APPLICATION OF SIDEBAND FOLDING TECHNIQUES TO THE NAVIGATION SATELLITE SYSTEM

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ABSTRACT

A satellite navigation system is proposed employing sideband folding techniques for measuring accurately time-correlated range and/or range rate between Earth and a satellite of known ephemeris to determine the position of a navigation station on the surface of Earth. The use of sideband folding combined with harmonically related VHF and microwave carrier frequencies provides maximum accuracy while conserving transmitter power. Sideband folding, although discarding some of the received signal power, permits reception of high modulation frequencies for precise range measurement in a very narrow bandwidth. Harmonically related VHF and microwave carrier frequencies provide the high ranging accuracy of a microwave carrier, with its minimal susceptibility to ionospheric propagation phenomena, and permit narrower microwave receiver bandwidths by aided tracking of the microwave frequency. Narrow bandwidths allow use of lower transmitter powers, particularly of interest in satellite transmitters. Economy of RF power transmission and generation is enhanced by using the VHF carrier frequency for noncritical satellite transmissions, including microwave acquisition data. Provisions are made for lesser accuracy microwave Doppler navigation without navigation station transmissions.

INTRODUCTION

The Navy Transit satellite navigation system represents a major breakthrough in the state of the art of naval navigation. Accurate determination of the position of an

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observer from an analysis of Doppler shift, with time and orbital parameters known, fills a much needed all-weather world wide navigation system requirement.

Certain features are discussed which, when added to the transit-type navigation system, will improve its already good characteristics. These improvements are reduced computation, reduced observation time, and increased accuracy. The method of transmission of ephemeris and time data necessary for the position solution is not discussed. It is assumed that these data are transmitted with the required accuracy, whether received via the transit carrier or by a separate communication link.

REVIEW OF TRANSIT TECHNIQUE

Some of the pertinent characteristics of the Transit satellite system, described in Refs. 1 and 2, are reviewed here. A Transit-type satellite transmits a signal that is controlled by a very stable crystal oscillator. This signal is received at a navigation station and the frequency compared with a second stable oscillator in the navigation station. The difference in the frequencies of the two is recorded as a function of time.

The primary factors that influence the frequency recorded are: 1) the difference between the frequency transmitted by the satellite and the frequency at the reference oscillator of the navigation station; 2) the Doppler frequency shift due to the rate of change in the line of sight distance between the satellite and the navigation station; and 3) the influence of the ionosphere on the signal transmission. The desired output information is latitude and longitude of the navigation station. The computational process involved may be described as establishing a mathematical model of the received frequency difference vs. time relationship to be expected as a function of latitude and longitude, and then solving this model to get a best fit solution to the input data. Ionospheric effects on the data are significant enough to warrant discussion under a separate heading.

A further look into the computations will aid in understanding the actual problem in more detail. The required inputs, both functions of time, are 1) satellite position and 2) a series of observed frequency differences between the satellite signal, as received at the station, and a frequency reference at the station. The satellite position as a function of time can be computed from an ephemeris established prior to time of use. Both ephemeris and time information can be relayed to the navigation station via the satellite or by other radio relay, depending on the system design. The means of relay of this data is not important to the principle of operation of the system but may be important from operational considerations. The series of observed frequency differences may actually be derived from more than one signal in order to reduce effects of the ionosphere and also, as proposed in this paper, to get better resolution. Limited smoothing may be applied to reduce noise on the measurement. Care must be taken not to distort the data needed for solution of the mathematical model by excessive smoothing. Any corrections for ionospheric effects on propagation must be accomplished before entering these measurements into the mathematical model.

Although only latitude and longitude output data are needed, other terms in the error model must be evaluated to solve the problem. There are two terms of principal importance: 1) the term that accounts for the uncertainty of the difference between the satellite transmitter frequency and the reference frequency at the navigation station; and 2) the term that has to be evaluated which corresponds to a Doppler integration constant. (This may be considered to be a range zero set.) The accuracy of determination of these terms is a function of a number of factors including:

1) The exactness of the representation of the physical problem by the mathematical model. Approximations may have been made to simplify the mathematics or to allow a solution because there is insufficient information to evaluate secondary terms. The validity of the assumption of no frequency drift over the observing intervals may also be questionable.

2) The amount of noise in the measurements. Noise is here defined as random errors in the observations which include such sources as quantizing (least count) errors, miscount errors, and random propagation fluctuation errors.

3) The accuracy of the knowledge of the constants in the mathematical model. Such things as inaccuracy in the satellite orbit data, time data, absolute frequency, or knowledge of Earth's shape enter in here.

4) The strength of the solution. This deals with the degree to which variables can be separated and is a function of the geometry of the particular satellite path

being observed with respect to the navigation station location and the interval of observation.

The accuracy of the navigation solution is directly dependent on the accuracy of evaluation of terms 1 and 2. Ref. 1 provides an estimate of the overall navigation errors to be expected from the sources described above.

IONOSPHERIC EFFECTS

In the transit system, two frequencies are employed in order that a compensation can be made for the effects of ionosphere on the transmission of VHF signals. At frequencies above 100 mc, ionosphere causes the velocity of propagation to differ from the velocity of propagation through a vacuum by an amount that is, to a close approximation, inversely proportional to the frequency squared. Thus, using higher frequencies reduces the ionospheric effect on the data. By using two frequencies in the VHF region which are harmonically related, the major portion of the influence of the ionosphere can be compensated. However, some residual will be present which limits system accuracy.

Another approach to the ionospheric problem is to use a higher microwave frequency. This will further reduce the effect of the ionosphere and also increase the resolution of the system because more cycles are present to be counted. The argument against increasing the frequency is that several factors make it more difficult to get sufficient signal transmitted from the satellite to be received and used by the navigation station. First, it is more difficult to produce power in the microwave regions than at VHF frequency regions, with solid state transmitters of the type desirable in satellites. Second, the transmission losses between the satellite and the ground station increase at higher frequencies. Third, the bandwidth required to track the Doppler information obtained in the microwave signal is greater than than required at the VHF frequency, since the Doppler shift is greater. This bandwidth is dictated by the second derivative of the Doppler information, when a conventional tracking filter is used.

The difficulties of signal transmission and reception at microwave frequencies are illustrated in Figs. 1 - 4. For practical antenna gains, as shown in Fig. 1, the total transmission loss as a function of frequency is shown in Fig. 2. The corresponding signal/noise ratios of the indicated power outputs and receiver noise figures and a receiver bandwidth of 1 kc are shown in Fig. 3. The actual equivalent IF noise bandwidths required to track a satellite in a 400 n mile orbit is shown in Fig. 4. A type-2 servo with a maximum lag of 0.2 radian was used for this graph. The resulting signal/noise ratio in the tracking filter is shown in Fig. 5. This curve is indicated as "S/N without aided tracking." Since about 15-db signal/noise ratio is required to satisfactorily track, it is apparent that some improvement is necessary if tracking at 3 kmc is to be achieved.

PASSIVE DOPPLER SYSTEM

The technique discussed in this paper proposes that the satellite transmit two frequencies. One is a frequency similar to one of the two used in the VHF transit system. The other, instead of being a second harmonic, is a much higher order harmonic in the S-band region. The microwave frequency can be produced in a satellite by means of presently available varactor multipliers in an all solid state transmitter. (See Ref. 3 and 4.) The state of the art has advanced to the point where a power output level of about 100 mw at 3000 mc is feasible with a transmitter input power of $2\frac{1}{2}$ w. This power is in the region of power that might reasonably be made available in a small satellite for continuous operation using solar cells and storage battery sources. Power outputs for a transmitter with this input power are shown over the frequency region of interest in Fig. 6.

The difficulty in tracking this increased information rate of microwave Doppler in the navigation station microwave receiver is overcome with aided tracking in the proposed system, as shown in Fig. 7. The VHF Doppler information is used as an input to "buck out" the major Doppler effect at the microwave frequency. The output frequency, determined by VHF measurement, is multiplied by the ratio "N" between the VHF carrier and the microwave carrier. This frequency, which contains Doppler information, is subtracted in a mixer from the information present on the microwave channel. As the frequency shift and rate of change of frequency shift are substantially reduced at the mixer output, the signal can be tracked in a much narrower filter. Very weak signals received in the microwave channel can consequently be tracked without requiring undue microwave antenna gain. After the signal has passed through this narrow tracking filter, it is combined with the frequency derived by multiplying the VHF signal to produce a composite measurement that contains frequency variations equivalent to the Doppler information on the microwave carrier alone. Thus the signal has been passed through a narrower band filter than would be feasible without this technique.

An alternate technique for aided frequency tracking would be to use computer derived information to replace the frequency information generated from the VHF signal. This technique can be used with the proposed satellite to allow passive microwave Doppler tracking without the use of the VHF signal and would allow a submarine to project a very small antenna above the water to make the required observations. This antenna could consist of a dielectric rod about 1 in. diam. and 18 in. long extended on a periscope type mount above the water and pointed approximately at the satellite.

Some means of using very narrow filter bandwidths is required to make microwave Doppler practical. Aided tracking provides a good solution to this problem. The result of a computation for the frequency of 3000 mc with aided tracking is shown in Fig. 5. Since the VHF aided tracking technique provides a straightforward method of frequency acquisition as well as tracking, it is recommended for most navigation station applications. On submarines, addition of a computer aided tracking and acquisition mode is justified. Under conditions in which possibility of surface detection must be minimized, this addition allows navigation while exposing only the microwave antenna.

A summary of the passive tracking portion of the proposed system is in order. A microwave signal will be transmitted from the satellite instead of one of the VHF signals such as now used in transit. The other VHF signal will be used for aided frequency tracking and aided frequency acquisition of the microwave signal. The microwave signal, by providing more Doppler cycles and less ionospheric error than a VHF signal, will allow improvement in accuracy, even when used in the passive mode. These signals serve additional functions allowing active mode operation.

FEATURES OF ACTIVE MODE

An active mode is incorporated in the proposed system to give a means of evaluation of terms 1 and 2 of the mathematical model described above to a higher accuracy than possible with the passive system. This simplifies the computation, reduces the observation time needed, and provides greater accuracy. It should be recognized that, to an extent, these are tradeoff improvements in that not all improvements can be achieved to the fullest extent simultaneously. However, all can be achieved simultaneously to a large extent. A significant improvement possible from the proposed active mode is that the application of this technique at the stations used for establishing the satellite ephemeris improves the accuracy of all navigation station measurements whether or not they operate in the active mode.

ACTIVE DOPPLER OPERATION

The active mode would provide both two-way Doppler (active Doppler) and two-way ranging (active ranging) without compromising the operation of the satellite with navigation stations operating in the receiving (passive) mode only. The active Doppler measurement described in this section provides the method of accurately evaluating term 1 in the mathematical model.

Frequency acquisition by the navigation station is relatively easy despite the narrow system bandwidths. At all times the satellite is transmitting a VHF signal and a harmonically related microwave signal. The navigation station initiates tracking of the satellite VHF signal, followed by tracking of the microwave signal, as described in the passive Doppler discussion. After the tracking filters are operating on both signals, a measurement of the frequency difference between the received satellite signal and the frequency reference at the navigation station is made. A transmitter control signal is generated from the measurement. This causes the transmitter in the navigation station, while still inoperative, to be tuned from its reference frequency to a new frequency opposite in direction to the apparent Doppler frequency shift, in the received signal. Manual adjustment is provided for trimming out the effects of any known frequency drifts between the satellite transmitter frequency and the navigation station reference frequency. On operator command, the navigation station transmitter is activated for a short burst transmission.

A simplified block diagram of the proposed active system is shown in Fig. 8. The microwave signal of frequency f_1 is transmitted to the satellite. There it passes from the antenna through a duplexer (not shown) to a microwave mixer. About 1/2 mw of the satellite transmitter power signal of frequency f_2 is also injected into this mixer to act as a local oscillator signal. At the output of the mixer the difference between the received and transmitted frequencies appears and is fed into a narrow band intermediate frequency amplifier. After amplification, this difference frequency signal is transmitted as a subcarrier fm_3 on the VHF carrier f_3 to the navigation station. After demodulation and filtering, it is subtracted from the microwave receiver and microwave transmitter difference frequency. The resulting signal gives the normal two-way Doppler information as if transmission had been both ways at the frequency f_1 of the navigation station transmission. This can be expressed as follows:

$$f_d = f_1 - f_2(1-D) - fm_3(1-D) \qquad [1]$$

$$fm_3 = f_1(1-D) - f_2 \qquad [2]$$

$$f_d = f_1 - f_2(1-D) - [f_1(1-D) - f_2](1-d) \qquad [3]$$

$$= 2f_1 d - f_1 D \exp 2 \qquad [4]$$

Since $D \lll 1$

$$D \approx f_d/2f_1$$

f_1 = carrier frequency of the navigation station transmitter

f_2 = carrier frequency of the satellite microwave transmitter

fm_3 = modulation subcarrier on the satellite microwave transmitter

f_d = measured Doppler frequency

D = Doppler coefficient = range rate/velocity of transmission

Since the passive frequency measurement shown in Fig. 7, but omitted from Fig. 8, can be carried out simultaneously with the active determination of the Doppler frequency, the difference between the navigation station reference oscillator and satellite transmitter can be accurately determined.

Since the transmitter at the navigation station is pretuned to account for Doppler shift, the bandwidth of the satellite narrow band IF amplifier need only be great enough to allow for a signal detuning of little more than twice the uncertainty in frequency difference between the satellite transmitter and the navigation station frequency reference. For example, a relative frequency accuracy of

10^{-7} should easily be attained, since even passive measurements allow this difference to be computed, and drifts between observations should be very low. At S-band this would correspond to a plus or minus 600 cycle detuning allowance. Thus a receiver bandwidth as narrow as 1.5 kc could safely be used.

Several features were omitted from the diagram and explanation for reasons of simplicity. A squelch circuit is employed to shut off the modulation signal when no signal is being received. A second mixer is also used. It is supplied with a subharmonic from the transmitter multiplier chain as the second LO signal and passed into a second IF amplifier before feeding into the VHF transmitter. This frequency offset is accounted for in reduction of the data.

ACTIVE RANGING

In addition to measuring the Doppler frequency in an active manner, the proposed system also provides means for measuring the range by measuring the phase delay of modulation frequencies. This provides data for determination of mathematical model term 2 (range zero set).

This active ranging technique, like the microwave active Doppler technique, is an extension of the techniques used in the Azusa tracking system. In these systems a series of modulation frequencies is transmitted from the tracking station and repeated by the transponder carried in a missile or satellite being tracked. (See Ref. 5). The phase delay of the signal out to the transponder and return is measured. The first measurement is made with a low frequency that has a long wavelength so there can be no uncertainty as to the number of whole cycles of phase delay. A single measurement is not precise enough and so a second frequency a decade or more higher is transmitted. The first measurement determines the whole number of cycles of phase delay of the second frequency, and the second frequency establishes the range measurement to an accuracy improvement of approximately the ratio of the two frequencies. If this accuracy is still not sufficient, a third measurement at an even higher frequency can be used for an additional measurement.

In order to keep the navigation station simple and its power requirements low, it is desirable to keep the satellite receiver sensitivity reasonably high, which dictates a narrow receiver bandwidth. In the proposed system a simple technique is employed which allows the satellite receiver bandwidth to be much narrower than with conventional FM ranging systems. High ranging accuracies require the use of higher modulation frequencies. Conventional FM receivers require bandwidths several times the modulation frequency. However, the information bandwidth of ranging signals is much lower than the frequency of the signal themselves. For example, the one-way Doppler frequency shift of a 50 kc signal to or from a navigation satellite would be a maximum of about plus or minus 1 cps, and the required tracking bandwidth, which is dictated by acceleration, can be less than 1 cps. This gives rise to the need for special detectors with extremely low thresholds, such as correlation detectors, in order to work down to minimum usable signal powers. These detectors can demodulate ranging signals that, although far below the noise level at the detector input, can be restored to useful signal to noise ratios by post-detector filtering. In a satellite, however, these techniques are too complicated to be reliable. A compromise technique known as sideband folding is used here on the basis of simplicity and adequacy.

The basic concept of sideband folding is shown in Fig. 9. Two signals are injected into a mixer. One is the received signal that is frequency modulated at fm_1 with an index ≈ 1 and the other the local oscillator signal that is frequency modulated at fm_2, also with an index ≈ 1. If fm_1 and fm_2 are very nearly equal, some of the resulting sidebands they produce are clustered around the intermediate frequency carrier resulting from the difference of the signal and local oscillator carriers. These signals are passed through a narrow band amplifier that will only pass the sidebands clustered around the carrier. This resulting signal is amplitude modulated at frequency $fm_1 - fm_2$. Further explanation of this technique is given in Ref. 6.

The sideband folding technique is applied in ranging in Fig. 8. In this system, the satellite microwave transmitter, which is also the LO signal, is frequency modulated at fm_2 (50.3 kc in the proposed system). The signal transmitted from the navigation station is frequency modulated at fm_1 (50.0 kc in the proposed system). The difference between the modulation frequency received at the satellite and transmitted on the microwave carrier appears as amplitude modulation on the subcarrier fm_3 (at approximately 300 cps + Doppler in the proposed system) transmitted over the satellite VHF transmitter. These three signals at the navigation station provide the ranging measurement. The frequency and phase information contained in the modulation on the microwave signal fm_2 (1-D) received from the satellite is combined with the modulation frequency on the microwave signal fm_1 transmitted to the satellite. This resultant phase is compared with the phase of the demodulated subcarrier fm_3 (1-D) received from the satellite on the VHF carrier. The difference in phase between these signals is a measure of the phase shift that would have occurred if the frequency modulation on the signal transmitted to the satellite had been directly repeated back.

In the proposed system a 10 kc satellite receiving bandwidth is planned. This permits repeating modulation signals with frequencies up to 5 kc directly and a 50 kc signal as a folded sideband.

The proposed system will provide ranging to an accuracy of about 50 ft. This is based on signal/noise ratios to be expected and assumes a two-second transmission from the navigation station. Ranging accuracy could be improved by higher gain antennas at the navigation station or longer transmission times.

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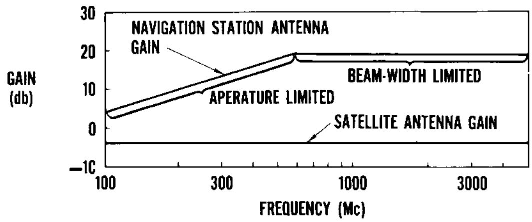

Fig. 1 Practical antenna gains

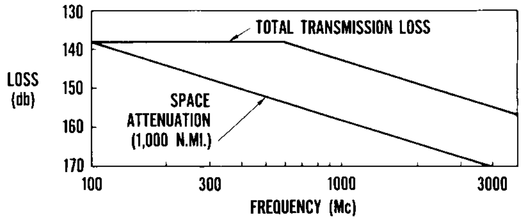

Fig. 2 Transmission characteristics

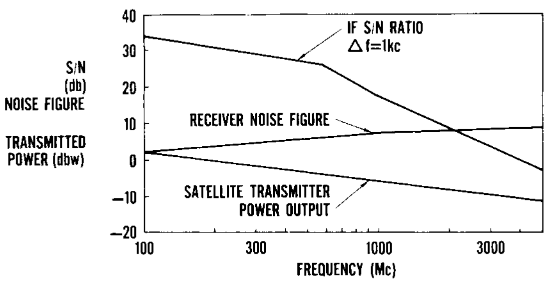

Fig. 3 Signal to noise ratio in 1 kc bandwidth for assumed power and noise figure

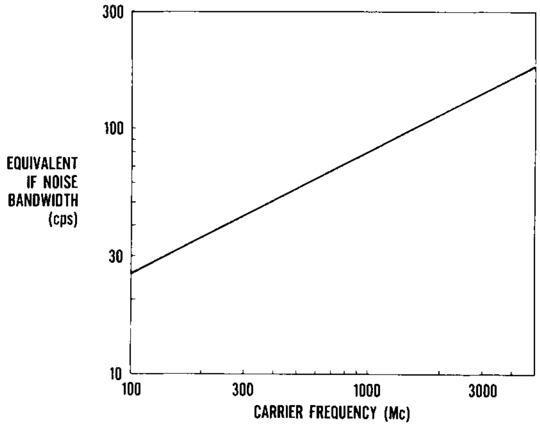

Fig. 4 Bandwidth required to pass doppler data

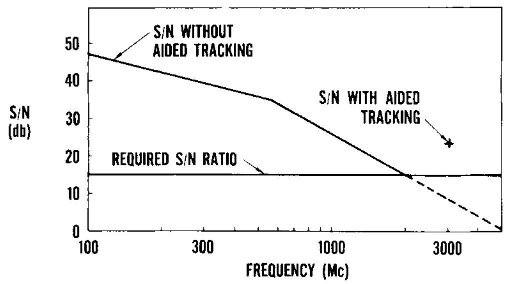

Fig. 5 Output signal to noise ratio

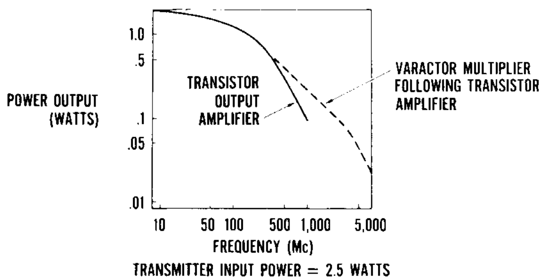

Fig. 6 Crystal controlled satellite transmitter

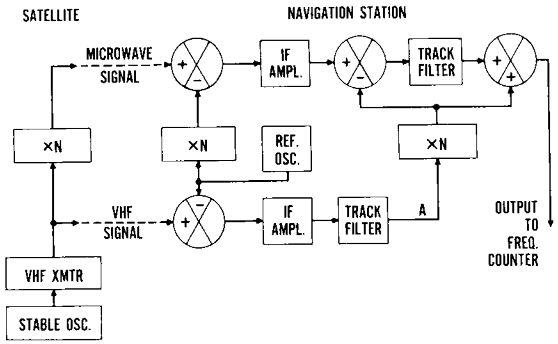

Fig. 7 Proposed passive Doppler system

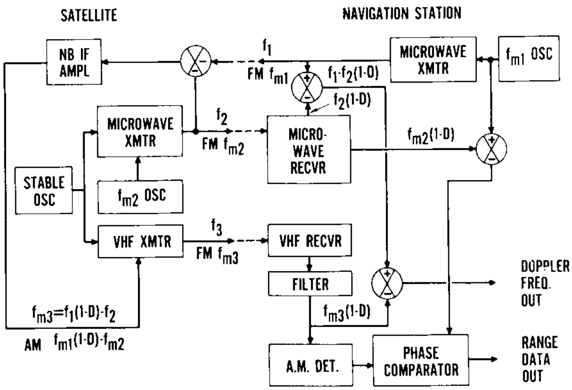

Fig. 8 Proposed active system

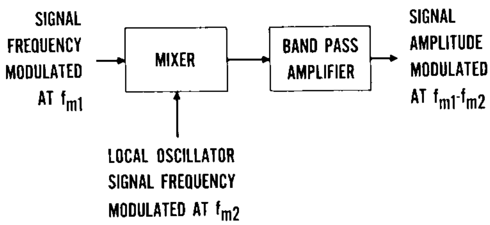

Fig. 9 Sideband folding technique