APPLICATION OF INTERMEDIATE FREQUENCY INTERFEROMETRY TO TRANSPORT VEHICLE CONTROL SYSTEMS

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Abstract

The extension of intermediate frequency interferometric (IFI) principles to range as well as bearing angle measurements suggests a number of applications in which IFI methods may provide inexpensive means for determining the positions of mobile vehicles, and in particular the relative distance between two vehicles in motion. Since the method requires radio transmission from one vehicle to the other, this radio link could be used for multi-function purposes, including the transmission of identification codes and similar auxiliary data.

INTRODUCTION

Though the U. S. Transportation System within Conus is currently based primarily on the use of motorized highway vehicles, future growth rates will be restricted within large metropolitan areas such as San Francisco, Los Angeles and along the northeast corridor from Boston to Washington, DC. Public transportation systems appear to be a logical alternative.

The need for higher capacity and more efficient public transportation challenges all of the technologies associated with vehicles, vehicle ways, terminals and control systems. An increase in capacity requirements leads to a concomitant increase in the frequency of vehicles entering and departing terminals, emphasizing the need for rigorous structuring of the dynamic flow characteristics of these systems, both in enroute and terminal space. Sequencing and spacing of vehicles is a prime function of the control system. Sequence rate requirements are determined by individual vehicle capacities and the time dependent capacity requirements of the total system. Vehicle separation distances are determined by sequencing schedules for both enroute and terminal area traffic, and by personnel safety assurance criteria imposed on the total system.

The control system consists of data processing and decision making centers, interconnected via communication links with data accumulation sensors. These sensors function to determine the current status of the system, i.e., those features of dynamic flow needed to project and assess the near future status on which decisions concerning flow control are based. Among the more important system status sensors are those which determine the positions of the vehicles and their motions within the system, as well as relative to each other. These sensors are the basic in situ auditors of the vehicle flow plan and provide the important source of data required to update vehicle flow efficiency and assure the safety of travelling personnel.

There are a number of methods used to determine vehicle positions. Selection of a particular method is usually influenced by the nature of the application, in particular the measurement accuracy requirements and the scenario. For a rail-type public transportation system the parameters of inter vehicle distance and relative velocity are particularly important for control system "following" modes and collision avoidance. Position angle measurement is clearly not as important as measurement of the distance between vehicles. The precision of the range measurement (range resolution) is intimately related to the relative velocity resolution desired, if the relative velocity is determined as a time derivative of the measured range.

There are three common methods for measuring range. One involves measurement of the round-trip propagation time of a signal which traverses the path to be measured in both directions. The second involves the use of precision clocks located at either end of the path whose length is to be measured, operating in conjunction with a signal transmitted in one direction over the path. An important characteristic of the signal is a unique relationship between a "time signature" and the time of transmission which allows a time difference measurement at the receiving end of the path whose length is to be measured. The third method involves trilateration. All three methods entail a broad variety of techniques.

One usually thinks of trilateration schemes as limited in their range measurement resolution. This results when angles are measured directly; however, if the angles are measured as a difference between two distance measurements, the range resolution capability is markedly improved. Of recent interest is the use of interferometric techniques in a hyperbolic navigation mode. This method of range measurement by trilateration is referred to as "differential phase ranging at an intermediate frequency".

IFI Principles

The geometry of bearing angle measurement by interferometric techniques is shown in Figure 1. The bearing angle Θ to a remote point is measured in the plane of the interferometer baseline and the remote point and is given by:

$$\Theta = \sin^{-1}\left[\frac{\ell}{d}\right] \qquad (1)$$

where ℓ is the path length difference from either end of the baseline to the remote point, and d is the baseline length. Measurement of Θ involves the measurement of ℓ.

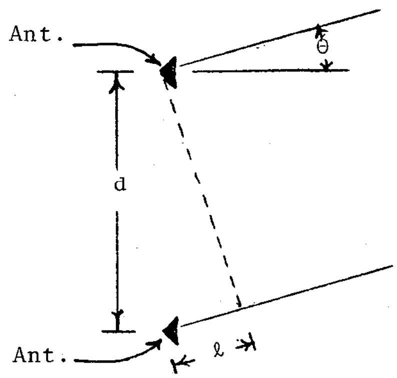

Figure 1. Two Element Interferometer

The major difference between conventional carrier frequency interferometric techniques and intermediate frequency interferometric techniques is the method by which the path length difference ℓ is measured, or more specifically the characteristics of the signals radiated from either end of the baseline, and the method for processing these signals to extract the path length difference ℓ.

In carrier frequency interferometry a carrier signal is transmitted from one end of the baseline simultaneous with the transmission of one phase related AM sideband from the other end of the baseline. The frequency separation between the carrier and its sideband (modulation frequency) is usually in the audio range in order to minimize Doppler errors due to vehicle motion. The modulation frequency is also transmitted on a subcarrier simultaneous with the transmission of the carrier and sideband signals. At the receiver the carrier and sideband are recombined (heterodyned) to develop the modulation frequency. This modulation frequency is phase shifted relative to the modulation frequency transmitted on the subcarrier, by an amount determined by the path length difference ℓ measured in wavelengths at the carrier frequency. Measurement of this phase difference is accomplished by comparing the phase of the modulation reference frequency with the phase of the modulation frequency derived from recombination of the carrier and sideband.

There is no angle ambiguity if the path length difference ℓ is less than one wavelength at the carrier frequency. If the baseline length is $n\lambda$ the total unambiguous angle sector coverage either side of the normal to the baseline will be:

$$\Theta_m = \sin^{-1}\left[\frac{1}{n}\right] \qquad (2)$$

A two element carrier frequency interferometric transmitter operating at a frequency of 5 GHz with a baseline of 3 meters will provide an unambiguous angle sector coverage of approximately 2.3 degrees, too narrow to be of significant value for most transportation system applications.

Intermediate frequency interferometry overcomes the angle ambiguity restraint by generating a lobe pattern at the modulation frequency rather than at the carrier frequency. This is accomplished by simultaneously transmitting both a carrier and sideband from each end of the transmitting baseline. The carrier frequencies are displaced to allow separate identification; however, each sideband bears the same frequency difference and phase relationship to its carrier through use of a common modulation frequency generator. At the receiver, each carrier is heterodyned with its own sideband, thereby deriving a modulation frequency whose phase is determined by the path between the transmitting antenna and the receiver, measured in wavelengths at the modulation frequency. The phase difference between the two modulation frequencies thus derived, provides a measure of the path length difference ℓ between either end of the transmitting baseline and the receiver, in fractional wavelengths at the modulation frequency. An important feature of this method of carrier and sideband transmission and signal processing is complete cancellation of Doppler effects due to vehicle motion.

It is apparent that the same geometrical equations apply to intermediate frequency interferometry as to carrier frequency interferometry, in particular the maximum half angle unambiguous sector coverage given by equation 2 takes the same form for intermediate frequency interferometry, with the singular exception that the value of n now applies to the length of the transmitting baseline measured in wavelengths at the modulation frequency. If, for example, a modulation frequency of 200 MHz were used with a baseline of 3 meters, the total unambiguous sector angle coverage would be 60°. Note that the sector angle coverage is completely independent of the carrier frequencies used. One might view the carrier signals as playing the classic role of a clock reference for the information, which is totally contained in the phase of the modulation frequency.

These same principles can be applied to a surveillance mode in which paired antennas on a common baseline receive and process a single carrier and sideband transmitted from a remote point. Only one carrier and sideband need be transmitted since the path lengths, whose difference is to be measured, are separately identified with the spatially separated receiving antennas.

Distance and Velocity Measurements

The foregoing description of the geometry of a two element interferometer is helpful in deriving the analytical form of the lobe structure or visibility pattern resulting from the interference of two waves transmitted simultaneously at the same frequency from either end of a baseline; however, it is the unique relationship between a fixed path length difference and a specific direction relative to the baseline direction that has immediate application to navigation. Viewed from this purely geometrical standpoint, it is of interest to recall that the locus of a point that maintains a constant path length difference from either end of a baseline defines a hyperbola with respect to the ends of the baseline as foci. At distances from the baseline large in comparison to the length of the baseline, the hyperbola approaches a straight line asymptote which passes through the midpoint of the baseline. Consequently, the typical interference pattern of a two element interferometer is describable in terms of hyperbolic geometry. The far-field or asymptotic case provides a direct measure of the bearing angle to a remote point as viewed from the midpoint of the baseline.

As the distance to the remote point decreases, the direction of the point relative to the baseline measured from either end and from its midpoint, will show small angle differences. As the point moves along a typical hyperbolic path, the non-parallel nature of the lines to either end point and the midpoint of the baseline become more apparent. Measurement of these angle differences immediately leads to a determination of the position of the point relative to the baseline. In particular the point is located at the intersection of two hyperbolae. One hyperbola is determined by the path length difference between the point and one end of the baseline, and the point and the midpoint of the baseline. In a similar manner, the second hyperbola is determined by the path length difference from the point to the other end of the baseline and from the point to the midpoint of the baseline.

Position measurements based on the measurement of two differences of distance are well known. The first radio navigation systems based on these principles were the Gee (British) and Loran (American) long-range navigation systems developed during World War II. Navigators obtain position fixes by measuring path length differences between a minimum of three Gee or Loran stations. Differences in the time of arrival of pulses transmitted from three stations are determined using radar-time measurement techniques. During World War I the reciprocal mode was used at audio frequencies to determine the location of gun implacements by measuring the difference between the time at which gun reports were heard at three different listening posts.

Since the angle measurement capability in intermediate frequency interferometry is obtained by the measurement of a path length difference, it is logical to extend this technique to the measurement of the difference between two path length difference measurements, thereby providing a measurement of position. This method has the advantage of providing a distance measurement by the processing of signals transmitted in only one direction over the path whose distance is to be measured. This overcomes several of the problems encountered by conventional radar or radar beacon techniques which determine path lengths through measurement of the round-trip propagation time of a signal which travels in both directions over a path whose distance is to be measured.

The efficacy of the IFI technique clearly depends on ability to measure phase differences between signals at a common frequency. As little as two decades ago the desired performance was at the frontier of measurement and the associated instrumentation a laboratory oddity. In other words, two decades ago the idea of instrumenting a mobile vehicle with a three element Loran station based on differential phase ranging at an intermediate frequency would have been considered ridiculous. Today it is routine, due to tremendous strides in digital clock and related computer circuit technology accomplished in recent years. Phase measurement accuracies of 0.05° with resolution capabilities of 0.01° are typical of commercially available units today.

The geometry of a three element receiving system and a transmitter is shown in Figure 2. Using the notation shown in that figure it is apparent that:

$$\ell_1 - \ell_0 = \frac{1}{2L}\left(a^2 - 2ad\right) \quad (3)$$

and that

$$\ell_0 - \ell_2 = -\frac{1}{2L}\left(a^2 + 2ad\right) \quad (4)$$

for the typical condition, L>>d and a. Hence the difference in the path length differences $\ell_1 - \ell_0$ and $\ell_0 - \ell_2$ is given by:

$$\delta\ell = \frac{a^2}{L} \quad (5)$$

and the sum of these path length differences by:

$$\Sigma\ell = \frac{2ad}{L} \quad (6)$$

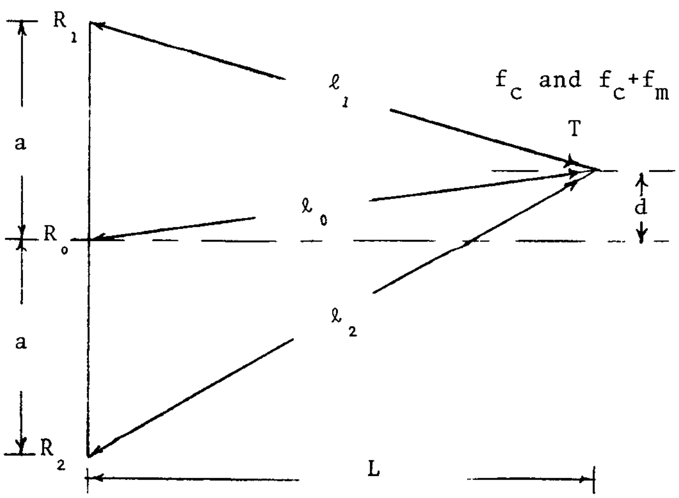

Figure 2. Distance Measurement Geometry

The important point to note with regard to equations 5 and 6 is that the difference between the path length differences, $\delta\ell$, is inversely proportional to the distance L between the transmitter and the receiving baseline, while the sum of these differences $\Sigma\ell$ provides a measure of the angular displacement of the transmitter, d/L from the perpendicular bisector of the receiving baseline.

Applying the previously described techniques of intermediate frequency interferometry, $\delta\ell$ and $\Sigma\ell$ are measured as a phase difference $\delta\phi$ and a phase sum $\Sigma\phi$ respectively, at the wavelength of the intermediate frequency associated with the transmitted signal. In particular, $\delta\phi$ and $\Sigma\phi$ may be expressed as:

$$\delta\phi = \frac{2\Pi}{\lambda_m}\left[\frac{a^2}{L}\right] \quad (7)$$

$$\Sigma\phi = \frac{4\Pi}{\lambda_m}\left[\frac{ad}{L}\right] \quad (8)$$

As a typical example of potential range measurement capabilities, an IFI system with a receiving baseline two meters in length, operating with an intermediate frequency of 300 MHz, would provide a range resolution capability of 12 meters, at a range of 300 meters with a receiving system equipped to resolve phase differences to 0.05°.

The carrier and sideband signals can be transmitted at any two frequencies consistent with the requirement that their frequency difference be equivalent to the intermediate frequency selected for system operation. This allows considerable flexibility in design. One possibility, for example, would be operation in the frequency range between 55 and 65 GHz, where the attenuation associated with molecular atmospheric oxygen is approximately 15 dB per kilometer. If transmitter power levels were adjusted to exceed the detection threshold limit by 10 dB at a range of 1 mile, the same signal would be 20 dB below the detection threshold for all vehicles at ranges of greater than two miles from the transmitter. The use of time and frequency diversity in combination with this natural phenomena of signal attenuation in the wavelength region near 6 millimeters, allows considerable latitude for discrimination against receiver jamming effects, associated with simultaneous reception of multiple transmissions.

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