The Consultative Committee for Space Data Systems

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The Consultative Committee for Space Data Systems

Recommendation for Space Data System Practices

DELTA-DIFFERENTIAL ONE WAY RANGING (DELTA-DOR) OPERATIONS

RECOMMENDED PRACTICE

CCSDS 506.0-M-1

MAGENTA BOOK
April 2011

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1 INTRODUCTION

1.1 PURPOSE

This Recommended Practice specifies a set of standard practices and message formats for use in the navigation technique known as Delta Differential One-Way Ranging (Delta-DOR). It has been developed via consensus of the Delta-DOR Working Group of the CCSDS Systems Engineering Area (SEA).

Delta-DOR is a Very Long Baseline Interferometry (VLBI) technique that can be used in conjunction with Doppler and ranging data to improve spacecraft navigation by more efficiently determining spacecraft angular position in the plane of sky. The establishment of interoperability for acquiring and processing Delta-DOR data at ground stations of different agencies, the standardization of service requests for Delta-DOR, the standardization of an exchange format for raw data, and standardization of interfaces for exchange of supporting products are key enablers for interagency execution of Delta-DOR operations.

The Recommended Practice addresses aspects of the technique that require standardization in order to enable Delta-DOR interoperability between space agencies, e.g., configuration requirements for interagency Delta-DOR measurement; interagency exchange of measurement data; parameters that are necessary in order to correlate and process the data at one of the agencies; interagency transfer of the generated observables; and the end-to-end flow of control. It is believed that such standards will reduce development and operations costs while improving navigation capabilities by increasing the number of intercontinental ground station baselines.

There are essentially three parts to providing Delta-DOR services, the first being the definition of the RF domain signals and reception, the second being the definition of the input and output data products, and the third being the definition of the method for requesting service and transferring data products. The first of these is allocated to the CCSDS Space Link Service (SLS) Area (reference [1]); the second is allocated to the Mission Operations and Information Management Services (MOIMS) Area (reference [3]); the third will be developed as SLE Service Request extensions which will be allocated to the Service Management Working Group within the Cross Support Services (CSS) Area (reference [D12]).

The purpose of this Magenta Book is the production of a set of recommendations for facilitating interagency Delta-DOR operations that can both be useful now and evolve to meet future needs. The present document is intended to provide a set of standard practices to be used for setting up Delta-DOR measurements among different agencies, covering all of the required elements and describing how they are combined to provide the desired service.

1.2 SCOPE AND 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. For operations where these requirements do not capture the needs of the participating agencies, Delta-DOR operations may not be appropriate.

This Recommended Practice addresses rationale, requirements and criteria that Delta-DOR operations processes should be designed to meet.

1.3 CONVENTIONS AND DEFINITIONS

Conventions and definitions of Delta-DOR concepts are provided in reference [D2], *Delta-DOR Operations—Technical Characteristics and Performance*. This reference provides a detailed description of the Delta-DOR technique, including guidelines for DOR tone spectra, guidelines for selecting reference sources, applicable foundation equations, and a discussion of error sources and measurement accuracy that are not germane to the recommendations presented in this document.

The following conventions apply throughout this Recommended Practice:

– the words ‘shall’ and ‘must’ imply a binding and verifiable specification;

– the word ‘should’ implies an optional, but desirable, specification;

– the word ‘may’ implies an optional specification;

– the words ‘is’, ‘are’, and ‘will’ imply statements of fact.

1.4 COMMON DELTA-DOR TERMINOLOGY

Part of the standardization process involves the determination of common interagency terminology and definitions that apply to interagency Delta-DOR. The following conventions apply throughout this Recommended Practice:

Term	Meaning
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 radio source, typical duration of a few minutes
spanned bandwidth	The widest separation between downlink signal components
P_T/N_0	Total Power to Noise Spectral Density ratio
P_{Tone}/N_0	Tone Power to Noise Spectral Density ratio
meteo data	Meteorological Data (as a minimum: pressure, temperature, relative humidity must be considered; slant total electron content might also be provided)

1.5 STRUCTURE OF THIS DOCUMENT

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

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

– Section 3 provides a set of definitions for the interagency Delta-DOR.

– Section 4 describes the Delta-DOR interoperability scenarios.

– Section 5 discusses the interagency Delta-DOR validation process.

– Section 6 discusses the interagency data exchange products and procedures.

– Section 7 discusses the generation and maintenance of the radio source catalog.

– Annex A lists a number of items that should be covered in an interagency Implementing Arrangement (IA) prior to commencing regular Delta-DOR operations. There are several statements throughout the document that refer to the necessity of such a document; this annex consolidates all the suggested IA items in a single list in the document.

– Annex B discusses security considerations applied to the technologies specified in this Recommended Practice.

– Annex C is a list of abbreviations and acronyms applicable to Delta-DOR Operations.

– Annex D contains a list of informative references.

1.6 REFERENCES

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

[1] *Radio Frequency and Modulation Systems—Part 1: Earth Stations and Spacecraft*. Recommendation for Space Data System Standards, CCSDS 401.0-B-20. Blue Book. Issue 20. Washington, D.C.: CCSDS, April 2009.

[2] *Orbit Data Messages*. Recommendation for Space Data System Standards, CCSDS 502.0-B-2. Blue Book. Issue 2. Washington, D.C.: CCSDS, November 2009.

[3] *Tracking Data Message*. Recommendation for Space Data System Standards, CCSDS 503.0-B-1. Blue Book. Issue 1. Washington, D.C.: CCSDS, November 2007.

[4] *Delta-DOR Raw Data Exchange Format*. Draft Recommendation for Space Data System Standards, CCSDS 506.1-R-1. Red Book. Issue 1. Washington, D.C.: CCSDS, April 2011.

[5] "Radio Source Catalog." May 26, 2006. Module 107 in *DSN Telecommunications Link Design Handbook*. DSN No. 810-005, Rev. E. Pasadena California: JPL, <http://eis.jpl.nasa.gov/deepspace/dsndocs/810-005/>

NOTE – Informative references are provided in annex D.

2 OVERVIEW

2.1 GENERAL

This section provides a high-level overview of the Delta-DOR technique, its advantages, and disadvantages.

2.2 THE DELTA-DOR TECHNIQUE

Very Long Baseline Interferometry (VLBI) 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 space missions where delay measurements of a spacecraft radio signal are compared against similar delay measurements of angularly nearby quasar radio signals. In the case where the spacecraft measurements are obtained from the phases of tones emitted from the spacecraft, first detected separately at each station, and then differenced, this application of VLBI is known as Delta Differential One-Way Ranging ('Delta-DOR' or 'ΔDOR'). (See 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 they have similar information content and similar sensitivity to sources of error (reference [D2]). The data produced in such a measurement session are complementary to Doppler and ranging data.

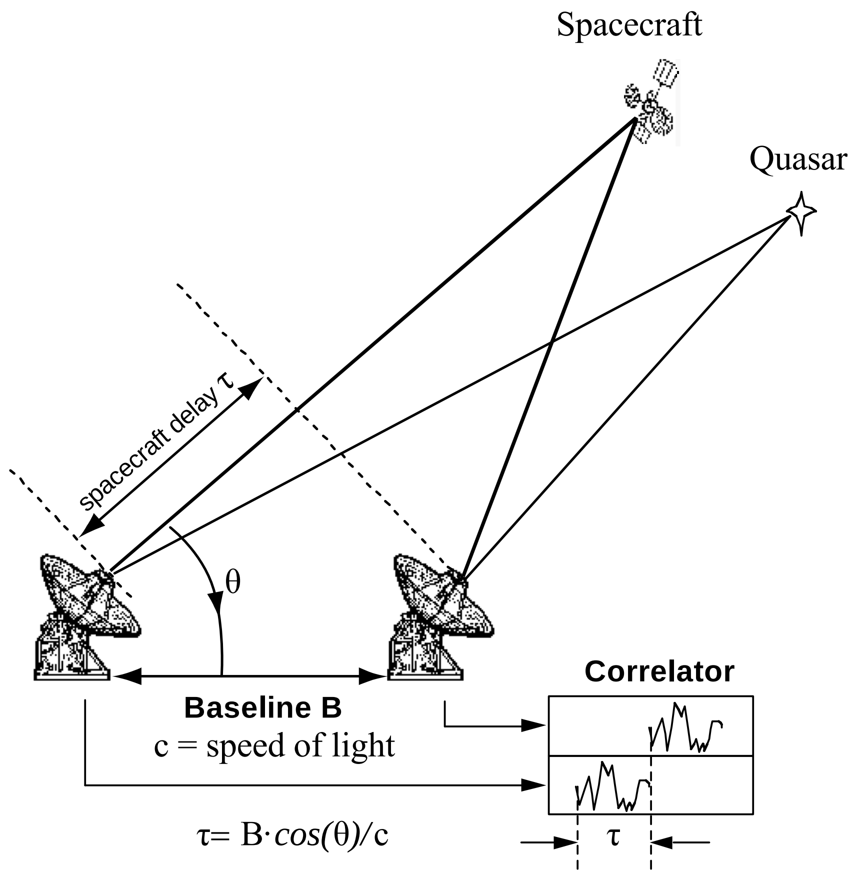

Figure 2-1: Delta-DOR Observation Geometry

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 the same quasar and spacecraft be tracked essentially simultaneously during the same tracking pass, at two distinct radio antennas. Thus a viewing overlap between the two antenna complexes is required; the degree of overlap is dependent upon the relative station locations, and varies for each pair of antenna complexes. Normally, a Delta-DOR pass consists of three or more scans of data recording, each of a few minutes duration. A scan consists of pointing the antennas to one radio source and recording the signal. The antennas must slew to another radio source for the next scan, and so on. The observing sequence is spacecraft-quasar-spacecraft, quasar-spacecraft-quasar, or a longer sequence of alternating observations, depending on the characteristics of the radio sources and the objectives of the measurement session. A minimum of three scans is required to eliminate clock-epoch and clock-rate offsets and then measure spacecraft angular position. Normally a three-scan sequence is repeated several times. Once collected, the received signals are brought to a common site and correlated. A Delta-DOR observable is generated from a differential one-way range measurement made between the spacecraft and the two ground antennas, and by a measurement of the difference in time of arrival, at the same two stations, of the quasar signal. The observed quantity in a Delta-DOR observation is time delay for each radio source.

For a spacecraft, the one-way range is determined for a single station by extracting the phases of two or more signals emitted by the spacecraft. The DOR tones are generated by modulating a sine wave or square wave onto the downlink carrier at S-band, X-band, or Ka-band. Either a pure waveform may be used, producing a spectrum of pure tones, or a modulated waveform may be used, producing a spectrum that more closely resembles the spectrum of a natural radio source. DOR observables are formed by subtracting the one-way range measurements generated at the two stations. While each one-way range measurement is affected by the unknown offset in the spacecraft clock, the station differencing eliminates this effect. However, DOR measurements are still biased by ground station clock offsets and instrumental delays.

For measuring the quasar, each station is configured to acquire data from it in frequency channels centered on the spacecraft tone frequencies. This receiver configuration choice ensures that the spacecraft-quasar differencing eliminates the effects of ground station clock offsets and instrumental delays. By selecting a quasar that is close in an angular sense to the spacecraft, and by observing the quasar at nearly the same time as the spacecraft, the effects of errors in the modeled station locations, Earth orientation, and transmission media delays are diminished.

In navigation processing, the delay or DOR observable is modeled for each scan of each radio source. The measured observable depends on both geometric factors and on delays introduced by transmission media. Meteo data are provided from each tracking site so that, possibly in conjunction with other data such as GPS measurements, corrections can be computed to account for tropospheric and ionospheric path delays. The modeled or ‘computed’ observable is based on geometric parameters and available calibrations for tropospheric and ionospheric delays. Residuals are formed by subtracting the computed observables from the measured time delay values. The ‘Delta’ between spacecraft and quasar observations is generated internal to the navigation processing by subtracting residual values of quasar observations from residual values of spacecraft observations.

Because each Delta-DOR measurement requires the use of two antennas, and navigation accuracy is improved by baseline diversity, this technique is highly conducive to interagency cooperation. Measurements from two baselines are required to determine both components of angular position, with orthogonal baselines providing the best two-dimensional coverage. While no agency has enough station complexes to provide orthogonal baselines by itself, the existing assets of more than one agency today could provide two or more pairs of angularly separated baselines and good geometric coverage for missions throughout the ecliptic plane. Stations from different agencies can be used as Delta-DOR data collectors for navigation purposes, assuming that the infrastructure has been laid to facilitate such cooperation. The use of Delta-DOR has been very beneficial for numerous NASA, ESA, and JAXA missions, beginning with Voyager in 1979. Current missions using Delta-DOR for navigation, as of this writing, include Messenger, New Horizons, Dawn, EPOXI, and Hayabusa. The technique is planned for future missions such as Mars Science Laboratory (NASA), BepiColombo (ESA), and Ikaros (JAXA), and it seems reasonably likely that its use will become a standard part of many mission navigation plans. CCSDS standardization will help expand the use of the technique by allowing interagency cross support.

2.3 ADVANTAGES OF DELTA-DOR

Earth-based radio metric tracking is the primary source of navigational data (Doppler and ranging) during interplanetary cruise. The advantages of using Delta-DOR measurements along with line-of-sight Doppler and ranging data include:

– Delta-DOR provides improved angular accuracy by direct geometric measurement of the plane-of-sky position of a spacecraft in the inertial reference frame defined by the quasars.

– Orbit solutions based on line-of-sight and Delta-DOR data show less sensitivity to systematic errors, as compared to orbit solutions based on only line-of-sight measurements, because of direct observation of all components of state. (See figure 2-2 below from Mars Exploration Rover data, reference [D10].) Targeting plane, commonly referred to as 'B-Plane', coordinates are typically used to describe planetary approach trajectories. Uncertainties in the approach trajectory are represented by error ellipses. Better planetary approach trajectories are characterized by smaller error ellipses.

– Solutions which incorporate Delta-DOR do not have singularities at low geocentric declinations or other adverse geometries.

– Comparable trajectory accuracy is obtained using either short arc (few days) or long arc (few months) solutions when Delta-DOR data are used. Spacecraft state can be recovered more quickly following a maneuver using Delta-DOR. By contrast, trajectory accuracy using Doppler and ranging typically depends strongly on data arc length.

– Navigation requirements can be satisfied by reduced tracking time per week, thus reducing both the duration and number of weekly tracking passes; e.g., Delta-DOR tracks may be used during an extended mission to meet navigation needs with a sparse tracking schedule.

– Delta-DOR data may be acquired in a listen-only mode; an uplink is not required.

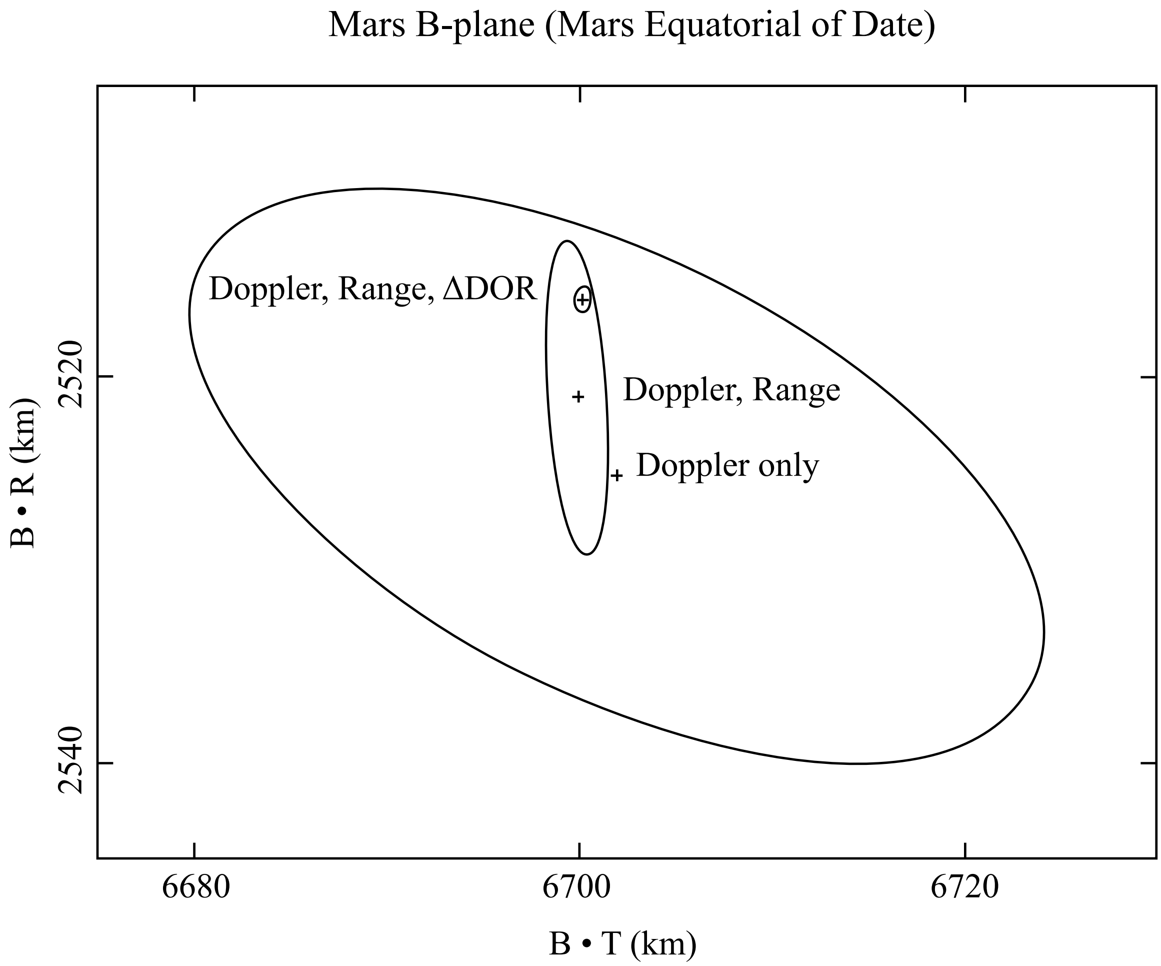

Figure 2-2: Error Ellipses in the Mars Targeting Plane[1]

2.4 LIMITATIONS OF DELTA-DOR

There are also some limitations of using Delta-DOR measurements, including:

- Because of the need to coordinate resources at two antenna complexes, and the requirement for view-period overlap, both the scheduling and execution of a Delta-DOR measurement session are more complex than measurement scenarios that involve only a single antenna or single antenna installation.
- It is usually not possible to collect telemetry data during the time that the Delta-DOR measurement is in progress.

[1] Courtesy of JPL/Caltech.

3 DEFINITIONS FOR INTERAGENCY DELTA-DOR

3.1 OVERVIEW

Delta-DOR operations requirements address functionality, processes, contents, and implementation approach for interoperability. Two kinds of scenarios are addressed: operational scenarios, in which Delta-DOR is used to support a flying mission, and validation scenarios, in which the validation of Delta-DOR capability is effected. First, roles of participating agencies in operational scenarios are defined. Then, roles of participating agencies in validation scenarios are also defined.

3.2 ROLES OF PARTICIPATING AGENCIES IN OPERATIONAL SCENARIOS

The following roles of participating agencies in operational scenarios are defined:

– Data Usage Agency (DUA): agency that provides the spacecraft (S/C) predicted trajectory and performs Delta-DOR observable modeling.

– Data Collection Agency (DCA): agency that collects the raw Delta-DOR data (there may be more than one).

– Data Processing Agency (DPA): agency that processes (correlates) the raw Delta-DOR data.

3.3 ROLES OF PARTICIPATING AGENCIES IN VALIDATION SCENARIOS

The following roles of participating agencies in validation scenarios are defined:

– Validating Agency (VA): agency that validates a specific function. Being the agency that validates part of the Delta-DOR system, this agency is supposed to have this system already operational and validated in terms of interoperability with other agencies.

– Under Validation Agency (UVA): agency that undergoes the validation process for a specific part of the Delta-DOR system.

The relationship between VA and UVA may be established at DUA, DCA, or DPA level.

3.4 DEFINITION OF THE OPERATIONAL SCENARIOS

The following table represents the four recognized interagency Delta-DOR operational scenarios. Each scenario is independent from the others. The notation A1=Agency 1, A2=Agency 2, etc., is used.

Table 3-1: Definition of Cross-Support Scenarios

	Agency		
Scenario	**DUA**	**DCA**	**DPA**
1	A1	A2	A2
2	A1	A1 &A2/A3	A1 or A2
3	A1	A2 & A3	A1
4	A1	A2 & A3	A2 or A3

NOTE – The scenarios identified in table 3-1 are described in section 4.

3.5 DEFINITION OF THE VALIDATION SCENARIOS

The following table identifies the three recognized interagency Delta-DOR validation steps. The notation adopted in 3.2 is used. Each scenario is independent from the others.

Table 3-2: Definition of Cross-Support Validation Scenarios

	Agency			
Step	**DUA**	**DCA**	**DPA**	**Validates**
1	UVA	VA	VA	Trajectory prediction and observable modeling
2	VA	UVA&VA, UVA	VA	Data collection
3	VA	VA	UVA	Data processing

NOTE – The scenarios identified in table 3-2 are described in section 5.

3.6 DEFINITION OF THE INTERFACES

The high-level Delta-DOR data flow below shows various interfaces (numbered 1 through 7 in figure 3-1) where standardization is beneficial in terms of establishing interoperability. Figure 3-1 also contains the roles of operational scenarios as defined in 3.2.

In general, the Recommended Practice covers the necessary parameters at each stage of the data flow. During data acquisition, radio source signals arrive at an antenna that belongs to a Data Collecting Agency, are detected by a receiver (Rx), and then stored at the site. Next, data from at least two sites are transferred to a Data Processing Agency and correlated to generate observables. Finally, reduced data (i.e., time delay observables) and meteo data used to calibrate path delays through transmission media are provided to the Orbit Determination (Data User Agency).

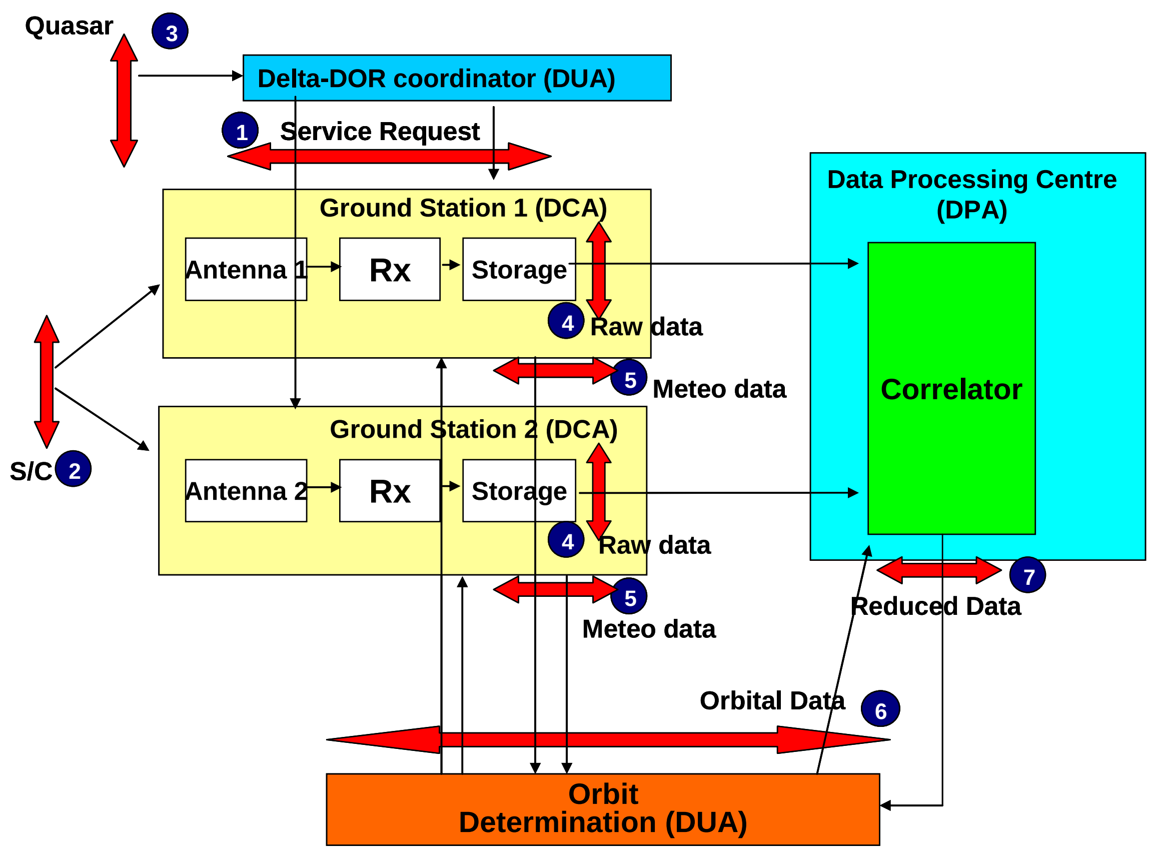

Figure 3-1: High-Level Delta-DOR Flow

With reference to figure 3-1 the following interfaces can be defined:

– IF-1: Service Request; includes observation schedule and sequence. This interface is described in 6.2.

– IF-2: DOR signal for S/C tracking. This interface is defined in CCSDS 401 (2.5.6B) B-2 (reference [1]).

– IF-3: quasar catalogue for Delta-DOR (reference [5]); provides quasar coordinates and flux that are used for measurement planning. This interface is described in section 7.

– IF-4: exchange format for raw Delta-DOR data. This interface is being standardized in reference [4] and may differ from the native format used for raw data by an Agency.

– IF-5: meteo data. This interface is defined by the Tracking Data Message (TDM—reference [3]).

– IF-6: orbital data. These data are used at all stations to define antenna pointing during data acquisition and received frequency predictions. These data are also input to the

Delta-DOR correlator. This input relies on the S/C orbit prediction, and therefore information is exchanged among agencies via Orbit Ephemeris Message (OEM) products (reference [2]).

– IF-7: reduced data. These are the products of the Delta-DOR. This interface is defined by the Tracking Data Message (TDM—reference [3]).

3.7 DEFINITION OF PARAMETERS INTERVENING IN THE MEASUREMENT

3.7.1 GENERAL

3.7.1.1 Basic information needed to enable cross support between Agencies shall first be documented in an Implementing Arrangement (IA). The IA shall contain at least the information listed in annex A.

3.7.1.2 In addition to the IA, three sets of parameters provide all information needed to perform a Delta-DOR session. These are:

a) Service Request parameters (interfaces affected: IF-1, IF-2, and IF-3);

b) orbit ephemeris parameters (IF-6);

c) correlation parameters (not mandatory).

3.7.1.3 Such parameters shall be exchanged either via the IA (annex A) or via the Service Request defined in 6.2.

NOTE – Each of the above sets of parameters is detailed in the following subsections.

3.7.2 SERVICE REQUEST PARAMETERS

The following parameters further described in 6.2 belong to the Service Request category:

a) Delta-DOR activity start/stop time;

b) spacecraft, quasar, and station IDs;

c) start and stop time of each scan;

d) radio source to observe for each scan;

e) signal polarization;

f) receiver channelization including bandwidth and sample resolution;

g) spacecraft signal components to record;

h) last estimated non-coherent carrier frequency;

i) frequency of the DOR tones or of the subcarrier harmonics that will be used for the measurement;

j) expected signal flux/flux density for each radio source.

3.7.3 ORBIT EPHEMERIS PARAMETERS

The following parameters belong to the orbit ephemeris category:

a) OEM file as defined in reference [2] of sufficient accuracy for antenna pointing during data acquisition;

b) OEM file as defined in reference [2] of sufficient accuracy for delay ambiguity resolution during data processing;

c) an estimate of the uncertainty in the OEM.

3.7.4 CORRELATION PARAMETERS

The following parameters belong to the correlation category:

a) total averaging time for the spacecraft signal;

b) coherent integration time for the spacecraft signal;

c) Phase Locked Loop (PLL) bandwidth (in Hz), if used, for each spacecraft tone;

d) total averaging time for the quasar signal;

e) coherent integration time for the quasar signal.

4 DESCRIPTION OF OPERATIONAL SCENARIOS

4.1 OVERVIEW

4.1.1 In this section, the four interoperability scenarios outlined in section 3 are described, using the following rules:

– each scenario is split in steps, respecting the timeline of events;

– all interfaces and categories of parameters to be exchanged at each step are mentioned.

Moreover, the following conventions are also adopted:

– *data processing* indicates the correlation of raw Delta-DOR data and generation of time delay observables;

– *Delta-DOR observable modeling* indicates reading of reduced Delta-DOR data and meteo data and computation of corresponding model values for the observables, i.e., generation of computed observables for use in orbit determination.

4.1.2 The IA described in annex A is a prerequisite to the execution of interagency Delta-DOR measurements. In particular the IA shall include time periods and number of occurrences for which service may be requested ('tracking schedule'). Instances of the Delta-DOR service, as required, are then requested based on the allowed tracking schedule. The information needed to request an instance of the Delta-DOR service is given in the 'Service Request' defined in 6.2.

4.2 SCENARIO 1

4.2.1 GENERAL

4.2.1.1 In scenario 1, following the conventions adopted in 3.2, the DUA is Agency 1, while the DCA and the DPA are Agency 2.

4.2.1.2 The scenario participating entities and tasks are:

a) tracked probe: DUA;

b) tracking stations: both stations operated by the DCA;

c) data processing: performed by the DCA/DPA;

d) data transfer:

   – OEM file from DUA to DCA,

   – meteo data from DCA to DUA,

   – reduced Delta-DOR data delivery by the DCA/DPA to the DUA;

e) Delta-DOR observable modeling: performed by the DUA.

4.2.2 OPERATIONAL SUPPORT PROCEDURE

The operational support procedure for scenario 1 shall be as follows:

a) The DUA provides the Service Request (through IF-1) to the DCA/DPA.

b) The DUA provides an OEM (through IF-6) to the DCA/DPA to be used for antenna pointing predicts and frequency predicts during data acquisition, and for correlation processing of the S/C.

c) The DUA configures the spacecraft for DOR downlink (through IF-2) at the scheduled times.

d) The DCA programs the detailed observation sequence, generates antenna pointing and frequency predicts, and configures the receiver as per the Service Request.

e) The DCA/DPA executes the observation and transfers both raw and meteo data to its facilities. For this data transfer step, in this scenario, either the native interfaces for the DCA or the interagency interfaces IF-4 and IF-5 may be used.

NOTE – Latitude is given here since data collection and processing are both native to the DCA/DPA.

f) The DPA correlates the data and provides reduced data (TDM, through IF-7) to the DUA.

g) The DCA provides the DUA with meteo data collected during the tracking (TDM, through IF-5).

h) The DUA makes use of the reduced data.

4.2.3 EXERCISED INTERFACES

The interfaces exercised in scenario 1 are:

a) IF-1: Service Request by the DUA to the DCA/DPA.

b) IF-2: Delta-DOR tone definition.

NOTE – The Service Request controls use of IF-2.

c) IF-3: quasar selection provided by the DUA to the DCA.

NOTE – The Service Request controls use of IF-3.

d) IF-5: meteo data to be provided by the DCA to the DUA.

e) IF-6: provision of OEM file by the DUA to the DCA/DPA.

f) IF-7: reduced data in the form of TDM files to be provided by the DPA to the DUA.

4.3 SCENARIO 2

4.3.1 GENERAL

4.3.1.1 In scenario 2, following the conventions adopted in 3.2, the DUA is Agency 1, while DCA 1 is Agency 1, DCA 2 is Agency 2 or Agency 3, and the DPA can be either Agency 1 or Agency 2.

4.3.1.2 The scenario participating entities and tasks are:

a) tracked probe: DUA;

b) tracking stations: one station operated by the DUA/DCA 1 and the other by DCA 2;

c) data processing: performed either by the DUA/DCA 1 or by DCA 2;

d) data transfer:

– OEM file from DUA to DCA 2,

– meteo data from DCA 2 to DUA;

in case the DUA is the DPA:

– exchange format raw Delta-DOR data from DCA 2 to DUA;

in case DCA 2 is the DPA:

– exchange format raw Delta-DOR data from DUA to DCA 2,

– reduced Delta-DOR data delivery by DCA 2 to the DUA in the form of a TDM file;

e) Delta-DOR observable modeling: performed by the DUA.

4.3.2 OPERATIONAL SUPPORT PROCEDURE

The operational support procedure for scenario 2 shall be as follows:

a) The DUA provides the Service Request (through IF-1) to DCA 2.

b) The DUA provides an OEM (through IF-6) to DCA 2 to be used for antenna pointing predicts and frequency predicts during data acquisition, and, if DCA 2 is the DPA, for correlation processing of the S/C.

c) The DUA configures the spacecraft for DOR downlink (through IF-2) at the scheduled times.

d) The DUA/DCA 1 and DCA 2 program the detailed observation sequence, generate antenna pointing and frequency predicts, and configure the receiver as per the Service Request.

e) The DUA/DCA 1 and DCA 2 perform the observation.

f) DCA 2 transfers the meteo data collected at its station to the DUA (through IF-5).

g) If DCA 2 is the DPA:

   1) the DUA/DCA 1 transfers the exchange format raw Delta-DOR data collected at its station to DCA 2 (through IF-4);

   2) DCA 2 provides reduced Delta-DOR data (TDM, through IF-7) to the DUA.

h) If the DUA/DCA 1 is the DPA:

   1) DCA 2 transfers the exchange format raw Delta-DOR data collected at its station to the DUA (through IF-4).

i) The DUA makes use of the reduced data.

4.3.3 EXERCISED INTERFACES

The interfaces exercised in scenario 2 are:

a) IF-1: Service Request by the DUA to DCA 2.

b) IF-2: Delta-DOR tone definition.

NOTE – The Service Request controls use of IF-2.

c) IF-3: quasar selection by the DUA.

NOTE – The Service Request controls use of IF-3.

d) IF-4: in case the DUA is the DPA, provision of exchange format raw Delta-DOR data by DCA 2 to the DUA/DPA; in case DCA 2 is the DPA, provision of exchange format raw Delta-DOR data by the DUA to DCA 2/DPA.

e) IF-5: meteo data to be provided by DCA 2 to the DUA.

f) IF-6: provision of OEM file by the DUA to DCA 2.

g) IF-7: reduced data in the form of TDM files to be provided by DCA 2 to the DUA only if DCA 2 is the DPA.

4.4 SCENARIO 3

4.4.1 GENERAL

4.4.1.1 In scenario 3, following the conventions adopted in 3.2, the DUA is Agency 1, while DCAs are Agency 2 and Agency 3, and the DPA is again Agency 1.

4.4.1.2 The scenario participating entities and tasks are:

a) tracked probe: DUA;

b) tracking stations: one station operated by DCA 1 and the other by DCA 2;

c) data processing: performed by the DUA;

d) data transfer:

  – OEM file from DUA to DCAs,

  – meteo data from DCAs to DUA,

  – exchange format raw Delta-DOR data from DCAs to DUA;

e) Delta-DOR observable modeling: performed by the DUA.

4.4.2 OPERATIONAL SUPPORT PROCEDURE

The operational support procedure for scenario 3 shall be as follows:

a) The DUA provides the Service Request (through IF-1) to both DCAs.

b) The DUA provides an OEM (through IF-6) to both DCAs to be used for antenna pointing predicts and frequency predicts during data acquisition.

c) The DUA configures the spacecraft for DOR downlink (through IF-2) at the scheduled times.

d) DCA 1 and DCA 2 program the detailed observation sequence, generate antenna pointing and frequency predicts, and configure the receiver as per the Service Request.

e) DCA 1 and DCA 2 perform the observation.

f) DCA 1 and DCA 2 transfer exchange format raw Delta-DOR data (through IF-4) and meteo data (through IF-5) collected at their stations to the DUA/DPA.

g) The DUA/DPA performs the correlation and makes use of the reduced data.

4.4.3 EXERCISED INTERFACES

The interfaces exercised in this scenario are:

a) IF-1: Service Request by the DUA to the DCAs.

b) IF-2: Delta-DOR tone definition.

NOTE – The Service Request controls use of IF-2.

c) IF-3: quasar selection by the DUA.

NOTE – The Service Request controls use of IF-3.

d) IF-4: provision of exchange format raw Delta-DOR data by the DCAs to the DUA.

e) IF-5: meteo data to be provided by the DCAs to the DUA.

f) IF-6: provision of OEM file by the DUA to the DCAs.

4.5 SCENARIO 4

4.5.1 GENERAL

4.5.1.1 In scenario 4, following the conventions adopted in 3.2, the DUA is Agency 1, while DCAs are Agency 2 and Agency 3, and the DPA is either Agency 2 or Agency 3.

4.5.1.2 The scenario participating entities and tasks are:

a) tracked probe: DUA;

b) tracking stations: one station operated by DCA 1 and the other by DCA 2;

c) data processing: the DPA could be either DCA 1 or DCA 2;

d) data transfer:

   – OEM file from DUA to DCAs,

   – meteo data from DCAs to DUA;

   in case DCA 1 is the DPA:

   – exchange format raw Delta-DOR data from DCA 2 to DCA 1/DPA;

   in case DCA 2 is the DPA:

   – exchange format raw Delta-DOR data from DCA 1 to DCA 2/DPA;

e) Delta-DOR observable modeling: performed by the DUA.

4.5.2 OPERATIONAL SUPPORT PROCEDURE

The operational support procedure for scenario 4 shall be as follows:

a) The DUA provides the Service Request (through IF-1) to both DCAs.

b) The DUA provides an OEM (IF-6) to be used for antenna pointing predicts and frequency predicts during data acquisition to both DCAs.

c) The DUA configures the spacecraft for DOR downlink (through IF-2) at the scheduled times.

d) DCA 1 and DCA 2 program the detailed observation sequence, generate antenna pointing and frequency predicts, and configure the receiver as per the Service Request.

e) DCA 1 and DCA 2 perform the observation.

f) DCA 1 and DCA 2 transfer meteo data to the DUA (through IF-5).

g) If DCA 1 is the DPA:

   1) DCA 2 transfers the exchange format raw Delta-DOR data collected at its station to DCA 1/DPA (through IF-4);

2) DCA 1/DPA correlates the data and provides reduced data (TDM, through IF-7) to the DUA.

h) If DCA 2 is the DPA:

1) DCA 1 transfers the exchange format raw Delta-DOR data collected at its station to DCA 2/DPA (through IF-4);

2) DCA 2/DPA correlates the data and provides reduced data (TDM, through IF-7) to the DUA.

i) The DUA makes use of the reduced data.

4.5.3 EXERCISED INTERFACES

The interfaces exercised in scenario 4 are:

a) IF-1: Service Request by the DUA to the DCAs.

b) IF-2: Delta-DOR tone definition.

NOTE – The Service Request controls use of IF-2.

c) IF-3: quasar selection by the DUA.

NOTE – The Service Request controls use of IF-3.

d) IF-4: in case DCA 1 is the DPA, provision of exchange format raw Delta-DOR data by DCA 2 to DCA 1/DPA; in case DCA 2 is the DPA, provision of exchange format raw Delta-DOR data by DCA 1 to DCA 2/DPA.

e) IF-5: meteo data to be provided by both DCAs to the DUA.

f) IF-6: provision of OEM file by the DUA to the DCAs.

g) IF-7: reduced data in the form of a TDM file to be provided by the DPA to the DUA.

5 DESCRIPTION OF VALIDATION PROCESS

5.1 OVERVIEW

There are several ways for validating the capability of an agency to be incorporated in an existing Delta-DOR network. First of all, the agency joining the Delta-DOR network should already be equipped with the necessary infrastructure. However, this cannot be considered as a sufficient step to be fully integrated in an operational network.

Following the description given in 3.5, three validation steps are here described.

Each step aims at validating part of the process (trajectory prediction and Delta-DOR observable modeling, data collection, and data processing) in order to reach complete interoperability. Each of the aforementioned is described in detail in the following subsections.

Each step is an independent case, and the steps can be undertaken in any order. In order to achieve a full interoperability, all of the steps must be successfully completed.

The validation process here described covers only the procedure needed; it does not contain a quantitative criterion for the achieved validation level. This information is provided in the Green Book (reference [D2]).

In order to make the process more effective, it should be performed using a spacecraft orbiting around a planet. Since the orbit of a planetary spacecraft can be estimated already with high precision using standard radiometric techniques such as integrated Doppler and ranging, the performance of the Delta-DOR system under test can be better characterized.

5.2 INTEROPERABILITY VALIDATION STEP 1—TRAJECTORY PREDICTION AND OBSERVABLE MODELING

5.2.1 GENERAL DESCRIPTION AND GOALS

5.2.1.1 In order to validate the interoperability process, one step is to test the navigation interfaces and related processing. Step 1 exercises all navigation interfaces in the form of OEM (reference [2]) and TDM files (reference [3]), consisting in the exchange of OEM for the pre-acquisition phase and of meteo and reduced data (i.e., the Delta-DOR observable) in the form of TDM files.

5.2.1.2 The Validating Agency (VA), which has already-proven capabilities of Delta-DOR interoperability, will provide both the DCA and DPA roles, from data acquisition to data processing. The Under Validation Agency (UVA) will test its capability to provide a predicted ephemeris (OEM file, IF-6 in figure 3-1) and to carry out Delta-DOR observable modeling using the reduced data (IF-7) and meteo data (IF-5) in TDM format.

5.2.1.3 The participating entities and tasks are:

a) Tracked probe: UVA.

If the probe belongs to the VA, the VA shall provide the UVA with the means to perform trajectory prediction and Delta-DOR observable modeling on the probe.

NOTE – It would be up to the VA to validate such capability before undertaking the Delta-DOR validation step under discussion.

b) Tracking stations: both stations operated by the VA.

c) Data processing: performed only by the VA.

d) Data transfer:

- Delta-DOR reduced data delivery by the VA to the UVA in the form of a TDM file;
- meteo data delivery by the VA to the UVA in the form of a TDM file;
- OEM file delivery by the UVA to the VA.

e) Delta-DOR observable modeling: performed by the UVA.

5.2.2 VALIDATION PROCEDURE

The validation procedure shall be as follows:

a) The UVA provides the Service Request (through IF-1) to the VA.

If the probe belongs to the VA, the VA shall provide the UVA with the relevant S/C parameters (as per annex A) so that the UVA can generate the Service Request.

b) The UVA provides the VA with an OEM file (through IF-6) of its spacecraft and related uncertainties to be used for antenna pointing during data acquisition, frequency predicts, and correlation processing.

If the probe belongs to the VA, the VA shall provide the UVA with the probe state and relevant S/C model parameters so that the UVA can generate the OEM.

c) The VA programs the detailed observation sequence, generates antenna pointing and frequency predicts, and configures the receiver as per the Service Request.

d) The VA executes the observation and transfers both raw and meteo data to its facilities. For this data transfer step, in this scenario, either the native interfaces for the VA or the interagency interfaces IF-4 and IF-5 may be used.

NOTE – Latitude is given here since data collection and processing are both native to the VA.

e) The VA correlates the data and provides reduced data (TDM, through IF-7) to the UVA.

f) The VA provides the UVA with meteo data collected during the tracking (TDM, through IF-5).

g) The UVA performs the Delta-DOR observable modeling.

h) The VA checks the computed observables provided by the UVA.

5.2.3 VALIDATED INTERFACES

The interfaces validated in this step are:

a) IF-1: provision of the Service Request by the UVA to the VA.

b) IF-2: Delta-DOR tone definition.

NOTE – The Service Request controls use of IF-2.

c) IF-3: quasar selection.

NOTE – The Service Request controls use of IF-3.

d) IF-5: provision of meteo data of both observing stations by the VA to the UVA.

e) IF-6: provision of OEM file by the UVA to the VA.

f) IF-7: provision of reduced Delta-DOR data by the VA to the UVA.

5.2.4 ACHIEVEMENTS

With interoperability validation step 1 the following are achieved:

a) validation of the UVA navigation products in the pre-acquisition phase (i.e., OEM files).

b) validation of the UVA capabilities to read and model Delta-DOR navigation products (i.e., TDM files) within the orbit determination phase.

c) The UVA can now provide the role of DUA.

5.3 INTEROPERABILITY VALIDATION STEP 2—DATA COLLECTION

5.3.1 GENERAL DESCRIPTION AND GOALS

5.3.1.1 Step 2 addresses the point of raw data exchange and validation of the raw data acquisition process by the UVA.

5.3.1.2 The participating entities and tasks are:

a) Tracked probe: VA.

If the probe belongs to the UVA, the UVA shall provide the VA with the means to perform trajectory prediction and Delta-DOR observable modeling on the probe.

b) Tracking stations: one station operated by the VA, one by the UVA (or both operated by the UVA).

c) Data transfer: exchange format raw Delta-DOR and meteo data transfer from the UVA to the VA.

d) Data processing: performed by the VA.

e) Delta-DOR observable modeling: performed by the VA.

5.3.2 VALIDATION PROCEDURE

The validation procedure shall be as follows:

a) The VA provides the Service Request (through IF-1) to the UVA.

If the probe belongs to the UVA, the UVA shall provide the VA with the relevant S/C parameters (as per annex A) so that the VA can generate the Service Request.

b) The VA provides the UVA with an OEM file (through IF-6) of its spacecraft and related uncertainties to be used for antenna pointing predicts and frequency predicts during data acquisition, and for the correlation process.

If the probe belongs to the UVA, the UVA shall provide the VA with the probe state and relevant S/C model parameters so that the VA can generate the OEM.

c) The UVA and the VA (or the UVA only, in case both stations belong to the UVA) program the detailed observation sequence, generate antenna pointing and frequency predicts, and configure the receiver as per the Service Request.

d) The UVA and the VA (or the UVA only, in case both stations belong to the UVA) execute the observation.

e) The UVA transfers the exchange format raw Delta-DOR data (through IF-4) and the meteo data (through IF-5) collected at its station(s) to the VA.

f) The VA performs the correlation process.

g) The VA performs the observable modeling and validates the results.

5.3.3 VALIDATED INTERFACES

The interfaces validated in this step are:

a) IF-1: provision of the Service Request by the VA to the UVA.

b) IF-2: Delta-DOR tone definition.

NOTE – The Service Request controls use of IF-2.

c) IF-3: quasar selection.

NOTE – The Service Request controls use of IF-3.

d) IF-4: provision of exchange format raw Delta-DOR data by the UVA to the VA.

e) IF-5: provision of meteo data by the UVA to the VA.

5.3.4 ACHIEVEMENTS

With interoperability validation step 2 the following are achieved:

a) validation of the UVA capability to make use of the navigation products generated by the VA (i.e., OEM files).

b) validation of exchange format raw Delta-DOR and meteo data acquisition of the UVA.

c) The UVA can now provide the role of DCA.

5.4 INTEROPERABILITY VALIDATION STEP 3—DATA PROCESSING

5.4.1 GENERAL DESCRIPTION AND GOALS

5.4.1.1 Step 3 addresses the correlation process performed by the UVA.

5.4.1.2 The participating entities and tasks are:

a) Tracked probe: VA.

   If the probe belongs to the UVA, the UVA shall provide the VA with the means to perform trajectory prediction and Delta-DOR observable modeling on the probe.

b) Tracking stations: both operated by the VA.

c) First data transfer: exchange format raw Delta-DOR data from the VA to the UVA.

d) Data processing: data correlation performed by the UVA.

e) Second data transfer: reduced Delta-DOR data transfer from the UVA to the VA.

5.4.2 VALIDATION PROCEDURE

The validation procedure shall be as follows:

a) The VA provides the Service Request (through IF-1) to the UVA.

   If the probe belongs to the UVA, the UVA shall provide the VA with the relevant S/C parameters (as per annex A) so that the VA can generate the Service Request.

b) The VA provides the UVA with an OEM file (through IF-6) of its spacecraft and related uncertainties to be used in the correlation process.

   If the probe belongs to the UVA, the UVA shall provide the VA with the probe state and relevant S/C model parameters so that the VA can generate the OEM.

c) The VA programs the detailed observation sequence, generates antenna pointing and frequency predicts, and configures the receiver as per the Service Request.

d) The VA executes the observation.

e) The VA transfers exchange format raw Delta-DOR data (through IF-4) collected at its tracking stations to the UVA.

f) The UVA performs the data processing. Discussion on the correlation parameters in 3.7.4 may be required as part of the validation process. The VA also performs data processing to be able to check the results from the UVA.

g) The UVA transfers the reduced Delta-DOR data to the VA (through IF-7).

h) The VA compares the reduced data to its own values, from data processing performed at the VA, and validates the results.

5.4.3 VALIDATED INTERFACES

The interfaces validated in this step are:

a) IF-1: provision of the Service Request by the VA to the UVA.

b) IF-2: Delta-DOR tone definition.

NOTE – The Service Request controls use of IF-2.

c) IF-3: quasar selection.

NOTE – The Service Request controls use of IF-3.

d) IF-4: provision of exchange format raw Delta-DOR data by the VA to the UVA.

e) IF-6: provision of OEM file by the VA to the UVA.

f) IF-7: provision of reduced Delta-DOR data by the UVA to the VA.

5.4.4 ACHIEVEMENTS

With interoperability validation step 3 the following are achieved:

a) validation of the UVA capability to make use of the navigation products (i.e., OEM files) generated by the VA in the data processing.

b) validation of data correlation capability of the UVA.

c) The UVA can now provide the role of DPA.

6 INTERAGENCY DATA EXCHANGE PRODUCTS AND PROCEDURES

6.1 GENERAL

6.1.1 In order to support Delta-DOR interoperability, it is necessary to transfer the following data products between agencies:

a) service request;

b) exchange format raw Delta-DOR data (if any);

c) meteo data (TDM);

d) orbit ephemeris files (OEM);

e) reduced Delta-DOR data (TDM).

6.1.2 Each participating agency shall agree upon a data transfer strategy for the data products defined in 6.1.1. The strategy shall include the definition of suitable transfer protocols, source machines, and repository machines.

6.2 SERVICE REQUEST EXCHANGE SPECIFICATION

6.2.1 GENERAL

The Delta-DOR Service Request contains all parameters needed to define a Delta-DOR measurement session. These include all the parameters discussed in 3.7.2. If all parameters are specified, then the Service Request completely defines the Delta-DOR session. Some of the parameters of the Service Request are optional. Some optional parameters may have default values that are provided in the IA. Or, if all stations are part of the same agency, then some or all of the optional parameters may have agency-specific default values. Default values, maintained in tables by each DCA, shall be used to fill in omitted parameters.

6.2.2 SERVICE REQUEST DATA EXCHANGE

The parameters in the Service Request are defined in table 6-1. All times are UTC Earth receive time.

Table 6-1: Definition of Delta-DOR Service Request Parameters

Parameter	Units	Required	Description
Request_ID	YYYY-DDDThh:mm:ss	Y	Issue date of the service request
Mission_ID	N/A	Y	Name of mission requesting the service
Config_ID	N/A	N	Receiver configuration to be used
DPA	N/A	N	Agency to perform the data processing
SC_Name_List	N/A	Y	An array containing the ID of each spacecraft to be observed
SC_Flux	dBm/m^2	N	An array containing the flux (total received power per unit area) of each spacecraft to be observed; flux is normalized to a transmission distance of 1 AU; entries correspond to entries in SC_Name_List
Quasar_Name_List	N/A	Y	An array containing the ID of each quasar to be observed
Quasar_Flux	Jy	N	An array containing the flux density (received power per unit area per unit bandwidth) of each quasar to be observed; entries correspond to entries in Quasar_Name_List
Quasar_RA	deg	N	An array containing the right ascension of each quasar, J2000 coordinates; entries correspond to entries in Quasar_Name_List
Quasar_DEC	deg	N	An array containing the declination of each quasar, J2000 coordinates; entries correspond to entries in Quasar_Name_List
Tracking_Station	N/A	Y	An array containing the ID of each participating tracking station

Parameter	Units	Required	Description
Network	N/A	N	An array containing the name of the network that each tracking station belongs to; entries correspond to entries in Tracking_Station
Track_Time	YYYY-DDDThh:mm:ss _To_YYYY-DDDThh:mm:ss	Y	An array containing the start and end times for observing at each tracking station; entries correspond to entries in Tracking_Station
Scan_Source	N/A	Y	A time ordered list of the radio source to observe for each scan; Note - the sources in this list must be chosen from the sources in either SC_Name_List or Quasar_Name_List
Scan_Start	DDDThh:mm:ss	Y	An array containing scan start times; entries correspond to entries in Scan_Source
Scan_Stop	DDDThh:mm:ss	Y	An array containing scan stop times; entries correspond to entries in Scan_Source
DOR_Tones_On	YYYY-DDDThh:mm:ss _To_YYYY-DDDThh:mm:ss	Y	An array containing time intervals for each spacecraft to specify when DOR tones are received at ground stations; Note: each spacecraft must be commanded to transmit DOR tones for an interval that is a one-way light time earlier; entries correspond to entries in SC_Name_List
Polarization	N/A	N	An array containing the received signal polarization (RCP or LCP) for each spacecraft; entries correspond to entries in SC_Name_List
Carrier_Transmit_Freq	Hz	N	An array containing the carrier transmitter frequency for each spacecraft; entries correspond to entries in SC_Name_List

Parameter	Units	Required	Description
SC_Chan_BW	Hz	Y	Channel bandwidth to be used for spacecraft signal recording
SC_Chan_Res	bits/sample	Y	Sample resolution to be used for spacecraft signal recording
QU_Chan_BW	Hz	Y	Channel bandwidth to be used for quasar signal recording
QU_Chan_Res	bits/sample	Y	Sample resolution to be used for quasar signal recording
Channel_Number	N/A	Y	An array containing logical channel numbers to use for recording
Spacecraft_Assoc	N/A	N	An array containing spacecraft IDs to associate with each recording channel; entries correspond to entries in Channel_Number
Signal_Component	N/A	N	An array containing spacecraft signal component names (CARRIER or SUBCAR or DORTONE); entries correspond to entries in Channel_Number
Delta_Flux	dB	N	An array containing spacecraft signal component fluxes relative to total spacecraft signal flux; entries correspond to entries in Channel_Number
Delta_Frequency	Hz	Y	An array containing spacecraft signal component transmitted frequency offsets from carrier; entries correspond to entries in Channel_Number

6.3 ORBITAL EPHEMERIS MESSAGE EXCHANGE SPECIFICATION

6.3.1 GENERAL

The orbital ephemeris data of the spacecraft to be tracked (IF-6) are used for antenna pointing predicts and frequency predicts during data acquisition, prior to data correlation. Therefore they shall be transferred from the DUA to the DCA(s) (see definitions in 3.2) prior to the execution of the planned Delta-DOR observation.

6.3.2 ORBITAL EPHEMERIS DATA EXCHANGE

The orbital information shall be transferred by means of OEM files, defined in reference [2].

6.3.3 DATA TRANSFER REQUIREMENTS

OEM files shall be delivered by the DUA to the DCA on a regular basis, to be agreed upon by the two agencies in the frame of the Implementing Arrangement.

6.4 RAW DATA TRANSFER/EXCHANGE SPECIFICATION

6.4.1 GENERAL

Raw Delta-DOR and meteo data exchanges are shown as ‘IF-4’ and ‘IF-5’ in figure 3-1. There is no CCSDS Recommended Standard for native Delta-DOR data format, since each agency has developed its own hardware and software for data collection. For an interagency Delta-DOR session, a raw Delta-DOR data exchange format is defined (reference [4]) and shall be used when performing cross-agency operations. In such cases, each agency shall therefore translate its data to the exchange format before transferring data to the processing site.

NOTE – The processing site may be located at another agency.

6.4.2 RAW DELTA-DOR DATA EXCHANGE

In case ground stations of two agencies are used in a Delta-DOR recording session, transfer of the exchange format raw data from both sites to the chosen correlator facility is necessary. In case different hardware is used by two agencies, the sampling format for native raw data may not be identical. However, if similar channel positions and sampling rates are agreed upon and used, then it is possible to re-sample one data stream to make it fully compatible with the second stream. Further, data with compatible samples may be converted from the format used by one DCA into the format required by the DPA. The re-sampling and re-formatting shall be done by the DCA before raw data transfer. Users should be aware that re-sampling may reduce effective signal-to-noise ratio of the data.

The exchange format raw Delta-DOR data file (or files) shall contain ancillary information to completely describe the recording session, as well as the primitive samples of the spacecraft and quasar signals.

NOTE – The exchange format for raw Delta-DOR data is described in reference [4].

6.4.3 DATA TRANSFER REQUIREMENTS

Raw Delta-DOR data exchange of necessity involves transfer of a large volume of data. Historically, VLBI experimenters have exchanged data by shipping tapes or disks from one site to another. On the other hand, measurement systems developed for Delta-DOR have relied on electronic file transfer. Data network connections are needed from each station to the correlator facility. Because of the large data volume expected, the number of transfer steps should be kept to a minimum. The necessary transfer rate that must be provided will depend on the data volume and the allowed latency for delivery of the reduced data.

As an example, 12 Gbytes of data may be transferred in 9 hr at a rate of 3 Mbits/sec. This typical data volume and latency can be supported by two T1 lines for a single transfer step.

The data volume and the required latency must be taken into account when sizing bandwidth requirements. Network connections, network bandwidth, suitable transfer protocols, source machines, and repository machines must all be provided and agreed upon.

6.5 METEO DATA EXCHANGE SPECIFICATION

6.5.1 GENERAL

The meteo data collected at the stations during the Delta-DOR tracking (IF-5) are used to develop path delay calibrations for signal transmissions through the Earth’s troposphere and ionosphere. These calibrations are then used in the navigation system as part of the observable model. Therefore they shall be exchanged immediately after the execution of the planned Delta-DOR observation.

6.5.2 METEO DATA EXCHANGE

The meteo data information shall be exchanged by means of Tracking Data Message (TDM) files, described in reference [3].

6.5.3 DATA TRANSFER REQUIREMENTS

TDM files shall be delivered by the DCAs (see definitions in 3.2) to the DUA after each Delta-DOR tracking session.

6.6 REDUCED DELTA-DOR DATA TRANSFER/EXCHANGE SPECIFICATION

6.6.1 GENERAL

Reduced Delta-DOR data transfer is shown as IF-7 in figure 3-1. Once the raw data have been collected, transferred, and correlated, the Delta-DOR observables shall be delivered to the spacecraft navigation team for use in the process of orbit determination.

6.6.2 REDUCED DELTA-DOR DATA EXCHANGE

The reduced Delta-DOR data information shall be transferred by means of TDM files, defined in reference [3].

The means and latency of data transfer shall be agreed upon by the specific exchange participants and documented in the Implementing Arrangement.

7 RADIO SOURCE CATALOGUE SPECIFICATION

Natural radio source (quasar) input is shown as IF-3 in figure 3-1. A common radio source catalogue shall be used by all agencies to facilitate consistency in radio source selection, pointing, and correlating.

To plan for a measurement, the catalogue is searched to find candidate sources that are angularly close to the spacecraft position at the measurement time, and of sufficient flux. Then specific sources are selected for observation based on some criteria such as minimizing measurement error.

The catalogue shall:

– have a unique name for each radio source;

– have coordinates and coordinate uncertainties for each radio source;

– have an estimate of flux and structure (i.e., coordinate variability) for each radio source.

The JPL radio source catalogue published in DSN document 810-005 (reference [5]) is currently recommended to be used as the standard Delta-DOR catalogue for S- and X-band observations. This catalogue meets the minimum requirements and is updated as new survey work is completed. It should be noted that up-to-date flux estimates and structure estimates are not available for all radio sources.

The CCSDS Delta-DOR Working Group may periodically review the available published radio source catalogues and issue a new recommendation for which catalogue shall be used as the standard.

The CCSDS Delta-DOR Working Group encourages all space agencies to support the extension of the existing catalogue as follows:

– increase the number of observed and catalogued of X-band sources;

– develop a Ka-band catalogue;

– provide separate correlated source flux estimates for each interagency baseline;

– provide information on flux variation versus time.

ANNEX A

ITEMS FOR AN IMPLEMENTING ARRANGEMENT (IA)

(NORMATIVE)

In several places in this document there are references to items which should be specified in an Implementing Arrangement (IA) between agencies participating in a Delta-DOR campaign, if they are applicable to the particular operation. This annex compiles those items into a single location. The IA should be jointly produced by both agencies participating in a cross-support activity involving the collection, analysis, and transfer of tracking data.

It might be feasible for participating agencies to have a generic baseline IA (‘standard service provider IA’) that specifies mission-/spacecraft-independent entities on the interface, e.g., those associated with the agency’s ground antennas (axis offsets, station locations, side motions, reference frame, epoch, supported frequency bands, etc.). Then smaller IAs could be used for the mission-/spacecraft-specific arrangements.

The following table lists the items that shall be covered in an IA, along with where they are discussed in the text.

Item	Section
1. Identification of roles of participating agencies	3
2. ID for mission and spacecraft to be supported	3, 6.2
3. Parameters to allow modeling of spacecraft observables; only needed if a second Agency will be using data for a spacecraft belonging to another Agency	5
4. Agreed schedule including number of passes, baseline or station IDs, network ID, dates and times (see NOTE)	3, 6.2
5. Functional characteristics of tracking stations, including passbands, locations, and G/T	N/A
6. Identification of operational scenarios for each pass	3
7. Service Request delivery lead time requirement	N/A
8. Delivery time for reduced Delta-DOR data (required data delivery time for each phase of the mission)	6.6
9. Identification of Delta-DOR official contact point for each agency	N/A
10. Spacecraft downlink signal structure, polarization, and nominal transmit frequency	6.2
11. Specific modulation format, DOR tone frequencies, and power levels selected for each spacecraft	6.2
12. Ground station configuration ID to be used; only needed if Agencies agree on standard configurations	
13. Delta-DOR observable accuracy	N/A
14. Transfer protocols	6
15. Specific information, security, interoperability provisions that may apply between agencies involved in the Delta-DOR campaign	6, annex B
NOTE – The schedule may be initially defined as a profile of resource usage and then become more detailed and specific.	

ANNEX B

SECURITY

(INFORMATIVE)

B1 INTRODUCTION

This section presents the results of an analysis of security considerations applied to the technologies specified in this Recommended Practice.

B2 SECURITY CONCERNS WITH RESPECT TO THIS RECOMMENDED PRACTICE

B2.1 DATA PRIVACY

Privacy of data formatted in compliance with the specifications of this Recommended Practice should be assured by the systems and networks on which this Recommended Practice is implemented.

B2.2 DATA INTEGRITY

Integrity of data formatted in compliance with the specifications of this Recommended Practice should be assured by the systems and networks on which this Recommended Practice is implemented.

B2.3 AUTHENTICATION OF COMMUNICATING ENTITIES

Authentication of communicating entities involved in the transport of data which complies with the specifications of this Recommended Practice should be provided by the systems and networks on which this Recommended Practice is implemented.

B2.4 DATA TRANSFER BETWEEN COMMUNICATING ENTITIES

The transfer of data formatted in compliance with this Recommended Practice between communicating entities should be accomplished via secure mechanisms approved by the IT Security functionaries of exchange participants.

B2.5 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.

CCSDS HISTORICAL DOCUMENT

B2.6 POTENTIAL THREATS AND ATTACK SCENARIOS

There are no known potential threats or attack scenarios that apply specifically to the technologies specified in this Recommended Practice. Potential threats or attack scenarios applicable to the systems and networks on which this Recommended Practice is implemented should be addressed by the management of those systems and networks. Protection from unauthorized access is especially important if the mission utilizes open ground networks such as the Internet to provide ground station connectivity for the exchange of data formatted in compliance with this Recommended Practice.

B3 CONSEQUENCES OF NOT APPLYING SECURITY TO THE TECHNOLOGY

There are no explicitly known consequences of not applying security to the technologies specified in this Recommended Practice. 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.

B4 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 IA.

ANNEX C

ABBREVIATIONS AND ACRONYMS

(INFORMATIVE)

Abbreviations used in this document are defined with the first textual use of the term. All abbreviations used in this document are listed below.

CCSDS	Consultative Committee for Space Data Systems
CSS	Cross Support Services
DCA	Data Collection Agency
DPA	Data Processing Agency
DUA	Data Usage Agency
Delta-DOR	delta Differential One-way Range
DOR	Differential One-way Range
DSN	Deep Space Network
ESA	European Space Agency
G/T	Antenna gain to system noise temperature ratio
Hz	Hertz
IA	Implementing Arrangement
ID	Identifier
IF	Interface
JAXA	Japan Aerospace Exploration Agency
JPL	Jet Propulsion Laboratory
MOIMS	Mission Operations and Information Management Services
NASA	National Aeronautics and Space Administration
OEM	Orbit Ephemeris Message
PLL	Phase Locked Loop
RF	Radio Frequency
Rx	Receiver

S/C	Spacecraft
SLE	Space Link Extensions
SLS	Space Link Services
TDM	Tracking Data Message (CCSDS)
UTC	Universal Time Coordinated
UVA	Under Validation Agency
VA	Validating Agency
VLBI	Very Long Baseline Interferometry

ANNEX D

INFORMATIVE REFERENCES

(INFORMATIVE)

NOTE – Normative references are provided in 1.6.

[D1] *Procedures Manual for the Consultative Committee for Space Data Systems*. CCSDS A00.0-Y-9. Yellow Book. Issue 9. Washington, D.C.: CCSDS, November 2003.

[D2] *Delta-DOR Operations—Technical Characteristics and Performance*. Draft Report Concerning Space Data System Standards, CCSDS 500.6-G-0. Proposed Green Book.[2]

[D3] *Navigation Data—Definitions and Conventions*. Report Concerning Space Data System Standards, CCSDS 500.0-G-3. Green Book. Issue 3. Washington, D.C.: CCSDS, May 2010.

[D4] *The Application of CCSDS Protocols to Secure Systems*. Report Concerning Space Data System Standards, CCSDS 350.0-G-2. Green Book. Issue 2. Washington, D.C.: CCSDS, January 2006.

[D5] Catherine L. Thornton and James S. Border. *Radiometric Tracking Techniques for Deep-Space Navigation*. JPL Deep-Space Communications and Navigation Series. Joseph H. Yuen, Series Editor. Hoboken, N.J.: Wiley, 2003.

[D6] *XML Specification for Navigation Data Messages*. Recommendation for Space Data System Standards, CCSDS 505.0-B-1. Blue Book. Issue 1. Washington, D.C.: CCSDS, December 2010.

[D7] Theodore D. Moyer. *Formulation for Observed and Computed Values of Deep Space Network Data Types for Navigation*. JPL Deep-Space Communications and Navigation Series. Joseph H. Yuen, Series Editor. Hoboken, N.J.: Wiley, 2003.

[D8] James S. Border and John A. Koukos. "Technical Characteristics and Accuracy Capabilities of Delta Differential One-Way Ranging (Δ-DOR) as a Spacecraft Navigation Tool." Presented at Meeting of CCSDS Subpanel 1E for Radio Frequency & Modulation Systems, September 20, 1993 (Oberpfaffenhofen, Germany). <http://trs-new.jpl.nasa.gov/dspace/bitstream/2014/35696/1/93-1419.pdf>

[D9] "Delta Differential One-way Ranging." July 15, 2004. Module 210 in *DSN Telecommunications Link Design Handbook*. DSN No. 810-005, Rev. E. Pasadena California: JPL, <http://eis.jpl.nasa.gov/deepspace/dsndocs/810-005/>

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[2] Will provide a detailed description of the Delta-DOR technique, including guidelines for DOR tone spectra, guidelines for selecting reference sources, applicable foundation equations, and a discussion of error sources and measurement accuracy that are not germane to the recommendations proposed in the Magenta Book.

[D10] Timothy McElrath, et al. "Mars Exploration Rovers Orbit Determination Filter Strategy." In *AIAA/AAS Astrodynamics Specialist Conference and Exhibit, August 16-19, 2004 (Providence, Rhode Island)*. Pasadena, CA: JPL, 2004. <http://trs-new.jpl.nasa.gov/dspace/bitstream/2014/39005/1/04-2575.pdf>

[D11] *Time Code Formats*. Recommendation for Space Data System Standards, CCSDS 301.0-B-4. Blue Book. Issue 4. Washington, D.C.: CCSDS, November 2010.

[D12] *Space Communication Cross Support—Service Management—Service Specification*. Recommendation for Space Data System Standards, CCSDS 910.11-B-1. Blue Book. Issue 1. Washington, D.C.: CCSDS, August 2009.