Reports

Velocity of Light and Measurement of Interplanetary Distances

Abstract. The combined availability of atomic clocks and of instrumented planetoids traveling in their own solar orbits will offer the possibility of determining their distance from us, and hence interplanetary distances, in terms of the wavelength of the radiation of atomic frequency standards. It can be anticipated that the accuracy of these measurements will be very high and will not depend upon our less accurate knowledge of the velocity of light in terms of the standard meter, the sidereal second, and so on.

Ever since observation of the eclipses of Jupiter's moons indicated that the velocity of light is finite—and gave the first measure of that velocity—much effort has been devoted to increasing the accuracy of our knowledge of this important physical constant. The purpose of this report is to suggest that a change of emphasis may be in the offing: As we learn how to make interferometric measurements of distances between earth-borne stations and instrumented planetoids gravitating in their own solar orbits, we may be led to accept *c* as just *c*, and to express important parameters of our solar system, such as interplanetary distances, and the products of the masses of the sun and planets by the gravitational constant, in terms of the wavelength and period of the radiation of atomic frequency standards.

Three great classical experiments, and the inventions which made them possible, stand out among the many contributions made toward the measurements of length and of time.

The first is the determination Foucault made of the speed of light, by means of a rotating mirror and over a measured distance, in terms of the standard meter and the sidereal second.

The second is the measurement Michelson made, by means of his interferometer, of the wavelength of the red cadmium line, in terms of the standard meter. Today this line is replaced by the green line of Hg^{198}. It may be noted that these two experiments in combination yield the period of the Hg^{198} green line in terms of the sidereal second.

The third experiment is the measurement made, by means of the atomic clock suggested by Rabi, of the period of certain microwave lines, such as the cesium line, in terms of the sidereal second.

It may be asked whether application of careful optical interferometric metrology to the measurement of the dimensions of cavities or wave guides could not serve to determine the wavelength of the cesium line in terms of the green line of Hg^{198}, but such an experiment would be subject to severe limitations. First, the width of the resonance line of the best microwave cavities, even superconductive cavities, sets an upper limit to the accuracy with which their resonance frequencies may be determined. Second, there is uncertainty about the surface penetration of these microwaves. Third, the fairly large natural relative width of the sharpest optical lines sets another upper limit to the accuracy with which the dimensions of cavities or wave guides may be determined in terms of standard optical wavelengths. These limitations would make any measurements based on cavities or wave guides inaccurate by comparison with the accuracy of our determinations for the period of the cesium line in terms of the sidereal second, or with the yet greater accuracy of agreement between cesium clocks that will eventually be obtained (the accuracy of agreement, at this writing, is already of the order of 1 part in 10^{10}). These new orders of accuracy may well spark the question: What measurements of length will be made eventually with an accuracy depending upon the accuracy of the cesium clock alone, and not upon other limitations such as the low *Q*'s of cavities or the large relative widths of optical lines?

The answer to this question appears to be, the measurement of long distances over line of sight and *in vacuo* by means of radio interferometry, these distances to be measured at first between an earth station and an instrumented planetoid, and the data thus obtained to be utilized subsequently to determine accurately interplanetary distances.

The radio interferometric procedure may be sketched as follows (*1*). Point *A* emits a continuous-wave signal of frequency *f*, regulated by an atomic clock. This continuous-wave signal is received at *B*, where a second signal is generated which is coherent with the first (say a continuous-wave signal of frequency $7f/6$) and which can be emitted by *B* without interfering with *B*'s reception of *f*. This second signal is received at *A*, where it is retransformed into a signal of frequency *f*. The phase of this second *f*-signal is compared to that of the original emitted *f*-signal, and the number of 360° phase changes observed between these two signals during a given time interval is exactly equal to the number of wavelengths by which the *AB* round-trip distance has increased (or decreased) during that given time interval.

It may be noted that the precision with which the relative phase of the two *f*-signals can be determined, while subject to certain instrumental limitations, is fairly independent of range. Thus, the fractional accuracy with which distance increments can be measured will increase with increasing distances, and will be determined eventually by $\triangle f/f$, when the distances measured are of the order of magnitude $\lambda f/\triangle f$, where $\triangle f$ designates the uncertainty in our knowledge of *f*. If we make $\lambda =$ 10 cm and assume $f/\triangle f = 10^{10}$, we get 10^6 km for the order of magnitude of the shortest vacuum distances measurable with an accuracy matching the cesium-clock accuracy just assumed. Vacuum distances of the order of 10^6 km are not available on the earth, and the only approximation of such experimental conditions is offered by the measurement of the distance between a point on the earth's surface and an instrumented satellite of long range or an instrumented planetoid. The concomitant requirement that line of sight be maintained at all times between the measuring points rules out most satellites but allows the measurement of distance between an earth station on a firm polar cap (Antarctica) and an instrumented planetoid gravitating on a suitable solar orbit.

The suggestion of a planetoid instrumented for radio interferometry is attractive for additional reasons. First, there is an uncertainty of several wavelengths (at S-band) in the distance

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Type manuscripts double-spaced and submit one ribbon copy and one carbon copy.

Limit the report proper to the equivalent of 1200 words. This space includes that occupied by illustrative material as well as by the references and notes.

Limit illustrative material to *one* 2-column figure (that is, a figure whose width equals two columns of text) or to *one* 2-column table or to *two* 1-column illustrations, which may consist of two figures or two tables or one of each.

For further details see "Suggestions to Contributors" [*Science* **125**, 16 (1957)].

measurement, due to imperfect knowledge of the refractive index in the small portion of the range included in the atmosphere, and due also to the unknown deformation of the earth crust. When the measurements are made over interplanetary distances, these uncertainties become much smaller than 1 part in 10^{10}. Second, the ranges involved, even though enormous when compared to anything with which we have any experience (three orders of magnitude above "moon-radar" ranges), are quite manageable with modern radio techniques. Indeed, it has been calculated that isotropic planetoid emissions of the order of 1 watt will yield more than adequate signal-to-noise ratios at the earth station. And third, comparison of the orbital data thus obtained with the orbital data of the planets would increase the accuracy of our determinations of interplanetary distances by several orders of magnitude.

This last point is the crux of the matter. Interplanetary distances are known today with an absolute accuracy of the order of 1 part in 10^3 only, owing to the poor degree of accuracy with which we know the parallax of the sun. On the other hand, interplanetary distances relative to each other are known with a much higher degree of accuracy, of the order of 1 part in 10^9. Thus, the availability, for a single orbit, of data known with an accuracy of the order of 1 part in 10^{10} would yield immediate knowledge of the other interplanetary distances with an accuracy of 1 part in 10^9. This means that a single successful planetoid experiment would increase the absolute accuracy with which interplanetary distances are known from a figure well below that realizable in laboratory measurements to a figure well above it. This means also that later and more elaborate planetoidal experiments will permit closer checks of the relativisitic gravitational correction, more accurate estimates of the distribution of large masses and of dust within the solar system, and so on. It even appears permissible to begin to speculate about the possibility of detecting spatial curvature or departures from the gravitational theory by means of these techniques.

It is also worth noting that if the experiments forecast here are successful, the standard meter, the wavelength of the green line of Hg^{198} and the sidereal second will play a secondary part in these measurements. The periods of the satellites and planets will be measured eventually in terms of (for instance) the cesium line period t_0; the orbital dimensions will be measured in terms of the wavelength of the cesium line λ_0; the product of the mass of a planet and the gravitation constant will be measured in terms of $\lambda_0^3 t_0^{-2}$, and so on. We shall have of course $\lambda_0 = ct_0$, by definition, but any determination of c in terms of "secondary" standards, such as the standard meter, the sidereal second, or the wavelength of the green line of Hg^{198}, will be of much lower accuracy than the measurement of planetary parameters for which λ_0 and t_0 will be the newly adopted primary standards.

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Note

1. A detailed and quantitative description of this technique has been published (M. J. E. Golay, "Interferometric rocket guidance," *Conf. Proc. PGMil of IRE, 2nd Natl. Conv.*, p. 182).

6 July 1959

High-Resolution Density Gradient Sedimentation Analysis

Abstract. The principle of stability for a sample layered in a density-gradient liquid column is discussed, and a method for separating ribonucleoprotein particles by means of sedimentation in the ultracentrifuge is described.

In the process of our studies of bacterial ribonucleoprotein particles (ribosomes), the need arose for a method of sedimentation analysis which would supply separated samples of the ribosomes of *Escherichia coli* (*1–3*). These particles have sedimentation constants of about 20, 30, 50, 70, and 100*S*. Adequate separation of these classes has been obtained by sedimentation at 105,000*g* through a density-gradient stabilized liquid column, use being made of the principle that the stabilizing density gradient must always exceed the inverted density gradient introduced by the sample. Since the method is mechanically simple and probably of general application, it is described separately in this report.

Density gradients are commonly applied to prevent mixing in liquid columns which are used for zone analysis by means of centrifugation or electrophoresis. However, this method has been limited to very small quantities of material, since the sample itself may introduce a region of density instability. So long as the density increases in the direction of the gravitational (or centrifugal) field, the gradient will exercise a stabilizing force against mixing which occurs as a result of mechanical disturbances or temperature gradients. If the density gradient is locally inverted due to the presence of a sample, the liquid containing the sample will stream through the less dense underlying layers. This process does not necessarily stop when the stream reaches a region of equal density, since the stabilizing solute (usually more rapidly diffusing than the sample) will diffuse into the stream and may continually reestablish a condition of instability.

The sample layer shown in Fig. 1*A* is initially stable. However, as soon as the sample is moved downward (or the stabilizing solute diffuses into the sample layer), the inverted density gradient will cause streaming. The inverted *density* gradient may be avoided if the sample is introduced (Fig. 1*B*) with a *concentration* gradient opposite to that of the stabilizing gradient, provided the inverted density gradient due to the sample itself is significantly less than the stabilizing density gradient.

Usually a maximum quantity of sample can be analyzed when both gradients are linear. The amount of sample which can be handled rises with the square of the width of the sample layer, since it is the *gradient* in density and not the maximum density of the sample which determines stability.

The instability of sharply defined sample layers has been previously recognized and offset (*4*) by stirring the sample layer to reduce the inverted gradient at the lower edge of the band. Stable inverted sample gradients of complex shape have been created through the use of mixing chambers (*5*). However, the large sample capacity and the simplicity of the inverted linear sample gradient have not previously been mentioned in the literature.

This principle has been applied successfully both for analysis by electrophoresis and for analysis by sedimentation in the ultracentrifuge. Since the latter application has been of great importance to our experiments on synthesis of (*1, 2*) and by (*6*) the ribosomes of *E. coli*, it is described here in detail.

A linear stabilizing density gradient of sucrose (20- to 5-percent) was prepared with a modification of the linear gradient mixing device of Bock and Ling (*7*), shown in Fig. 2. Such gradients are stable for many hours, and only moderate care need be taken in handling the tubes. The same device was then used to introduce the inverted sample gradient. For this purpose the left-hand chamber was loaded with 0.2 ml (for example) of buffer containing 5 mg of ribosomes per milliliter, and the right-hand chamber with 4-percent sucrose in the same buffer. The sudden step in sucrose concentration from 5 to 4 percent makes it possible to start the sample gradient without undue mixing. The stabilizing gradient can be reduced when the sample to be analyzed is small. Gradients of 10- to 3-percent sucrose