities a random pattern of intensity fluctuations will be measured in the vicinity of the receiver. The pattern radius corresponding to (38) is given by[11]

$$\rho = (1 + z_1/z_2)\, d/2. \tag{39}$$

If we take $z_1 = z_2$ again, (39) yields

$$\rho = d \approx 4 \text{ m}. \tag{40}$$

The pattern radius is closely related to the distance between uncorrelated parts in the field measured near the receiver. This concept is important for our discussion of aperture averaging, given below. Lawrence[11] displays the normalized covariance of log-intensity fluctuations η as a function of $\zeta = \delta(\pi\lambda L/2)^{-1/2}$, where L is the line of sight path length and δ is the distance between two small-aperture detectors. For our present assumption of $d = \sqrt{\lambda L/2}$ we have

$$\zeta = (\delta/d)\,\pi^{-1/2} \approx \delta/(2d). \qquad (41)$$

It is realized that the theory corresponding to Fig. 25.6[11] is more intricate, however, we use the results here to get a rough idea of the parameters involved. Thus by inspection (Fig. 25.6[11]), it is found that $\zeta = 1$ roughly corresponds to zero correlation, i.e., $\eta = 0$, and

$$\delta = 2d \approx 8\ \text{m} \qquad (42)$$

between detectors will ensure uncorrelated statistical measurements

The problem of decreasing scintillation is very similar to overcoming fading in radio wave propagation, and one obvious method is spatial diversion reception. The analog for the present problem is the increasing of the receiver's aperture. Loosely speaking, if the aperture collects more rays, at different phases, the random phase factors will be eliminated, and the coherent component of the radiation will be enhanced. This is usually referred to as aperture averaging and is discussed by Ishimaru[3] and Tatarski[10], for example. For the aperture averaging to be effective, enough uncorrelated "portions" of radiation must be added through the aperture. In systems where good imaging quality is also required, this implies large aperture, costly and heavy telescopes. The imaging problem does not enter into our considerations, therefore for the present system a large array of small aperture receivers will suffice. This poses the unrealistic requirement of having an aperture many times larger than $\delta = 8$ m. Fortunately, the present configuration corresponds to a detector moving at about 10 km/sec. This means that during one second as many as 1250 uncorrelated samples can be gathered. Of course, we are limited by the fact that the satellites change position continuously, sweeping through different parts of the atmosphere. However, during the time of the order of one second, the distance traversed is of the order of a few kilometers. This still allows for good resolution of the order of 10 km. The error in phase due to scintillation may be considered as noise present in the process of measuring $\Delta\phi$. The present method of "synthetic" aperture averaging will improve the signal to noise ratio. By taking the average of a few hundred samples, $\Delta\phi$ will be enhanced and the noise diminished.

The above is a somewhat pessimistic evaluation of the system, since there are additional factors working in our favour. For example, we have to take into account the fact that the transmitter is moving too, continuously changing the line of sight, at different positions and angles. This should have an effect at least as significant as the moving receiver. Consequently $\delta = 4$ m and twice as much independent data can be accumulated in a given time period. It is well known that scintillation is rapidly reaching saturation, and does not grow with the length of the line of sight path[3,10,11,12]. Lawrence[11] puts the saturation distance for visible light at a path near the ground in the vicinity of one kilometer. This phenomenon, combined with the low scattering in the atmosphere in the 10μ IR band might result in very low noise levels. The subject will have to be discussed in more detail.

SUMMARY

A method has been proposed for measuring atmospheric wind velocity from space platforms. The present method is based on the Fizeau effect, and consists of transmitting two laser beams through the atmosphere, one upwind and the other downwind, and measuring the phase difference.

Typical numbers for the atmosphere indicate that the effect should be measurable. The question of carrying out the measurement in the presence of Doppler effects has been considered in detail, and it has been shown that although these effects make the measurement more difficult, the wind velocity can be measured, in spite of the fact that it is several orders of magnitude lower than the satellite velocity.

Inasmuch as a coherent measurement is proposed, the mechanisms introducing incoherence have been discussed. The main effect is expected from scintillation, which can be decreased by averaging the measurement over a short time period.

The present study is only preliminary, and many questions must still be answered to determine the practicality of this method for measuring wind velocity.

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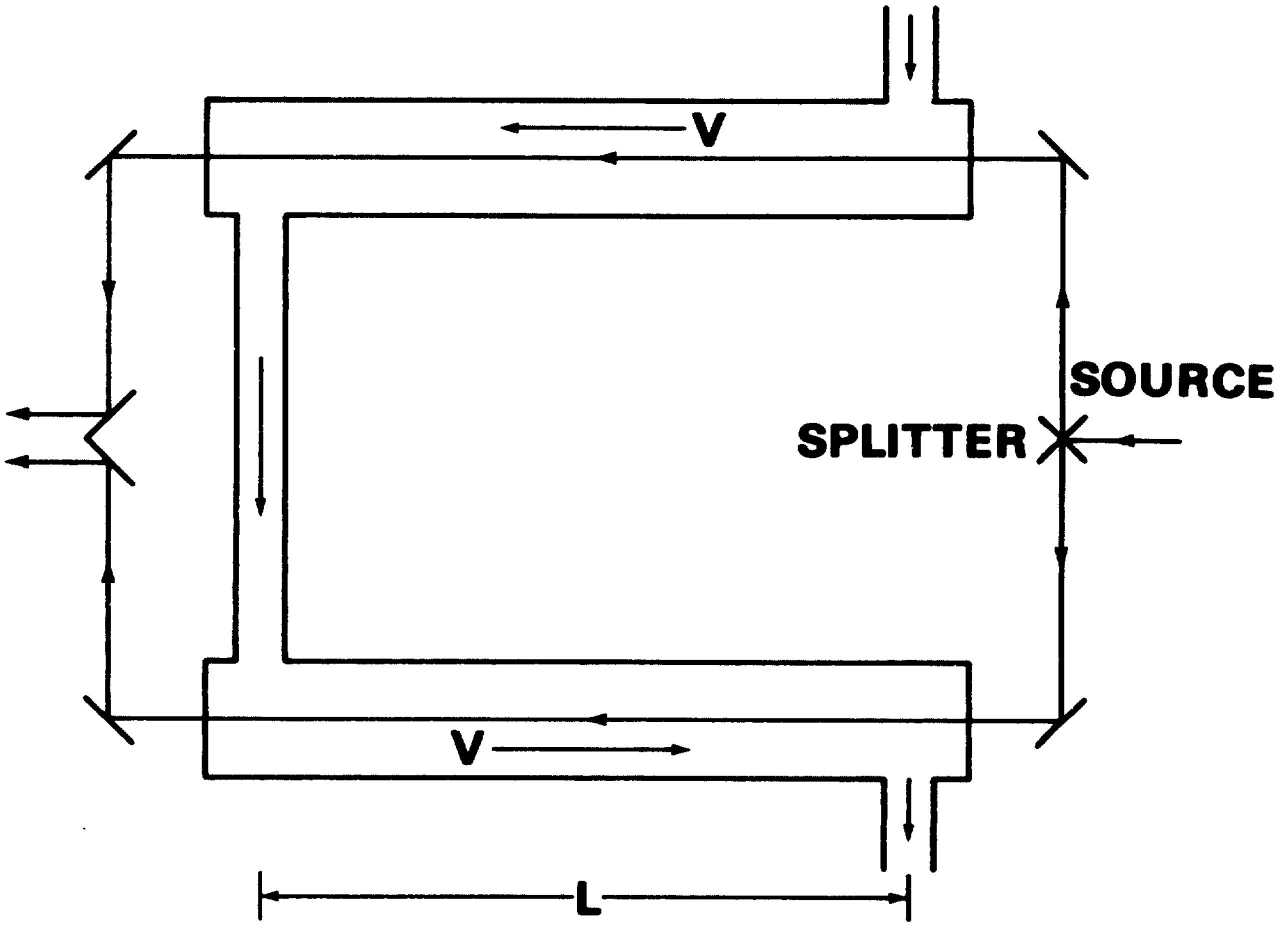

Figure 1. Schematic of the Fizeau experiment. Two coherent light beams traverse a moving liquid in opposite directions. The phase difference measured at the output is proportional to the medium's velocity.

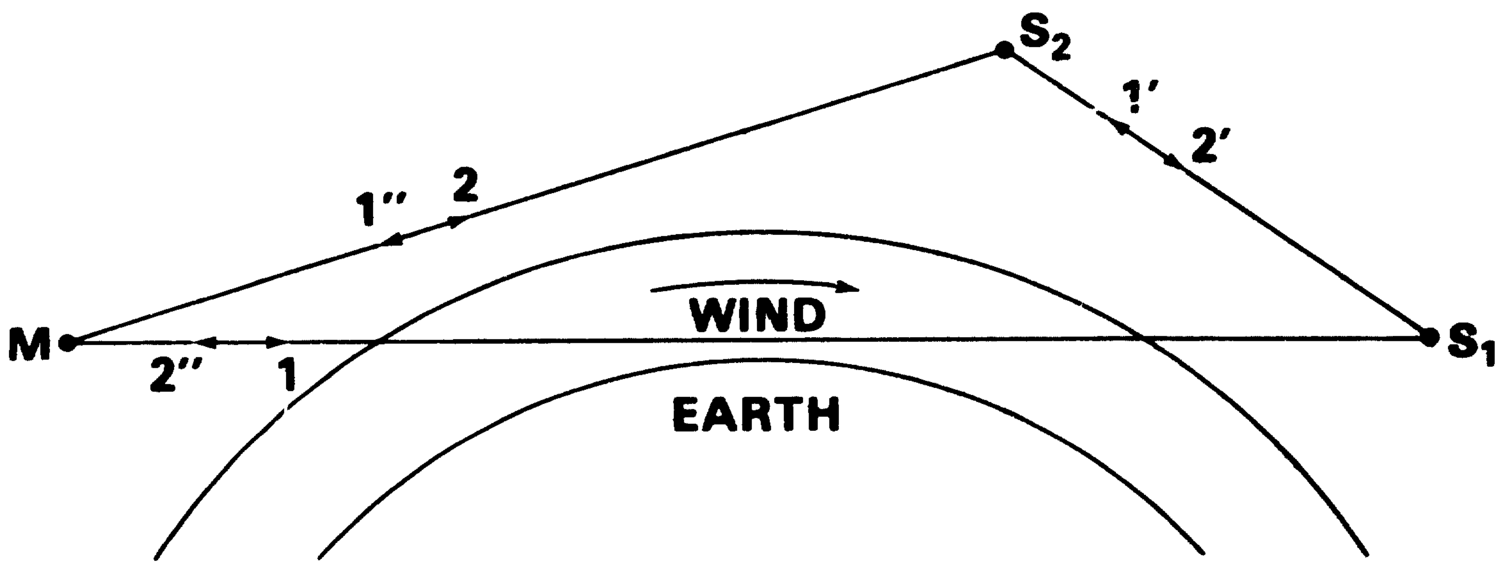

Figure 2. Satellite configuration for wind velocity measurement. Source and signal processing equipment are carried by M, reflectors are provided on board S_1 and S_2.

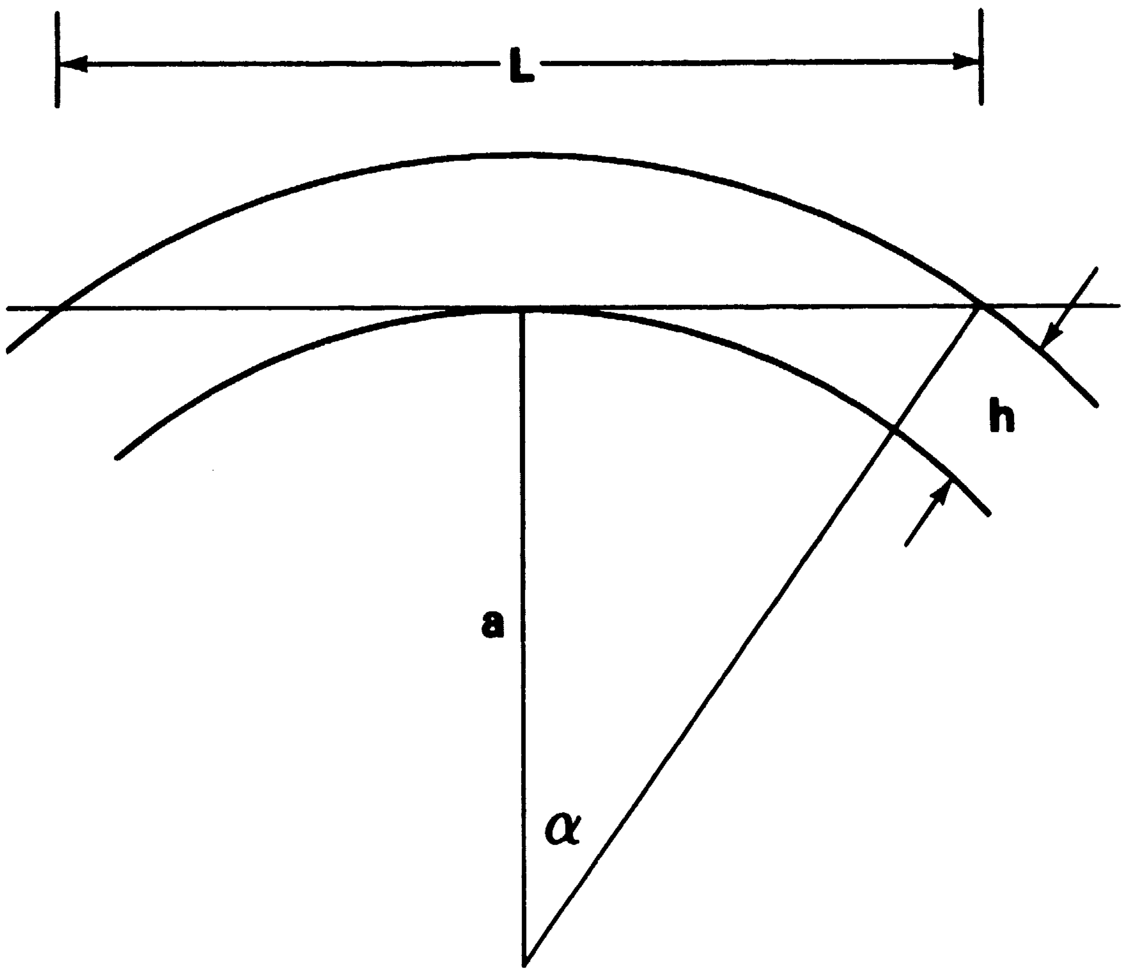

Figure 3. Estimation of atmospheric path length.

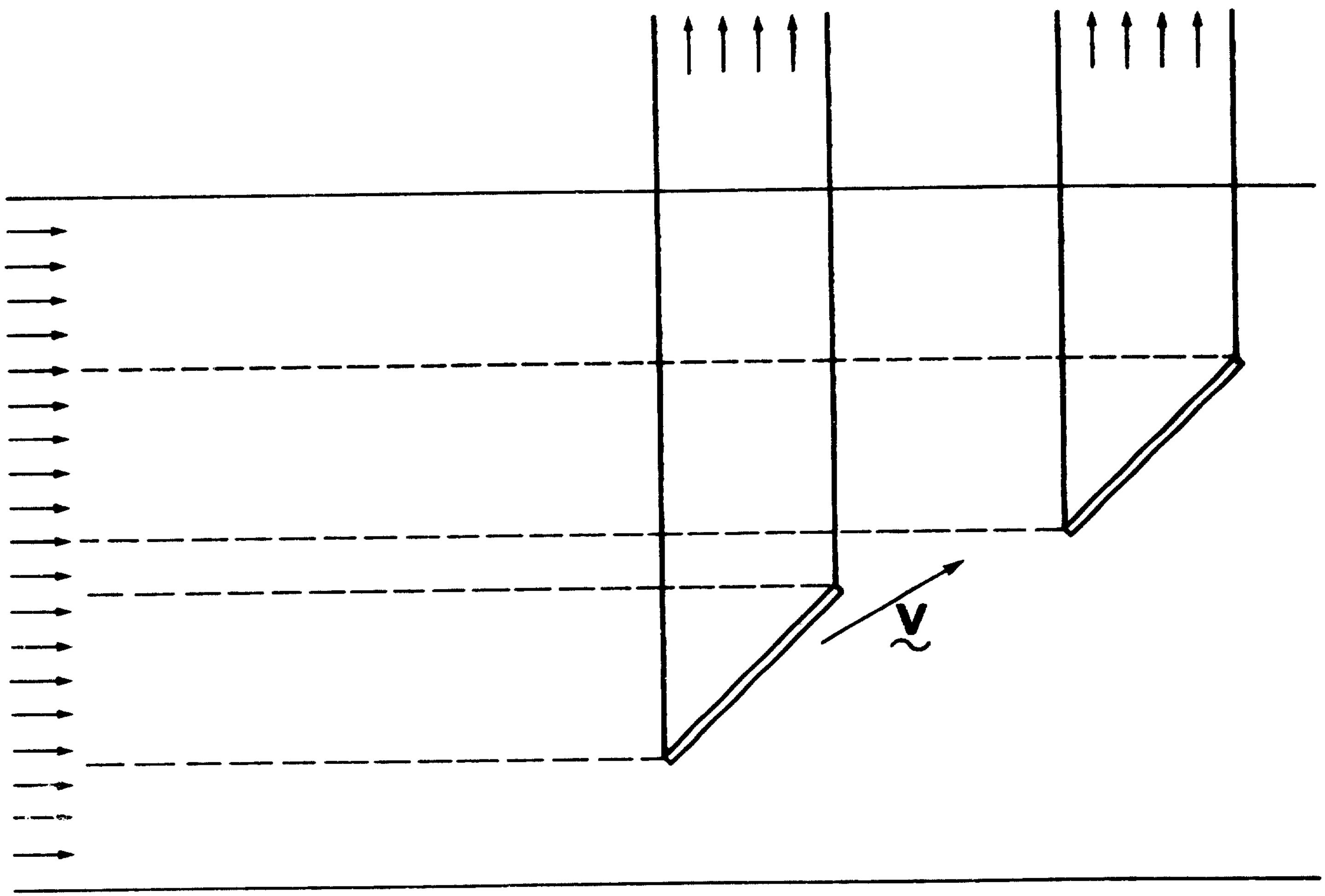

Figure 4. Effect of reflector motion on lateral displacement of beams.

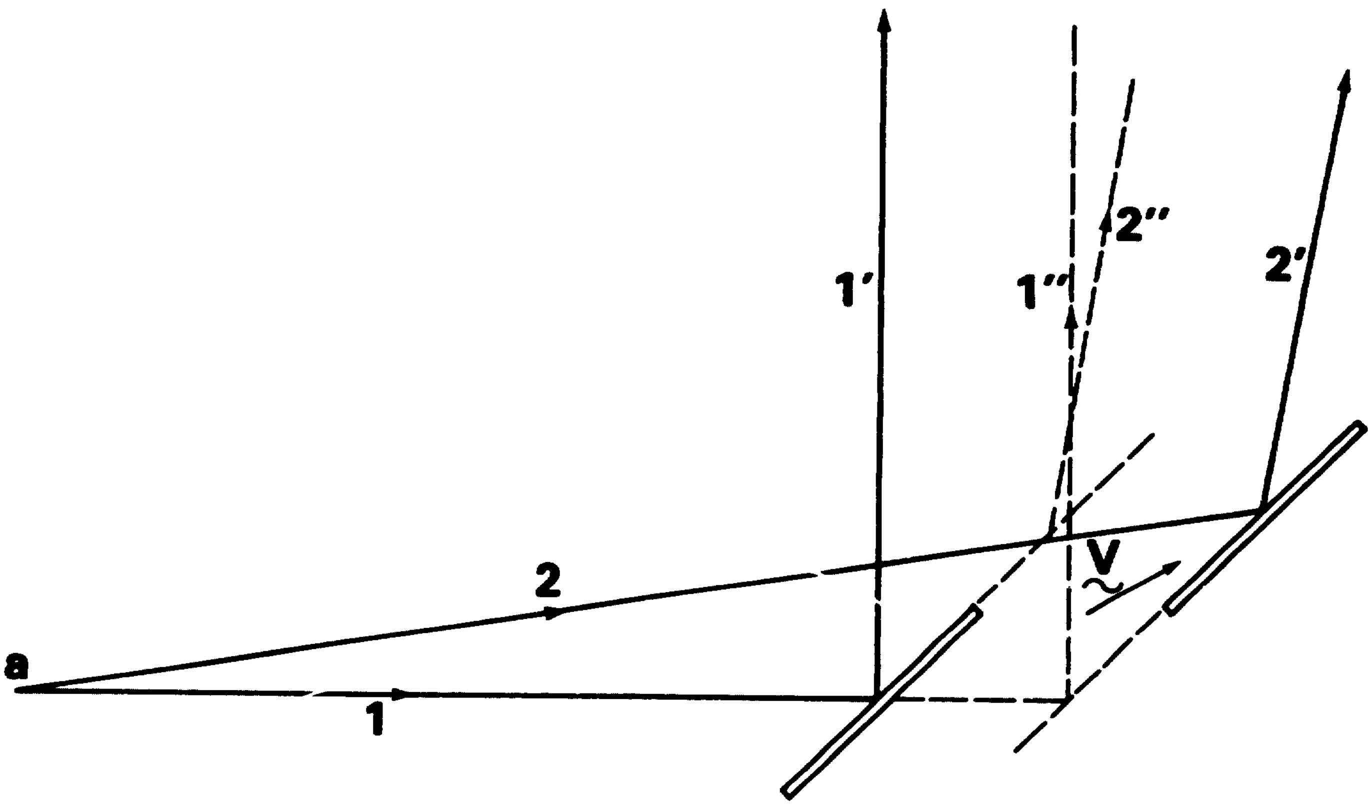

Figure 5. Effect of reflector motion in the presence of curved wavefronts.

APPENDIX A: A LIST OF OPEN PROBLEMS

1. Detectability of Signals: Existing and projected instrumentation must be examined for implementation of the present method. This applies especially to lasers and detectors.

2. Atmospheric Attenuation: Based on available data for standard atmospheres and special deviating cases, estimate the bounds on the applicability of the present method.

3. Cloud Cover: Using climatological data, estimate the fraction of time for which the method is operable. Compare to limitations on other methods.

4. Ocean Reflection Configuration: This configuration has been abandoned in the present study, because it was felt it might be too noisy. The method is attractive because it requires two satellites only. Check if aperture averaging technique, as described above, facilitates the use of this configuration.

5. Coherence Problems: Provide a quantitative analysis of the incoherence introduced by the atmosphere and the reduction of scintillation by synthetic aperture averaging.

6. Resolution: Consider inversion techniques relevant to the present system for improving resolution.

7. Computer Model: The combined effect of many factors described above is too complicated to be investigated analytically. A computer model should be constructed in order to test various ideas given above.

8. An Acoustical Analog for Doppler Effects: The design of a laboratory or ground based experiment which can simulate the high velocities of the satellites is probably as complicated as using the system itself. In acoustics it is relatively easy to achieve strong Doppler effects (although we cannot simulate the second order relativistic effects discussed above). Design an appropriate experiment, in air or water, that will test the feasibility of coherent measurements in the presence of strong Doppler effects.