# Helios Spin-Modulation Doppler Effects

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*It is predicted that the spin-stabilized Helios spacecraft when communicating via its low-gain antenna to the deep space stations of the Deep Space Network will affect the observed radio frequency doppler signal which is normally only a function of the spacecraft-to-Earth radial velocity. The effect is due largely to the spin modulation created by the spacecraft rotation and the right-circularly-polarized element of the spacecraft antenna system that is physically offset several radio frequency wavelengths from the rotational axis. The discussion develops the expected effects to the general doppler equation, and expressions for the resultant one-way uplink and downlink and two-way coherent doppler frequency cases are presented.*

## I. Introduction

The effects on the doppler frequency induced from the spin modulation generated by the Helios spacecraft rotating low-gain antenna (LGA) will be discussed, and equations expressing the resultant effects will be developed for the one-way, uplink and downlink, and two-way coherent doppler cases.

A spacecraft traveling at a radial velocity $v_R$ away from the ground transmitter will receive the transmitted RF signal changed by this velocity (Fig. 1). If $D$ is the instantaneous distance between the transmitter and spacecraft, the total number of RF wavelengths $\lambda$ contained in this one-way uplink path is $n_\lambda = D/\lambda$, and since there are $2\pi$ radians angular excursions of the phase angle $\gamma$ per wavelength, the total number of these angular excursions made by the transmitted wave is $\gamma = 2\pi\ D/\lambda$.

With the spacecraft in motion, $D$ and the phase $\gamma$ are changing, and the change in $\gamma$ with respect to time is frequency and is the doppler angular frequency $\omega'_D$ given by

$$\omega'_D = 2\pi f'_D = \frac{d\gamma}{dt} = \frac{2\pi\, dD/dt}{\lambda} = \frac{2\pi\, v_R}{\lambda} \tag{1}$$

## II. Rotating Spacecraft With Offset LGA for Uplink Case

Consider now the case of a spacecraft rotating at an angular rate $\omega_r$ (approximately 1 revolution per second) containing a right-circularly-polarized (RCP) horn antenna displaced physically approximately $6\lambda$ from the spin axis $z$, as is the Helios spacecraft (Fig. 2). The effect of the uniformly rotating offset antenna is equivalent to varying a distance cyclically about $D$, or $D + \Delta D$, where $\Delta D$ varies sinusoidally along the velocity path; thus $D = D' - (\sin\psi\, 6\lambda) \cos \omega_r t$, where $\psi$ is the aspect angle formed by the spacecraft–Earth line and the spacecraft spin axis, and $D'$ is the mean distance. Equation (1) now becomes:

$$\omega_D = \frac{2\pi}{\lambda} \frac{d}{dt} [D' - (\sin\psi\, 6\lambda_{RCV}) \cos \omega_r t]$$

$$= \frac{2\pi}{\lambda} \left[ \frac{dD'}{dt} + (\sin\psi\, \omega_r\, 6\lambda_{RCV}) \sin \omega_r t \right]$$

where $6\lambda_{RCV}$ is the displaced value of the horn antenna in wavelengths, at the spacecraft receive frequency, or

$$\omega_D = \frac{2\pi}{\lambda} [v_R + (\sin\psi\, \omega_r\, 6\lambda_{RCV}) \sin \omega_r t], \text{ rad/s} \tag{2}$$

The doppler angular frequency, related to the ground transmitted RF angular frequency $\omega_{T,GRD}$, is

$$\omega_D = \omega_{T,GRD} \left[ \frac{v_R + (\sin\psi\, \omega_r\, 6\lambda_{RCV}) \sin \omega_r t}{C} \right] \tag{3}$$

where $\lambda = C/f$, and $C$ is the velocity of propagation.

An additional factor results from the rotating RCP horn antenna when receiving the transmitted wave. The orientation of the antenna E plane vector rotates through 360 deg at the rotational rate $\omega_r$ and results in an additional angular frequency component of approximately 1 rad/s, adding to or subtracting from the carrier angular frequency depending upon the rotational sense of the spacecraft (Ref. 1). For the Helios case, the resultant carrier is less by the value of $\omega_r$. If the transmitted wave were left-circular-polarized, the transmission efficiency would be low, and the received signal level would be greatly attenuated (Ref. 2) relative to RCP, with the rotational component now appearing additive.

Therefore, the resultant spacecraft received angular frequency is comprised of three components which modify the ground transmitted frequency: the doppler angular frequency related to spacecraft–Earth radial velocity, a bias angular frequency equal to the spacecraft angular rate due to the rotating RCP antenna, and a cyclic deviating angular frequency (about the resultant of two above components) also occurring at the spacecraft angular rate with the deviation magnitude related to the antenna displacement and aspect angle.

The spacecraft received signal, considering all of the components becomes

$$\omega_{R,S/C} = \omega_{T,GRD} \left[ 1 + \frac{v_R + (\sin\psi\, \omega_r\, 6\lambda_{RCV}) \sin \omega_r t}{C} \right] - \omega_r, \text{ rad/s} \tag{4}$$

which is the resultant received one-way uplink case, and these doppler components are illustrated in Fig. 3.

## III. Downlink Received Signal

By reciprocity, similar results are observed at the ground receiver when receiving a signal transmitted by the spacecraft in a one-way downlink configuration, i.e.,

$$\omega_{R,GRD} = \omega_{T,S/C} \left[ 1 + \frac{v_R + \left(\sin\psi\, \omega_r \frac{240}{221} 6\lambda_{RCV}\right) \sin \omega_r t}{C} \right] - \omega_r, \text{ rad/s} \tag{5}$$

where the physical horn antenna displacement in wavelengths is approximately greater by 240/221 at this frequency.

## IV. Two-Way Coherent Doppler

The next configuration to consider is that of the two-way coherent mode. The physical rotation of the spacecraft with a displaced RCP antenna can be considered as an equivalent angular frequency generator additive circuit to the transmitted carrier angular frequency. The generator frequencies are the angular rate of the spacecraft, which frequency deviates the carrier at a deviation proportional to the horn displacement and aspect angle, the bias signal proportional to the spacecraft angular rate, and the doppler angular frequency component proportional to the radial velocity and transmitted frequency.

The transponder functions to coherently transform the resultant spacecraft received angular frequency by a constant factor 240/221 and transmit this signal through the same rotating RCP horn antenna to the ground receiving system. However, in addition, a delay $\zeta$ occurs in the transponding process. This delay is to the carrier frequency (phase delay $\zeta_\gamma$) and the modulation (or group delay $\zeta_g$) which can be influenced by the spacecraft thermal temperature, received signal level and resultant signal-to-noise ratio.

The carrier phase delay variation is assumed to be small during a normal DSS tracking period such that $d\zeta_\gamma/dt << d\gamma/dt$ and should not alter the doppler frequency, as expressed by Eq. (1).

The group delay $\zeta_g$ is a factor only if it becomes a significant value, since this would have the effect of effectively shifting the horn antenna for the downlink signal to a lagging angle relative to the actual horn antenna location receiving the uplink signal.

Equation (4) is the expression for the received signal appearing at point A of Fig. 4, and the transpond ratio and group delay $\zeta_g$ modifying this to give the expression at point B as,

$$\omega_{T,S/C} = \frac{240}{221}\left(\omega_{T,GRD}\left[1 + \frac{v_R + (\sin\psi\,\omega_r\,6\lambda_{RCV})\sin(\omega_r + \zeta_g)\,t}{C}\right] - \omega_r\right), \text{rad/s} \quad (6)$$

The result of a significant apparent lag angle is that the frequency deviation component cyclic zero crossing (Fig. 3) as a function of time would be the vector sum of the contributing uplink and downlink angular modulating signals. Fortunately, the group delay at 1 Hz will probably be very low through the transponder circuits so that the effective horn location for downlink will be coincident with the uplink horn location and preserve any reference to the spacecraft frame structure.

Progressing further through the system configuration, the rotating offset horn antenna has the effect of varying $\Delta D$ about the mean distance $D$ to the downlink signal with effects similar to those of the uplink signal.

A study of Eqs. (4) and (5) for the uplink and downlink received signals reveals that the values of the velocity, frequency deviation, and bias components are not dependent upon the signal amplitude, or the characteristics of the antenna gain patterns, for either link case. Specifically the coefficient to the frequency deviation components is proportional to the sine function of the aspect angle. Thus, in this two-way coherent mode, dissimilarity in the antenna gain patterns at a given aspect angle is incidental to the value of this component.

The overall doppler signal $\omega_{D,TOTAL}$ can be found by the comparison of the ground transmitted signal to the ground received signal. The general equation for this overall two-way doppler condition is expressed as

$$\omega_{D,TOTAL} = \frac{240}{221}\omega_{T,GRD} - \frac{240}{221}\omega_{T,GRD}\left(1 + \frac{2v'_R}{C}\right) - \frac{240}{221}\omega_r\left(1 + \frac{v'_R}{C}\right) - \omega_r$$

where the ground system functionally multiplies the transmitter frequency by 240/221 during the doppler extraction process as shown in Fig. 4.

Or

$$\omega_{D,TOTAL} = \frac{240}{221}\omega_{T,GRD}\left(\frac{2v'_R}{C}\right) - \frac{461}{221}\omega_r - \frac{240}{221}\omega_r\left(\frac{v'_R}{C}\right) \quad (7)$$

where $v'_R$ is the velocity factor which is a function of the change in distance $D$.

The factor for the rotating offset horn antenna was developed in Eq. (2) and is applicable here; thus, the final overall doppler expression is

$$\omega_{D,TOTAL} = \frac{\left(\frac{240}{221}\omega_{T,GRD}\right)2\left(v_R + (\sin\psi\,\omega_r\,6\lambda_{RCV})\sin\omega_r t\right)}{C} - \frac{461}{221}\omega_r - \frac{\frac{240}{221}\omega_r\left(v_R + (\sin\psi\,\omega_r\,6\lambda_{RCV})\sin\omega_r t\right)}{C}, \text{rad/s} \quad (8)$$

or expressed in terms of frequency as

$$f_{D,TOTAL} = \frac{\left(\frac{240}{221}F_{T,GRD}\right)2\left(v_R + (\sin\psi\,f_r\,12\pi)\sin 2\pi f_r t\right)}{C} - \left(\frac{461}{221}f_r + \frac{\frac{240}{221}f_r\left(v_R + (\sin\psi\,f_r\,12\pi)\sin 2\pi f_r t\right)}{C}\right), \text{Hz} \quad (9)$$

where $f_r$ is the spacecraft rotational frequency.

Thus, in this two-way coherent mode it can be seen that the doppler velocity component has increased by a factor of 2 relative to the one-way, downlink mode; and similarly, the deviation frequency component value has doubled. However, the bias frequency component has been modified by the factor

$$-\left(\frac{461}{221}\omega_r + \frac{\frac{240}{221}\omega_r\left(v_R + (\sin\psi\,\omega_r\,6\lambda_{RCV})\sin\omega_r t\right)}{C}\right)$$

## V. Doppler With Ground System Antenna Linear Polarization

The complete spacecraft LGA is comprised of the RCP horn antenna and a vertical-linear-polarized dicone antenna. The vertical-linear component of the horn element combines with the dicone antenna element to create interferometry effects at aspect angles in the vicinity of $\psi \simeq 42 \rightarrow 50$ deg (Ref. 3).

A mode to lessen these effects would be to utilize a horizontal-linear polarization on the ground transmitter/receiver system to operate only with the horizontal-linear component of the RCP horn LGA. This mode essentially reduces the influence of the dicone antenna and caters largely to the horn LGA over the aspect angles of $0 \rightarrow 40$ deg.

Owing to the fact that the spacecraft horn antenna is still rotating, and physically the E-plane vector is also rotating, the same equations stated for the ground system RCP mode are applicable to this linear polarization mode. The signal level, however, would be attenuated approximately $-3$ dB because of receiving only the linear component of the RCP wave (Ref. 2).

## VI. Polarization Definition

The bias angular frequency component due to the rotating E-plane vector shift direction as discussed above is based on the standardized convention of the Institute of Radio Engineers (IRE) and the spacecraft rotation sense.

The direction of the spacecraft rotation is such that, after the spin axis has been properly pointed so that it is approximately normal to the ecliptic plane, the spin is counterclockwise as viewed from the northern ecliptic pole (Ref. 4) and is illustrated in Fig. 2 as seen by the ground stations.

The uplink radiated wave to the spacecraft is similarly rotating clockwise (clockwise wave receding) as adopted by the discussion of paragraph 2 following the IRE standard for a RCP wave (Ref. 1), which is opposite to the classical physics usage. Hence, the net resultant spacecraft received signal appears as a longer wavelength, or a shift to a lower frequency, as shown in Fig. 3.

# References


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4. "Deep Space Network/Helios Spacecraft Telecommunications Interface Definition," Document 613-6, Rev. A, Change 1, Jet Propulsion Laboratory, Pasadena, Calif., Mar. 1, 1974 (an internal document).

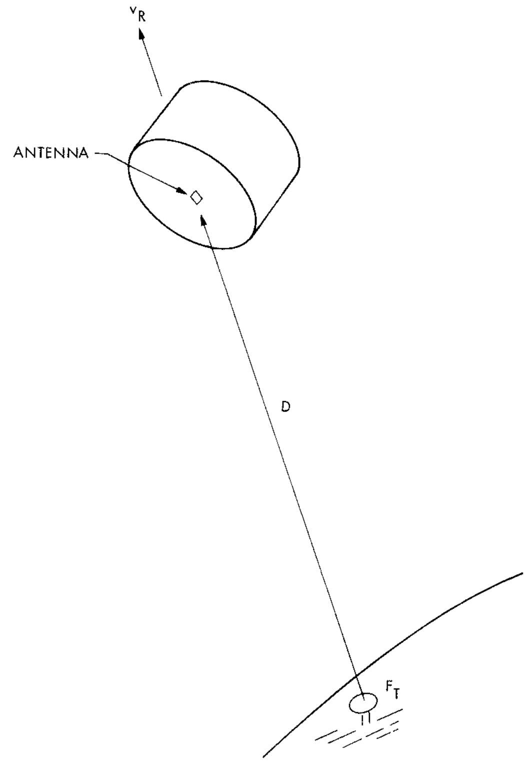


**Fig. 1. Typical ground transmitter and spacecraft geometry**

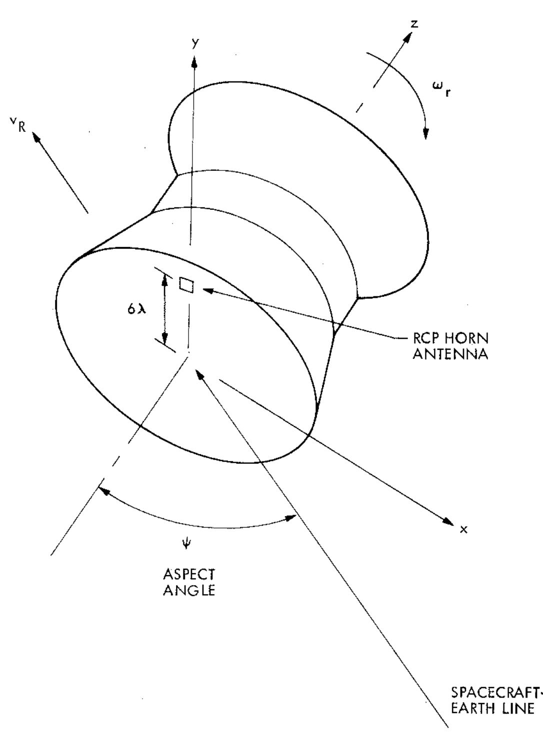


**Fig. 2. Rotating spacecraft with displaced antenna configuration**

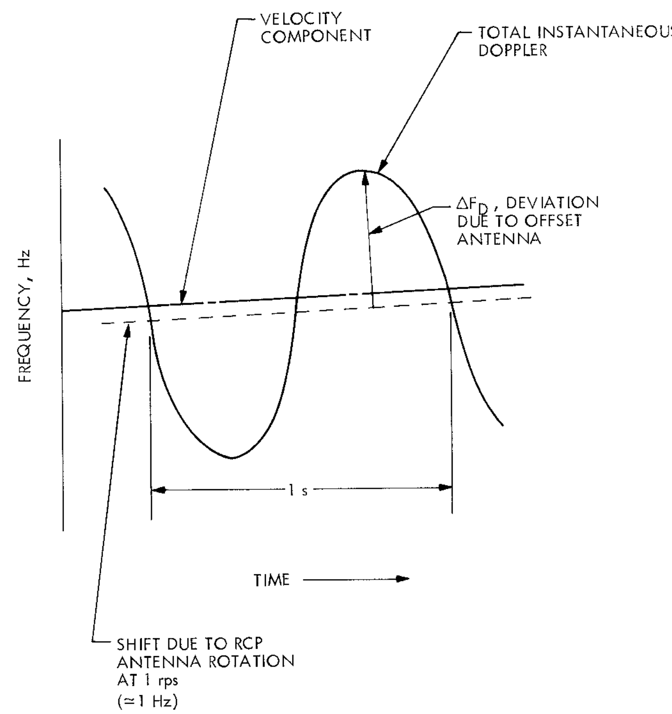


**Fig. 3. Instantaneous doppler components of spacecraft received RF signal**

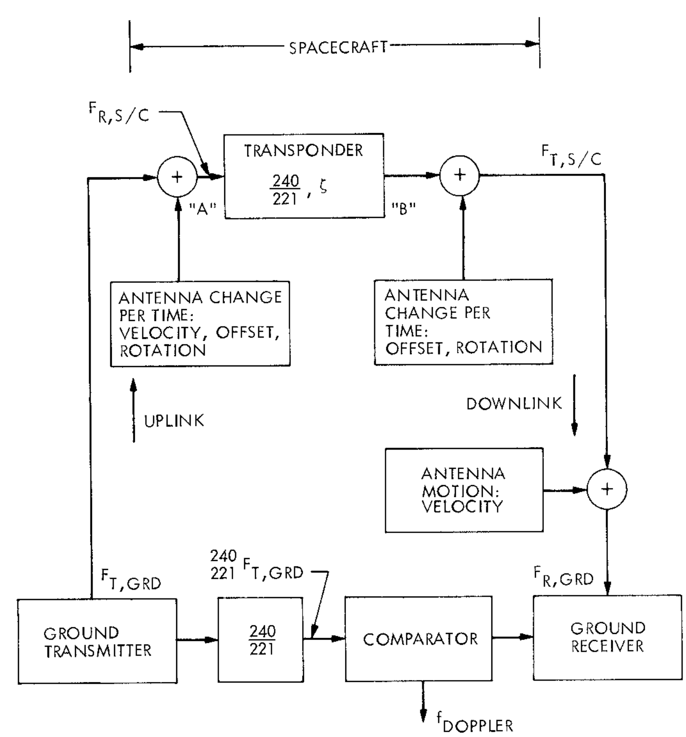


**Fig. 4. Coherent two-way doppler model for spacecraft with rotating offset antenna**