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USING THE USCCS FOR SUB MICROSECOND SPACECRAFT CLOCK CALIBRATION

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Summary

The Return Data Delay technique which requires knowledge of spacecraft range is commonly used for correlating a spacecraft clock against a ground time standard when millisecond accuracy is required. An analysis is presented that allows using the user spacecraft clock calibration system (USCCS) to correlate a spacecraft clock to better than one microsecond accuracy. The basic USCCS algorithm has been simplified and it is shown to results in about one microsecond accuracy without requiring orbital information. By considering the relative motion of the user satellite, the TDRS and the earth station about the center of the earth, a correction of almost two orders of magnitude can be made. Such accuracy is required for scientific investigations that require correlating coincident radiation or particle detection with a remote laboratory.

Background

An accurate absolute time reference is required on scientific spacecraft for operational purposes and for correlating scientific data. Typical accuracy required for many satellites has been of the order of one millisecond; examples are ERBS, SMM, SME, UARS, EUVE, LANDSAT and HST. This accuracy is obtained by reading the spacecraft clock (or oscillator count values) simultaneous with a particular bit edge in the telemetry. As the telemetry is received on the ground an absolute time reference is recorded periodically for selected bits in the telemetry. The absolute ground receipt time of the bit edge that was simultaneous with the onboard clock reading can thus be determined. Orbital knowledge and equipment time delays then allow the calculation of the time the particular bit was created on board and, hence, the time the spacecraft clock was read based on the ground clock. The reading on the spacecraft clock is sent to the ground in a later portion of the telemetry and serves as a clock calibration by comparing it with the earth based standard.

The main limitation in this method, which is referred to as the return data delay (RDD) or return channel telemetry delay (RCTD), is accurate knowledge of the spacecraft range (and thus the space propagator delay) from the ground receiving station. The calculations are done after a pass with the tracking, data and relay satellite system (TDRSS) and uses predicted orbital positions. The results are extremely sensitive to the quality of the orbital data but can be accurate to about 3 μs with respect to the ground time reference (atomic clock at the NASA Ground Terminal (NGT)). The RDD method is an open loop method.

The CGRO project decided that because they required a 10 μs clock setting accuracy, they would take advantage of the pulses used in the TDRSS spacecraft ranging system and implement a closed loop time correlation technique. This became the user spacecraft clock calibration system (USCCS). GPS accuracy is approximately 1μs and today would be a competing technique.

Using Range Pulses for Time Correlation

The standard ranging technique used in the TDRSS is a closed loop method in which a pulse is sent from the TDRSS ground station at White Sands New Mexico (WSGT) to a user via a TDRS and then returned from the user to the WSGT via the same TDRS. The signal propagation time which is used to determine the range to the user is combined with the known TDRS orbit to determine the user satellite orbit. The time accuracy between pulses is specified to be ± 35 nanoseconds. For orbit determination, doppler shift is also used.

The changes required to use the range pulses for timing were:

1. to extract the range pulse from the spacecraft transponder and use it to trigger a reading of the spacecraft clock.

2. to make an absolute time reading of the ground station range pulse transmission time, and the range pulse receipt time. For range purposes the delta between these times were measured accurately but the absolute times were not.

The range pulses, referred to as pseudo random (PN) code epoch pulses, are the part of the PN spectrum spreading code used in the TDRSS where there are 18 ones in a row. The code has a length of 256 x 1023 chips (PN bits) generated at a rate of approximately 3MHz. This results in a PN epoch pulse approximately every 0.085 milliseconds (25500 Km at the speed of light).

USCCS

The basic concept of the USCCS time correlation method is extremely simple. When a PN epoch pulse is transmitted from the ground the time is recorded, t_1. It arrives at a spacecraft at some time t_2 which is unknown. The spacecraft transponder immediately retransmits the pulse to the ground where its arrival time, t_3, is recorded. Upon receipt of the pulse at the spacecraft, the spacecraft's clock is read and the reading, t_{2sc}, is transmitted to the ground along with other telemetry. On the ground, t_2 is calculated from t_1 and t_3 and compared to t_{2sc} for calibration. The pulse arrival time at the spacecraft t_2 is approximately half-way between t_1 and t_3.

$$t_2 = \frac{t_1 + t_3}{2} \tag{1}$$

When the signal propagation is viewed by an observer on the earth it may seem that this in not an approximation. Proper analysis, however, requires that the system be viewed from an inertial reference frame.

For a low earth orbiting (LEO) spacecraft at about a 400 Km altitude, and a geosynchronous relay satellite, the round trip distance traveled by an epoch pulse never varies by as much as 25500 Km, thus, there is no ambiguity between a transmitted epoch and its corresponding return epoch. No orbital information is needed, other than t_1 and t_3, when correlating epochs to approximately determine t_2.

Accuracy of the USCCS

The correction to half-way between t_1 and t_3 does not depend on the LEO spacecraft velocity or the RF signal doppler shift. The correction does depend on the LEO position and the fixed quantities: earth rotational speed; geosynchronous relay satellite rotational speed; relative position of earth station; and, of course, the speed of light. The solution for t_2 with the various motions is now examined and numerical values are given for an example of orbits in the earth equatorial plane. It will be shown that the required correction of up to about 1 μs is asymmetric with the relative position of the LEO and relay satellite and, thus, not related to the doppler which is almost symmetric. The doppler can be used if orbital data is not otherwise available to determine the longitudinal component of the relative ground station, TDRS, and user position, which can then be used to determine the required correction to Equation 1.

Doppler

Consider the example of an object (user spacecraft) moving away from a fixed observer at a constant velocity, Figure 2. The frequency transmitted from the observer, f_1, and received by the observer, f_3, are different (doppler), BUT the transmitted epoch pulse is at the user at a point in time t_2, which is exactly half-way between when it leaves the observer, t_1, and returns to the observer, t_3. Note that the relative velocity, v, between observer and user spacecraft can be determined from the observer's measurement of forward and return PN periods, T_1 and T_3, respectively. For the USCCS, an observer at the WSGT on a slowly rotating earth and a spacecraft in orbit, the above concept is approximately true. For the constant velocity case this equation is exactly true no matter how fast the user spacecraft is moving.

A simulations viewing earth, TDRS, and user spacecraft actual motion from a reference frame moving with the center of the earth shows the correction term to Equation 1 to be less than 1 μs and, again, independent of the user spacecraft motion, Figure 3. This analysis thus tells us that Equation 1 is accurate to 1 μs.

Special relativistic considerations are not included since they are of the order v^2/c^2 and which is about one nanosecond (v^2/c^2 x round trip time of 0.5 second).

Simulation

We observe the three bodies from above the north pole of the earth with the earth center being the center of our reference frame, and the TDRS and user orbit in the same plane, Figure 3. Due to the earth's curved path (orbit) around the sun this also is not a true inertial reference frame, but the remaining errors are below our desired accuracy.

From Figure 3, we see that the forward path and return path are not the same. Since the forward and return paths are different, the signal that left the ground at t_1 and returned at t_3 is not at the spacecraft exactly half-way in between. Since the signal is at the user for only an instant of time at t_2, it may be intuitive that the difference in forward and return time is independent of the user spacecraft velocity. This is similar to the constant velocity example given earlier.

The difference in forward and return travel time is due to both the earth and TDRS motion. Clearly the TDRS motion during the 0.25 second that the signal travels from the TDRS to user and back to TDRS causes a difference in forward and return travel time. In addition, a more subtle effect is the difference between the GT-to-TDRS and TDRS-to-GT travel time. As a signal moves through space from the GT to TDRS-E, the TDRS is moving away. Thus, the distance traveled by the signal is greater than the instantaneous GT-to-TDRS distance. Similarly, as a signal travels from TDRS-E to the GT, the GT moves toward the signal so the distance traveled by the signal is less than the instantaneous distance. Since the TDRS and GT are always in fixed relative positions, the forward travel time of one pulse is the same as the forward travel time of the following pulse. Similarly, the return travel time from TDRS to GT for successive pulses is the same. For TDRS-E the forward time is .395 μs longer than the return time. For TDRS-W the values are reversed.

We now consider the portion of the signal path between the TDRS and the user. The computer simulation shows the signal travel time from TDRS to the user to be a maximum of 0.466 μs longer than the travel time from the user to the TDRS. This occurs when the angle between the TDRS and the user spacecraft is approximately 90°, the LOS point. At AOS the values are reversed because the user is approaching the TDRS and the TDRS-to-user time is less than the user-to-TDRS portion. For a user in a polar orbit, the effect is less.

The net effect of combining the GT-TDRS and TDRS-user portions is such that for TDRS-E at LOS the forward travel time is 0.86 μs longer than the return travel time. At AOS it is about 0.072 μs less, Figure 4. For TDRS-W the conditions are reversed.

As in the constant velocity example of Figure 2, the forward and return PN periods T_1 and T_3 can be used to determine the longitudinal component of the user's velocity, v. In the real case the complete motion, as shown in Figure 3, must be taken into account, but the results will be approximately equal to that given by the equation for v in Figure 2.

The maximum doppler effect will cause the PN period at the spacecraft to vary by about 2 μs from the period transmitted from the GT. Thus, the return PN period at the GT will be a maximum of 4 μs different from the transmitted. Even though the PN periods as measured at the GT reflect the longitudinal component of the velocity of the user spacecraft, Figure 5, their magnitude does not directly relate to the correction needed in the USCCS to determine t_2. The values of T_1 and T_3 serve only to tell us where the user is in his orbit relative to TDRS. The geometry of Figure 3, the TDRS motion and earth rotation, must then be used to calculate the sub-microsecond correction needed to obtain the correct value of t_2. That is, T_1 and T_3 at a given time are used to find v. Knowing v we can find the relative orbital angle between TDRS and the user, Figure 5. Once the angle is known, the difference between the forward and return travel time, t_F - t_R, can be found from Figure 4 and used to find the correction required for Equation 1.

$$t_2 = \frac{t_1 + t_3}{2} + \frac{t_F - t_R}{2} \qquad (2)$$

Correction Term

Using Figures 3, 4 and 5, we can model the correction term $t_F - t_R$ as follows. The user velocity as seen from TDRS (not orbital velocity) varies approximately sinusoidally as

$$v \doteq v_u \sin \frac{\pi}{2}\frac{\theta_r}{\theta_c} \quad , \qquad -100^\circ <= \theta_r <= 100^\circ \qquad (3)$$

where:

θ_r is the relative angle between the TDRS and user measured from earth center,

θ_c is $\cos^{-1} \frac{r_u}{r_T}$, the relative angle at which the user is moving directly toward or away from TDRS,

v_u is the user's orbital speed.

In terms of T_1 and T_3, v is approximately

$$v = \frac{T_3 - T_1}{T_1 + T_3} c \tag{4}$$

Equation 3 is used to solve for θ_r

$$\theta_r \doteq \frac{2\theta_c}{\pi} \sin^{-1} \frac{v}{v_u} \tag{5}$$

where v is known in terms of T_1 and T_3 from Equation 4.
From Figure 4, the correction term $t_F - t_R$ can be represented by

$$t_F - t_R \doteq .4665 \sin \theta_r + .3945\ \mu s \tag{6}$$

Using Equation 2 with this correction yields about two orders of magnitude correction over Equation 1. T_1 and T_3 are sufficiently slowly varying that $T_1(t_1)$ and $T_3(t_3)$ will suffice.

Conclusion

Exploring the physics of the USCCS for the CGRO because of a problem that was found to be simply a misplacement of data in the telemetry, lead to the previous analysis. After examining the full signal path from an inertial point of view it became clear that the basic formula, $t_2 = (t_1+t_3)/2$, is accurate to 1 μs without any further correction (except of course, equipment delays). The analysis did show that greater accuracy, approaching that of the TDRSS ranging system, is possible but requires knowledge of the relative position of the user spacecraft and ground station relative to the TDRS. Other limitations in the system as currently implemented are that the time tags are only resolved to 0.1 μs; and, although sub microsecond accuracy with respect to the ground station time standard is possible, it is only kept within about 1 μs of UTC.

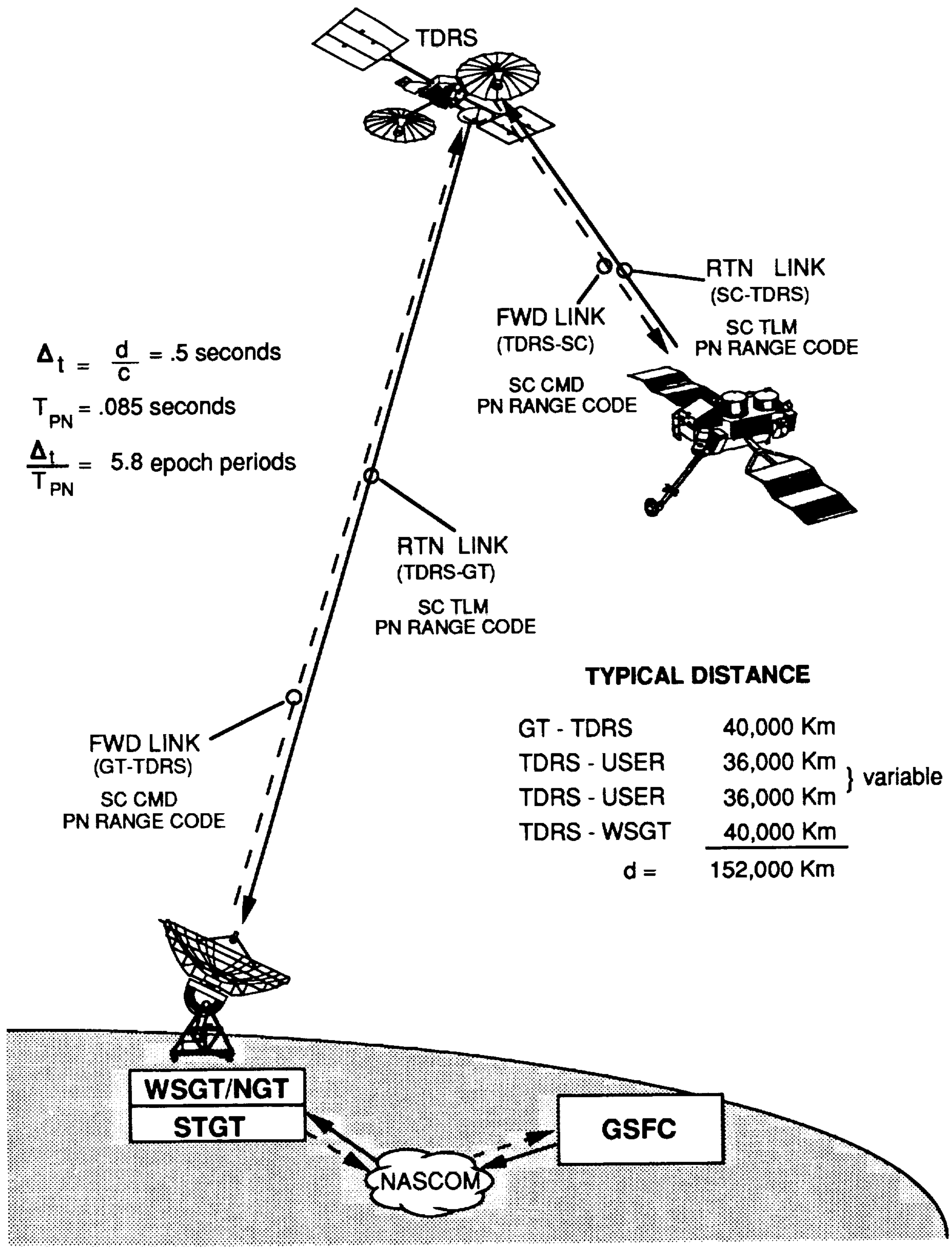


Figure 1. System Overview

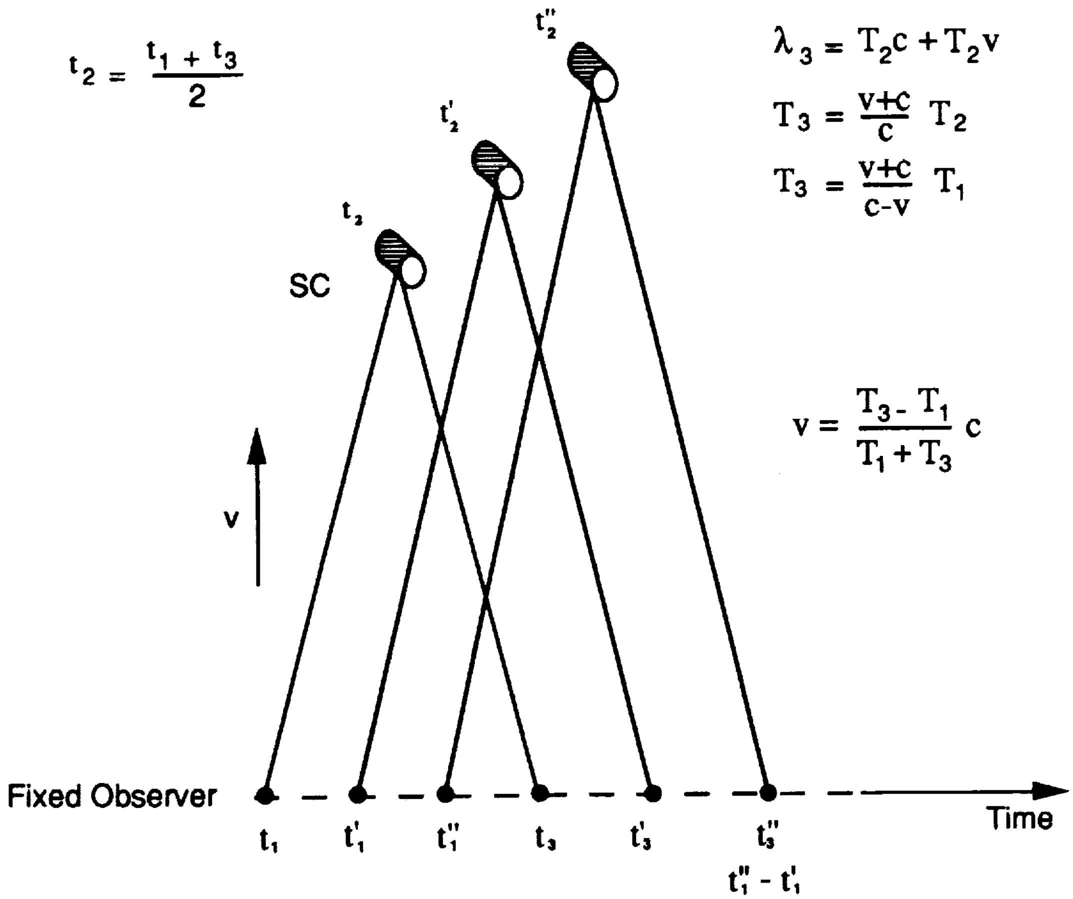
v = constant
T_1 = FWD PN period at GT
T_2 = PN period at SC
T_3 = RTN PN period at GT
λ_1 = FWD PN wavelength at GT
λ_2 = PN wavelength at SC
λ_3 = RTN PN wavelength at GT
c = speed of light

$$\frac{\lambda}{T} = c$$
$$\lambda_2 = \lambda_1 - v\,T_2$$
$$T_2 = \frac{c}{c-v}\,T_1$$

$$t_2 = \frac{t_1 + t_3}{2}$$

$$\lambda_3 = T_2 c + T_2 v$$
$$T_3 = \frac{v+c}{c}\,T_2$$
$$T_3 = \frac{v+c}{c-v}\,T_1$$

$$v = \frac{T_3 - T_1}{T_1 + T_3}\,c$$



$$T_1 = t'_1 - t_1 = t''_1 - t'_1$$
$$T_2 = t'_2 - t_2 = t''_2 - t'_2$$
$$T_3 = t'_3 - t_3 = t''_3 - t'_3$$

$$T_1 < T_2 < T_3$$

Figure 2. Signal Path For Object At Constant Velocity

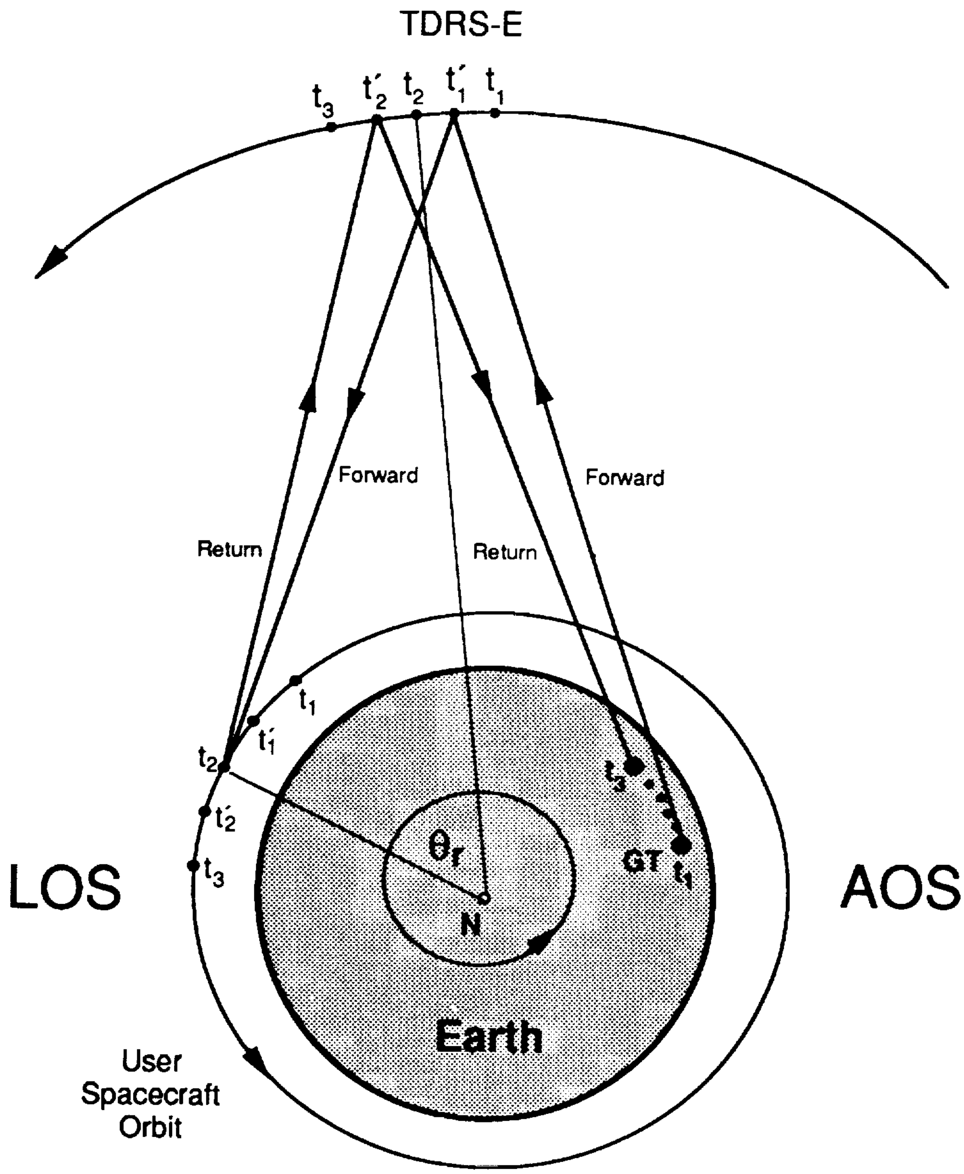


Figure 3. RF Signal Path

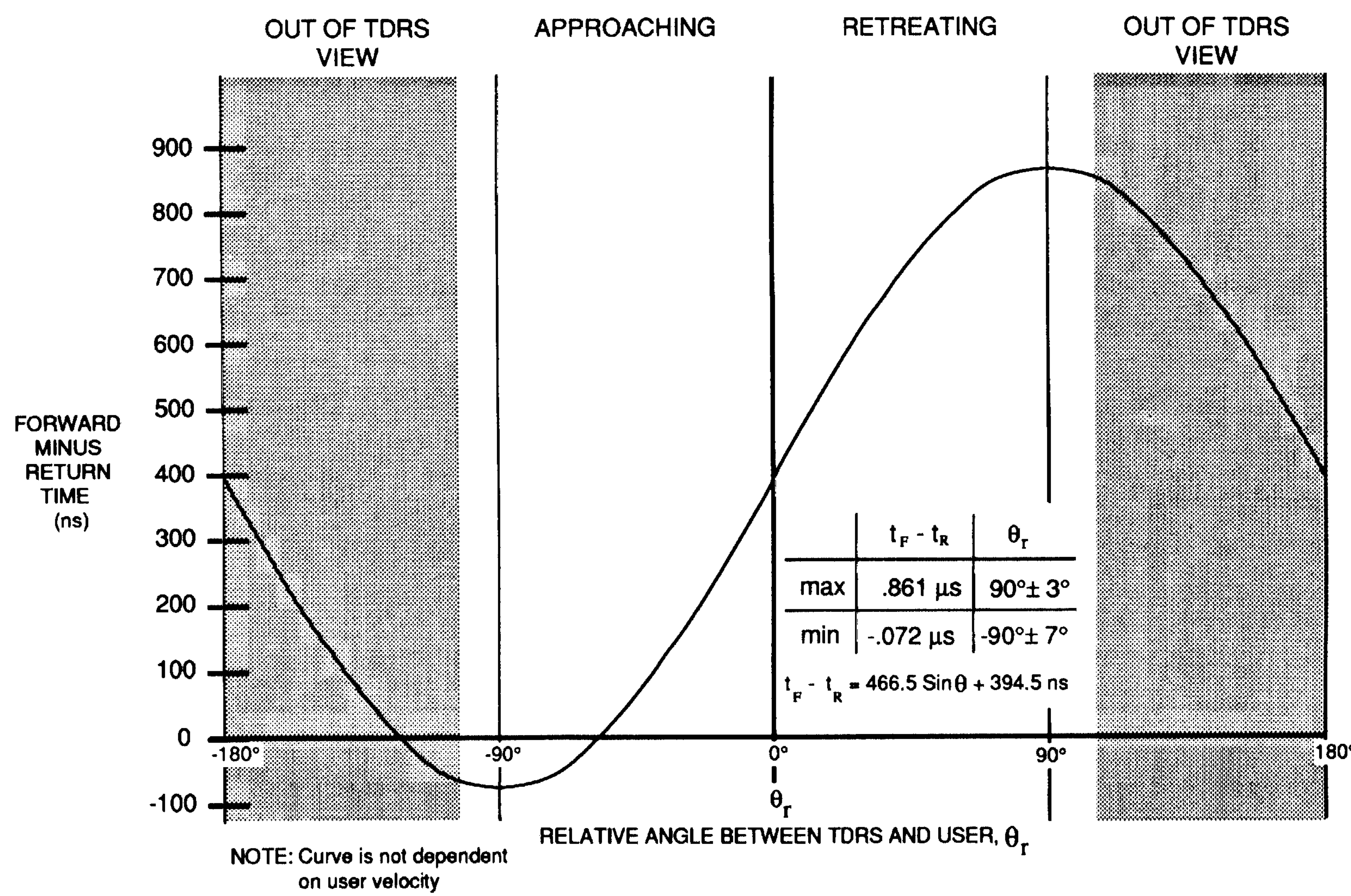


Figure 4. Difference Between Forward And Return Signal Travel Time ($t_F - t_R$)

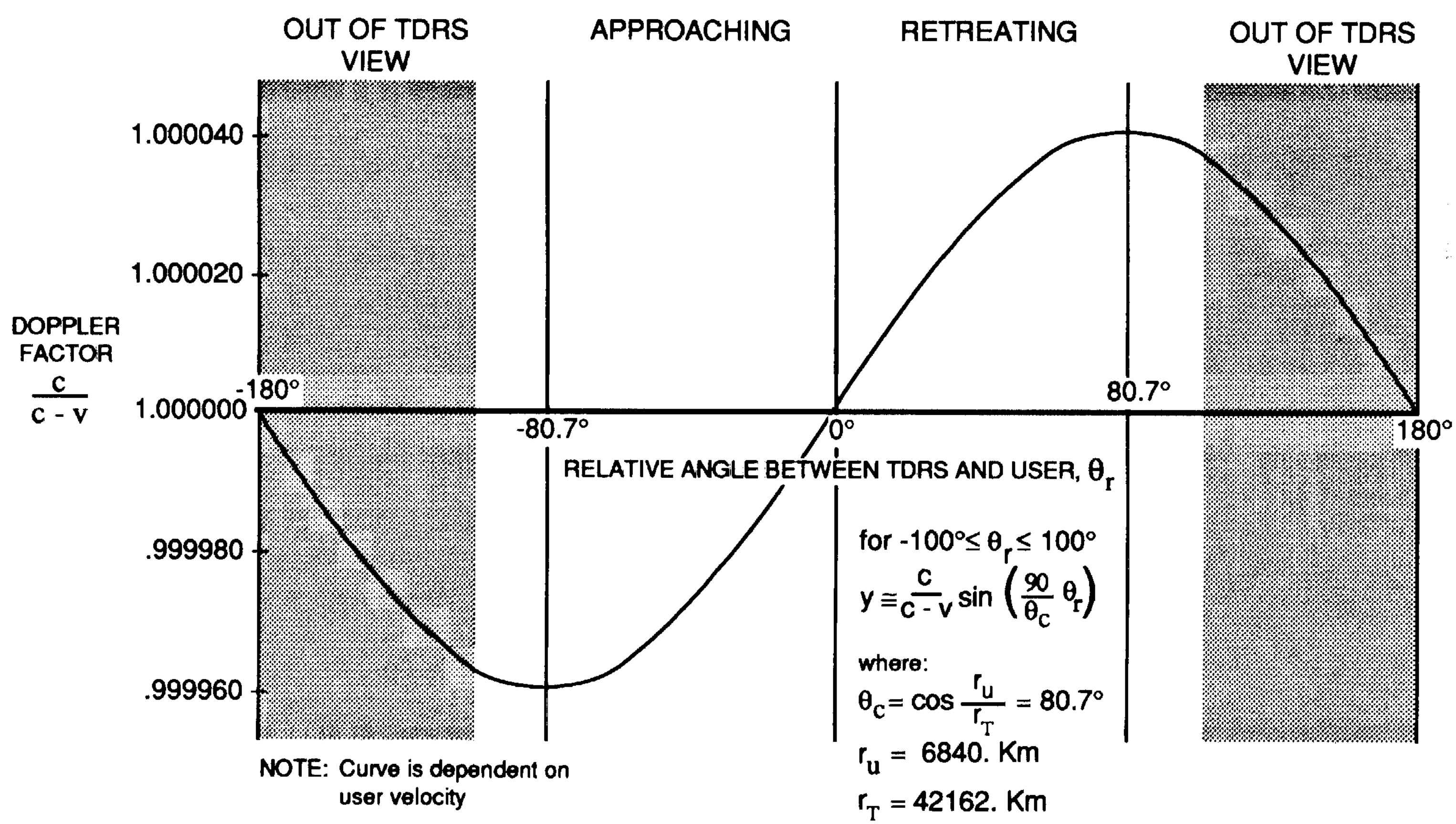


Figure 5. Doppler Factor $\frac{c}{c-v}$