APPLICATIONS OF RADIO INTERFEROMETRY TO NAVIGATION

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ABSTRACT

Radio astronomy experiments have demonstrated the feasibility of making precise position measurements using interferometry techniques. The application of this method to navigation and marine geodesy is discussed, and comparisons are made with existing navigation systems. The very long baseline technique, with a master station, can use either an artificial satellite or natural sources as position references; a high-speed data link is required. A completely ship-borne system is shown to be feasible, at the cost of poorer sensitivity for natural sources. A comparison of doppler, delay and phase-track modes of operating a very long baseline configuration is made, as that between instantaneous measurements and those where a source can be tracked from horizon to transit. Geometric limitations in latitude and longitude coverage are discussed. The characteristics of natural radio sources, their flux, distribution on the sky, and apparent size are shown to provide a limit on position measurement precision. The atmosphere and frequency standard used both contribute to position measurment uncertainty by affecting interferometric phase.

INTRODUCTION

The Navy, as well as civilian mariners, have been looking for the ideal navigation system for centuries. Recent developments in radio frequency navigation techniques, together with inertial navigation, have made navigation much more reliable, but a study of future possible techniques is still of considerable interest. One such technique is radio interferometry. The radio interferometer technique combines radio signals from two antennas spaced a distance apart to obtain the angular resolution of an antenna whose diameter equals this distance. In principle the radio interferometer is similar to the Michaelson interferometer used at optical wavelengths with both signals being combined coherently (with phase preserved) to produce an interference pattern. However, while the earth's atmosphere limits optical coherent interferometers to baselines of a few meters because of atmospheric phase degradation, this effect is much less serious at radio wavelengths, and baselines of thousands of kilometers have been used. Radio interferometers have determined positions of radio-emitting galaxies more precisely than can be done by optical means, and have measured the distance between fixed antennas with a precision of centimeters. The attractive characterictics of radio interferometry for a navigation system include, besides its high inherent precision, a possible savings on the cost and complexity of a satellite navigation system, and an all-weather capability.

The radio interferometer technique was developed several years ago by radio astronomers as a means to overcome the inherently poor angular resolution available from a radio-astronomy antenna. Figure 1 shows the basic principle of operation. A radio interferometer consists of two antennas spaced a distance apart, pointing at the same radio emission source, which may be either natural or artificial. The two incoming radio signals are amplified separately, and then brought toghether and correlated. The maximum correlation occurs when the signal from one antenna is delayed an amount equal to the excess travel time along a line from the radio source to the other antenna; the source must be smaller than the resolution of the interferometer. Thus, the interferometer measures, for a source at a distance much greater than the baseline, the dot product of the baseline and the source position vector. Early interferometers had the two antennas located close enough together so that the two signals, and also the oscillator needed to beat to base band, could be communicated by means of cables. This limited interferometer baselines to several kilometers. To overcome this, independent master oscillators were used at each station and the signals brought together by means of microwave link or high-speed tape recording. This technique is known as the Very Long Baseline Interferometer, or VLBI, technique, and has enabled antennas placed on opposite sides of the earth to form a successful interferometer. The longest baseline used so far is that between Westford, Massachusetts, U.S.A. and Semeiz, U.S.S.R. (near Yalta), a distance of about 8000 kilometers.

As mentioned in the preceding paragraph, the principle of interferometer operation is straightforward. When applied to a navigation system, however, there are many possible choices to be made. Figure 2 shows some of these. Either natural or artificial (artificial satellite) illuminating sources can be used. The two most suitable classes of natural sources are the quasars, which have a broad spectrum, and the water-vapor sources, which emit narrow band radiation near 1.35 centimeter wavelength. The natural sources are in general weaker than an artificial source, and are variable in signal intensity, but of course spare us the cost of an artificial satellite. The basic operating configuration can be either the VLBI one, with a shore-located master station, or a shipboard configuration, using two antennas on the bow and stern of a ship. If an artificial signal source is used, a "one-station" interferometer configuration is also possible, with the satellite generating the signal reference. The basic observable in all interferometers is relative phase. However, in VLBI measurements, the oscillator stability is usually too poor to measure phase directly, and either delay or relative doppler rate is measured. An instantaneous measurement of one radio source always gives a line of position on the earth's surface. There are several ways to obtain the two intersecting lines of position needed to determine ship position. This includes observing two radio sources, observing both delay and doppler from one source, observing one source at different positions on the sky, or, for the shipboard interferometer, rotating the ship. Rotating the ship adds no information for a VLBI system. The same is true for simultaneous use of more than one master station.

Although land-based interferometry is now done on a routine basis, there are several practical problems to be solved in implementing a shipboard, real-time system. Figure 3 shows in symbolic form a block diagram of a possible system, using natural sources and the VLBI concept. Note that both ship and master station require two antennas, one at each station pointed at the same natural radio source, and one each pointed at the data link satellite. Since both antennas on the ship must be kept pointed accurately, they must be mounted on an inertial platform. Second, random phase excursions must be kept to less than 1/4 of the observing wavelength (or about one centimeter) over the integration interval of several seconds. This may be done using a three-axis accelerometer as input to a phase-compensating network. Finally, the correlation peak shows up as one point in a plane in which one dimension is time delay, and the other is differential doppler. The width in both planes is affected by the ship's position uncertainty, the frequency-standard's accuracy, and ship's velocity uncertainty. A special-purpose, real-time computer is required to do this search.

The configuration diagram for the shipboard system is shown in Figure 4. The requirement for phase stability is easier to meet than for the VLBI system, since only differential acceleration must be measured, but the ship's heading must be accurately known, since this system measures angles. In addition, there is a problem obtaining sufficient signal from natural sources with two antennas small enough to be easily mounted on board ships. Figure 5 illustrates this. Two one-meter antennas can produce a usable signal for water-vapor sources in about two minutes integration, but at least 10-meter antennas would be required for a quasar system. This is not a problem for artificial sources.

Artificial satellites may be used with interferometers in various ways; in some ways, this is an extension of techniques already in use. For example, coherent doppler tracking of a space probe corresponds closely to the interferometer phase-track concept. One important use of interferometer techniques developed by radio astronomers is to point out the feasibility of measuring the range, as well as range-rate, to a target to within one carrier cycle, by the use of wide-band modulation techniques. With a precise clock on board the satellite, the range to the satellite can be measured without a real-time master station, making a "one-station" interferometer. A system with less dependence on the satellite orbit results if the satellite is observed simultaneously with a master station, and triangulation is used. The range can be tracked during a satellite pass, thus enabling determination of both coordinates of mobile station position.

Use of a shipboard interferometer with an aritifcial satellite enables determination of one angular co-ordinate at the same time its range is measured, thus enabling instantaneous position determination.

Although exact observation geometry is often complex, Figure 6 shown approximate precision that can be obtained for various modes if a favorable geometry is assumed (a signal-to-noise ratio of 10 is assumed for all sources). All measurments in the bottom half of the graph are limited by atmospheric constraints to a precision of about three meters. From this graph the inherent high precision of radio interferometer measurements may be appreciated.

Thus the concept of radio interferometric navigation may add to the complement of techniques already available for navigation. Its high inherent precision makes it especially suitable for high-accuracy applications. Although some practical problems remain to be solved for a shipboard configuration, these are believed to be easily masterable if the system is pursued.

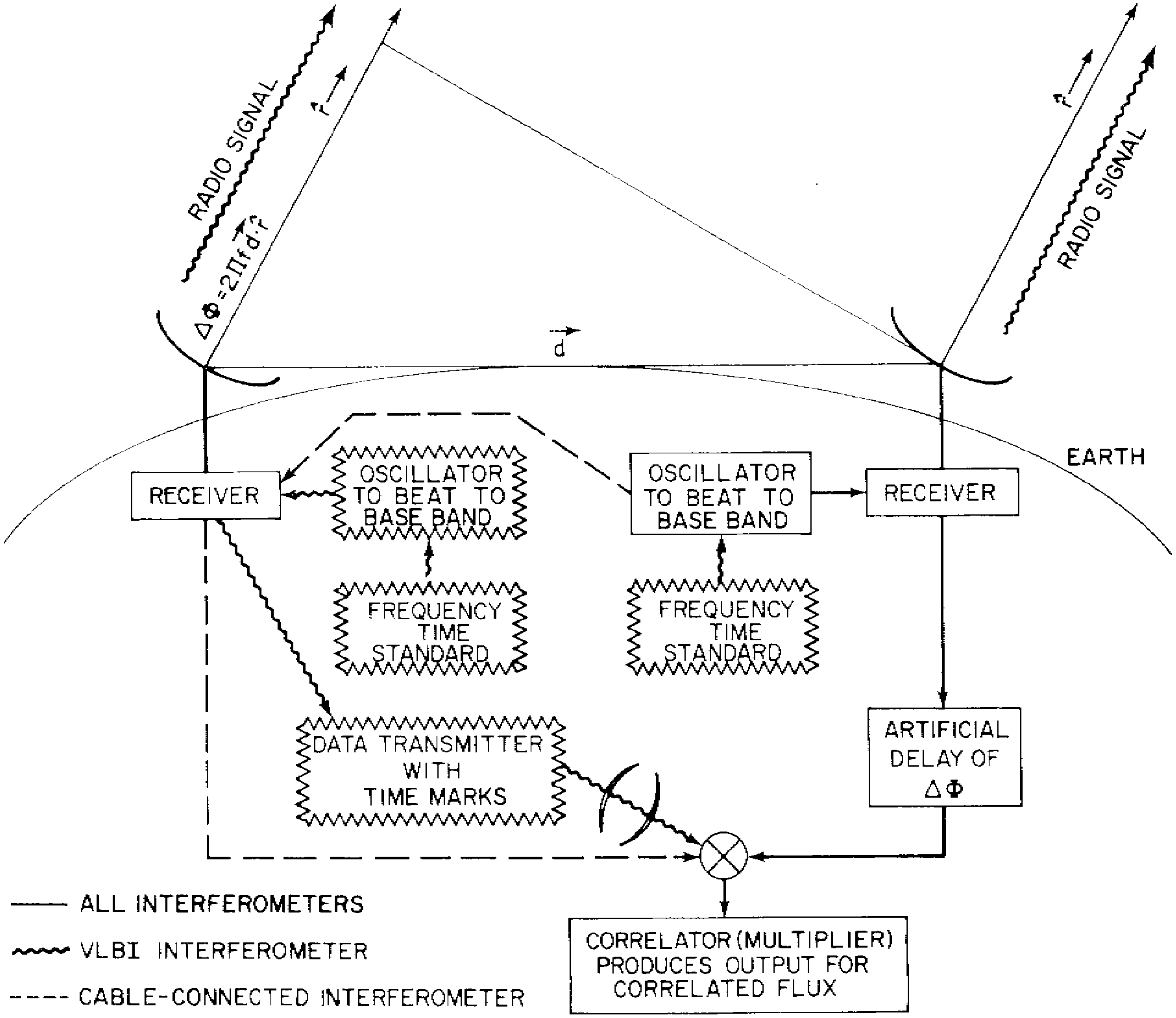

Figure 1. Basic Interferometer Configurations

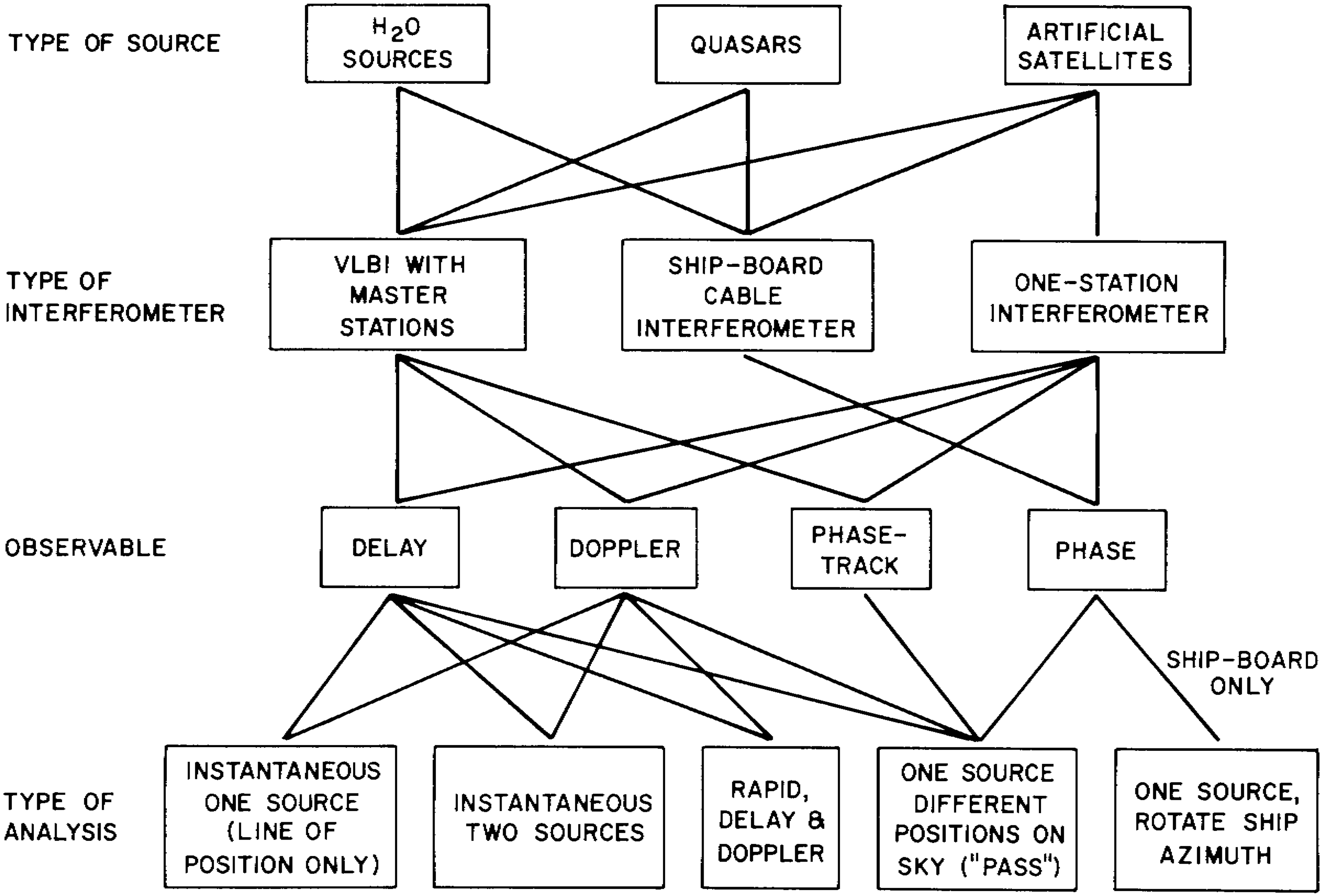

Figure 2. Interferometer Navigation System Operating Modes

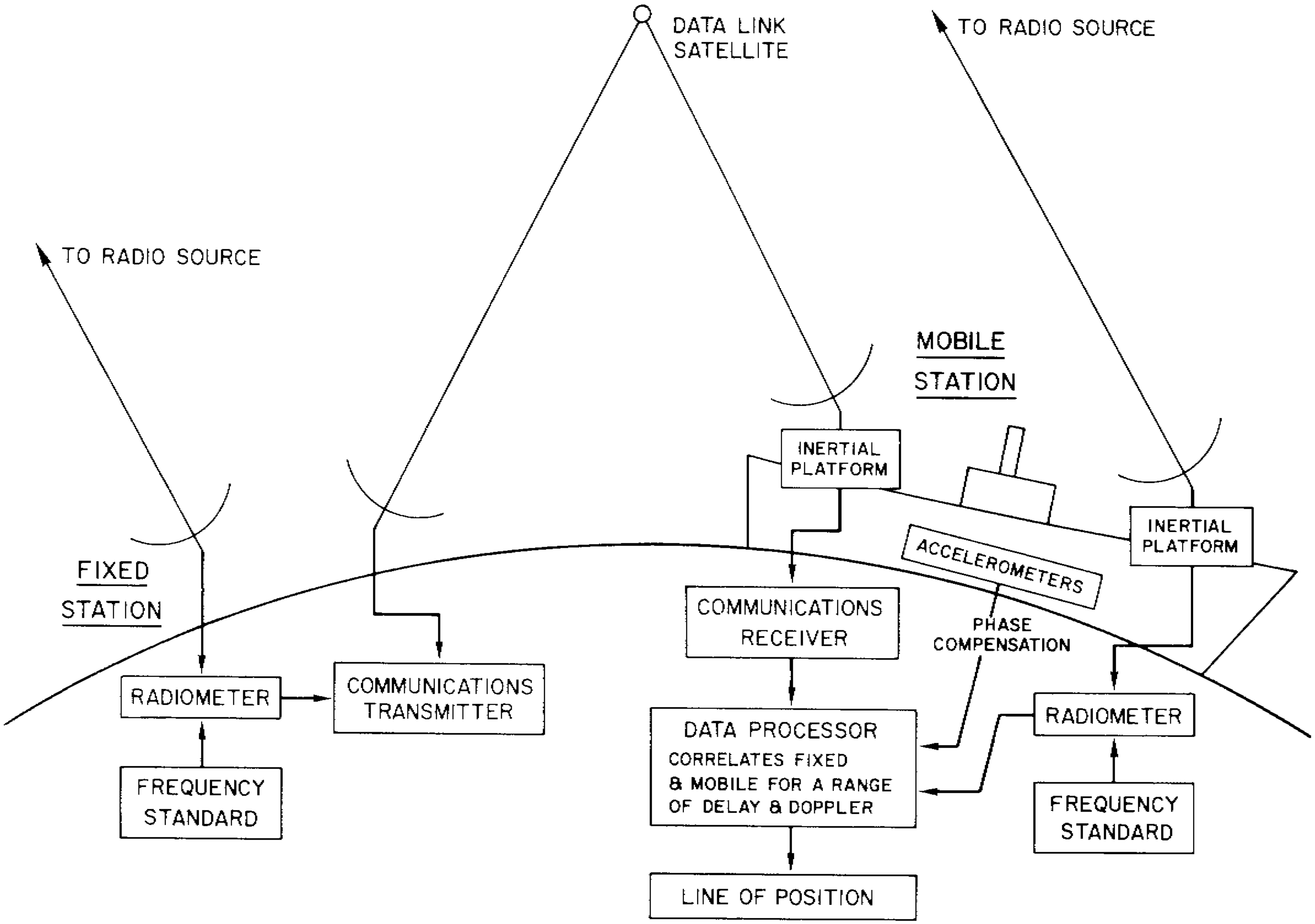

Figure 3. Very Long Baseline Interferometer Navigation System

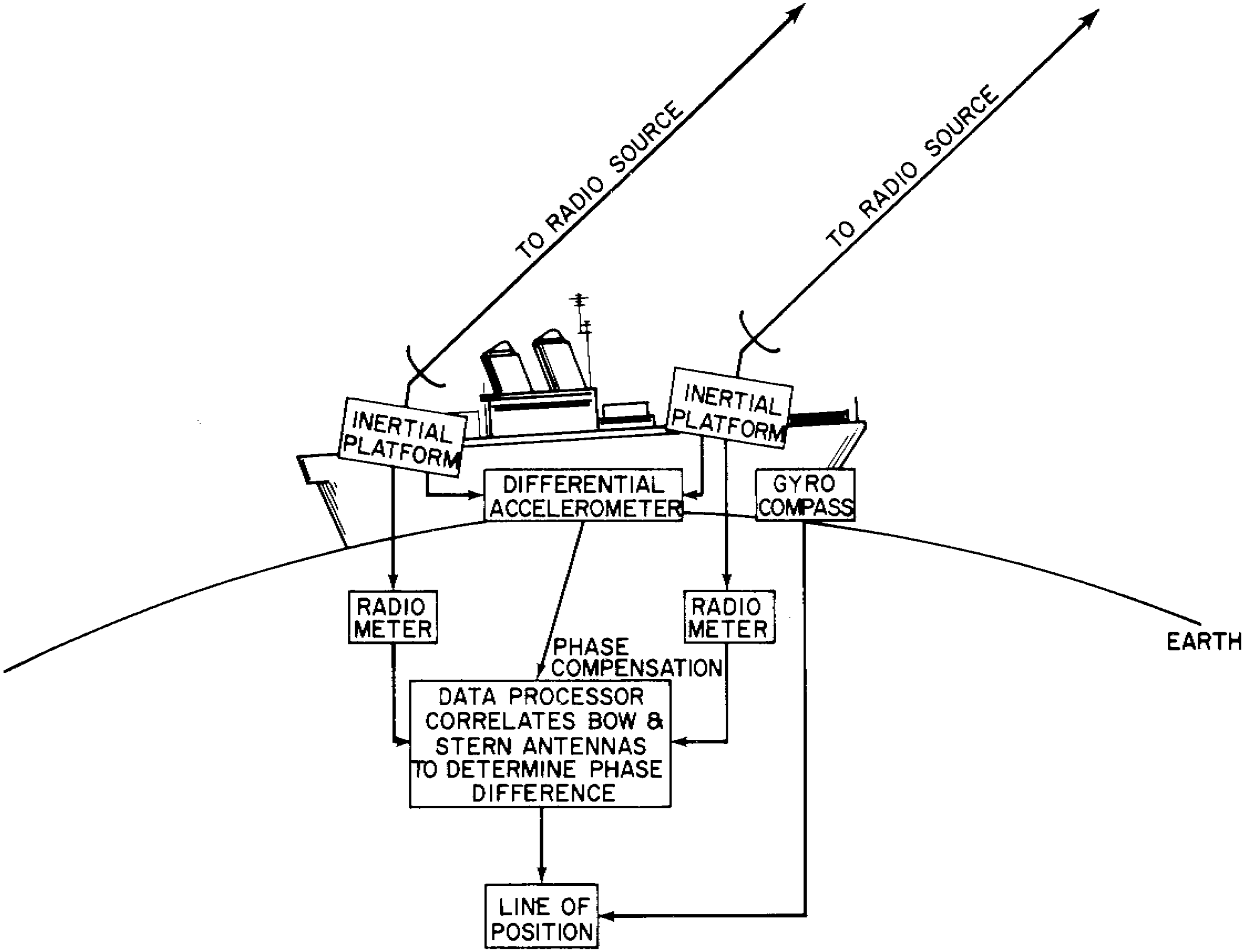

Figure 4. Shipboard Interferometer Navigation System

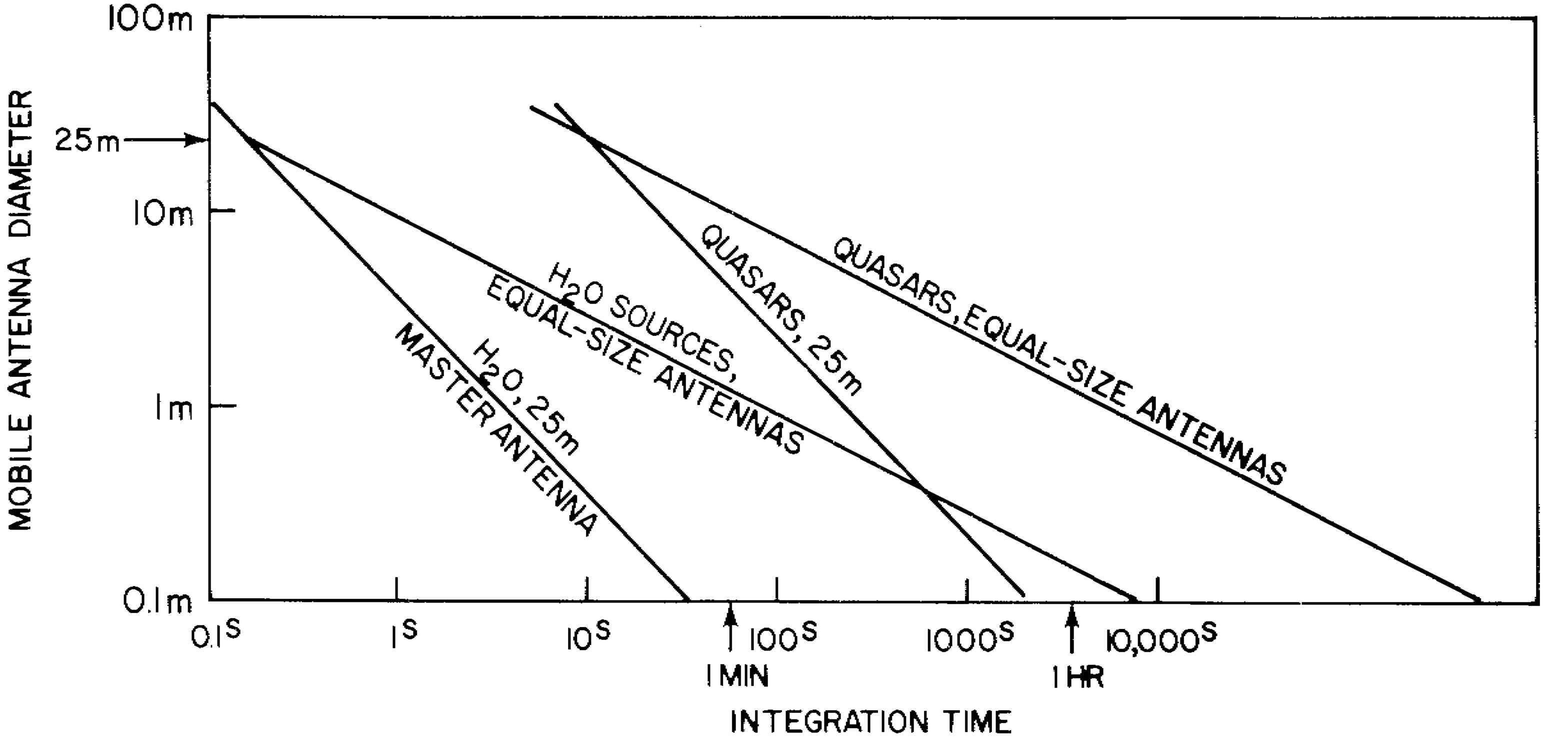

Figure 5. Required Integration Time for a Signal-to-Noise Ratio of 10 for Natural Radio Sources

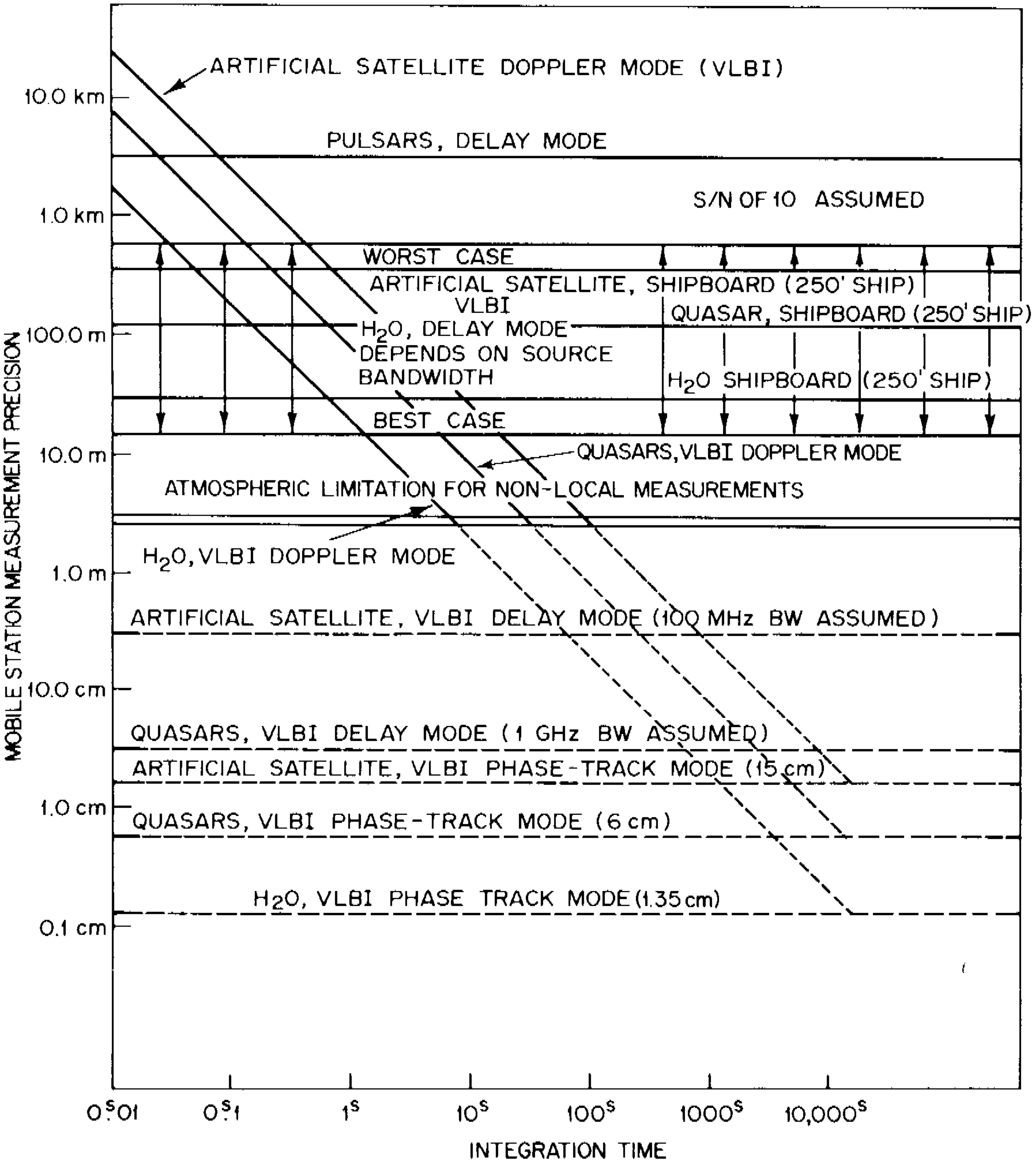

Figure 6. Inherent precision for a signal-to-noise ratio of 10 for various interferometric navigation systems. S-band operation is assumed for artificial satellites, and X-band for the quasar system.

QUESTION AND ANSWER PERIOD

MR. CHI:

Are there any questions?

MR. BLACK:

Harold Black, of Johns Hopkins APL. I misunderstood what you intended to say, when you said that a doppler system didn't work on the Equator.

DR. KNOWLES:

A doppler system will not determine latitude for you on the Equator.

MR. BLACK:

That is not correct. The Navy Navigation Satellite System, which is a doppler system, works beautifully on the Equator. It gives both components of position.

Now, you have to qualify your statement somehow.

DR. KNOWLES:

Yes, you are right, I am sorry. I should have qualified it, that applies to natural sources that travel from east to west. It doesn't apply to artificial satellites, which can get an inclination in there.

MR. BLACK:

Thank you.

MR. SWANSON:

Eric Swanson, NELC. I would like to make a comment. The whole use of VLBI for navigation, as you quite properly pointed out, requires a very wide down link. Given that the inherent function of navigation actually demands a very slight band width – it can be argued the real need is zero on transmission – you are now talking of a method that will impact the spectrum by some megacycles or worse.

Could you comment on that?

DR. KNOWLES:

Yes. It is a disadvantage of it, but I am not clear as to the statement that the real need for band width on a navigation system is zero.

And particularly, on the other point that on a satellite system there is definitely a finite band width in there.

This is, by the way, one thing which I didn't mention on the VLBI technique. When you use it on artificial satellite techniques it is really more an extension of other satellite techniques. If its essential contribution is trying to tell you to use a transmitter with a wide band width coding on it, so that you can get a lock in on the absolute phases of the transmission, the problem is that you could get by with a zero band width if you were not at all concerned about ambiguity problems. In particular, on the water vapor sources, we can get very accurate position measurements with the narrow band width, and you could let that go to infinitely narrow and still get position.

The reason you need the band width is to provide you with longer waves as well as shorter ones, to let you zero in on your position.

I am not clear that that is the answer to your question. I will just leave that up for thought.

MR. CHI:

Thank you very much.

The next paper, No. 6, which has been withdrawn, and in place of it is a paper under the title of "Application of Radio Interferometry to Clock Synchronization," by Dr. William Hurd, of Jet Propulsion Laboratory.