CCSDS SLS RF and Modulation Working Group

ESA HQ, Paris (France), 3-7 May 2004

Document SLS-RNG_04-01

Delta-DOR recommendation - proposal for change (Rec. 2.5.6B)

Giovanni Boscagli and Enrico Vassallo (ESA)

1. Introduction

Several questions of clarification nature for CCSDS Recommendation 2.5.6B were raised at the CCSDS meeting in College Park but could not be answered. An action was given to the chairman to try and contact the most likely author of such recommendation and if needed propose an updated recommendation.
Moreover, some modifications are proposed, based on the current baseline as for BepiColombo mission and on the measurements performed on the Mars-Express spacecraft.

2. Discussion

2.1. Clarification on questions from CCSDS meeting in College Park

As reported in the Annex-1, the originator of 2.5.6B was contacted and possible changes identified. Such changes are mainly of editorial nature to improve clarity of the recommendation with exception of the removal of recommends (7) and the associated considering (q), which are no longer needed.

2.2. Proposal based on BepiColombo baseline

As reported in Annex-2, the present baseline proposed for BepiColombo includes also DOR square-wave modulation with lower frequency tones. This change is indicated as a note to the TABLE 2.5.6-1: RECOMMENDED DOR TONES**.**

3. Proposed revised CCSDS 401 (2.4.10)B-1

A proposal for a revised recommendation CCSDS 401 (2.5.6B) is attached for discussion at the meeting.

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;

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

(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;

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

(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 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:

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

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

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

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

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

ANNEX 1 - Correspondence with author of recommendation 2.5.6B

Jim,

thanks for your reply. I will take your comments into consideration when proposing an update to the CCSDS recommendation on delta-DOR.

Best Regards, Enrico

"James S. Border" <James.S.Border@jpl.nasa.gov>

11/02/2004 23:57

To:Enrico.Vassallo@esa.int
cc:
Subject:Re: Greetings and Questions on delta-DOR (CCSDS Ranging WG AI_03-05)

Enrico,

I apologize that it has taken so long for me to respond. I was completely occupied with my work on Mars Express and MER. The Delta-DOR measurements worked quite well for these two projects. It would be helpful, and could lead to even better measurements, to have standards for spacecraft transponders to enable these types of measurements.

I did write the 1993 document titled "Technical Characteristics and Accuracy Capabilities of Delta Differential One-Way Ranging as a Spacecraft Navigation Tool" that you found. This is still generally applicable, but some sources of error are now better controlled, and we are getting better performance.

I will provide answers to the questions you have asked below. But keep in mind that the answers to questions about signal power and signal stability are really guidelines, rather than absolute requirements. For example, if a measurement is possible for some specified values of signal power and signal stabilty, then it would also be possible to make a valid measurement for a signal with more power but less stability, by shortening the integration time. The guidelines I recommend are based on practical measurement issues to provide robust detection of the spacecraft signal and a total observation time of less than one hour.

Regards,
Jim

>1. Spanned bandwidth
>
>In considering (f) but also in other sections, mention is made of the DOR tone

>spanned bandwidth fbw. Is it 2 times the tone frequency? This would be in
line
>with your e-mail on Mars-Express. If the answer is yes, would you have any
>problem in defining the spanned bandwidth as 2 times the tone frequency in
the
>recommendation?

You are correct. 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. I have no problem recommending this as the
standard. But you should be aware that a square wave could be used
as a modulating signal, and then the spanned bandwidth could be some
higher multiple of the fundamental square wave frequency.

>
>2. RF carrier stability
>
>In considering (p) it is stated that the carrier stability over 1-s averaging
>time shall be adequate for signal detection. This is understood for (one-way
>Doppler) carrier loops of about 1 Hz or larger and/or open loop receivers
with
>less than 1 s processing time.
>Recommend (6) seems to be related to this requirement. For the case
>of 8 GHz for
>instance, such recommend (6) gives a maximum delta_f/f of 1.0*10^-10
>where delta_f/f is denotes the spacecraft's oscillator frequency variations.
>
>Is this delta_f/f linked to the detection of the carrier? In this
>case, why the
>1-s averaging time is not specified? Again, judging from your e-mail on
>Mars-Express this seems to be the case. If the answer is not, we still need
an
>averaging time for delta_f/f to be specified. Could you please confirm our
>interpretation?
>
>For the case of a 8 GHz carrier such requirement would yield a
>frequency offset
>of the carrier of 0.8 Hz, which is a fair requirement.

The purpose of specifying f/f is to ensure that the carrier can be
detected and that the phase of the carrier can be accumulated without
cycle slips. Recommendation (6) was meant to guarantee that (p)
would be satisfied. A good guideline for carrier detection at 8 GHz
is f/f = 1.e-10 over 1 sec, with Pc/No = 12 dB*Hz. For every factor
of two decrease in signal stability, another 3 dB of power is needed.
For 32 GHz, either a x4 increase in stability, a 6 dB increase in
power, or some combination is needed.

>
>3. Frequency stability of the spanned bandwidth
>
>Considering (q) states that the stability of the spanned bandwidth of the DOR
>tones over 1000-s must be adequate for converting the measured phase
>difference
>to time delay.

>Recommend (7) specifies such stability to be delta_fbw/fbw <= 1.0*10^-9 over
>1000-s where delta_fbw denotes spanned bandwidth variations due to on-board
>oscillator instabilities.
>We did not understand the concept of spanned bandwidth stability.
>Typically, the
>spacecraft has only one frequency reference and therefore it would be
clearer
>to specify delta_f/f stating that such delta_f is the instability at the tone
>frequency. Is our a correct interpretation of the problem or are we missing
>something?
>Secondly, if we understand the DOR concept correctly, it is a
>measurement of the
>delta-phase on the recovered tones at two ground stations and therefore in
our
>opinion the on-board instability should cancel out, assuming that
>the carrier is
>correctly detected (see bullet 2 above.) Is this requirement to cover the
case
>of imperfect cancellation at the two stations? Is this the reason
>why it is less
>stringent than the requirement on carrier detection?

This requirement can now be dropped. We have found that we can
measure the tone separation during the Delta-DOR data processing.
The measured tone separation is used to convert from units of cycles
to units of seconds.

>
>4. Frequency stability in general
>
>The CCSDS recommendation just talks about frequency stability delta_f/f or
>delta_fbw/fbw. In your e-mail you correctly talk about fractional frequency
>stability. We were wondering in our far we could not just talk about the
>classical Allan deviation while keeping the same specifications as in 2.5.6B.

Yes, I do mean classical Allan standard deviation when I say
'frequency stability' or f/f.

>Dear Jim,
>
>I have not heard from you on this issue. Since I experienced several major
>problems with the e-mail system at ESA, I decided to send it out
>again hoping to
>get at least an acknowledgement from you.
>
>Meanwhile, I was able to get and read a document you must have submitted to
>CCSDS in 1993 called "Technical Characteristics and Accuracy Capabilities of
>Delta Differential One-Way Ranging as a Spacecraft Navigation Tool".
>Such document defines the spanned bandwidth as the frequency
>separation between
>the two outermost DOR tones. This is in my opinion equivalent to 2 times the
>highest tone frequency as proposed under bullet 1 below.
>
>I was, however, unable to find any discussion concerning frequency
>stability in

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>your paper so that questions 2-4 remain unanswered.
>
>Please let me know if you receive this e-mail and if/when you will be able to
>look at my questions. I would like to send out an answer to CCSDS by
>the end of
>January latest.
>
>Thanks in advance, Enrico
>
>----- Forwarded by Enrico Vassallo/esoc/ESA on 18/12/2003 16:55 -----
>|--------+---------------------->
>|        |          Enrico      |
>|        |          Vassallo    |
>|        |                      |
>|        |          02/12/2003  |
>|        |          14:37       |
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>>-----------------------------------------------------------------------------
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>   |
>|
>   |       To:     "James S. Border" <James.S.Border@jpl.nasa.gov>
>|
>   |       cc:     Giovanni Boscagli/estec/ESA@ESA
>|
>   |       Subject:     Greetings and Questions on delta-DOR (CCSDS
>Ranging WG  |
>   |       AI_03-05)
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>>-----------------------------------------------------------------------------
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>
>Jim,
>
>we haven't been in touch for quite some time. I understand from
>Trevor, however,
>that the delta-DOR measurements on Mars-Express are fine and I am
>happy we could
>find the right solution for that.
>
>The reason for this e-mail has to do with my job as chairman of the CCSDS
>working groups on RF&modulation and ranging.  In the frame of the systematic
>review of all current recommendation, we started reviewing the one
>on Delta-DOR
>and several questions arose. This is because the groups are mostly formed by
>young engineers new to CCSDS. Not knowing the answer within the group I was
>tasked together with my colleague Giovanni to try and contact the initial
>developers of such recommendation. I thought that most likely you
>would be that
>person or would know the answer anyway!
>
>Here are our questions on CCSDS recommendation 401 (2.5.6B). I hope
>you have it
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>because due to a problem with my new PC I cannot extract it from the 401 book
>and I do not want to flood your e-mail server with MB of data. If
>you don't have
>it and you cannot access the CCSDS site (www.ccsds.org) let me know and I
will
>forward the whole 401 document to you.
>
>
>Would you be so kind and help us out here?
>
>
>Best Regards, Enrico

ANNEX 2 – BepiColombo X/X/Ka Deep Space Transponder: current approach

In the frame of BepiColombo activity it has been proposed to use a different approach with respect to the CCSDS Recommendation 2.5.6B, reducing the DOR tones frequency down to 1 MHz. This allows implementing the DOR modulator entirely in the digital domain, with considerable reduction of design complexity.
In the current transponders, the implementation of the base-band functions is mainly performed using Digital Signal Processing Techniques (based on VLSI circuits) both for receiver (demodulation) and transmitter (modulation) side. So the proposed approach is to use the digital modulator (already present inside the transponder for TM and turn-around ranging function) for implementing the DOR modulation as well. Of course the limit (in terms of speed) of the digital devices defines a limit for the maximum DOR tone frequency. So at present we have proposed the following baseline:

- Digital DOR modulator for the X-band downlink with maximum spanned bandwidth of about 6 MHz
- Digital DOR modulator for the Ka-band downlink (with maximum spanned bandwidth of about 6 MHz) plus RF analogue modulator (spanned bandwidth according to the CCSDS Recommendation 2.5.6B)

Note that, for the digital DOR modulation, the square-wave tone instead of the sinusoidal approach has been proposed. This is against the CCSDS Recommendation 2.5.6B. However it must be underlined that with respect to the sinusoidal approach

- The square-wave modulation represents a simplification in terms of implementation
- The square-wave harmonics have a level higher than the sinusoidal modulation products
- That proper RF filtering (inside the transponder transmitter side) shall be performed in order to restrict the occupied bandwidth.

Of course according to the expression indicated in the CCSDS Recommendation 2.5.6B point (f), the reduction of the spanned bandwidth can be compensated by an increase of the needed observation time with a power of two. Assuming the same P_{DOR} / N_O and the measurement's precision and reducing the spanned bandwidth from 40 MHz to 4 MHz we have to consider a longer observation time (100 bigger). For typical BepiColombo link budget values and for an accuracy of 0.15 nsec we have:

- 0.8 sec for a spanned bandwidth of 40 MHz
- 80 sec for a spanned bandwidth from 4 MHz

<u>It must be underlined that in the frame of Mars Express mission the Delta DOR measurements were performed using the 10th harmonics of the square-wave TM sub-carrier (which corresponds to a spanned band-width of 5.28 MHz) with errors down to 0.1÷0.2 ns.</u>

In the following lines the current DOR specification for the BepiColombo X/X/Ka Deep Space Transponder is reported**.**

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The transponder shall provide DOR tones generated for downlink carrier phase modulation (both for X and Ka band) in non-coherent mode[2]. The downlink signal can be described (for X and Ka band) in the time domain by:

- $S_{down,X}(t) = (2P_T)^{1/2} \cos[2\pi f_{down,X} t + m_{X1} \operatorname{sgn}(\sin(2\pi f_{X1} t))]$
- $S_{down,Ka}(t) = (2P_T)^{1/2} \cos[2\pi f_{down,Ka} t + m_{K1} \operatorname{sgn}(\sin(2\pi f_{K1} t)) + m_{K2} \sin(2\pi f_{K2} t) + m_{K3} \sin(2\pi f_{K3} t)]$

The tones shall be coherent with downlink carrier frequency values[3]. The tones frequencies shall be (TBC):

- *for the X-Band case[4]* $f_{X1}=f_{down,X}/8800$
- *for the Ka-Band case[5]* $f_{K1}=f_{down,Ka}/33440$, $f_{K2}=f_{down,Ka}/1672$, $f_{K3}=f_{down,Ka}/418$[6]

The peak modulation indices $(m_{X1}, m_{K1}, m_{K2}, m_{K3})$ *shall be (TBD).*

\- - - - - - - -

[2] Note that the DOR function can be selected in non-coherent mode only, so both exciters (X-band and Ka-band) must be configured in non-coherent mode. Separate DOR commands are foreseen for X and Ka-band exciters.

[3] The DOR tone at lowest frequency (i.e. 1 MHz, approximately) can be generated in a digital device. In order to simplify the hardware implementation and to reduce the power consumption the 1MHz-DOR tone is proposed as square-wave. Note that this is against the CCSDS recommendation, which addresses the use of sine-wave tones.

[4] This value corresponds to a frequency value of about 1 MHz. Assuming as minimum a transmitter bandwidth of about +/- 3 MHz around the TX frequency (the bandwidth shall be limited to avoid interference), we can consider also the third harmonic for DOR measurements (around 3 MHz). Note that the proposed filtered square-wave approach allows getting better performances on the harmonic components with respect to the sine-wave tones (as recommended by CCSDS).

[5] These values correspond to: f_{K1} about 1 MHz, f_{K2} about 19 MHz, f_{K3} about 76 MHz. The f_{K1} component can be generated and the modulation achieved in a digital fashion. So the same consideration above reported for f_{X1} are still applicable. For the other two components, we can consider only a dedicated analogue implementation.

[6] For the Ka-Band, the ratio between the second DOR and first DOR tone frequencies is equal to 20, while the CCSDS recommends 5. However it is 20/3 for the third harmonics of the lowest components. The highest Ka-Band DOR tone frequency is equal to 76 MHz (approximately) instead of 120 MHz as recommended by CCSDS. The compatibility of the selected DOR frequencies with on-ground stations shall be confirmed.