2.5.6B DIFFERENTIAL ONE-WAY RANGING FOR SPACE-TO-EARTH LINKS IN ANGULAR SPACECRAFT POSITION DETERMINATION, CATEGORY B

The CCSDS,

considering

(a) that Very Long Baseline Interferometry (VLBI) measurement allow determination of geometric delay for space radio sources by the simultaneous reception and processing of radio signals at two stations;

(b) that using the VLBI geometric delay measurements from two stations, the angular position of a spacecraft can be accurately determined for navigational purposes;

(c) that the VLBI technique requires differencing phase measurements of sinusoidal tones or harmonics (known as Differential One-way Ranging [DOR] tones), modulated on the spacecraft's downlink RF carrier, which have been acquired at two (or more) stations;

(d) that VLBI accuracy depends upon a priori knowledge of both the length and orientation of the baseline vector between the stations, the station clock drift, and the media delays;

(e) that measurement errors can be greatly reduced by observing a quasar or Extra-Galactic Radio source (EGRS), that is angularly near the spacecraft, and then differencing the delay measured from the ERGS observation with the delay measured from observing the spacecraft (ΔDOR);

(f) that the spacecraft delay measurement's precision depends upon the received power (P_{DOR}) in the two most widely spaced DOR tones, f_{BW} Hz apart, as shown in the error relationship:

$$\varepsilon_\tau = \left[f_{BW} \sqrt{4\pi \frac{P_{DOR}}{N_0} T_{obs}} \right]^{-1}$$ seconds, where:

f_{BW} = DOR tone spanned bandwidth[1] (Hz)
T_{obs} = observation time (seconds);

(g) that a narrow spanned bandwidth is needed for integer cycle ambiguity resolution because the ΔDOR time delay ambiguity equals the reciprocal of the minimum spanned bandwidth;

(h) that, contrary to *considering (g)*, a wide spanned bandwidth is needed for high measurement accuracy;

(i) that doubling the spanned bandwidth of spacecraft DOR tones, while holding the other parameters fixed, will reduce errors resulting from low spacecraft SNR, low quasar SNR, and instrument phase ripple by half;

[1] NOTE: The spanned bandwidth is the widest separation between detectable tones in the downlink spectrum. This is usually given as twice the frequency of a sinusoidal "DOR Tone" modulated onto the carrier.

(j) that delay ambiguities in observables generated from wider bandwidths are resolved successively by using delay estimates from the narrower spanned bandwidths;

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(k) that a typical ΔDOR error budget is dominated by errors due to low quasar SNR, quasar position uncertainty, instrument phase ripple, and the troposphere;

(l) that EGRS delay measurement precision and instrument errors vary as $1/f_{BW}$;

(m) that direct phase modulation of a sinewave tone on the downlink RF carrier is more spectrum efficient than squarewave modulation and allows appropriate choices of spanned bandwidth and tone power;

(n) that the received spacecraft DOR tone power must be adequate for tone detection, with the threshold approximately determined by:

$$Threshold = \left[\frac{P_{DOR}}{N_0}\right] = 13 \text{ dB} \bullet \text{Hz if no carrier aiding is used;}$$

(o) that the DOR tone threshold reduces to:

$$Threshold = \left[\frac{P_{DOR}}{N_0}\right] = 1 \text{ dB} \bullet \text{Hz}$$ provided that the spacecraft RF carrier's SNR is greater than 13 dB and that the extracted carrier phase is used to aid in tracking the DOR tone whose frequency is a coherent submultiple of the spacecraft's RF carrier frequency;

(p) that the stability of the spacecraft's RF carrier stability, over a 1-second averaging time, must be adequate for signal detection;

~~(q) that the stability of the spanned bandwidth of the DOR tones, over a 1000-second averaging time, must be adequate for converting the measured phase difference to time delay;~~

(q~~r~~) that the *Space Research service* frequency allocation for Category B missions is 10 MHz in the 2 GHz band, 50 MHz in the 8 GHz band, 400 MHz in the 32 GHz band, and 1 GHz in the 37 GHz band;

(r~~s~~) that quasar flux is reduced and system noise temperature is higher at 32 and 37 GHz as compared to 8 GHz;

recommends

(1) that DOR tone be sinewaves;

(2) that either direct tone detection or carrier-aided tone detection be used;

(3) that DOR tones be coherent with the downlink RF carrier frequency if carrier-aided detection is used;

(4) that one DOR tone pair be used in the 2 GHz band, two DOR tone pairs be used in the 8 GHz band, and three DOR tone pairs be used in the 32 and 37 GHz bands;

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(5) that the approximate DOR tone frequencies used in each band be those in Table 2.5.6-1;

TABLE 2.5.6-1: RECOMMENDED DOR TONES

Space-to-Earth Frequency Band	Number of DOR Tones	Approximate DOR Tone Frequencies (± 10%)
2 GHz	1	4 MHz
8 GHz	2	4 MHz and 20 MHz
32 & 37 GHz	3	4 MHz, 20 MHz, and ~~120~~ 76 MHz

Note: Depending on mission requirement (accuracy versus integration time), lower tone frequencies (< 4 MHz) may be used. In this case, if the down-link modulator is to be implemented digitally, square-wave DOR modulation may be applied in order to reduce transponder complexity.

(6) that, if spacecraft DOR data are to be acquired in the one-way mode, the spacecraft's oscillator stability over a 1-second averaging time shall be:

$\Delta f/f \le 4.0 \times 10^{-10}$ at 2 GHz,
$\Delta f/f \le 1.0 \times 10^{-10}$ at 8 GHz,
$\Delta f/f \le 0.3 \times 10^{-10}$ at 32 and 37 GHz

where: $\Delta f/f$ denotes the spacecraft oscillator's frequency variations (square root of Allan's variance);

~~(7) that the frequency stability of the spanned bandwidth, f_{BW}, of the DOR tones must satisfy:~~

~~$\Delta f_{BW}/f_{BW} \le 1 \times 10^{-9}$ over a 1000-second averaging time~~

~~where: Δf_{BW} denotes spanned bandwidth variations due to on-board oscillator instabilities.~~