The Consultative Committee for Space Data Systems

Draft Recommendation for
Space Data System Practices

DELTA-DOR ARCHITECTURAL GUIDELINES

DRAFT RECOMMENDED PRACTICE

CCSDS 506.2-R-1

RED BOOK
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PREFACE

This document is a draft CCSDS Recommended Standard. Its 'Red Book' status indicates that the CCSDS believes the document to be technically mature and has released it for formal review by appropriate technical organizations. As such, its technical contents are not stable, and several iterations of it may occur in response to comments received during the review process.

Implementers are cautioned **not** to fabricate any final equipment in accordance with this document's technical content.

Recipients of this draft are invited to submit, with their comments, notification of any relevant patent rights of which they are aware and to provide supporting documentation.

DOCUMENT CONTROL

Document	Title	Date	Status
CCSDS 506.2-R-1	Delta-DOR Architectural Guidelines, Draft Recommended Practice, Issue 1	February 2024	Current draft

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1 INTRODUCTION

1.1 PURPOSE AND SCOPE

This Recommended Practice provides architecture guidelines for the navigation technique known as Delta Differential One-Way Ranging (Delta-DOR, ΔDOR, or DDOR).

Derived from Very Long Baseline Interferometry (VLBI), Delta-DOR is a technique that can be used in conjunction with Doppler and ranging data to improve spacecraft navigation by more efficiently and more accurately determining spacecraft position in the plane of sky. The establishment of interoperable standards and processes for acquiring Delta-DOR data at ground stations of different agencies, the standardization of an exchange format for raw data, the means for exchanging these data, for standardizing requests for Delta-DOR services, and standardization of interfaces for exchange of supporting products are key enablers for interagency execution of Delta-DOR operations. The specifics of interfaces relevant for interagency Delta-DOR and the supporting CCSDS standards, as well as some recommended practices, are discussed in references [1], [2], [3], [4], [5], and [6].

Conventions and definitions of Delta-DOR concepts, a detailed description of the Delta-DOR technique, guidelines for DOR tone spectra, guidelines for selecting reference sources, applicable foundation equations, and a discussion of error sources and measurement accuracy are provided in reference [1]. This book describes choices for system architectures to provide either a low-performance, medium-performance, or high-performance Delta-DOR capability.

1.2 APPLICABILITY

Delta-DOR operations are applicable to space agencies that operate deep space missions that require accurate determination of the spacecraft position in the plane of the sky. Accurate position determinations are often needed in critical mission phases such as planetary encounters, Entry, Descent, and Landing (EDL), and flybys. For operations in which these requirements do not support the needs of the participating agencies, Delta-DOR operations may not be appropriate.

1.3 COMMON DELTA-DOR TERMINOLOGY

For the purposes of this document, the following definitions apply.

baseline: The vector joining two tracking stations.

channel: A slice of the frequency spectrum that contains a spacecraft or quasar signal.

scan: An observation of a natural radio source or a spacecraft, typical duration of a few minutes.

session: The time period of the Delta-DOR measurement including several scans.

spanned bandwidth: The widest frequency separation between downlink signal components.

DOR tone: Tone generated by a spacecraft for purpose of enabling Delta-DOR measurement; more generally, any spacecraft signal component used for Delta-DOR.

P_{Tone}/N_0: Ratio of tone power to noise spectral density.

G/T: Ratio of antenna gain to system noise temperature.

meteo data: Meteorological data (consists of pressure, temperature, relative humidity).

1.4 STRUCTURE OF THE DOCUMENT

In addition to this section, this document contains the following sections and annexes:

– Section 2 provides a general overview of the Delta-DOR technique.

– Section 3 provides a description of the Delta-DOR architecture.

– Section 4 provides conclusions.

– Annex A discusses security and SANA considerations applied to the technologies defined in this document.

– Annex B lists informative references.

– Annex C lists abbreviations and acronyms applicable to Delta-DOR.

1.5 REFERENCES

The following publications contain provisions which, through reference in this text, constitute provisions of this document. At the time of publication, the editions indicated were valid. All publications are subject to revision, and users of this document are encouraged to investigate the possibility of applying the most recent editions of the publications indicated below. The CCSDS Secretariat maintains a register of currently valid CCSDS publications.

[1] *Delta-DOR—Technical Characteristics and Performance*. Issue 2. Report Concerning Space Data System Standards (Green Book), CCSDS 500.1-G-2. Washington, D.C.: CCSDS, November 2019.

[2] *Delta-DOR Raw Data Exchange Format*. Issue 1. Recommendation for Space Data System Standards (Blue Book), CCSDS 506.1-B-1. Washington, D.C.: CCSDS, June 2013.

[3] *Tracking Data Message*. Issue 2. Recommendation for Space Data System Standards (Blue Book), CCSDS 503.0-B-2. Washington, D.C.: CCSDS, June 2020.

[4] *Orbit Data Messages*. Issue 3. Recommendation for Space Data System Standards (Blue Book), CCSDS 502.0-B-3. Washington, D.C.: CCSDS, April 2023.

[5] *Delta-Differential One Way Ranging (Delta-DOR) Operations*. Issue 2. Recommendation for Space Data System Practices (Magenta Book), CCSDS 506.0-M-2. Washington, D.C.: CCSDS, February 2018.

[6] *Extensible Space Communication Cross Support—Service Management—Concept*. Issue 1. Report Concerning Space Data System Standards (Green Book), CCSDS 902.0-G-1. Washington, D.C.: CCSDS, September 2014.

[7] *Efficient Spectrum Utilization for Space Research Service, Deep Space (Category B), in the Space-To-Earth Link*. SFCG Recommendation SFCG 23-1R4. Darmstadt, Germany: SFCG, 7 June 2023.

[8] *Radio Frequency and Modulation Systems—Part 1: Earth Stations and Spacecraft*. Issue 32. Recommendations for Space Data System Standards (Blue Book), CCSDS 401.0-B-32. Washington, D.C.: CCSDS, October 2021.

2 OVERVIEW OF THE DELTA-DOR TECHNIQUE

2.1 SPACECRAFT AND QUASAR OBSERVATIONS

Very Long Baseline Interferometry is a technique that allows determination of angular position for distant radio sources by measuring the geometric time delay between received radio signals at two geographically separated stations. The observed time delay is a function of the known baseline vector joining the two radio antennas and the direction to the radio source.

An application of VLBI is spacecraft navigation in missions in which delay measurements of a spacecraft radio signal are compared against similar delay measurements of angularly nearby quasar radio signals. The case in which the spacecraft measurements are obtained from the phases of tones emitted from the spacecraft, first detected separately at each station and then differenced, is an application of VLBI known as Delta-DOR. (The observation geometry is illustrated in figure 2-1.) Even though data acquisition and processing are not identical for the spacecraft and quasar, both types of measurements can be interpreted as delay measurements and have similar information content and sensitivity to sources of error. The data produced in such a measurement session are complementary to Doppler and ranging data.

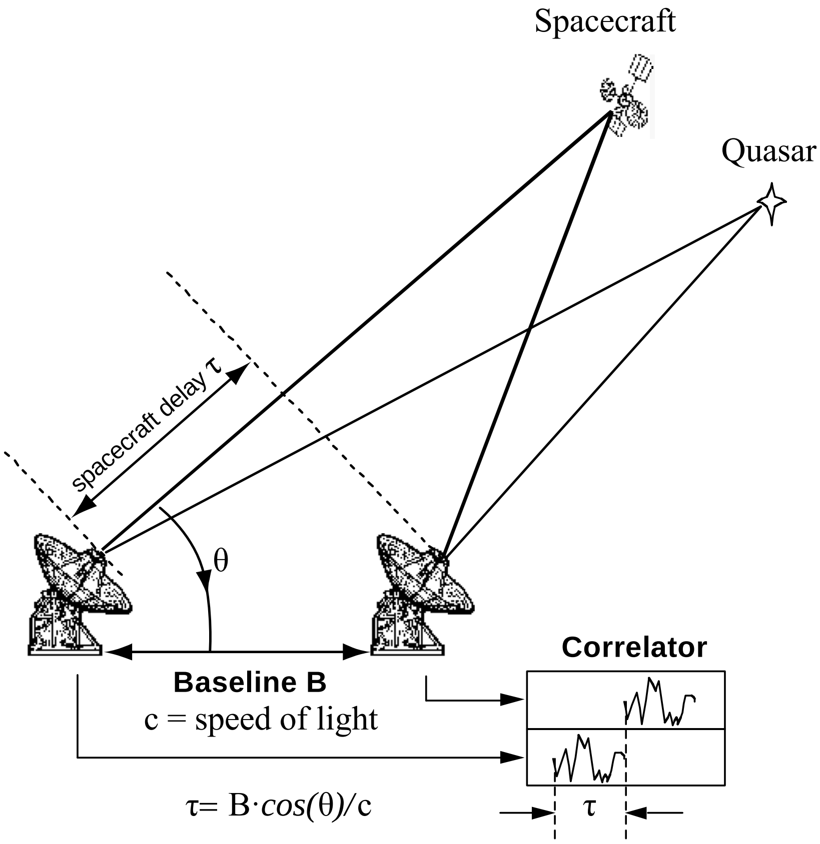

Figure 2-1: Delta-DOR Observation Geometry

To enable a Delta-DOR measurement, a spacecraft must emit several tones or other signal components spanning at least a few MHz. The characteristics of the tones are selected based on the requirements for phase ambiguity resolution, measurement accuracy, efficient use of spacecraft signal power, efficient use of ground tracking resources, and the frequency allocation for space research.

The Delta-DOR technique requires that spacecraft be tracked simultaneously at two distant radio antennas. A quasar must also be tracked just before and/or after the spacecraft observation. Thus a viewing overlap between the two antenna complexes is required. The degree of overlap varies for each pair of antenna complexes, is dependent upon the relative station locations, and depends on spacecraft declination.

The Delta-DOR history, technique, and applications are discussed in reference [B1]. An X-band (reference [B2]) quasar catalog is maintained online in the CCSDS Space Assigned Numbers Authority (SANA) and may be used for DDOR observation planning and operations. A Ka-band quasar catalog is planned in the near future.

2.2 THE REFERENCE ARCHITECTURE

Delta-DOR navigation performance has improved from the 100 nrad level in the early 80s to the current goal of one nanoradian accuracy, as required to fulfil the most demanding mission navigation requirements. This impressive breakthrough has been the result of a combination of several factors, among which, the use of higher frequency bands, wider bandwidths, dedicated Delta-DOR signal structures, better media calibration means, improved quasar catalogues, better ground station location, and improved ground station equipment must be mentioned. Latency times from Delta-DOR observations to the availability of Delta-DOR products have also improved significantly.

While the major components of a Delta-DOR ground system (shown in figure 2-2) are common to any Delta-DOR observation, large performance differences may result from their specific implementation. One nanoradian performance will require the use of higher-end and state of the art equipment in all areas, while more modest implementations may still be sufficient to achieve the navigation requirements of missions with less stringent requirements.

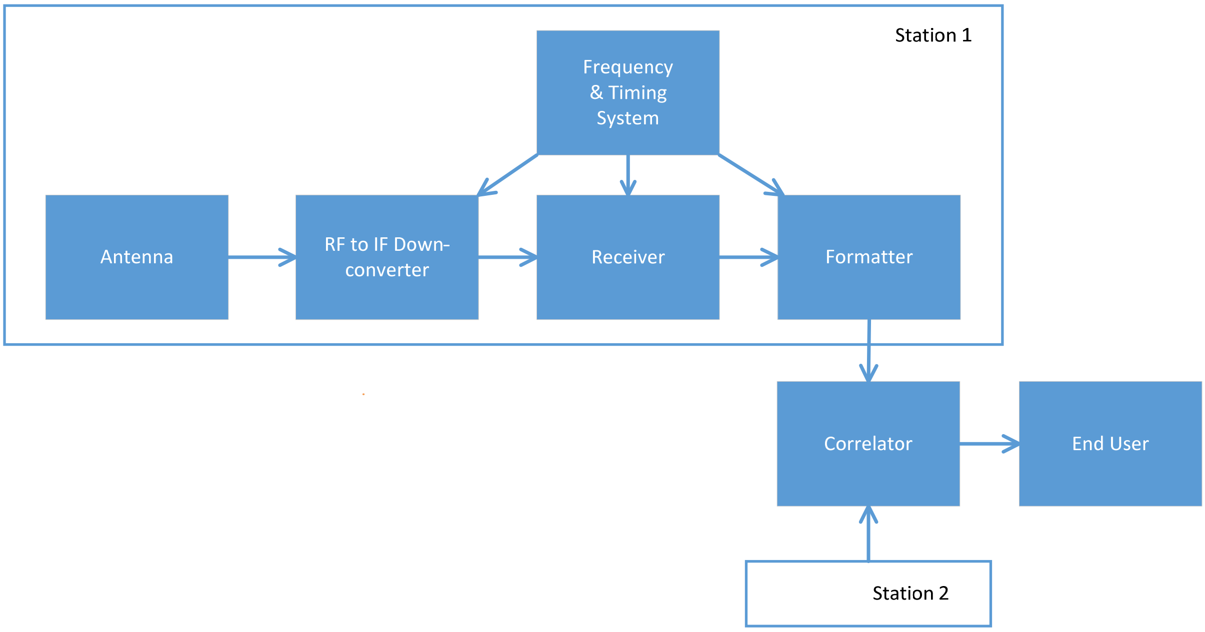

Figure 2-2: Block Diagram of Major Components of Delta-DOR Ground System

Several aspects of geometric, propagation, instrumental, and thermal characteristics contribute to the accuracy of Delta-DOR measurements. The Delta-DOR error budget given in reference [1] is the basis for any architecture design aiming for a performance improvement. A summary of good practices follows.

While natural radio sources generate broadband signals that enable Delta-DOR measurements, the spacecraft transponder must specifically include the capability to also emit signals spanning a wide bandwidth.

Received signals are typically weak because of the limited power available for spacecraft transmissions and the vast distances to the quasars. Therefore large antennas with good sensitivity are necessary for data acquisition. Precise clocks and stable frequency distribution must be used within a station to allow lengthy coherent integration of weak signals and to avoid degradation (jitter) of time delay measurements. The station coordinates must be well known, and media delays for received signals must be well calibrated. Because of the signal weakness, and in order not to introduce unwanted delays or phase instabilities, it is essential for the signal path from front end to the receiver to also be well known and stable.

Precise timing and high frequency stability are enabling capabilities for radio interferometric systems with components separated by large distances. Generally, the level of timing stability provided by a Hydrogen Maser is necessary to support these measurements.

An open loop recording system must be used, at least for signals from natural radio sources, since the received signal has a white noise spectrum and cannot be modeled or compressed. Common instrumental paths for spacecraft and quasar signals are necessary for common mode error cancellation. A large data volume must be recorded to provide sensitivity for weak quasar signals. This large data volume must then be transferred, from each participating station, to the common correlator site. A typical data volume per session may be 10 to 40 GB at each station, though this could vary quite a bit depending on circumstance. The ability to transfer data volumes of this size rapidly may be needed to support time-critical navigation events. A high-speed network connection and high-performance data transfer protocols are generally used to meet latency requirements. The correlator output is provided to the end user, which is usually a flight dynamics team.

Data are recorded in multiple frequency channels, centered on the received frequencies of spacecraft tones. There are three different parameters related to bandwidth involved, and performance generally improves as each of these parameters is increased:

a) the bandwidth of a single frequency channel, which is typically in the range of 2 to 32 MHz for quasar signals;

b) the data rate for a recorder, which is the product of the channel bandwidth times 2 (for Nyquist sampling) times the number of bits per sample times the number of channels (a given recorder will have a maximum sample rate, so selection of channels will be constrained);

c) the spanned bandwidth, which is the frequency separation between the two widest spaced channels.

A correlator facility is needed for the processing of data. It mainly consists of a computer server, a high-speed network connection, and application software for data correlation.

Raw data are transferred using the SSH File Transfer Protocol (SFTP) (reference [B3]) between servers used for operational DDOR processing within an agency, or between servers that have been identified in a cross-support agreement for interagency measurements.

Reduced data, that is, the output of the correlation processing step, follow the formulation given in reference [1]. The output of spacecraft correlation processing is as given in equation (16). The output of quasar correlation processing is as given in equation (18). Reference [1] provides the definitions for both observed and computed observables.

3 ARCHITECTURE VS PERFORMANCE REQUIREMENTS

3.1 OVERVIEW

The accuracy provided by Delta-DOR measurements results from the contribution of various terms linked to geometry, media, instrumental, and thermal noise effects:

- thermal noise:
  - quasar thermal noise,
  - spacecraft thermal noise;
- instrumental:
  - clock instability,
  - dispersive phase;
- media:
  - zenith troposphere,
  - fluctuating troposphere,
  - ionosphere shell,
  - fluctuating ionosphere,
  - solar plasma;
- geometry:
  - quasar coordinate,
  - Earth orientation,
  - station location.

Contributions of a thermal-noise nature (in particular, the one due to quasar thermal noise) very often dominate the error budget. Quasar thermal noise is dictated by quasar flux, stations G/T, sampling rate, integration time, and spanned bandwidth of the scan. Provided that sufficient quasar flux is available, a proper selection of the last three parameters (in particular, the spanned bandwidth; see figure 3-1) is key to achieving significant reductions in the quasar thermal error term. Missions with demanding Delta-DOR requirements will adopt dedicated Delta-DOR tones with spanned bandwidths of a few tens of MHz in order to minimize quasar error noise.

NOTE – The same spanned bandwidth must be used for quasar and spacecraft scans in order to have common mode error cancellation of ground station instrumental effects.

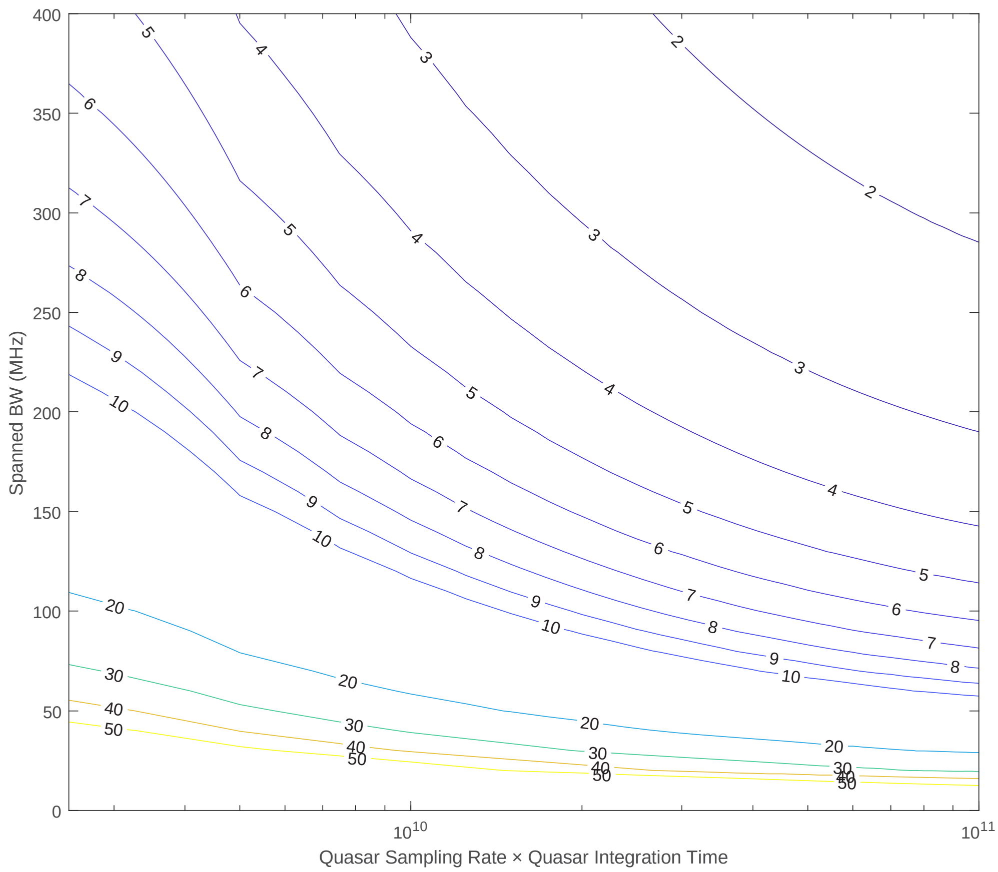

Figure 3-1: Total Thermal Noise Error (Quasar and Spacecraft) Contribution (Picoseconds) vs Spanned BW and Sample Rate × Integration Time Product (G/T = 52.56 dBk, f_RF = 8.42696 GHz, Quasar Flux = 0.4 Jy, P/N_0 = 27 dBHz, Tsc = 480 s)

In order to provide Delta-DOR support for spacecraft not equipped with dedicated tones (often the case for deep space missions launched in the ’90s or early ’00s), telemetry harmonics can be used as DOR tones. This solution yields modest results, as result of the limited spanned bandwidth and the low tone levels (the latter may eventually cause the spacecraft thermal noise term to become dominating).

For those cases in which the contribution resulting from thermal noise effects can be reduced (by careful selection of the parameters in figure 3-1), instrumental errors (via the dispersive phase contribution, which describes the difference in phase response of ground station equipment between the narrowband spacecraft and the wideband quasar signal) will become the limiting factor.

As shown in figure 3-2, for a sufficiently stable ground clock (say better than 10^{-14}), phase dispersion constitutes the only term driving the instrumental error. In addition to a careful design of ground station equipment (filters in particular), a reduction of dispersive phase is possible by spreading the spacecraft signal with a Pseudo Noise (PN) code and applying a shaping filter in the attempt to make it resemble a white noise signal (reference [1]).

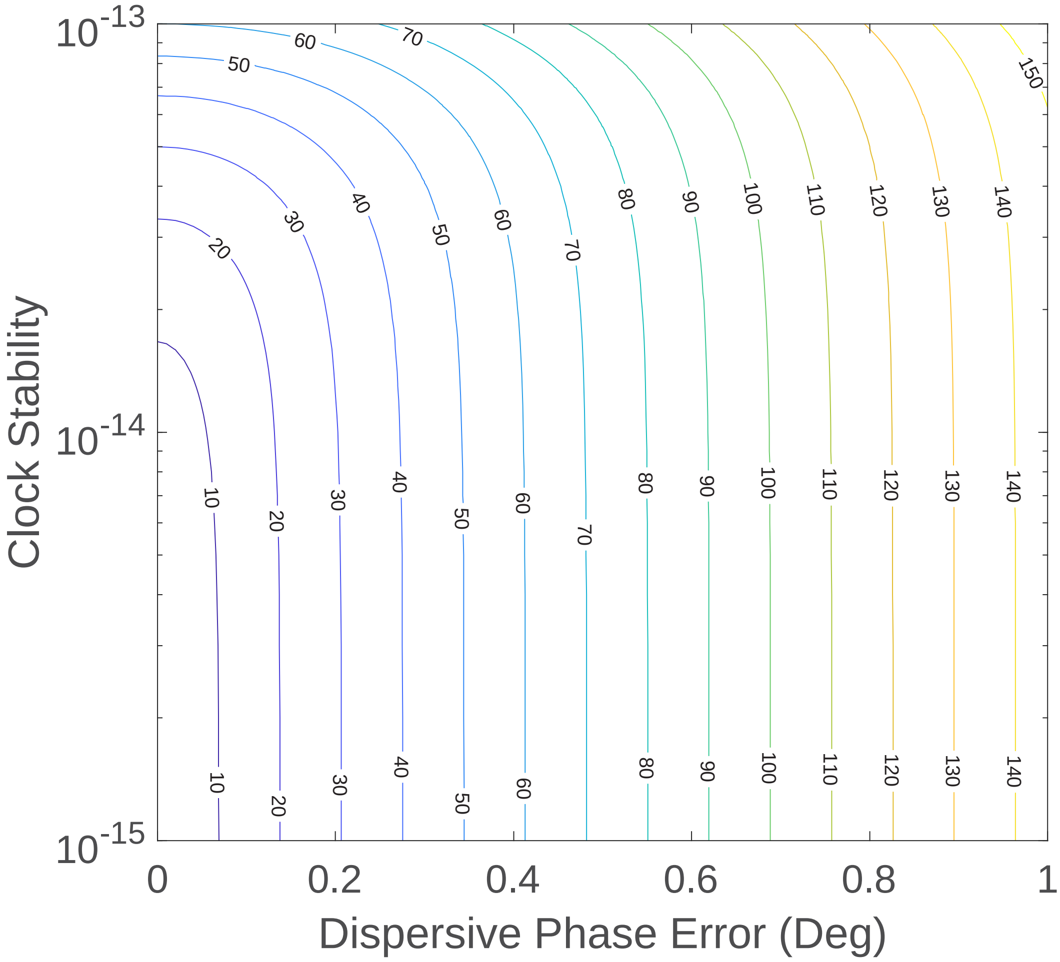

Figure 3-2: Instrumental Error (Picoseconds) vs Dispersive Phase and Clock Stability (Spanned BW = 38.25 MHz, Time between Centers of Quasar and Spacecraft Scans: 600 S)

Contributions from media effects may be significant to the overall error budget once thermal noise and instrumental related effects are controlled. Their mitigation requires the use of accurate media calibration methods to estimate the delay introduced by the troposphere and the ionosphere. Media errors tend to decrease as the angular separation between spacecraft and quasar decreases.

Modelling of tropospheric effects from meteorological (meteo) data can be accurate (at zenith) to about 4 cm and to a few millimeters for the wet and dry components, respectively (see reference [B4]). A mapping function (typically close to the reciprocal of the sine of the spacecraft's elevation) is then required to obtain an estimate of the tropospheric delay in the direction of the spacecraft, under the assumption (often invalid) of a homogeneous behavior of the troposphere.

Improved tropospheric estimates can be obtained from Global Navigation Satellite System (GNSS) data. In this case, the total tropospheric content (wet and dry) at zenith was already reported in the early ’90s to be within 1 cm (reference [B5]). The increase in GNSS constellations has allowed the acquisition of near real-time tropospheric delay estimates (reference [B6]). The estimated values in the line of sight of the spacecraft require the use of the corresponding mapping function, which will yield worse estimates for the lower elevations.

An additional improvement can be expected from water vapor radiometers, particularly those featuring narrow beamwidths and steering mechanisms to observe in the line of sight of the spacecraft. A few of these units have been deployed at various Deep Space Sites (references [B7] and [B8]), mainly in support of radioscience research, and do not require the use of mapping functions. Another advantage of these units is the provision of tropospheric delay estimates in real time.

Because of its dispersive nature, the effect of the ionosphere becomes basically negligible at Ka-band for DDOR observations. In the case of X-band, the ionosphere can still play a significant role, particularly during daytime observations.

Solar plasma is another effect of dispersive nature. The DDOR error budget is less sensitive to it when higher frequencies are used, even though its effect may still be significant when missions (as seen from Earth) fly close to the Sun.

For platform related errors, and provided that station location is known to an accurate enough degree, the availability and accurate knowledge of quasar sources is a prerequisite for the success of any DDOR observation. Quasar cataloguing activities at X-band have been underway for many years (references [B9] and [B10]), constituting an invaluable input for DDOR. Quasar cataloguing activities in Ka-band are at a much earlier phase, and still require many more observations to increase the number of suitable catalogued sources. Indeed, very few sources have been identified in certain portions of the sky (i.e., near the Galactic Center and at southern declinations). Cataloguing activities in the optical domain (reference [B11]) can also complement radio observations, and the establishment of ties between optical and radio celestial frames constitutes a crucial element in the quest for quasar sources at the various bands.

The stronger quasars were discovered years ago, and early quasar catalogs consisted of a relatively small number of strong quasars. Such a catalog could not provide good performance for DDOR since there would rarely be a source in close angular proximity to the spacecraft. Over the years, the catalog density of coverage has been improved by adding weaker and weaker quasars (selection of a weaker quasar is usually necessary to provide a small angular separation between spacecraft and quasar to reduce media and baseline errors). But this requires higher sensitivity (G/T, record rate, spanned bandwidth) to keep quasar thermal noise to a reasonable level. Also, with the wider channel bandwidths used for quasar recordings, PN spreading of the DOR signal may be needed to keep the dispersive phase error to a reasonable level.

Architectural guidelines are given in this document for X-band missions and three performance targets:

– low performance (accuracy worse than 5 nrad);

– medium performance (accuracy between 1 and 5 nrad);

– high performance (accuracy better than 1 nrad).

Guidelines are also given in this document for the DDOR support to Ka-band missions, for both medium- and high-performance architectures. The former allows DDOR to support high data rate missions with communication links at 32 GHz only (also for navigation functions). The latter exploits the inherent advantages of Ka-band to push the boundaries of DDOR performance. In particular, the higher bandwidth allocation at Ka-band (500 MHz) opens the field to larger spanned and channel bandwidths. DDOR also profits from the inherent advantage of Ka-band operation in regards to the mitigation of effects of dispersive nature (e.g., solar plasma and ionosphere), and further improvements can be pursued from the use of spread spectrum DOR signals. As consequence, however, tropospheric media calibration emerges as the most significant error term in the Ka-band DDOR error budget. If the latter effect is properly contained, Ka-band DDOR thus provides the means for unrivaled DDOR accuracies. The higher sensitivity of Ka-band (as compared to X-band) to weather effects (in terms of attenuation and noise), however, calls for a careful assessment of the relevant DDOR navigation scenarios during the mission design phase.

The following sections provide estimates of system performance for several candidate architectures. Measurement errors for the time delay observables used in DDOR are normally presented in units of nsec. It is more useful in flight dynamics applications to consider the corresponding angular accuracy in units of nrad. A 10000 km baseline projection is assumed in the following analyses for conversion between time delay measurement accuracy (nsec) and angular accuracy (nrad).

3.2 LOW PERFORMANCE SYSTEM ARCHITECTURE

This architectural option describes how to provide support to missions that are not equipped with dedicated DOR tones, in which the presence of telemetry harmonics will still allow the execution of Delta-DOR measurements. Following the maximum allowable bandwidth recommendation in reference [7], the spanned bandwidth resulting from the spacecraft's telemetry will be limited to 12 MHz (for non-Mars missions). Furthermore, the low 'tone' to noise density levels that can be expected will almost certainly make contributions of a thermal nature dominant. The little margin for improvement can be exploited making use of longer integration times (for both quasar and spacecraft, as required), which may not be possible because of operational constraints.

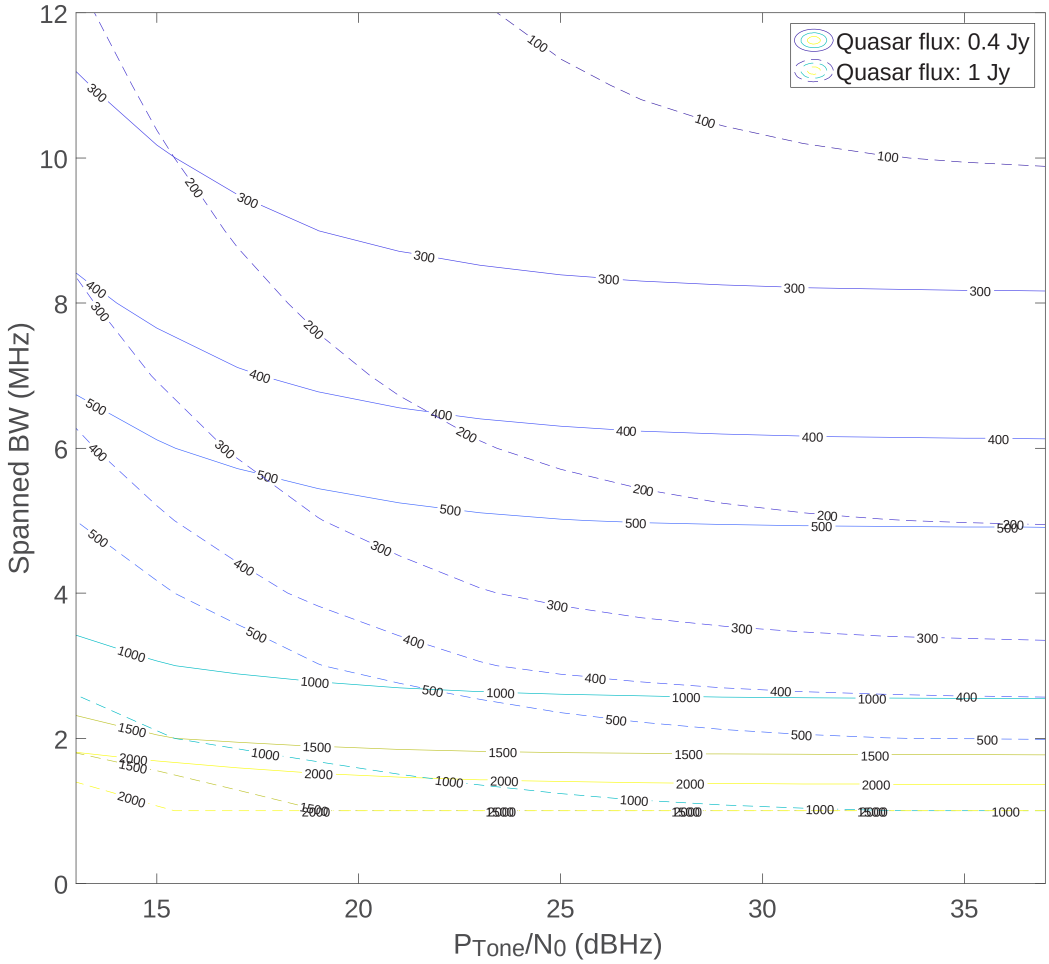

Figure 3-3: Thermal Noise Error (Picoseconds) vs Spanned BW and P_{Tone}/N_0 for a 2 MHz Channel Bandwidth (S/C Integration Time: 480 s, Quasar Integration Time: 960 s, f_RF:8.42696 GHz, G/T of Both Stations: 52.56 dBk)

Figure 3-3 shows the thermal noise error contribution for various spanned bandwidths and P_{Tone}/N_0 (rather $P_{harmonic}/N_0$ in this case) levels, for the X-band test case in reference [1]. Results are provided for two quasar types (0.4 and 1 Jy) and show the importance of using strong quasar sources.

In view of all the limitations described above, the preferred spectrum would look similar to figure 3-4. Power is concentrated in sinusoidal sidebands near the edge of the allowed downlink bandwidth. This might be achieved in several ways, depending on transponder and telemetry system design. For example, this could be achieved by modulating the carrier with an unmodulated subcarrier, or by selecting an appropriate symbol pattern for direct carrier modulation. This technique has the advantage of improving P_{Tone}/N_0 values compared to what would be possible using a narrower telemetry spectrum.

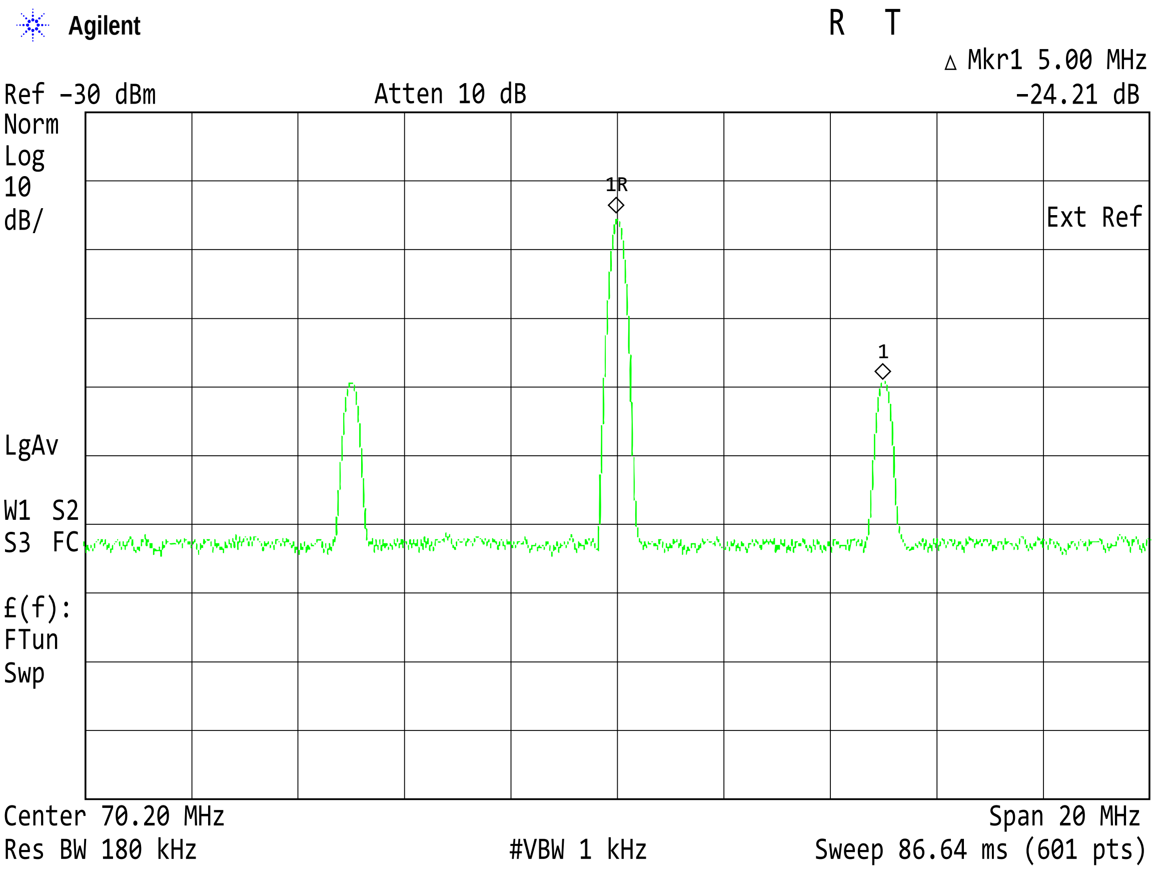

Figure 3-4: GAIA DDOR Spectrum for Fixed Pattern (Uncoded 010101…) Gaussian Minimum Shift Keying

The following guidelines can be given:

– spanned bandwidth: 10 MHz;

– quasar sampling rate: > 2 MHz;

– P_{Tone}/N_0 levels: > 25 dBHz;

– quasar power: > 1 Jy;

– media calibration: meteo or GNSS;

– station clock: > 1E-13 @ time between spacecraft and quasar observations;

– antenna class: > 30 m.

3.3 MEDIUM PERFORMANCE SYSTEM ARCHITECTURE

3.3.1 X-BAND

This architectural option describes how to provide support to missions that are equipped with dedicated DOR tones, but can only use narrow spanned bandwidths. Figure 3-3 shows the limitation resulting from this approach. For the selected parameters, a 10 MHz spanned bandwidth and a P_{Tone}/N_0 of 25 dBHz fails to reach the 0.1 nsec boundary, which already accounts for a 3 nrad error in the case of a 10000 km baseline. As described in 3.1, any pursuit for improvement in such case requires the use of larger spanned bandwidths in order to reduce the contribution of thermal noise effects. The use of dedicated DOR tones, up to 40 MHz (as per recommendation 2.5.6B of reference [8], ensures a significant reduction of effects of thermal nature (figure 3-5).

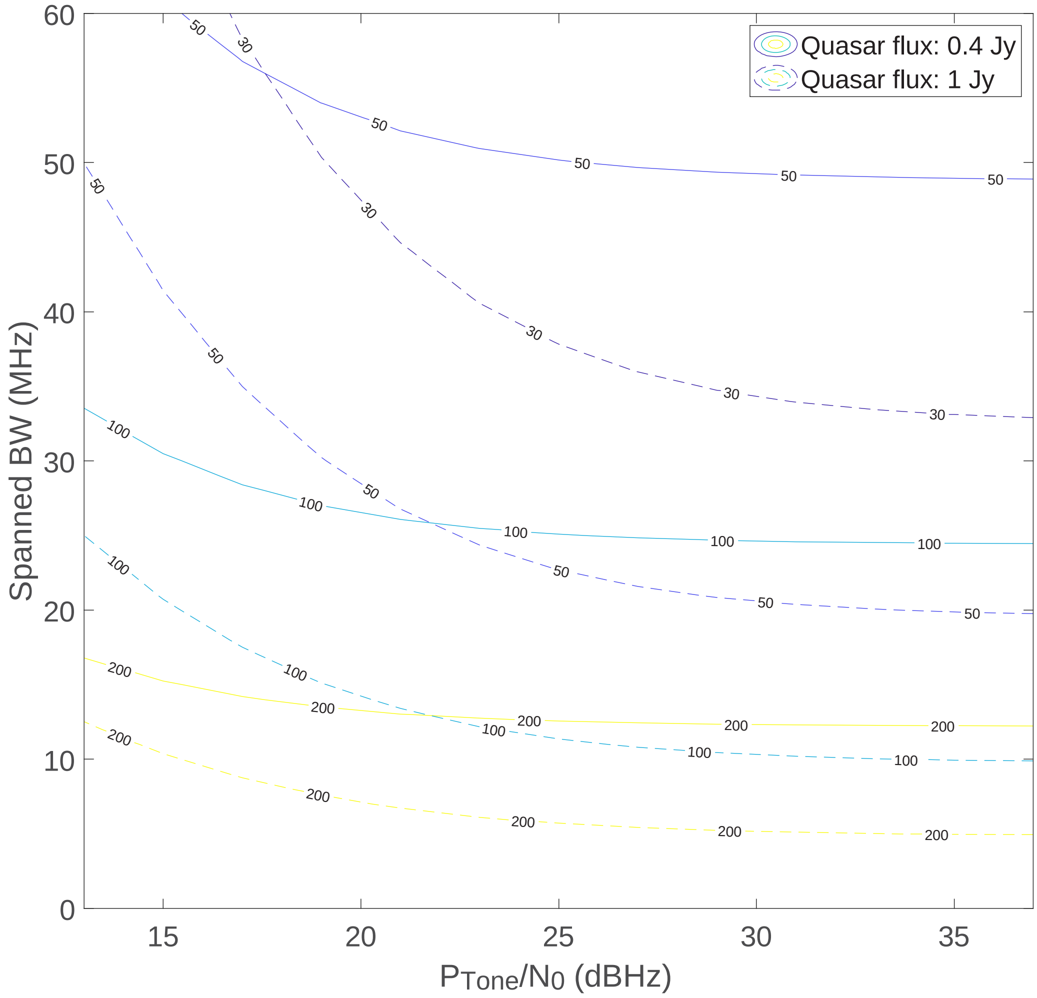

Figure 3-5: Thermal Noise Error (Picoseconds) vs Spanned BW and P_{Tone}/N_0 for a 2 MHz Channel Bandwidth (S/C Integration Time: 480 s, Quasar Integration time: 960 s, f_RF:8.42696 GHz, G/T of Both Stations: 52.56 dBk)

Since the quasar thermal noise error improves proportionally to the reciprocal of the square root of the channel bandwidth, the use of channel bandwidths above 2 MHz yields a significant improvement of the error budget. The drawback, however, will be an increase in the amount of collected data and the transfer time to the correlator. Figure 3-6 shows the thermal noise error as a function of channel sample rate and quasar integration time. Although the use of larger quasar integration times provides a similar improvement to a channel bandwidth increase (reciprocal of square root), this option should be exercised with caution as other effects (e.g., propagation media instabilities) may become relevant. In any case, an increase of any of these values (quasar bandwidth or integration time) is justified as long as effects of thermal nature remain dominant.

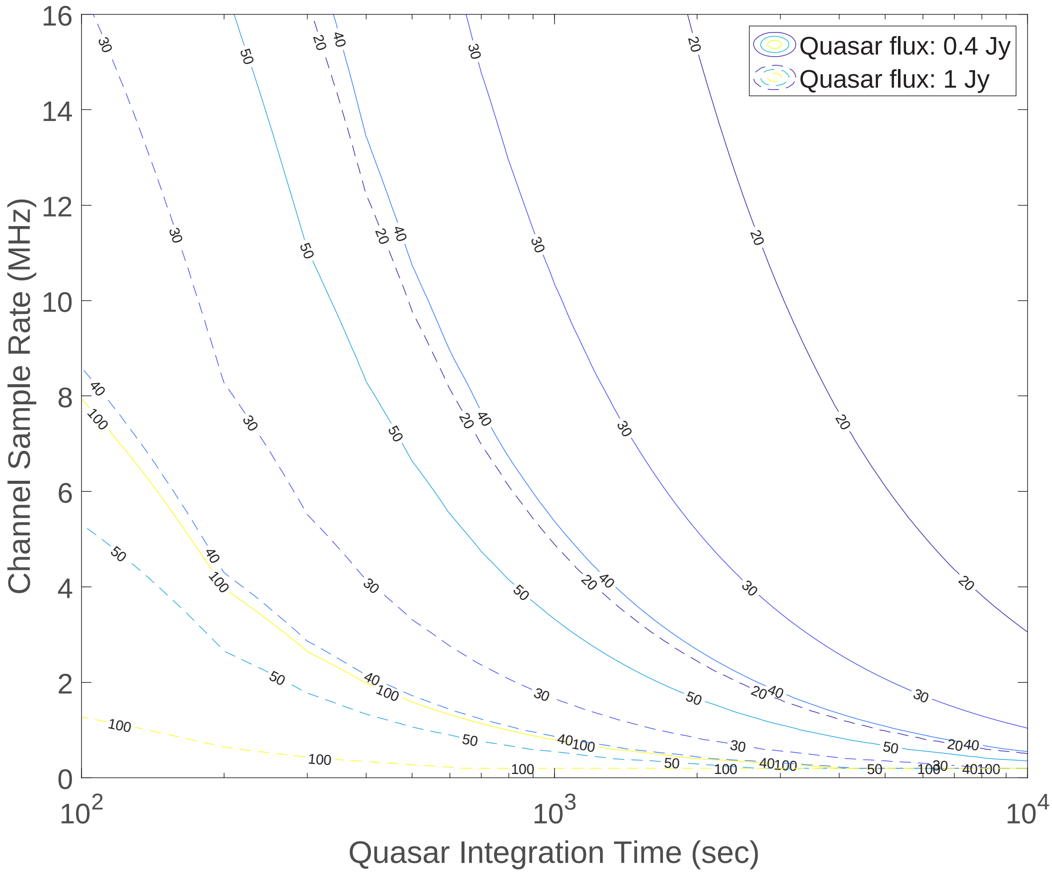

Figure 3-6: Thermal Noise Error (Picoseconds) vs Channel Sample Rate and Quasar Integration Time (S/C Integration Time: 480 s, Spanned BW: 38.25 MHz: 960 s, f_RF: 8.42696 GHz, G/T of Both Stations: 52.56 dBk)

The following guidelines can be given:

– spanned bandwidth: 38 MHz (use of dedicated DOR tones);

– quasar sampling rate: > 4 MHz;

– P_{Tone}/N_0 levels: > 25 dBHz;

– media calibration: GNSS;

– station clock: > 1E-14 @ time between spacecraft and quasar observations;

– antenna: 35 m class with cryogenic Low Noise Amplifier (LNA).

3.3.2 KA-BAND

This architectural option addresses the support to Ka-band-only missions (not equipped with X-band links) that do not have very demanding navigation requirements. As such, this option benefits from the availability of larger spanned bandwidths (and as a result also of larger channel bandwidths) to minimize thermal noise effects, but does not seek additional improvements for other noise contributions to the DDOR error budget.

Recommendation 2.5.6B of reference [8] defines the use of DDOR sinewave tones at ±1, 4, 20, and 76 MHz, allowing (when the higher tones are used) to compensate for the lower quasar correlation SNR in Ka-band (see equation 19 of reference [1]) with respect to X-band. Additionally, since achievable spacecraft P_{Tone}/N_0 values may be lower in Ka-band as the result of the increased system noise temperature, the use of large spanned bandwidths to bring the thermal noise contribution to a minimum is justified.

The following guidelines can be given:

– spanned bandwidth: > 40 MHz (use of dedicated DOR tones);

– quasar sampling rate: > 8 MHz;

– P_{Tone}/N_0 levels: > 15 dBHz;

– media calibration: GNSS;

– station clock: > 1E-14 at time between spacecraft and quasar observations;

– antenna class: > 35 m with cryogenic LNA.

3.4 HIGH PERFORMANCE SYSTEM ARCHITECTURE

3.4.1 X-BAND

Any attempt to surpass 1 nrad accuracy performance imperatively requires careful control of all error contributions. Minimizing thermal noise effects requires the use of high spanned bandwidths and sampling rates, as well as the availability of powerful quasars. Effects of instrumental and media nature also have to be carefully controlled, requiring the use of PN spread signals (currently presented in reference [1], and for which a specific recommendation is planned in reference [8]) and, when possible, the use of dedicated media calibration equipment (which can point in the direction of the spacecraft or quasar, rather than be based on meteo or GNSS observations).

Interestingly enough, and following the adoption of the previous measures, effects of geometrical nature (e.g., quasar coordinates) may emerge as significant, in particular in view of the fact that highly accurate knowledge of the position of X-band radio sources varies among quasars (reference [B10]). Efforts aiming at the improvement of quasar catalogues (both in terms of population and position accuracy) are therefore key to enable state of the art DDOR navigation.

The following recommendations are given:

- spanned bandwidth: 38 MHz;
- quasar sampling rate: > 4 MHz;
- high quasar flux and accurate knowledge of quasar position;
- use of spread PN tones with P_{Tone}/N_0 levels: > 25 dBHz;
- media calibration: Dedicated tropospheric calibration (in spacecraft's direction);
- station clock: > 1E-14 @ time between spacecraft and quasar observations;
- antenna: 35 m class with cryogenic LNA.

3.4.2 KA-BAND

The higher bandwidth allocation in Ka-band (500 MHz) must be exploited (by using large spanned and channel bandwidths) to minimize the contribution of effects of thermal nature, which are particularly critical in Ka-band as the result of reduction in quasar flux compared to X-band by a factor of approximately 2.5 (reference [1]). The use of spanned bandwidths of up to a few hundred MHz is therefore foreseen (a specific recommendation on PN DOR signals and Ka-band is planned in reference [8]). Similar to the X-band high performance case, effects of instrumental and propagation nature have to be carefully controlled. The use of PN DOR signals allows a reduction of instrumental effects, while the use of dedicated media calibration equipment (e.g., pointing instruments to improve estimated media content in the direction of the spacecraft or quasar) results in a reduction of the error terms that are mainly the result of the troposphere. For other propagation terms, and with respect to lower bands, Ka-band DDOR is unaffected by the ionosphere and is less sensitive in the presence of solar plasma.

If all above measures are adopted, quasar coordinates emerge once again (as per the X-band high performance case) as a dominant term, with the additional hindrance that knowledge of quasar position for Ka-band radio sources will be less accurate until more VLBI passes are completed to improve coordinates (reference [B10]). Ultimately, the smaller observed quasar core size at the higher frequency will allow more accurate coordinates for Ka-band as compared to X-band.

The following guidelines can be given:

- spanned bandwidth: > 150 MHz;
- quasar sampling rate: > 8 MHz;
- high quasar flux and accurate knowledge of quasar position (more difficult in Ka-band at the present time);
- use of spread PN tones with P_{Tone}/N_0 levels: > 15 dBHz;
- media calibration: water vapor radiometers pointing in direction of spacecraft and quasar;
- station clock: > 1E-14 @ time between spacecraft and quasar observations;
- antenna: 35 m class with cryogenic LNA.

4 THE CORRELATOR'S ARCHITECTURE

The different nature of spacecraft and quasar signals requires the implementation of dedicated algorithms in the correlator.

The correlation of the spacecraft data is carried out by stopping the phasors of the incoming signals at the two antennas, followed by tone filtering and down-sampling. The phasors are stopped after tracking of the frequency of the tone, either with a phase-locked or open loop if good a priori dynamics are provided. In the latter, the precision of the a priori dynamics is such that the tone is always contained in the filtering bandwidth. After filtering and down sampling to reduce the correlation bandwidth, the two streams are cross-correlated, and the phase of the maximum of the correlation function is computed. As last step, the estimated phases for all channels are used in the ambiguity resolution to extract the DOR. Examples of this technique can be found in references [B12], [B13], and [B14].

The white noise nature of the quasar signal requires a different correlation approach, which can be basically implemented in two different ways. The so-called XF technique (X for correlation, F for Fast Fourier Transform [FFT]) is carried out by cross correlating the two data streams after alignment in time and rotation in phase of one of the two signals with respect to the other one. The alignment in time can be done either with interpolation or shift by an integer number of samples. In the latter, the correction for the fractional delay can be applied directly on the correlation function in the frequency domain, and the fractional bit shift arising from applying the same delay to a certain number of samples can be mitigated by dividing the correlation time in short chunks (1–10 ms) and summing up the correlation function for all chunks. The correlation functions for all channels are Fourier transformed over the time axis to get information about the residual delay rate. The outputs of the Fourier transform are interpolated for a finer estimation of the delay and finally bandwidth synthetized to extract the DOR. Examples of XF correlators can be found in references [B12] and [B13].

In the FX method, the two data streams are transformed to the frequency domain with FFT after alignment in time and rotation in phase of one of the two signals with respect to the other. Following this, a fractional delay compensation is performed for one of the two streams, and cross-correlations are performed by multiplying the same frequency channels of the output of the two FFTs. While the first FX correlator was hardware based and developed for radio astronomy (reference [B15]), software-based FX correlators are used for DDOR (reference [B14]). An example of the architecture of FX correlator used for DDOR is given in figure 4-1.

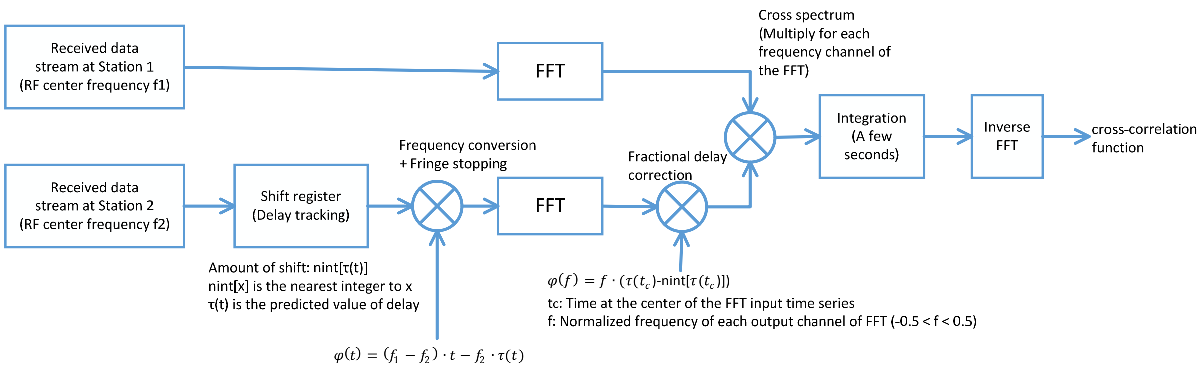

Figure 4-1: Example Architecture of FX Correlator

5 SUMMARY

This document provides high-level guidelines for architecting different options of DDOR measurement systems, as required to meet different navigational accuracies and operational configurations. Spacecraft signal structure, ground station functionality and performance, and choices of frequency bands and quasar sources are covered.

The accuracy of DDOR measurements is the result of several individual contributions of thermal, instrumental, propagation media, and geometric natures. The design of any DDOR implementation (e.g., as result of specific mission needs) must ensure that these contributions are understood and properly apportioned in order to meet the required performance at a commensurate cost.

DDOR signal structure implementations (i.e., spanned and channel bandwidth, tone or PN DOR) have a direct impact on contributions of thermal and instrumental natures. Contributions resulting from propagation media can also play a significant role and require the implementation of media calibration techniques, which can range from estimates obtained from meteo data to direct line-of-sight media calibrations. Contributions of a geometric nature are often negligible compared to other terms in the overall DDOR error budget but become significant when accuracies better than 1 nrad are sought. For such cases, the invaluable contribution of improved radio source catalogues, which constitute a key element in any DDOR observation, requires that the position of radio sources is known with the highest accuracy.

ANNEX A

SECURITY AND SANA

(INFORMATIVE)

A1 SECURITY CONSIDERATIONS

A1.1 OVERVIEW

This annex presents the results of an analysis of security considerations applied to the technologies and processes specified in this Recommended Practice. This document does not formalize these security approaches; they are provided as suggested approaches to these various topics.

A1.2 CONSEQUENCES OF NOT APPLYING SECURITY TO THE TECHNOLOGY

The consequences of not applying security to the systems and networks on which this Recommended Practice is implemented could include potential loss, corruption, and theft of data, as well as damage to the systems themselves.

A1.3 POTENTIAL THREATS AND ATTACK SCENARIOS

Potential threats or attack scenarios include, but are not limited to, (a) unauthorized access to the programs/processes that generate and interpret the data and (b) unauthorized access to the data during transmission between exchange partners. Protection from unauthorized access during data transmission is especially important if the mission utilizes open ground networks such as the Internet to provide ground-station connectivity for the exchange of data. It is strongly recommended that potential threats or attack scenarios applicable to the systems and networks on which this Recommended Practice is implemented be addressed by the management of those systems and networks and by the utilization of adequate access control, authentication, suitably secure protocols, and secured interfaces for the exchange of this information.

A1.4 SECURITY CONCERNS RELATED TO THIS RECOMMENDED PRACTICE

A1.4.1 Data Privacy

Privacy of data and systems involved in this process should be assured by the systems and networks on which this Recommended Practice is implemented. This may include securing access to the data storage and processing systems as well as the data transfers between centers.

A1.4.2 Data Integrity

Integrity of data should be assured by the systems and networks on which this Recommended Practice is implemented. This may include use of digital signatures and calculation and transfer of a hash-based message authentication scheme.

A1.4.3 Authentication of Communicating Entities

Authentication of communicating entities involved in the transport of data should be provided by the systems and networks on which this Recommended Practice is implemented. This may include use of pre-agreed-upon user IDs/passwords or other authentication approaches.

A1.4.4 Data Transfer between Communicating Entities

The transfer of data between communicating entities should be accomplished via secure mechanisms approved by the IT security functionaries of exchange participants. This may be done using secure FTP or other high performance file transfer protocols that include user authentication and agreed-upon, clearly identified end points. Access to servers supporting these transfers may involve configuring firewall access.

A1.4.5 Control of Access to Resources

This Recommended Practice assumes that control of access to resources will be managed by the systems upon which provider formatting and recipient processing are performed. This will usually be accomplished by securing the resources behind a firewall and only allowing secured access via service management requests for service and secured file transfers of data.

A1.4.6 Auditing of Resource Usage

Auditing of resource usage should be handled by the management of systems and networks on which this Recommended Practice is implemented.

A1.5 UNAUTHORIZED ACCESS

Unauthorized access to the systems on which this Recommended Practice is implemented should be prohibited in order to minimize potential threats and attack scenarios. (See control of access to resources and other items in A1.4.)

A1.6 DATA SECURITY IMPLEMENTATION SPECIFICS

Specific information-security interoperability provisions that may apply between agencies involved in an exchange of data formatted in compliance with this Recommended Practice should be specified in an Interface Control Document (ICD).

A2 SANA CONSIDERATIONS

A2.1 GENERAL

The architectural guidelines provided in this document are independent of SANA registries, but the implementation of DDOR techniques typically rely on their use (reference [5] provides a complete overview of the SANA registries required for DDOR activities).

Consider the following:

a) Organizations that provide DDOR services should be registered in the SANA organizations registry with the DDOR Service Provider role set: https://sanaregistry.org/r/organizations/.

b) Organizations with sites that provide DDOR services should register their sites, services, and points of contact in the Service Site and Aperture registry: https://sanaregistry.org/r/service_sites_apertures/.

c) An X-band quasar catalog is available as a SANA registry (https://sanaregistry.org/r/radio_sources/). This registry, as well as the procedures to update it are described in reference [B16].

New assignments in these registries, in conformance with the policies identified, will be available at the SANA website:

http://sanaregistry.org.

Therefore the reader needs to look at the SANA Web site for all the assignments contained in these registries.

The policies that govern the management of SANA registries are defined in reference [B17].

ANNEX B

INFORMATIVE REFERENCES

(INFORMATIVE)

[B1] 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* 42, no. 193 (May 15, 2013).

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[B13] Stephen T. Lowe. “Softc: An Operational Software Correlator.” In *International VLBI Service for Geodesy and Astrometry 2004 General Meeting Proceedings (9–11 February 2004, Ottawa, Canada)*, 191–194. Washington, DC: NASA, 2004.

[B14] H. Takeuchi, et al. “VLBI Tracking of the Solar Sail Mission IKAROS.” In *Proceedings of the XXXth URSI General Assembly and Scientific Symposium, 2011 (13–20 August 2011, Istanbul, Turkey)*. Piscataway, New Jersey: IEEE, 2011.

[B15] Y. Chikada, et al. “A 6 × 320-MHz 1024-Channel FFT Cross-Spectrum Analyzer for Radio Astronomy.” *Proceedings of the IEEE* 75, no. 9 (September 1987): 1203–1210.

[B16] *Delta-DOR Quasar Catalog Update Procedure*. Issue 1. Recommendation for Space Data System Practices (Magenta Book), CCSDS 506.3-M-1. Washington, D.C.: CCSDS, February 2018.

[B17] *CCSDS SANA Registry Management Policy*. Issue 2. CCSDS Record (Yellow Book), CCSDS 313.1-Y-2. Washington, D.C.: CCSDS, October 2020.

ANNEX C

ABBREVIATIONS AND ACRONYMS

(INFORMATIVE)

ΔDOR	delta differential one-way ranging
CCSDS	Consultative Committee for Space Data Systems
DDOR	delta differential one-way ranging
Delta-DOR	delta differential one-way ranging
DOR	differential one-way ranging
EDL	entry, descent, and landing
FFT	fast Fourier transform
GNSS	Global Navigation Satellite System
G/T	antenna gain-to-noise-temperature
ICD	interface control document
LNA	low noise amplifier
PN	Pseudo Noise
RF	Radio Frequency
SANA	Space Assigned Numbers Authority
SNR	Signal-to-Noise Ratio
SFTP	SSH File Transfer Protocol
SSH	Secure Shell
VLBI	Very Long Baseline Interferometry