17th International Conference on Space Operations, Dubai, United Arab Emirates, 6 - 10 March 2023.

SpaceOps-2023, ID # 495

Delta-DOR with multiple spacecraft

M. Menapace[b*], J. de Vicente[a]

[a] *European Space Agency, ESA/ESOC, Robert Bosch Strasse 5, D-64293 Darmstadt (Germany)*
javier.devicente@esa.int
[b] *Serco Services GmbH, c/o ESA/ESOC, Lise-Meitner-Strasse 10, D-64293 Darmstadt (Germany)*
marco.menapace@ext.esa.int
* Corresponding Author

Abstract

Delta-DOR is a navigation technique, derived from Very Long Baseline Interferometry (VLBI), that complements line of sight Doppler and Ranging measurements providing very accurate plane of sky spacecraft measurements. The Delta-DOR technique requires that the spacecraft is tracked simultaneously at two distant radio antennas. A quasar must also be tracked just before and/or after the spacecraft observation, allowing for media calibration and the removal of clock offset effects between the two stations. Since the development of its own software correlator in 2005, Delta-DOR is part of the ESA navigation portfolio and is used regularly for the support to ESA deep space missions, in particular during critical phases such as orbit insertion and gravity assist manoeuvres. In addition to its own missions, the reliability of ESA Delta-DOR infrastructure has allowed the provision of Delta-DOR supports to other space agencies. The interest in Delta-DOR techniques has triggered the creation of a specific working group within CCSDS, which deals with the standardization of the Delta-DOR technique and fosters interagency cooperation. This has increased the available Delta-DOR infrastructure, permitting the use of mixed baselines (with stations from different agencies). Delta-DOR navigation performance, which has improved significantly over the years, is now approaching the 1 nrad goal, thanks to recent progress in various areas, among which the use of higher frequency bands (e.g. Ka), dedicated signal structures (e.g. pseudo-noise spread DOR tones) and improved media calibration means (e.g. directive water vapour radiometers), must be mentioned. An additional challenge for Delta-DOR is the optimization of station time, as dictated by the limited network capacity and the increasing number of missions to be supported. This paper presents current capabilities in ESTRACK to optimise the duration of Delta-DOR measurements when various spacecraft are located in the same region of the sky, by making use of improved sequences (e.g. the same quasar or quasars are shared by the various Delta-DOR observations). Consecutive spacecraft scans can be scheduled (i.e., Q-S1-S2-Q) or in case the signals from various spacecraft allow Multiple Spacecraft per Aperture (MSPA) operation, a further enhancement is possible, allowing simultaneous Delta-DOR measurements (e.g. Q-S1-Q & Q-S2-Q) on multiple spacecraft. The first ESA demonstration of a Multiple Spacecraft Per Aperture (MSPA) Delta-DOR measurement was given in 2021, with Mars Express and ExoMars TGO, and allowed two simultaneous sessions in a single Delta-DOR slot. In this paper the operational concept and its implementation in ESTRACK are presented, together with the obtained results. The validity of the approach is demonstrated by the successful correlation and the good agreement of the result with the orbit determination performed independently by Flight Dynamics, on both spacecrafts involved. Formation flying spacecraft (e.g. cubesats) are triggering increased interest and constitute a clear use case for this technique.

Keywords: (Delta-DOR, MSPA, SBI, ESTRACK)

1. Introduction

Delta-Differential One Way Ranging (Delta-DOR) is a navigation technique derived from Very-Long-Baseline Interferometry (VLBI) and introduced by JPL in the late 1970’s [1], which allows the determination of the angular position (with respect to a baseline determined by two ground stations) for distant spacecraft. The open loop recordings collected at the ground stations are later processed at a central facility (correlator) to calculate the difference in time of arrival of the spacecraft’s signal at the two stations, and compared against a similar delay measurement for an angularly nearby quasar source, for which the position is well known. The use of quasar sources is used as calibration of the measurement and allows the cancellation of errors that are common to both spacecraft and quasar. The geometry of a Delta-DOR measurement is shown in Fig.1a.

The Delta-DOR technique is part of the ESA navigation portfolio since 2005 and is used regularly for the support to ESA deep space missions during critical navigation phases. ESA baselines (see Fig.1b) are Cebreros-New Norcia (X-Band, ~11600 km) and Cebreros-Malargüe (X & Ka-Band, ~9600 km). Mixed baselines (e.g. one ESA ground station + one station from another Agency) can also be supported thanks to standardisation work within CCSDS, where a dedicated DDOR WG performs its work. In addition to Delta-DOR accuracy, which is currently approaching the one nanoradian mark, development efforts [2] are focusing on operational aspects. In this regard, the quick delivery of Delta-DOR results and the optimisation of Delta-DOR sessions are topics of growing interest. The typical one-hour duration of an ESA Delta-DOR session is not negligible considering the high operational load of ESTRACK antennas (many spacecraft to be supported) and the fact that two ground antennas are required for the Delta-DOR technique. Additionally, the number of Delta-DOR supports is expected to grow in the years to come, with new requirements to support fleets of formation flying spacecraft.

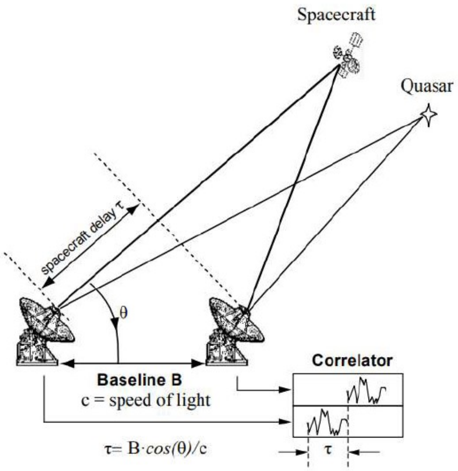

Fig.1 a. Delta-DOR geometry, credits [4]

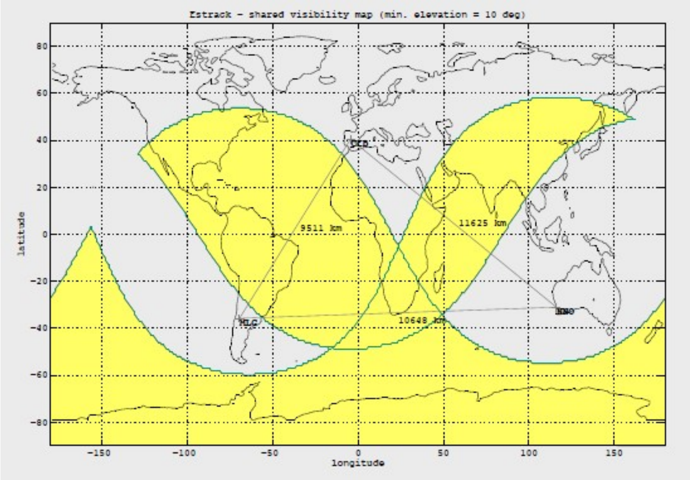

Fig.1 b. ESA Delta-DOR baselines

Simultaneous Delta-DOR sessions on multiple spacecraft are a way to optimise station time. If the signal from various spacecraft falls within the ground station’s antenna beam it is possible to track them simultaneously, as well as to perform single quasar recordings that can be used for the calibration of all spacecraft involved. A similar technique called Same Beam Interferometry (SBI) [3] profits from the simultaneous observation of the various spacecraft to make very accurate relative measurements between them. In the latter case (e.g. when the navigation product is the relative plane of sky position between the spacecraft) the quasar measurement is not required.

ESA’s first multiple spacecraft Delta-DOR test session was organised with ESA Mars Express and ExoMars TGO spacecraft on Nov. 28th, 2021, and is presented in this paper. As both spacecraft had at that time already reached their final orbits around Mars, the MSPA session was not necessary for navigation, but offered a perfect test case for the validation of ESA Delta DOR operation in the case of multiple spacecraft.

2. Signal structure

Mars Express was launched in 2003. As deep space transponders developed at that time were not equipped with dedicated DOR tones, Delta-DOR sessions relied on the availability of distant (but still powerful enough for the measurement) telemetry harmonics. This was also the approach used with ESA Venus Express and Rosetta missions, before the introduction of dedicated DOR tones (ExoMars TGO in 2016 in the case of ESA). In the case of MEX in particular, the 2nd, -14th and +20th harmonics of the telemetry subcarrier are recorded during Delta-DOR sessions, thus producing an overall spanned bandwidth (distance between left most and right most tones) of almost 9 MHz. This is a modest figure compared to the bandwidths obtained with later implementations using dedicated DOR tones. Overall, the combination of a small spanned bandwidth with low power tones (harmonics in this case) has a direct implication on the quality of the measurement, in particular for what regards thermal noise error terms (see Appendix A, a detailed description of Delta-DOR error terms can be found in [4] and will not be further given in this paper).

ExoMars TGO is equipped with dedicated DOR tones at 1/2200 and 1/440 ratios of the non-coherent carrier frequency. Using the most distant tones, this results in an overall spanned bandwidth of roughly 38 MHz, a 4.3 ratio improvement with respect to that of Mars Express. The reader should be aware that the contribution due to the quasar thermal noise error term (see Appendix A) will also improve accordingly, since its value is inversely proportional to the spanned bandwidth (quasar channels are recorded at the same frequencies as spacecraft tones and therefore the same spanned bandwidth applies also for the quasar).

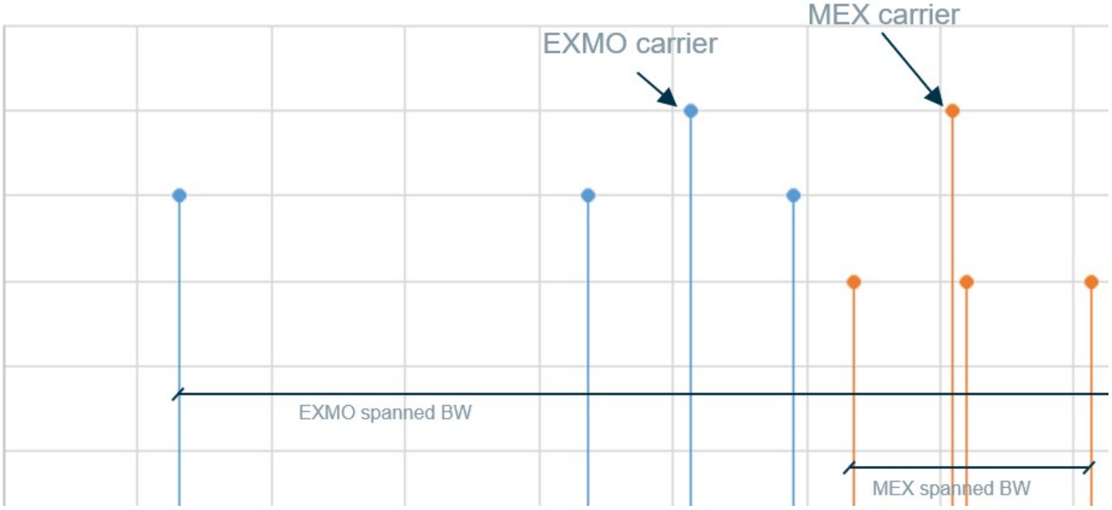

Fig.2. Distribution of Delta-DOR tones (MEX and EXMO)

3. Configuration

Each ESA deep space ground station hosts two TTCP modems of deep-space type. This type of TTCP is equipped with two sub-receivers, commonly referred to as 'slices'. For the MSPA case described in this paper, each slice was configured with a different frequency plan (slice 1 for ExoMars TGO, slice 2 for Mars Express), thus allowing the simultaneous recording of the signals from both spacecraft. Due to the need to record the quasar at the same frequencies used for the spacecraft tones, both TTCP slices were configured to record the quasar simultaneously, albeit at different subchannel frequencies (see Fig. 2).

Compared to typical Delta-DOR scenarios, where the relatively limited Doppler shift of the spacecraft (in X-band) during a Delta-DOR session can be handled by 50 kHz wide open loop channels, the higher dynamics of Mars orbiters for the test case described on this paper required the use of 100 and 200 kHz bandwidths for Mars Express and ExoMars TGO respectively. However, in order to allow an automated operation by the Station Computer (STC) it was necessary to set all subchannel bandwidths (on both slices) to a common value (200 kHz) for the spacecraft recording. This was not an issue for the quasar recording, as the standard 4 MHz subchannel bandwidth that is used operationally was kept.

A standard SQS sequence with seven scans (resulting in three SQS sequences for a total duration of one hour) was defined.

Open-Loop 1

OL1 Session	Active	Started:	2021.340.11.04.52.000	Stopped:	2021.340.11.03.30.516
OL1 Scan	Active	Started:	2021.340.11.04.57.000	Stopped:	2021.340.11.03.27.374

OL1 Receiver

Frequency Plan	FP1/FP2
Doppler Action	No Doppler
Doppler Action 2	No Doppler
Sampling Rate	200 kHz
Quantization Bits	8-bit
Gain level	0 dB
Frequency Offset	0 Hz
Current gain	84.0 dB

OL1 Dataset Information

Agency	ESA
Station id	24
Tx Station Name	n.a.
Rx Station Name	CB11
Quasar Name	QSG1
DDOR/RS mode	DDOR
RS dset duration	1 min

	FP 1	FP 3
Mission Name	EXMO	test
Receiver Name	R1	
Spacecraf Name	EXMO	sc_test
Spacecraft Id	143	0

Could not be configured differently due to STC automation

Changed to 4 MHz, 2 bit for Quasar

Slice 1 - EXMO

OL1 Channels

	Configuration		Status				
	Source	Add. Offset	Active	Actual Freq	Nb Frames	Dropped	Last Frame Date
Ch1	X	0 Hz	Active	8[redacted] Hz	648	0	2021.340.11.05.11.999
Ch2	X	-38[redacted]Hz	Active	8[redacted] Hz	648	0	2021.340.11.05.11.999
Ch3	X	3[redacted] Hz	Active	8[redacted] Hz	648	0	2021.340.11.05.11.999
Ch4	X	-191[redacted] Hz	Active	8[redacted] Hz	648	0	2021.340.11.05.11.999
Ch5	X	19[redacted]Hz	Active	8[redacted] Hz	648	0	2021.340.11.05.11.999
Ch6	off	0 Hz	Idle	8[redacted] Hz	0	0	1970.001.00.00.00.000
Ch7	off	0 Hz	Idle	8[redacted] Hz	0	0	1970.001.00.00.00.000
Ch8	off	0 Hz	Idle	8[redacted] Hz	0	0	1970.001.00.00.00.000

Open-Loop 2

OL2 Session	Active	Started:	2021.340.11.04.54.000	Stopped:	2021.340.11.04.27.574
OL2 Scan	Active	Started:	2021.340.11.04.57.000	Stopped:	2021.340.11.03.22.446

OL2 Receiver

Frequency Plan	FP1/FP2
Doppler Action	No Doppler
Doppler Action 2	No Doppler
Sampling Rate	200 kHz
Quantization Bits	8-bit
Gain level	0 dB
Frequency Offset	0 Hz
Current gain	96.0 dB

OL2 Dataset Information

Agency	ESA
Station id	24
Tx Station Name	n.a.
Rx Station Name	CB11
Quasar Name	QSG1
DDOR/RS mode	DDOR
RS dset duration	1 min

	FP 2	FP 4
Mission Name	MEX1	test
Receiver Name	R2	
Spacecraf Name	MEX1	sc_test
Spacecraft Id	80	0

Slice 2 - MEX

OL2 Channels

	Configuration		Status				
	Source	Add. Offset	Active	Actual Freq	Nb Frames	Dropped	Last Frame Date
Ch1	X	0 Hz	Active	84[redacted]0 Hz	112	0	2021.340.11.05.12.999
Ch2	X	[redacted] Hz	Active	84[redacted]0 Hz	112	0	2021.340.11.05.12.999
Ch3	X	-[redacted] Hz	Active	84[redacted]0 Hz	112	0	2021.340.11.05.12.999
Ch4	X	[redacted] Hz	Active	84[redacted]0 Hz	112	0	2021.340.11.05.12.999
Ch5	off	0 Hz	Idle	84[redacted]0 Hz	0	0	1970.001.00.00.00.000
Ch6	off	0 Hz	Idle	84[redacted]0 Hz	0	0	1970.001.00.00.00.000
Ch7	off	0 Hz	Idle	84[redacted]0 Hz	0	0	1970.001.00.00.00.000
Ch8	off	0 Hz	Idle	84[redacted]0 Hz	0	0	1970.001.00.00.00.000

Fig.3. TTCP configuration

It is worth noting that the parallel activation of the Open Loop receivers in slice 1 and 2 had already been successfully tested during the Dual Band (X- and Ka-Band) Bepi Colombo passes supported in 2020 and 2021 [2]. In that case, each slice was configured for a different frequency band.

4. Results

The signals were correctly acquired at the two stations, following the predefined seven scan sequence. The two independent sets of data were correlated in a standard way (e.g. no special action required), using the corresponding Flight Dynamics models as input. The residuals obtained during the measurement (after removal of the clock offset, allowing a better comparison of jitter effects) is shown in Fig.4. A summary of the results (as reported by the correlator) is given in Table 1.

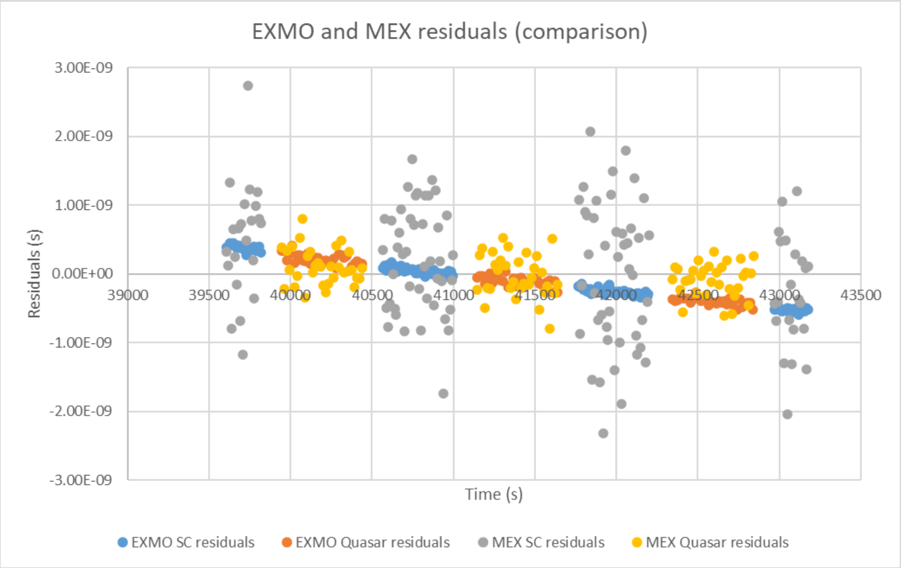

Fig 4. Delta-DOR residuals of MSPA pass

Main correlation results are summarised in the next table.

	Venus	Sequence 1	Sequence 2	Sequence 3
EXMO	Quasar Q0431 Flux (Jy)	0.98	0.96	1.00
	Quasar Accuracy (ns)	0.014	0.012	0.009
	Expected Quasar Accuracy (ns)	0.011	0.012	0.011
	Average spacecraft accuracy (ns)	0.009	0.008	0.006
	Expected average spacecraft accuracy (ns)	0.007	0.007	0.007
MEX	Quasar Q0431 Flux (Jy)	1.08	1.02	1.08
	Quasar Accuracy (ns)	0.045	0.055	0.042
	Expected Quasar Accuracy (ns)	0.039	0.041	0.039
	Average spacecraft accuracy (ns)	0.163	0.202	0.189
	Expected average spacecraft accuracy (ns)	0.179	0.109	0.105

Table 1. Summary of main results – Expected values are calculated using the equations in Appendix A

The obtained values are in good agreement with the expectations:

- Similar quasar fluxes are seen (the same quasar was used for the ExoMars TGO and Mars Express Delta-DORs)
- Quasar accuracies in the case of ExoMars show a ratio between 3.21 and 4.67 compared to Mars Express, reasonably close to the expected 4.3.
- A reasonably good agreement has been observed between the measured and the expected spacecraft accuracy. For the estimation of the expected value, the P_{DOR}/N_0 levels measured by the correlator have been used.

The post-fit residuals observed in the reconstructed orbit by ESOC Flight Dynamics are shown in Fig.5 and confirm the quality of the measurements. For MEX the mean of the residuals is -0.1 ns and the peak-to-peak spread 0.4 ns. For EXMO the mean of the residuals is +0.01 ns and the peak-to-peak spread is 0.04 ns. The plots with the post-fit residuals for the two missions are shown below.

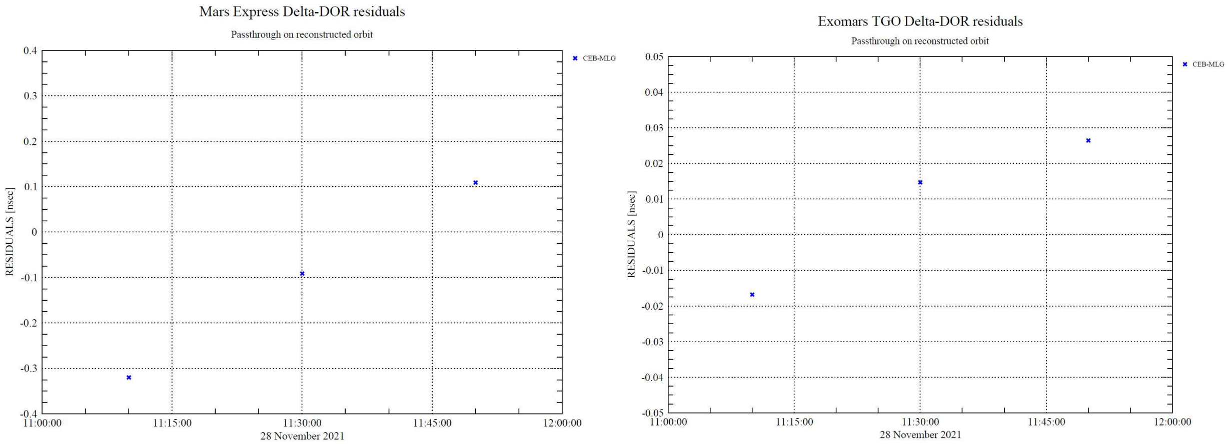

Fig 5. Post-fit residuals (after passthrough by ESOC Flight Dynamics on reconstructed orbit)

5. Further considerations

The results shown in this paper confirm the suitability of ESTRACK stations for multiple spacecraft Delta-DOR. For a fully redundant TTCP configuration (e.g. two hot redundant TTCPs configured identically) a maximum of four simultaneous spacecraft can be currently supported, resulting from the four different frequency plans (two per slice) allowed by each TTCP. The significant time savings resulting from this approach will allow, in cases where MSPA Delta-DOR is possible, to free additional station time to support other missions. In the case of nearby spacecraft whose signals do not fall within the antenna beamwidth, optimised scans can still be defined (i.e. Q-S1-S2-Q), which will also result in time savings and can also be supported with ESA Delta-DOR baselines.

MSPA Delta-DOR measurements can also be used to perform relative measurements between the spacecraft. These measurements are very accurate, as error contributions of angular (e.g. same beam) and temporal (e.g. same recording times) nature are highly reduced. In the case of Same Beam Interferometry (SBI) applications particular attention must be given to the synchronization accuracy between the slices. Indeed, the test presented in this paper has been useful to identify slight differences in the timetagging by each slice, which need to be accounted for in the case of SBI measurements. This would not be relevant in the case of multiple DDORs, thanks to the "calibrating" effect provided by the quasar.

A promising future evolution is the combination of MSPA Delta-DOR with pseudo-noise spread DOR tones [2], which will be operational soon (the first ESA mission to be equipped with PN DOR will be HERA, scheduled to be launched in 2024). Larger sample rates (several MHz) will be used to acquire the PN DOR spread tones and a possible overlap of subchannels of different spacecraft could occur. A CDMA approach (each spacecraft will make use of a unique code to spread its DOR tones for transmission), would however prevent mutual interference and allow a further optimisation in terms of the number of recording channels.

An additional area of interest is the evolution of ground station modems. In particular, the move into software based platforms will reduce the number of limitations posed by specific hardware and possibly allow a dynamic allocation of multiple receivers.

6. Conclusions

The results of the first ever ESA MSPA Delta-DOR test are shown in this paper and confirm ESTRACK's capability to support Delta-DOR on multiple spacecraft. This capability is expected to become increasingly important in view of the advent of numerous formation flying missions and the high load of tracking assets.

The simultaneous evolution of Ground Stations and PN DOR techniques are expected to allow a more powerful exploitation of the concept demonstrated in this paper, contributing both to the pursue of a better accuracy and the optimization of station time allocation.

Acknowledgements

The authors would like to thank ESA Mars Express and ExoMars TGO Flight Control Teams for their support for this test, as well as ESOC Flight Dynamics for the evaluation of the Delta-DOR data.

Appendix A (Thermal noise error contributions taken from [4])

Quasar Thermal noise ($\varepsilon_{\tau QU}$):

$$SNR_{QU} = K_L \frac{10^{-26}}{2k}\frac{\lambda^2}{4\pi} S_c \sqrt{\left(\frac{G}{T}\right)_1 \left(\frac{G}{T}\right)_2} \sqrt{DT_{QU}}$$

$$\varepsilon_{\tau QU} = \frac{\sqrt{2}}{2\pi f_{BW}} \frac{1}{SNR_{QU}} \quad \text{, s}$$

where:

K_L:	System loss factor
k:	Boltzmann constant, Joules/K
λ:	RF wavelength, m
S_c:	Quasar flux, Jy
$(G/T)_n$:	G/T of antenna n, K^{-1}
D:	Channel sampling rate, samples/s
T_{QU}:	Averaging time of quasar samples, s
f_{BW}:	Spanned bandwidth

Spacecraft Thermal noise ($\varepsilon_{\tau sc}$):

$$SNR_{SC_i} = \sqrt{2\left(\frac{P_{DOR}}{N_0}\right) T_{SC}}$$

$$\varepsilon_{\tau_{sc}} = \left[\left(\frac{\sqrt{2}}{2\pi f_{BW}} \frac{1}{SNR_{sc_1}}\right)^2 + \left(\frac{\sqrt{2}}{2\pi f_{BW}} \frac{1}{SNR_{sc_2}}\right)^2\right]^{0.5}$$

where:

P_{DOR}/N_0:	DOR tone power to noise density ratio
T_{SC}:	Averaging time of S/C samples, s
f_{BW}:	Spanned bandwidth

References

[1] David W. Curkendall and James S. Border, "Delta-DOR: The One-Nanoradian Navigation Measurement System of the Deep Space Network — History, Architecture, and Componentry", The Interplanetary Network Progress Report, vol. 42-193, Jet Propulsion Laboratory, Pasadena, California, pp. 1-46, May 15, 2013.

[2] Marco Menapace, J. de Vicente, A. Ardito, " ESA Delta-DOR technique: achievements and future challenges" , ESA TT&C conference, Nov.2022

[3] J.S.Border, W.M.Folkner, R.D.Kahn, K.S.Zukor, "Precise Tracking of the Magellan and Pioneer Venus Orbiters by Same-Beam Interferometry. Pat 1: Data Accuracy Analysis" TDA Progress Report 42-110 Aug.15th, 1992

[4] Delta-DOR – Technical characteristics and performance. Informational report, CCSDS 500.1-G-2, Green Book Nov.2019