Doppler Tracking of Planetary Spacecraft

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***Abstract*—This article concerns the measurement of Doppler shift on microwave links that connect planetary spacecraft with the Deep Space Network. Such measurements are made by tracking the Doppler effect with phase-locked loop receivers. A description of equipment and techniques as well as a summary of the appropriate mathematical models are given. The two-way Doppler shift is measured by transmitting a highly-stable microwave (uplink) carrier from a ground station, having the spacecraft coherently transpond this carrier, and using a phase-locked loop receiver at the ground station to track the returned (downlink) carrier. The largest sources of measurement error are usually plasma noise and thermal noise. The plasma noise, which may originate in the ionosphere or the solar corona, is discussed; and a technique to partially calibrate its effect, involving the use of two simultaneous downlink carriers that are coherently related, is described. Range measurements employing Doppler rate-aiding are also described.**

I. Introduction

Although several radiometric techniques are available for determining trajectory parameters of planetary spacecraft [1], the measurement of Doppler shift on microwave links is the most common. As is well known [2], the Dopper shift is (in the non-relativistic approximation) proportional to the rate of change of distance separating transmitter and receiver. In measuring the Doppler shift on microwave links connecting a planetary spacecraft with a ground station, it is possible to obtain a wealth of information about the trajectory of that spacecraft. The speed with which a planetary spacecraft recedes from the earth (or approaches the earth) may, in this way, be determined. In addition, it is possible to infer the position in the sky of a planetary spacecraft; this is accomplished by examining the diurnal variation imparted to the Doppler shift by the rotation of the earth. As the ground station rotates underneath a planetary spacecraft, the Doppler shift is modulated by a sinusoid whose amplitude depends on the declination angle of the spacecraft and whose phase depends upon the right ascension [3]. These angles can therefore be estimated from a record of the Doppler shift that is (at least) of several days duration. In addition to providing information about the trajectory of a planetary spacecraft, Doppler measurement data can be used for the purpose of radioscience: for example, to measure the electron concentrations of ionospheres and interplanetary plasmas [4].

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An accurate Doppler measurement for a spacecraft must ordinarily involve two microwave links. An uplink carries a stable frequency reference from the ground station to the spacecraft, and a downlink returns the reference with a two-way Doppler shift. This configuration is dictated by the requirement that the frequency reference be highly stable [5]. The reference must, in fact, be stable to a degree that is difficult to achieve with any oscillator that is suitable for spaceflight. The Deep Space Network [6], the network of ground stations that are employed to track planetary spacecraft, uses hydrogen masers to generate the necessary frequency references. These devices have Allen deviations of approximately 2×10^{-14}, 3×10^{-15} and 1×10^{-15} for integration times of 10 100 and 1000 seconds, respectively [7]. These masers are good enough that the quality of Doppler measurement data is limited by thermal noise or plasma noise and not by the inherent instability of the frequency references.

An essential feature of a Doppler measurement with a spacecraft is the tracking of the microwave carriers by Phase-Locked Loop (PLL) receivers [8]. There is such a receiver at the spacecraft for tracking the uplink carrier and at the ground station for tracking the downlink carrier. When communicating over planetary distances, the arriving carriers are weak enough that noise bandwidths of a few hertz are required to achieve acceptable signal-to-noise ratios. A typical arriving carrier will, however, wander some tens of kilohertz due to a varying Doppler shift. In every case, the noise bandwidth has to be quite small compared with the dynamic range of the incoming frequency. A PLL receiver acts as a narrow bandpass filter whose center frequency adaptively tracks the frequency of the arriving carrier, permitting a noise bandwidth that is orders of magnitude smaller than the excursion range over which the receiver tracks.

This article is a description of the Doppler measurement technique used for planetary spacecraft as practiced within the Deep Space Network. This article discusses both the phase-locked transponding of the uplink carrier at the spacecraft and the measurement of the downlink carrier frequency at the ground station. The two most important sources of measurement error, thermal noise and plasma noise, are discussed. Finally, there is a brief description of range measurement to a planetary spacecraft; the instrumentation for such a measurement makes use of Doppler rate-aiding. For more information on phase-locked transponders, the interested reader may consult the companion article in this issue of the Transactions [9].

II. Phase-Locked Transponding

A planetary transponder incorporates a PLL receiver for tracking a single uplink carrier; it also has frequency synthesis electronics to generate one or more downlink carriers that are coherent with the uplink [9]. The instantaneous frequency of each downlink carrier equals that for the arriving uplink carrier multiplied by a constant—the transponding ratio. This is what is meant by coherency between downlink and uplink. Coherency is essential for the two-way Doppler measurement. The transponding ratio is always a ratio of two integers: 240/221 and 880/221 are typical values. A transponder is a multi-purpose device which also must demodulate commands, modulate the downlink carriers with telemetry, and echo a ranging signal. The mechanization of carrier and ranging-signal transponding within a planetary transponder are best discussed by considering a typical design. The following paragraphs explain the operation of the transponder that is on board the Galileo spacecraft to Jupiter.

The Galileo transponder will phase-lock on a 2113 MHz uplink and generate two downlink carriers with the transponding ratios 240/221 and 880/221. This function of the transponder is shown in Fig. 1. The phase-locking is achieved by a multiple-conversion heterodyne PLL. This is the type of loop needed to track a residual carrier and to achieve good image band rejection. The first Local Oscillator (LO) has frequency $208\omega_V$, where $2\omega_V$ is the frequency of the Voltage-Controlled Oscillator (VCO) and is related to the incoming frequency ω (when the loop is in lock) by $2\omega_V = (2/221)\omega$. The frequency of the first Intermediate Frequency (IF) stage is approximately 124 MHz—the exact value ($13\omega_V$) depending on the Doppler effect. The second LO has frequency $13\omega_V - \omega_S$, and the second IF stage is at 12.25 MHz (ω_S). It is necessary that the signal at this stage remain at the center of the passband so that the ranging modulation not be subject to a varying group delay. A constant frequency at this stage is achieved by using a spacecraft-based 12.25 MHz reference as the LO for the phase detector. The VCO is coherent with the uplink and independent of the 12.25 MHz reference. This latter independence is achieved by including the 12.25 MHz reference in the second LO; thus, at the phase detector the 12.25 MHz reference exactly cancels. The downlink carriers are generated by multiplying the frequency of the VCO. The first downlink has frequency $\omega_1 = 240\omega_V = (240/221)\omega$, and the second downlink has frequency $\omega_2 = 880\omega_V = (880/221)\omega$.

The ranging signal on the uplink is also transponded. The reference frequency ω_S is used to demodulate the uplink carrier (as well as to provide a phase error signal for the PLL). There is a ranging channel in the transponder that filters the demodulated uplink ranging signal and adjusts its level (using automatic gain control) for phase modulation onto the downlink carriers.

Not shown in Fig. 1 but essential for the operation of this transponder in space is the Automatic Gain Control (AGC) function. The AGC governs the amplification in the IF stages; it is needed to allow operation of the loop over a wide dynamic range of input levels with relatively small changes in loop tracking characteristics.

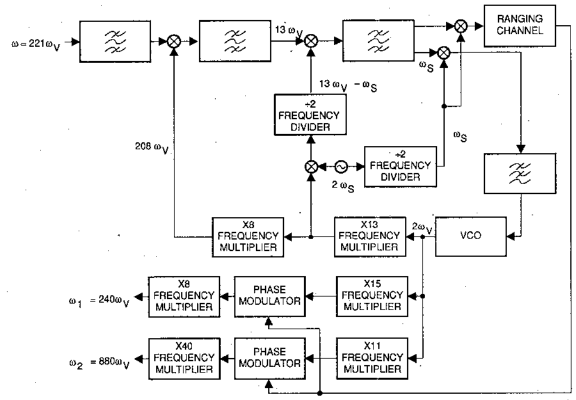

Fig. 1. Galileo transponder.

III. Two-Way Doppler Measurement

Two-way Doppler measurement, including carrier transponding at the spacecraft, is illustrated in Fig. 2 for the case of two simultaneous downlinks. The second downlink permits calibration of the plasma delay on the downlink, as will be discussed later. The uplink microwave carrier is synthesized from the stable reference provided by the hydrogen maser and amplified by a klystron. Upon reception at the spacecraft, the uplink carrier is transponded. The resulting downlink carriers are amplified by Travelling-Wave Tube Amplifiers (TWTA). Back on earth, the downlink carriers are amplified by super-cooled maser Low Noise Amplifiers (LNA) and tracked by PLL receivers, permitting an accurate measure of the downlink frequencies. The measurement is completed by a comparison of the incoming and outgoing frequencies.

A PLL receiver for the tracking of a downlink carrier is shown schematically in Fig. 3. In this type of design, the loop is closed with the first Local Oscillator (LO). The second LO frequency is independent of the VCO and is derived instead from the stable reference that is available at the ground station. The feedback action of the loop causes the downconverted carrier in the first IF stage to have a frequency that equals that of the second LO. The purpose of the frequency synthesizer is to reduce the dynamic range over which the VCO must track. That is to say, the receiver may be tuned by controlling this frequency synthesizer. This tuning must, of course, be done in a phase-continuous fashion. It is desirable to measure the frequency not at the VCO, but rather at the first LO (or at the input to the frequency multiplier in the first LO path). The frequency of the first LO is different from the arriving downlink carrier frequency by exactly the amount of the second LO, and this latter number is a highly stable constant. If the VCO frequency were to be measured instead, then it would become necessary to take into account the tuning down on this receiver in order to calculate the frequency of the arriving downlink carrier.

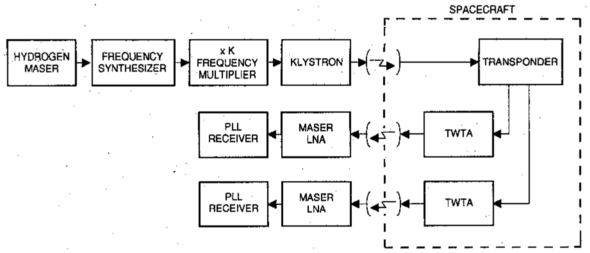

Fig. 2. Two-way coherent Doppler measurement.

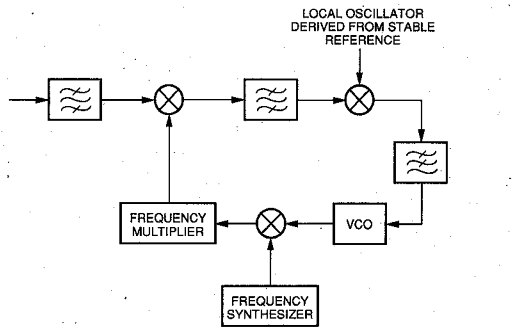

Fig. 3. PLL receiver at ground station.

It is sometimes desirable to vary the frequency of the uplink carrier. By varying the uplink frequency in just the right way, the bulk of the Doppler shift on the uplink can be compensated so that the carrier arriving at the spacecraft has a nearly constant frequency. This has the advantage of minimizing the range of frequencies that must be tracked by the transponder PLL. Of course, the uplink Doppler shift can be compensated in this manner only to the extent that the Doppler can be predicted. (If the Doppler shift could be completely predicted, there would be no need for a Doppler measurement.) When the uplink frequency is varied, the hydrogen maser still serves as the ultimate reference. The frequency synthesizer in the uplink path is controlled by a computer to produce the desired profile in uplink frequency. It is essential that the frequency synthesizer produce a phase-continuous carrier; in the Deep Space Network, phase-continuous synthesizers employing the Digiphase technique [10] are used.

The only remaining task is to compare the frequencies of the outgoing uplink and the incoming downlink in such a way as to estimate the rate of change of the two-way delay. It is more convenient in the kind of mathematical analysis that follows to deal with the rate of change of two-way delay rather than with two-way Doppler shift, but these two quantities are intimately related. The more general case of a time-varying uplink frequency is considered in the analysis to follow. The analysis will suggest an appropriate observable from which the rate of change of two-way delay may be inferred.

The uplink carrier phase at the ground station shall be represented here by $\omega t + K\theta(t)$, where ω is the nominal angular frequency of the uplink carrier and $\theta(t)$ is the instantaneous phase change caused by the frequency synthesizer in the transmitter. It should be noted that ω is a constant parameter because the time-varying part of the uplink carrier frequency is in $\theta(t)$. The factor K is due to a frequency multiplier in the transmitter.

The phase of a downlink carrier as it arrives back at the ground station is of the form $G_i\omega[t - \tau] + G_iK\theta(t - \tau)$, where G_i is the transponding ratio for this downlink. The two-way delay is denoted τ; it is an implicit function of time.

The processing needed to obtain an appropriate observable is described here. The frequency of the first LO of the receiver shown in Fig. 3 is measured and adjusted by the correct offset to obtain a measure of the downlink carrier frequency. The transmitted uplink frequency is multiplied by G_i and then subtracted from the downlink frequency. This difference is then divided by the nominal value of the downlink frequency $G_i\omega$, and the result is an observable $\xi_i(t)$ that equals

$$\xi_i(t) = \frac{d}{dt}\left[-\tau + \frac{K}{\omega}\theta(t - \tau) - \frac{K}{\omega}\theta(t)\right]. \tag{1}$$

From this observable may be calculated the rate of change of two-way delay, $(d/dt)\tau$, by taking into account the tuning history of the frequency synthesizer in the transmitter.

The error in this Doppler measurement (in velocity units) due to thermal noise can be computed by

$$\sigma_v = \frac{c\sqrt{2BN_0/P}}{2\omega G_i T} \tag{2}$$

where P/N_0 is the effective signal-to-noise spectral density ratio, B is the noise bandwidth of the ground station PLL receiver, T is the integration time, and c is the speed of light in vacuum. This equation assumes that the downlink thermal noise dominates over that for the uplink. This error formulation also assumes that a simple averaging of the observed instantaneous frequency is done over time T. If $T >> 1/B$, then better algorithms exist for the estimation of the Doppler effect in the presence of thermal noise. However, these algorithms offer no improvement if the measurement error is dominated by something besides thermal noise. Often, in fact, it is plasma noise that dominates.

Fig. 4 shows typical Doppler measurement performance; in this case, the Pioneer 10 spacecraft was being tracked on July 20, 1989 with an uplink carrier of 2111 MHz and a transponding ratio of 240/221. P/N_0 was 11 dB-Hz and B was 2.5 Hz. The straight line in Fig. 4 shows the expected performance from thermal noise theory. For the small integration times, the actual performance follows that straight line; hence, for these small integration times the measurement error was dominated by thermal noise. For the larger integration times, however, the measurement error was dominated by phase scintillations picked up in transit through the solar corona (The angle between Pioneer 10 and the sun as seen from earth was, at the time of measurement, 44 degrees). This is typ-

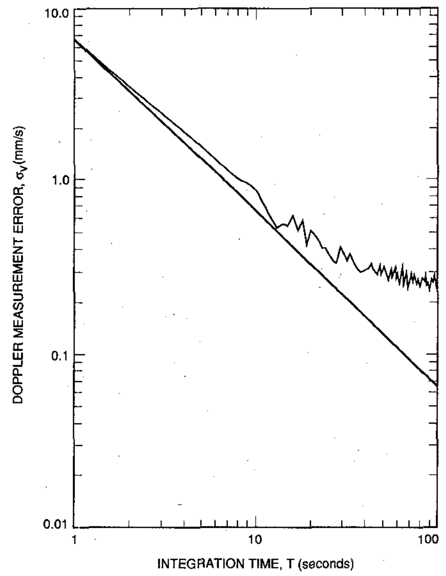

Fig. 4. Doppler measurement error for Pioneer 10 (P/N_0 = 11 dB-Hz and B = 2.5 Hz).

ical, because the thermal noise contribution decreases with T, until something else (usually plasma noise) begins to dominate.

The local phase velocity of a microwave carrier passing through a plasma depends on the local concentration of free electrons N_e [11] and is of the form

$$\frac{c}{\sqrt{1 - \dfrac{N_e q_e^2}{m_e \epsilon_0 \omega^2}}}$$

where m_e is the mass of an electron, q_e is the charge of an electron, ϵ_0 is the permittivity of free space, ω is the nominal (angular) link frequency, and N_e is the free electron concentration in units of electrons/m^3. In order to compute the delay due to the presence of a plasma, it is necessary to integrate the reciprocal of the local phase velocity along the ray path [12].

In the presence of plasma, then, the observable $\xi_i(t)$ acquires extra terms that are due to time-varying plasma phase delays on uplink and downlink.

$$\xi_i(t) = \frac{d}{dt}\left[-\tau + \frac{K}{\omega}\theta(t-\tau) - \frac{K}{\omega}\theta(t)\right] - \frac{C_e}{\omega^2}\dot{I}_u - \frac{C_e}{\omega^2 G_i^2}\dot{I}_d. \quad (3)$$

The parameters $\dot{I}_u$ and $\dot{I}_d$ represent the rate-of-changes of the columnar free electron contents of the uplink and downlink paths, respectively. Columnar free electron content is computed as the integral of N_e along the ray path. The constant C_e is

$$C_e = \frac{q_e^2}{2cm_e\epsilon_0}. \quad (4)$$

In general, $\dot{I}_u$ and $\dot{I}_d$ will not be the same because the line-of-sight through the plasma will have changed between the time of passage of the uplink and that of the downlink. For planetary spacecraft, contributions to $\dot{I}_u$ and $\dot{I}_d$ will come from both the ionosphere and the solar corona. These terms are stochastic and unpredictable [13]. They are larger when a planetary spacecraft is in the same area of the sky as the sun and beyond it, and larger too when the solar cycle is at a maximum.

If two coherent downlinks are available, it is possible to identify $\dot{I}_d$. This is accomplished by subtracting the observable $\xi_1(t)$ from that for the second downlink, $\xi_2(t)$, and then scaling:

$$\dot{I}_d(t) = \frac{\omega^2}{C_e}\frac{G_1^2 G_2^2}{G_2^2 - G_1^2}[\xi_2(t) - \xi_1(t)]. \quad (5)$$

Once determined, the downlink plasma noise may be removed from the Doppler record. The uplink plasma noise can be removed only if two simultaneous uplinks of different frequencies are available [14].

IV. Range Measurement

A range measurement is made by phase modulating a ranging signal onto the uplink carrier and having it echoed by the transponder. The transponder demodulates this ranging signal, filters it, and then remodulates it back onto the downlink carrier. At the ground station, this returned ranging signal is demodulated and filtered. An instantaneous comparison between the ranging signal that is going up and the ranging signal that is coming down would yield the two-way delay. Unfortunately, an instantaneous comparison is not possible. The reason is that the signal-to-noise ratio on the incoming ranging signal is small and a long integration time (typically minutes) must be used. During such a long integration time, the range to the spacecraft is constantly changing. It is therefore necessary to "electronically freeze" the range delay long enough to permit an integration to be performed. The result represents the range at the moment of freezing.

This "electronic freezing" is achieved by Doppler rate-aiding. The technique is illustrated in Fig. 5. A simultaneous carrier Doppler measurement must be available for this technique to be used. If the uplink ranging signal is $r[t + (K/\omega)\theta(t)]$, then the returned ranging signal is $r[t - \tau + (K/\omega)\theta(t - \tau)]$. From Fig. 5 it will be noted that the clock that governs the generation of the ranging signal is derived from the uplink carrier frequency; this is essential for Doppler rate-aiding. A local model of the returned ranging signal is generated by making a copy of the transmitted ranging signal and then subjecting this copy to Doppler rate-aiding. Doppler rate-aiding consists of advancing the phase of the copy (beginning at time T_0) according to information available from the carrier Doppler measurement. In particular, the local model is

$$r\left[t + \frac{K}{\omega}\theta(t) + \int_{T_0}^{t}\xi_i(t')\,dt'\right].$$

When the returned ranging signal is correlated with the above local model, the measured delay difference is τ_0 −

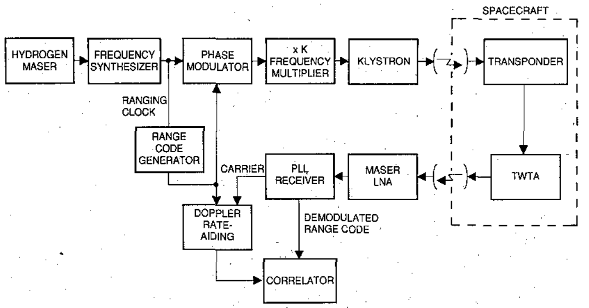

Fig. 5. Range measurement.

$(K/\omega)\theta(T_0 - \tau_0) + (K/\omega)\theta(T_0)$. The round-trip delay for a ranging signal arriving at the ground station at time T_0 is denoted τ_0. With a history of how the uplink carrier phase was varied, it is possible to solve for τ_0. The range is inferred from a record of the round-trip delay τ_0.

In practice, a series of squarewaves is used for a ranging signal [15]. These squarewaves are transmitted consecutively. For example, a squarewave will be transmitted for a few minutes, then it is replaced by a second squarewave with twice the original period, then a third squarewave with another doubling of the period replaces the second, and so on. The determination of τ_0 on the first squarewave results in ambiguities. That is to say, one measures $\tau_0 - NT_1$, where T_1 is the period of the first squarewave and N is a positive integer, rather than τ_0. Without the benefit of the subsequent squarewaves of longer period; it would never be possible to know the value N, and the correct round-trip delay would be just one among an array of equally-spaced possibilities. All of the squarewaves after the first, however, do make it possible to resolve the ambiguity. If the correlation changes sign when the delay comparison is made for the second squarewave, then it becomes possible to say that N is an odd integer (otherwise N is even). This eliminates half of the possibilities, and the spacing between the remaining possibilities will have been doubled. One may continue in this way, using ambiguity-resolving squarewaves of ever longer periods to finally bring the spacing between surviving possibilities to a large enough value to permit identification of the true round-trip delay based on *a priori* knowledge. With this technique, the squarewave of smallest period determines the accuracy of the round-trip delay measurement, and the *a priori* knowledge of this delay determines how many ambiguity-resolving squarewaves must be used. It is essential that the Doppler rate-aiding be done in an uninterrupted fashion from time T_0 through the correlation of the last ambiguity-resolving squarewave.

The dominant source of error in a range measurement can be any of the following: thermal noise, plasma noise, calibration inaccuracies. The contribution to range measurement error made by thermal noise is

$$\sigma_r = \frac{c}{f_r}\sqrt{\frac{N_0/P_r}{256T}} \tag{6}$$

where the range error σ_r is in units of meters, f_r is the frequency of the first squarewave, T is the integration time, and P_r/N_0 is the signal-to-noise spectral density ratio for the downlink ranging signal. Certain assumptions about the filtering of the range squarewaves are included in (6).

When a planetary spacecraft is in the same area of the sky as the sun, the plasma noise may dominate the measurement. In this case, the error is highly variable, increasing as the angle between spacecraft and sun diminishes. Finally, there are always inaccuracies in the characterization of the group delay through the electronics of the ground station. Typically, the overall range measurement error is 1 to 10 m.

V. Conclusion

Microwave links connecting a planetary spacecraft and ground stations of the Deep Space Network carry information about the speed of that spacecraft and even about its position in the sky. The important trajectory parameters for the spacecraft may be obtained by comparing the received downlink carrier frequency with the transmitted uplink carrier frequency. Essential to such a measurement are a highly stable frequency reference at the ground stations and a phase-locked transponder on the spacecraft. Often, the dominant source of error is the phase delay fluctuation caused by the presence of plasma (either ionosphere or solar corona) in the path of the microwave links. Range measurements are also performed, but these require the assistance of the Doppler measurements in order to compensate the rate-of-change of range.

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