Deep Space Network

301
DSN Uplink Tuning

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Signature provided	12/01/2022	Signature provided	12/12/2022
Jeff B. Berner DSN Project Chief Engineer	Date	Timothy T. Pham Communications Systems Chief Engineer	Date
Prepared by:		Released by:	
Signature provided	12/01/2022	Signature provided	01/06/2023
Jeff B. Berner DSN Project Chief Engineer	Date	Christine Chang DSN Document Release Authority	Date

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Jet Propulsion Laboratory
California Institute of Technology

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Signature provided	12/14/2022	Signature not provided	
Scott Bryant Tracking Subsystem Engineer	Date	John Cucchissi Antenna System Engineer	Date
Signature provided	12/14/2022	Signature not provided	
Michael Settember Uplink System Engineer	Date	Shan Malhotra Service Preparation Subsystem Engineer	Date

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Section 1
Introduction

1.1 Purpose

The DSN provides the capability to tune the uplink carrier to significantly reduce the Doppler shift seen by the spacecraft receiver. This document provides a description of the DSN capability.

1.2 Scope

The basic description of the capability and the main interfaces with the mission users is provided. A description of how the uplink carrier tuning is used by the DSN ranging process is also provided.

Section 2
Description

2.1 Uplink Tuning

All DSN uplinks provide the capability to phase continuously vary the uplink carrier frequency with time. This capability cancels out most, if not all, of the uplink Doppler on the carrier, as seen by the spacecraft transponder. This process of changing the uplink frequency is called "tuning the uplink carrier", or "uplink tuning".

Any uplink signal transmitted to a spacecraft will undergo a Doppler shift, due to the motion in the Earth ground antenna – spacecraft line of sight direction. The velocity and acceleration of the spacecraft relative to the ground antenna causes a frequency offset (f_{off}) and a frequency rate (df/dt) on the carrier that the spacecraft transponder's carrier processing must track out. These frequency shifts are a linear function of the starting frequency. For example, at the same velocity, the shift for an X-band carrier will be about 3.4 times the shift for an S-band carrier, because X-band frequencies are around 3.4 times higher than S-band frequencies. The type of spacecraft trajectory also affects the dynamics of the shift. For example, a spacecraft in cruise has variation due to the Earth rotation, while a spacecraft orbiting a planet (such as Mars) has significantly more variation, due to the movement of the spacecraft, relative to Earth.

There are several cases where there may be a need to tune the uplink:

1) Spacecraft transponder carrier loop is a second order phase locked loop – many deep space transponders use a second order phase locked loop (PLL) for the carrier tracking. This includes older analog transponders, and many more recent digital transponders. A standard way to measure the performance of the carrier tracking is the Static Phase Error (SPE). A larger SPE means that the PLL is not correctly tracking the carrier, which introduces losses in the demodulation process. Per [1], when tracking with a second order loop, the SPE is a function of the frequency rate (df/dt) and the frequency acceleration (d^2f/dt^2), equal to C_1* df/dt + (C_2*t + C_3)* d^2f/dt^2), where C_1, C_2, and C_3 are constants that are functions of the PLL bandwidth, and t is time. Depending on the various values, this means that the SPE could be high enough to significantly degrade the carrier tracking performance. Note that for a third order loop, the SPE is only a function of the acceleration, without any time component.
2) Narrow loop bandwidths – if the carrier loop has a relatively narrow loop bandwidth, then the PLL will be able to track less of the frequency shift. This is due to the fact that the constants mentioned above are inversely proportional to the square of the loop bandwidth (C1 and C2), or inversely proportional to the cube of the loop bandwidth (C3), so smaller loop bandwidths mean that it takes less frequency shifts to drive up the SPE. This is true for both second order and third order PLLs. Spacecraft use narrow loop bandwidths due to tracking weak signals, or, as in the Voyager 2 case, due to a component failure on the transponder.

3) Transceivers and ranging – a transceiver differs from a transponder in that the downlink carrier is not a scaled version of the uplink carrier. This makes the uplink and downlinks independent and the uplink and downlink frequencies are not coherent. While two-way Doppler measurements can be derived by the transceiver making measurements of the uplink carrier and reporting them back in the downlink telemetry [3], ranging cannot be done that way. As described in [2], ranging processing depends on the uplink and downlink being coherent, or very close to coherent. The only way for ranging to work with a noncoherent spacecraft is for there to be no significant uplink frequency shift as seen by the spacecraft, so that the ranging signal only has the downlink frequency shift. The details of this will be discussed in section 3.5.

Section 3
Implementation

3.1 General Description

In the DSN, all exciters generate uplinks using the same baseband signal processing for generating the uplink carrier. This means that this capability is available for S-band, X-band, Ka-band, and K-band uplinks. The signal processing has the capability to vary the carrier frequency according to a linear ramp, while keeping the carrier phase continuous. The ramping is set by a ramp rate value, that is applied on an exact second (the ramp rate value is applied at time HHMMSS.000000, where HH is hours, MM is minutes, and SS is seconds). This value can be changed at any second, as specified by uplink predicts or an uplink tuning template (a tuning template is a script that adds frequency rate changes to the uplink predicts, or directly to a constant frequency). The signal processing will continue with the new frequency ramp value, without any discontinuity or “glitching” of the carrier phase. The exciter uses commands, uplink predicts, and uplink templates to produce a time-ordered list of frequency and ramp rates table entries to drive the exciter hardware. This table can accept up to 5000 sets of (time, frequency, ramp rate) points in a pass.

The ramp points are generated by the Service Preparation Subsystem (SPS) in the uplink predict file format. If a mission has selected the option to do uplink ramping, the SPS is configured to generate a set of linear ramps for each scheduled uplink pass. The SPS generates two types of uplink predicts – the first, called Best Lock Frequency (XA), provides the desired frequency tune computed to have the received uplink arriving at the spacecraft be at the spacecraft’s Best Lock Frequency (BLF), with no Doppler. The ideal XA transmitted from Earth would need to be a smooth curve with many orders of smooth derivatives to arrive at the spacecraft with a constant BLF. The second, called Uplink Frequency (ULF), provides the set of linear ramps that will be used to generate the uplink carrier. The ULF is a linear approximation to the ideal XA profile. The mission has to provide the DSN with an accuracy goal, which is the maximum allowed frequency error between the linear fit and the ideal uplink frequency, for the process. This accuracy goal is how close the DSN should try to get the received uplink carrier to the transponder PLL’s rest frequency. In other words, if the value is set to 10 Hz, the SPS will try to keep the carrier within 10 Hz of the spacecraft rest frequency, when it arrives at the spacecraft. The SPS uses the mission’s submitted trajectory file, the accuracy goal, and the limitation on the number of points to generate the set of ramp parameters. Figure 1 shows an example of the two frequency predicts. Rarely, due to highly dynamic trajectories and the limitation in the number of points, the SPS is unable to meet the accuracy goal. Note, that since this process depends on the SPS knowing the rest frequency of the transponder, if the mission operations detect that it has changed (due to component aging, or swapping to a redundant transponder), the updated value needs to be provided to the SPS.

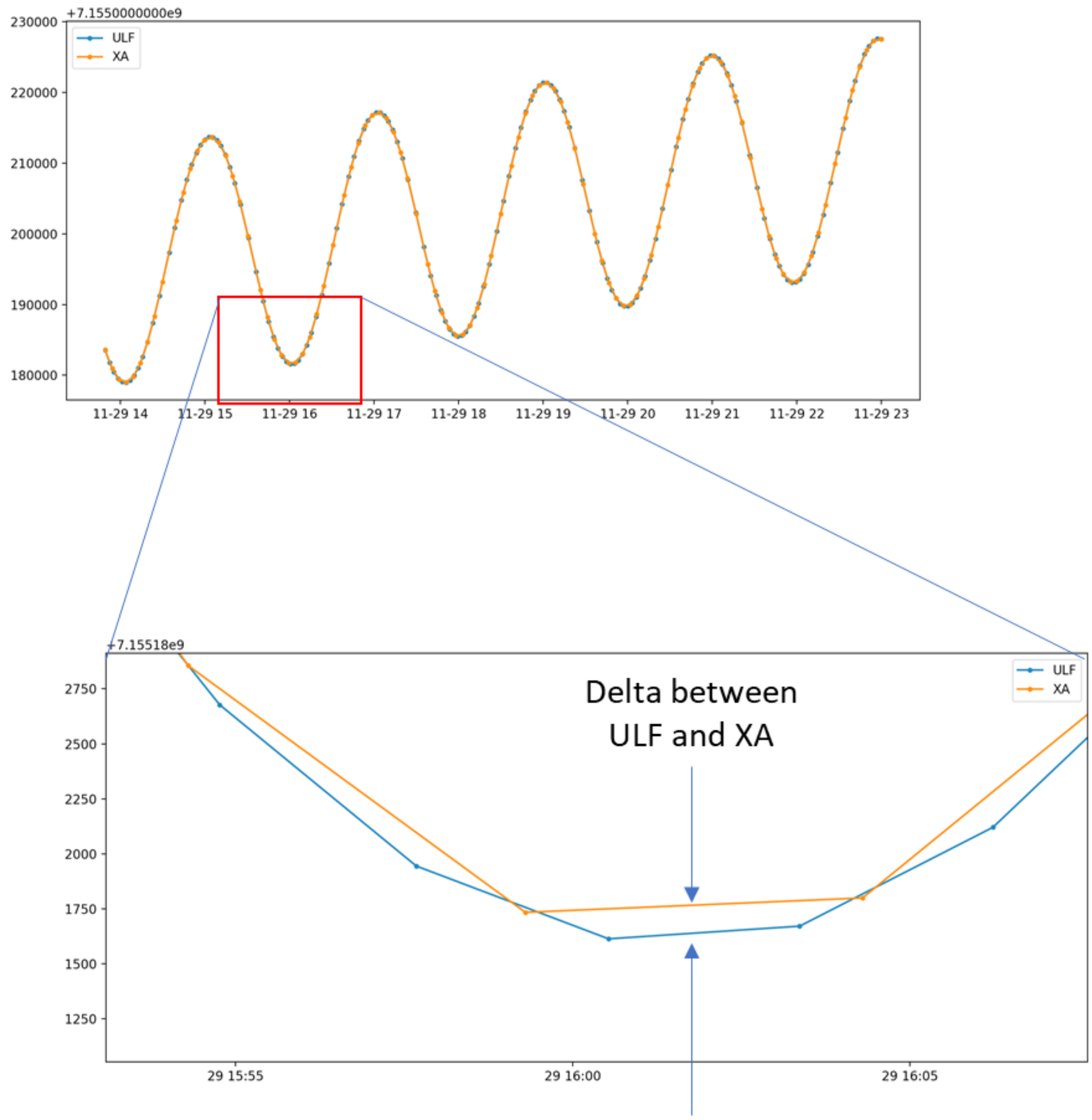

Figure 1. XA and ULF Predicts Example

Since the uplink Doppler is not perfectly cancelled out (due to the linear fit), the measured downlink carrier phase and frequency will have the downlink Doppler shifts, plus the remaining uplink Doppler effects. To correctly process the Doppler measurement, the actual transmitted uplink frequency needs to be provided to Navigation. This is done with Ramp Table data type in the tracking interface [4] or [5]; this data type provides the time, frequency, and frequency rates of the different ramps over the pass.

3.2 Mathematical Description

The process can be expressed mathematically as follows:

$$F_u(t) = F_T * df_{ut}(t) * df_{ud}(t) = F_{rest} + f_{err}(t) \quad (1)$$

Where:

$F_u(t)$ is the uplink carrier frequency (in Hz) as received by the spacecraft, as a function of time (t).
F_T is the static frequency (in Hz) that would be transmitted if no uplink tuning is done on the ground. It is not a function of time.
$df_{ut}(t)$ is the fractional uplink tuning that is done on the uplink carrier before transmission, as a function of time (t). It is unitless.
$df_{ud}(t)$ is the fractional uplink Doppler that the carrier experiences on the outbound path to the spacecraft, due to movement of the Earth and the spacecraft, as a function of time (t). It is unitless.
F_{rest} is the estimated rest frequency (in Hz) of the spacecraft transponder receiver. This is the frequency that is the goal of the uplink tuning. It is not a function of time during the pass. However, the actual rest frequency may change during the mission, and the estimate may be updated to account for these changes.
$f_{err}(t)$ is the error (in Hz) in uplink tuning (due to imperfect cancellation of the Doppler shift) at the spacecraft transponder receiver. It is a function of time.

Three things to note:

1. The output of the exciter (the frequency out the antenna) is $F_T * df_{ut}(t)$.
2. If $df_{ut}(t)*df_{ud}(t) = 1$, then the uplink tuning perfectly cancels out the uplink Doppler shifts, and the static frequency, F_T, would be set to the rest frequency, F_{rest}.
3. If $df_{ut}(t) = 1$, then the entire Doppler shift would be seen by the transponder.

As described in the section 3.1, the exciter outputs linear ramps in frequency. So, the output of the exciter, $F_T * df_{ut}(t)$, is a set of linear ramps, $F_{RAMP}(t)$. The uplink tuning process goal is to select a set of linear ramps, $F_{RAMP}(t)$, that keeps the difference between the transponder rest frequency and the actual frequency, $f_{err}(t)$, less than the specified value by the mission (the accuracy goal).

3.3 Uplink Tuning and Ranging

The DSN supports two types of ranging, Sequential [6] and PN [2]. The ranging signal is typically much weaker than the telemetry signal, due to the desire to not take power away from the telemetry data. To make up for the weak ranging signal, the received downlink ranging signal is integrated for seconds to tens of minutes, depending on the ranging signal strength. For the integration to successfully accumulate the signal, any frequency variations seen by the signal (such as Doppler) need to be removed.

The ranging integration process depends on the received downlink carrier being coherent with the uplink carrier. The two-way carrier frequency is defined by:

$$F_d(t) = F_T * df_{ut}(t) * df_{ud}(t) * G * df_{dd}(t) \tag{2}$$

Where:

$F_d(t)$ is the downlink carrier frequency (in Hz) as received by the ground, as a function of time (t).
G is the transponder turn around ratio. It is a ratio of two integers and is dependent on the uplink and downlink bands being used.
$df_{dd}(t)$ is the fractional downlink Doppler that the carrier experiences on the return path to Earth, due to movement of the Earth and the spacecraft, as a function of time (t). It is unitless.

All other parameters are as previously defined.

Note, that this can also be expressed as:

$$F_d(t) = F_{RAMP}(t) * df_{ud}(t) * G * df_{dd}(t) \tag{3}$$

The ranging signal has a base frequency that the various signal components (tones for Sequential, or chips for PN) are generated from. The ranging base frequency is the highest frequency used in the selected type of ranging – it is the Clock Tone for Sequential ranging and it is the Chip rate for PN ranging. As will be shown, the ranging base frequency must be frequency synchronous with the transmitted uplink carrier. The ranging base frequency is related to the ground transmitted frequency by:

$$F_{rng}(t) = F_{RAMP}(t) * R \tag{4}$$

Where:

$F_{rng}(t)$ is the base ranging frequency (in Hz), as a function of time (t).
R is the scaler for the ranging clock. It is a ratio of two integers and is dependent on the uplink band being used.

Finally, the actual ranging component frequencies are just another scalar times the base ranging frequency:

$$F_{rc}(t) = F_{rng}(t) * C \tag{5}$$
$$F_{rc}(t) = F_{RAMP}(t) * R * C \tag{6}$$

Where:

$F_{rc}(t)$ is the ranging component frequency (in Hz), as a function of time (t).
C is the scaler for the ranging component. It is a ratio of two integers and is dependent on the selection of the desired ranging component frequency.

The ranging modulation undergoes the same fractional Doppler shifts as the carrier does. But, at the spacecraft, the ranging signal is demodulated from the uplink carrier at the transponder, filtered, and then modulated onto the downlink carrier. Therefore, the ranging signal is not multiplied by the transponder turn around ratio (G). Thus, the received ranging component frequency is:

$$F_{rc\_r}(t) = F_{rc} * df_{ud}(t) * df_{dd}(t) \qquad (7)$$
$$F_{rc\_r}(t) = F_{RAMP}(t) * R * C * df_{ud}(t) * df_{dd}(t) \qquad (8)$$

Where:

$F_{rc\_r}(t)$ is the received (on the ground) ranging component frequency (in Hz), as a function of time (t).

Examining the term $F_r(t)$ shows we can relate the downlink ranging to the downlink carrier:

$$F_{rc\_r}(t) = F_{RAMP}(t) * df_{ud}(t) * df_{dd}(t) * R * C \qquad (9)$$
$$= (F_d(t) / G) * R * C \qquad (10)$$

The transponder turnaround ratio (denoted G in the present document) is discussed in [8]. For sequential ranging, the ratio R of the range-clock frequency to the uplink-carrier frequency can be inferred from equations provided in [6]. For PN ranging, the factor R can be inferred from equations provided in [2]. The ratio C can be inferred from equations provided in [6] for sequential ranging and in [2] for PN ranging. $F_d(t)$ is the received frequency from the carrier tracking loop in the ground station. All of the variation in the downlink ranging signal due to Doppler can be removed using the time-varying value of $F_d(t)$. As long as the downlink is coherent with the uplink, and the uplink tuning is included in the ranging frequency generation, using the received carrier removes all of the Doppler variation and the ranging signal will have a stable frame of reference for long integration times.

3.3.1 Non-coherent Ranging

As mentioned previously, when using a transceiver, the uplink and downlink frequencies are non-coherent. Since the ranging processing assumes that the uplink and downlink are coherent, this will introduce an additional error in the ranging result. As discussed in section 2.5.6 of [2], the additional error is dependent on how well the uplink tune removes the Doppler as seen by the spacecraft, and how long the ranging signal is integrated on the ground; further details are provided in section 2.5.6 of [2] and in [7].

Appendix A
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Appendix B
Abbreviations

BLF	Best Lock Frequency
PLL	Phase Locked Loop
SPE	Static Phase Error
SPS	Service Preparation Subsystem
ULF	Uplink Frequency
XA	Best Lock Frequency