D. Multiple Wavelength Electromagnetic Distance Measurement

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1. Introduction

Electromagnetic distance-measuring techniques are an essential part of horizontal control networks. All such techniques determine the length of a path by measuring the transit time of an electromagnetic signal between the two endpoints.

In order to convert a transit time to a physical distance, it is necessary to know the velocity of light at the time and place of the measurement. These measurements are almost always made through the earth's atmosphere, so that a determination of the velocity of light requires a measurement of the atmospheric index of refraction.

The atmosphere has an index of refraction that differs from unity by about 300 parts per million in the visible portion of the spectrum. Since it is usually desirable to measure distances, with an uncertainty of no more than 0.1 part per million, the refractivity (i.e., the deviation of the atmospheric index from unity) must be known with an uncertainty of no more than 3 parts in 10000.

Instruments which measure the refractivity of the atmosphere using multiple wavelength methods have been described by Slater and Huggett (1976), and by Bouricius and Earnshaw (1974) and Earnshaw and Hernandez (1972). The instruments constructed to date have only been able to measure rather short baselines of 5 km to perhaps 15 km in length. They operate by measuring the time it takes light to travel along the path to a reflector and back. These instruments are limited by spreading, attenuation and turbulence in the atmosphere, and by an inability to simply distinguish between a true return signal and light scattered backwards from the exit optics of the transmitter.

If these systems are converted to one-way operation by replacing the retro-reflector with an active receiver, the resulting increase in the signal power at the receiver should permit longer baselines to be measured. The increase in range using one-way operation should be at least a factor of two if the system is limited primarily by attenuation and shot noise. However, the main limitation is almost certainly the noise introduced by atmospheric scintillations. In this case, a considerably larger improvement in range appears to be feasible by raising the frequency at which measurements are made. This point will be discussed later.

We have calculated the range of a one-way instrument using the following parameters: 0.1% modulation amplitude at each modulator; 10% sensitivity to the undesired polarization; an atmospheric attenuation coefficient of 0.25/km; path length of 40 km; 10 arc second beam diameter at the receiver; and scintillations of 1% of the transmitted light in a 1 kHz bandwidth centered at the difference frequency between the two modulators. For these conditions, we estimate that the atmospheric correction can be determined with an uncertainty of 0.1 ppm in 10 seconds of averaging time. The amplitude fluctuations due to atmospheric scintillation dominate the shot noise for this case, so that the atmospheric attenuation (by a factor of 20000) is not the main limitation in this case.

2. Instrument Design--General Principles

The simplified schematic diagram of a multiple wavelength instrument is shown in fig. 1. Linearly polarized light from the source is sent through a local modulator, traverses the path, and then goes through a second modulator at the far end of the path before it is detected by a photomultiplier. Each modulator converts a small percentage of the light to circular polarization. This polarization modulation is converted to amplitude modulation by passing the light through an analyzer immediately in front of the photomultiplier. The two modulators operate at slightly different frequencies, and the light at the detector will have a component that is amplitude modulated at a frequency given by the difference between the frequencies applied to the two modulators. If two different optical wavelengths are sent through the system simultaneously, the two photomultiplier signals will show a phase difference proportional to the dispersion of the atmosphere, i.e., to the difference in the indices of refraction of the atmosphere at the two wavelengths. The atmospheric dispersion is proportional to the density of the air along the path, and a dispersion measurement can be used to determine this atmospheric parameter.

At the same time a microwave signal is sent along the path. This signal is derived from the signal used to modulate the optical beams. It arrives at the distant end with a phase shift related to the refractivity of the atmosphere at microwave frequencies. The difference between the optical and microwave phase shifts can be used to determine the contribution of water vapor to the atmospheric refractivity.

These two difference measurements determine the refractivity of the atmosphere along the path and can be used to correct an electromagnetic distance measurement. The uncertainty in this correction is

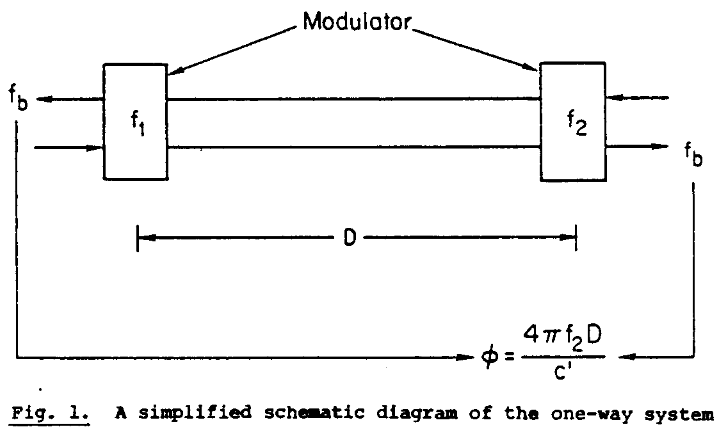

Fig. 1. A simplified schematic diagram of the one-way system

limited in principle by the validity of the assumed simple relationship between refractivity and atmospheric parameters, but it is likely that any practical device will in fact be limited by other uncertainties.

3. Instrument Design--Engineering Tradeoffs

A field qualified instrument must be designed with certain engineering tradeoffs borne in mind. These considerations may be most easily understood in terms of a specific measurement capability.

If we propose to measure distances up to 50 km with an uncertainty of no more than 0.1 ppm, then the maximum length uncertainty is 5 mm. Due to the refractivity of the atmosphere, the optical distance will differ from the actual distance by about 15 m. The refractivity is determined by measuring the difference between the optical distance at two different wavelengths, and this will be about 65 cm if the two wavelengths are at opposite ends of the visible spectrum (red and blue). This dispersive term depends on the atmospheric constants in the same way as the index itself, so that a determination of the refractivity with an uncertainty of no more than 3 parts in 10000 requires that the apparent length difference be determined to about 0.2 mm. Thus the dispersive term must be measured more accurately than the distance itself, and any method capable of determining the index can probably measure the distance.

The requirement to measure relative distances with an uncertainty of no more than 0.2 mm is satisfied in practice by using a very short modulation wavelength. If the modulation wavelength is 10 cm, for example (S-band modulation frequency), the phase meters must be able to accurately measure phases with an uncertainty of no more than about 0.75 degrees. There is an obvious tradeoff between modulation wavelength and phase meter accuracy, and this tradeoff is made more complicated by the fact that the efficiency of the modulators (and hence the sideband power) varies significantly with modulation wavelength.

At frequencies below about 300 MHz, modulation efficiency approaches 100% and becomes essentially independent of frequency, while at frequencies above about 3 GHz, modulation efficiency becomes so low that shot noise becomes a serious problem. We are currently using S-band modulators operating at 2.7 GHz at the upper end of this spectral region. These modulators were chosen to simplify the design of the phase meters, since we initially felt that the phase meter problem would be very difficult to solve. As we will discuss below, this is no longer true. We have constructed new phase-meters using a second intermediate frequency between the microwave modulation frequency and the phase-meter measurement frequency. With the new phase-meters we can probably lower the modulation frequency somewhat and still achieve our accuracy goal. If we lowered the modulation frequency to 900 MHz, we could improve the modulator efficiency by about an order of magnitude.

Since all modulators operating above 300 MHz are relatively inefficient devices, only a small fraction of the optical power will be modulated. This will also be true at the second modulator. The detected signal then consists of unmodulated light plus a small component at a frequency given by the difference in the operating frequencies of the two modulators. The phase difference between the two wavelengths is preserved in the difference frequency signals so that the phase meters can be constructed to operate at the relatively low difference frequency.

The phase meters must have systematic errors (due to propagation delay through the electronics, for example) of a small fraction (say 0.1%) of the period of the difference frequency, and this requirement would suggest the lowest possible difference frequency. If the difference frequency were 1 kHz, for example, the systematic errors in the phase meter would have to be held to less than 1 microsecond.

The "noise" in this measurement would come from atmospheric turbulence amplitude modulating the beam. Since most of the optical power is unmodulated, amplitude modulation of the d.c. beam is potentially very serious and may be larger than the true signal. If we start out with light polarized along some arbitrary direction and set the axis of the final polarization detector to be perpendicular to this direction, then in principle no light reaches the photomultiplier. The amplitude that actually reaches the detector depends on the static depolarizaion produced by the modulator crystals and the rest of the optics. In what follows we shall assume as a worst case that the depolarizaton is large and that much of the unmodulated light passes through to the photomultiplier. Our experience suggests that this is in fact usually the case in an operating system.

The spectrum of the modulation produced by atmospheric turbulence is difficult to predict in general. If the turbulence is not too strong and the air is not too quiet, the turbulence may be estimated using the "frozen" model. In this model the scintillations are produced when small inhomogeneities in the atmosphere are transported through the beam by the wind. The size of the inhomogeneities that produce the largest effect is roughly the size of a Fresnel zone, that is the square root of the wavelength times the path length. In our case, the scale size would be about 10 cm. If the wind velocity is 5 m/sec, the inhomogeneities will move one scale length in about 20 msec, giving a peak in the power spectrum at about 50 Hz. These scintillations will vary inversely as the 7/6 power of the optical wavelength and will therefore be somewhat more serious at the blue end of the spectrum. The power spectrum of these scintillations decreases with frequency, and has fallen by a factor of about six at ten times the peak frequency. The literature on this point is somewhat misleading since what is usually plotted is the variance of the log amplitude rather than the variance of the power itself. It is clear that under these assumptions, 500 Hz is definitely too low for the difference frequency and even 1 kHz is marginal.

These quantities do not change rapidly either with a decrease in range or an increase in receiver aperture. If the range is made shorter, the peak in the frequency spectrum is shifted to higher frequencies since the Fresnel zone diameter decreases. At the same time a given receiving aperture averages more zones and the fluctuations decrease as the square root of the number of zones averaged. These two effects act in opposite directions and the net improvement will depend on the details of the scintillation spectrum. Since the scintillation amplitude changes rather slowly with frequency, the primary effect should be an improvement due to the increase in the number of zones averaged by the receiving aperture.

As the turbulence increases, its character changes from the "unsaturated" case described above and becomes "saturated." From our point of view the most serious consequence of this "saturation" is a shift in the peak of the turbulence spectrum towards higher frequencies. The characteristic frequency is again determined by the time it takes for the wind to move the air by one scale size, but the scale size is a function of the turbulence. In general it is smaller than a Fresnel zone. There is some reduction in the variance due to aperture averaging, but the improvement is not as great as might be expected since the incoming wavefront is quite distorted and the image quality is therefore poor.

For strong saturation, the scale size might be on the order of 1 mm. If the wind speed is 5 m/sec, the characteristic frequency will be on the order of 5 kHz.

A more detailed discussion of the properties of atmospheric turbulence may be found in the literature (Lawrence et al. 1970; Lawrence and Strohbehn 1970; Clifford 1971; Clifford et al. 1971; Kerr 1972; Hansen and Madhu 1972; Vartanyan et al. 1972).

In all previous designs it has never been possible to raise the measurement frequency high enough to be well above the saturated-turbulence peak in the spectrum, and this has been one of the most serious limitations on electromagnetic distance measuring systems.

We have recently designed a system that appears to solve this problem. It uses a new phase measuring circuit. We have used this new circuit to design a measurement system operating at 40 kHz, a frequency far higher than has ever been used by any other instrument. At this frequency, the atmospheric turbulence should present almost no problem.

Alternatively, this problem can be viewed as resulting primarily from the low efficiency of the optical modulators. Higher efficiency modulators are being developed; commercial modulators now claim 10% efficiency at 900 MHz. If these modulators were used, the gain in sideband power would more than compensate for the decreased resolution produced by the longer wavelength.

There is one way to increase the amplitude of the modulated component of the optical beams without changing the modulators. If the S-band input power to the modulators is increased, the fraction of the light that is modulated will also increase. This cannot be done arbitrarily because the increase in the microwave input power produces an unacceptably large increase in the temperature of the modulating crystal. However if the duty cycle of the modulators were reduced by an order of magnitude (to 10% on -- 90% off, for example), the peak power could be increased by an order of magnitude while the average power would remain the same. (This sort of scheme is mandatory for the Slater and Huggett system since the red and blue measurements are multiplexed. However it is optional for one-way, phase-measuring systems.) If the detection system were synchronized with this modulator switch so that it would be active only when the modulators were on, the improvement in the signal-to-noise ratio might be appreciable. The improvement would depend on the fact that the optical sidebands would be proportional to average microwave power and hence would be independent of duty cycle while the scintillation noise power would decrease with decreasing duty cycle.

Since duty-cycle enhancement is used in present two-way systems, this advantage may reduce the theoretical range improvement factor that a one-way system should possess. Duty cycle enhancement is more difficult to implement in a one-way system than in a two-way system since the duty cycle switch must be synchronized at both ends in the former. If the switching time is made rather long (e.g. 100 msec on -- 900 msec off), the travel time will be a small fraction of the cycle time so that both ends can be switched simultaneously. The phase meters are already designed to deal with random dropouts in the signals and they will work without modification.

4. Proposed Instrument Design

Using the design considerations discussed above, a refractometer can be constructed using S-band modulation of the optical beams with a difference frequency of 40 kHz. The microwave signal will be generated by tripling the optical modulation signal. This will produce a signal at X-band and will result in a difference frequency of 120 kHz.

The phase meters will be designed to measure with 14-bit accuracy, so that the least count will be approximately 0.02 degrees which corresponds to a distance of about 0.0005 cm at S-band. This is roughly 40 times better than it needs to be for a goal of 0.1 ppm uncertainty in the distance and may allow a measurement with an instrumental precision approaching 0.01 ppm (assuming no degradation due to turbulence). The overall measurement accuracy will probably be limited by other factors including the stability of the benchmarks.

If a refractometer with these capabilities can be demonstrated, the incremental equipment needed to measure distances can be added later. As discussed above, the determination of the refractivity is the most difficult part of the job, and any system that can determine the refractivity can determine the distance.

The instrument requires at least one secondary telemetry link for synchronization purposes. This link may be at any convenient frequency. It is possible to use the microwave system as the telemetry link, although a totally separate VHF link is simpler to build.

Additional links may be necessary, depending on where the data are to be recorded. The simplest scheme has the lasers at one end and the detectors, phase meters and recorders at the other end of the path. This scheme may be somewhat awkward in a field situation, and it may be desirable to use secondary telemetry links to send the data back to the laser end of the path. If these links are necessary, they could be implemented using various digital transmission methods, and their use would therefore not degrade the quality of the measurements.

5. Current Instrument

An engineering test instrument designed along the principles outlined above is nearly finished.

The engineering test instrument includes 1 m diameter microwave antennas for making the radio distance measurements at 8.1 GHz. The reason for the large size is to avoid any possible problems due to ground reflections. Such reflections can combine with the direct signal to give shifts in the apparent radio distance. The size of the antennas probably can be reduced in the field instrument. Provisions have been included for measuring the radio distance at two frequencies near 8.1 GHz differing by about 1%, so that the ambiguity in the difference between the radio and optical path lengths can be resolved. This is necessary because a change of only 0.15 millibar in the partial pressure of water in the atmosphere can cause an error of one wavelength in the measured radio distance at 50 km. Measurements of the partial pressure of water at the end points may not be adequate if the path is over water or is inhomogeneous.

The current instrument uses two minicomputers to record the phase differences and to compute the refractivity.

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