Proposed Recommendation for Space Data System Standards

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

PROPOSED RECOMMENDED STANDARD

CCSDS 506.0-W-2a

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This document is a Recommended Standard for Delta-Differential One Way Ranging (Delta-DOR) and has been prepared by the Consultative Committee for Space Data Systems (CCSDS). The Delta-DOR process described in this Recommended Standard is the baseline concept for Delta-DOR operations that are cross-supported between Agencies of the CCSDS.

This Recommended Standard establishes a common framework and provides a common basis for Delta-DOR operations and the exchange of Delta-DOR data between space agencies. It allows implementing organizations within each Agency to proceed coherently with the development of compatible derived standards for the flight and ground systems that are within their cognizance. Derived Agency standards may implement only a subset of the optional features allowed by the Recommended Standard and may incorporate features not addressed by this Recommended Standard.

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- National Oceanic and Atmospheric Administration (NOAA)/USA.
- National Space Organization (NSPO)/Taiwan.
- Naval Center for Space Technology (NCST)/USA.
- Space and Upper Atmosphere Research Commission (SUPARCO)/Pakistan.
- Swedish Space Corporation (SSC)/Sweden.
- United States Geological Survey (USGS)/USA.
PREFACE

This document is a proposed CCSDS Recommended Standard. Its ‘White Book’ status indicates that its contents are not stable, and several iterations resulting in substantial technical changes are likely to occur before it is considered to be sufficiently mature to be released for review by the CCSDS Agencies.

Implementers are cautioned not to fabricate any final equipment in accordance with this document’s technical content.
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<td>June 2007</td>
<td>Current proposed draft</td>
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<td>8.1 GENERAL</td>
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1 INTRODUCTION

1.1 PURPOSE

This Recommended Standard specifies a set of standard processes and message formats for use in the deep space navigation technique known as Delta Differential One-Way Ranging (Delta-DOR). It has been developed via consensus of the Delta-DOR Special Interest 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 Delta-DOR data at antennas of different agencies, the standardization of service requests for Delta-DOR, and the standardization of data format and delivery will be key enablers for the eventual emergence of interagency execution of Delta-DOR operations.

The Recommended Standard will address aspects of the technique that would 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 will be necessary in order to correlate and process the data at one of the agencies; interagency transfer of the computed observables; and the end-to-end flow of control. It is believed that such standards will reduce development and operations costs while improving deep space 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 definition of the data products, and the third being definition of the method for requesting service and transferring data products. The first of these is allocated to the CCSDS Space Link Service Area (SLS); the second is allocated to the Mission Operations and Information Management Services (MOIMS) Area; 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.

The purpose of the Delta-DOR Working Group is to coordinate the production of a set of CCSDS Recommended Standards for facilitating interagency Delta-DOR operations that can be both useful now and able to evolve to meet future needs. The present document is intended to provide an end-to-end discussion of the Delta-DOR processing that covers all of the required elements and describes how they are combined to provide the desired service.

1.2 SCOPE AND APPLICABILITY

Delta-DOR operations are applicable to space agencies that fly deep space missions and have requirements for accurate determination of the spacecraft position in the plane of sky. For operations where these requirements do not capture the needs of the participating Agencies, Delta-DOR operations may not be appropriate.
This Recommended Standard addresses rationale, requirements and criteria that Delta-DOR operations processes should be designed to meet. In its current iteration, it is both broad and narrow in scope. It is broad to the extent that it is intended to address the entire scope of Delta-DOR operations in an end-to-end fashion. But it is narrow to the extent that it does not delve into many of the technical requirements of Delta-DOR operations. It discusses briefly the areas where standardization seems feasible, and in some cases presents alternatives that must be considered as the full specification evolves. Future iterations of the document will expand upon the concepts listed herein.

1.3 CONVENTIONS AND DEFINITIONS

Conventions and definitions of Delta-DOR concepts are provided in reference [C1] Delta-DOR Operations—Definitions and Conventions. This future reference provides a detailed description of the Delta-DOR technique, including guidelines for DOR tone spectra, guidelines for selecting reference sources, the end-to-end flow, applicable foundation equations, operational considerations, 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 Standard:

- 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 will involve the determination of common interagency terminology and definitions that will apply to interagency Delta-DOR. The following conventions apply throughout this Recommended Standard:

<table>
<thead>
<tr>
<th>Term</th>
<th>Meaning</th>
</tr>
</thead>
<tbody>
<tr>
<td>baseline</td>
<td>the vector joining two tracking stations</td>
</tr>
<tr>
<td>channel</td>
<td>a slice of the frequency spectrum that contains a spacecraft or quasar signal</td>
</tr>
<tr>
<td>scan</td>
<td>an observation of a radio source</td>
</tr>
<tr>
<td>spanned bandwidth</td>
<td>the widest separation between downlink signal components</td>
</tr>
</tbody>
</table>
1.5 STRUCTURE OF THIS DOCUMENT

Section 2 provides a general overview of Delta-DOR techniques.

Section 3 discusses the Service Request Specification.

Section 4 discusses the generation of spacecraft DOR tones.

Section 5 discusses the radio source catalogue.

Section 6 discusses the transfer of raw Delta-DOR observation data.

Section 7 discusses the correlation of the Delta-DOR observation data and the generation of observables.

Section 8 discusses the transfer/exchange of processed Delta-DOR observables.

Section 9 discusses security issues associated with the Delta-DOR processes.

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

Annex B lists a number of items that should be covered in interagency ICDs prior to commencing regular Delta-DOR operations. There are several statements throughout the document that refer to the desirability or necessity of such a document; this annex consolidates all the suggested ICD items in a single list in the document.

Annex C contains a list of informative references.

Annex D contains a number of questions and work items for consideration by the CCSDS Delta-DOR SIG.

1.6 REFERENCES

The following documents contain provisions which, through reference in this text, constitute provisions of this Recommended Standard. At the time of publication, the editions indicated were valid. All documents are subject to revision, and users of this Recommended Standard 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 Recommended Standards.


NOTE – Informative references are provided in annex C.
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 deep space missions where the measurements at two stations of the phases of tones emitted from a spacecraft are differenced and compared against similarly differenced phase measurements of angularly nearby quasar radio signals. This application of VLBI is known as Delta Differential One-Way Ranging (‘Delta-DOR’ or ‘\(\Delta\)DOR’). See figure below. The data produced in such a measurement session is complementary to Doppler and ranging data.

To enable a Delta-DOR measurement, a spacecraft must emit several tones. 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 deep space tracking.

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 to nine ‘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 or quasar-spacecraft-quasar, depending on the characteristics of the radio sources and the objectives of the measurement session. A minimum of three scans are 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 measuring 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 locally at each 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. Differential One-way Range (DOR) observables are formed by subtracting the one-way range measurements generated at the two stations. The station differencing eliminates the effect of the spacecraft clock offset, but DOR measurements are biased by ground station clock offsets and instrumental delays.

For measuring the quasar, each station is configured to acquire data from the quasar 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 which 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 ‘Delta’ between spacecraft and quasar observations is generated internal to the navigation processing.

Because each Delta-DOR measurement requires the use of two antennas, and navigation accuracy is improved by baseline diversity, this technique may be 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 NASA, ESA, and JAXA today could provide two pairs of orthogonal baselines and good geometric coverage for missions throughout the ecliptic plane. Stations from different agencies can be used as Delta-DOR data collectors for deep space 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, including Voyager, Vega, Magellan, Ulysses, Mars Observer, Galileo, Nozomi, Mars 2001 Odyssey, Mars Exploration Rovers, Muses-C, Mars Express, Deep Impact, Venus Express, and the Mars Reconnaissance Orbiter. The technique is planned for missions such as Phoenix (NASA), Mars Science Laboratory (NASA), Rosetta (ESA), and Bepi-Colombo (ESA); and it seems reasonably likely that its use will become a standard part of many mission navigation plans. It is anticipated that 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 compared to long arcs of 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 ‘Mars B-Plane’ below from Mars Exploration Rover data, reference [C2]. ‘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.
2.4 DISADVANTAGES OF DELTA-DOR

There are also some disadvantages of using Delta-DOR measurements, which include:

- 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.

2.5 ORGANIZATION OF STANDARD, INTERAGENCY DELTA-DOR

There are many conceivable ways of organizing a set of standards for interagency Delta-DOR operation. This document provides a starting point for potential items to be
standardized by the CCSDS as they relate to Delta-DOR activities. Delta-DOR operations requirements must address functionality, processes, contents, and implementation approach for interoperability, and must prioritize which elements need to be addressed in the developed Recommended Standards.

2.6 HIGH LEVEL DELTA-DOR DATA FLOW

The High Level Delta-DOR Data Flow below shows various points (numbered ‘1’ through ‘7’) where standardization would be beneficial in terms of establishing interoperability. The actual set of attributes which must be negotiated for inclusion in the Recommended Standards may be greater or lesser in number, at the discretion of the Working Group(s). In general, the Recommended Standard considers the necessary parameters at each stage of the data flow, including the formats of parameters, structure/substructure of the files, data block format (especially for the binary data), ordering requirements of the data (sort order), and transmission mechanisms.

![High Level Delta-DOR Flow Diagram]

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<tr>
<th>Interface</th>
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<th>Priority</th>
<th>Availability</th>
<th>Covered by</th>
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<td>Service Request</td>
<td>Medium</td>
<td>Long Term</td>
<td>TBD, to include schedule, orbit predict, receiver setup</td>
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<td>2</td>
<td>DOR Tones</td>
<td>High</td>
<td>Available</td>
<td>Covered by existing standard, CCSDS 401.0-B (2.5.6B)</td>
<td>SLS Ranging WG</td>
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<tr>
<td>3</td>
<td>Quasar Catalogue</td>
<td>Medium</td>
<td>Available</td>
<td>Available in the open literature</td>
<td>DDOR SIG</td>
</tr>
<tr>
<td>4</td>
<td>Raw Data</td>
<td>Low</td>
<td>Medium Term</td>
<td>As provided by existing hardware</td>
<td>DDOR SIG</td>
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<tr>
<td>5</td>
<td>Service to TransferData</td>
<td>Medium</td>
<td>Long Term</td>
<td>TBD, to include Raw Data, ODM, Reduced Data</td>
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<td>Available</td>
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<td>MOIMS NAV WG</td>
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<td>7</td>
<td>Reduced Data</td>
<td>High</td>
<td>Near Term</td>
<td>NAV TDM Standard (draft Red Book)</td>
<td>MOIMS NAV WG</td>
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Figure 2-1: High Level Delta-DOR Flow
### 2.7 POSSIBLE INTERAGENCY DELTA-DOR SCENARIOS

The following represent some possible interagency Delta-DOR scenarios. The notation A1=Agency 1, A2=Agency 2, etc., is used. Note that only the first of these is currently possible without some level of standardization.

<table>
<thead>
<tr>
<th>Scenario</th>
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<th>Data Correlation</th>
<th>Data Usage</th>
<th>Interfaces To Be Agreed</th>
<th>Status</th>
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</thead>
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<td>1.</td>
<td>A1</td>
<td>A1</td>
<td>A2</td>
<td>1, 2, 3, 6, 7</td>
<td>JPL to ESA in use today; ESA to JPL to be tested</td>
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<td>2.</td>
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<td>A2</td>
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<td>A2</td>
<td>1, 2, 3, 4, 5</td>
<td>Requires standardization of raw data exchange</td>
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<td>A1 &amp; A2</td>
<td>A3</td>
<td>A3</td>
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<td>5.</td>
<td>A1 &amp; A2</td>
<td>A2</td>
<td>A3</td>
<td>1, 2, 3, 4, 5, 6, 7</td>
<td>Requires standardization of raw data exchange, observable exchange</td>
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<td>A1</td>
<td>A2</td>
<td>A3</td>
<td>1, 2, 3, 4, 5, 6, 7</td>
<td>Requires standardization of raw data exchange, observable exchange</td>
</tr>
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</table>
3 SERVICE REQUEST SPECIFICATION

3.1 GENERAL

The Service Request is shown in figure 2-1 as ‘Interface 1’. Defining the required service parameters for a Delta-DOR session is the first step in the process. In order to initiate an interagency Delta-DOR measurement session, the details of the measurement session must be conveyed to the participating agencies. There will need to be a Delta-DOR service request extension to the existing SLE Service Management/Service Request structure (reference [1]).

3.2 CONFIGURATION INFORMATION FOR DELTA-DOR SCHEDULING

3.2.1 At the very minimum, there will need to be an exchange of information about

a) configuration and schedule parameters for the data collection session between the two agencies;

b) the predicted spacecraft orbit; and

c) the DOR tone spectrum.

3.2.2 The information to be provided as part of Interface 1 should include at least:

a) configuration and scheduling:
   – stations;
   – receiver configuration including channel setup for recording:
     • number of channels,
     • channel center frequency,
     • channel sampling rate,
     • sample quantization levels;
   – for each measurement scan:
     • source ID (e.g., spacecraft number or quasar name),
     • recording start and stop time;

b) orbital information:
   – ODM (Interface 6) to be used for antenna pointing predicts, frequency predicts, and correlation processing (reference [2]);

c) spacecraft signal spectrum:
   – nominal spacecraft carrier and DOR tone frequencies;
   – nominal spacecraft carrier and DOR tone signal power.
3.2.3 The content and format of the information needed for a Delta-DOR service request should be agreed upon and then it will be proposed to include any missing information in a revision of reference [1].

3.2.4 If data collection occurs using assets of Agency 1, for a spacecraft of Agency 2 (Scenario 1 in 2.7), then less information is required to be exchanged between agencies. As an example, cross support for this case could be accommodated as follows:

- The two agencies agree on a nominal schedule for observations, e.g., two measurements per week for six months.
- The second agency provides information about the spacecraft downlink signal (spectral components, signal power), for the spacecraft configuration that will be used for DOR measurements, to the first agency.
- The second agency provides an ODM (Interface 6) to be used for antenna pointing predicts, frequency predicts, and correlation processing.
- The first agency schedules specific stations and times for the measurements, selects radio sources, and confirms the times and sources with the second agency.
- The second agency has the spacecraft configured for DOR downlink at the scheduled times.
- The first agency selects the scan sequence, generates predicts, configures the receiver, makes the observation, correlates the data, and provides reduced data (TDM, Interface 7) to the second agency.

3.2.5 If data collection and/or correlation processing occurs using assets of multiple agencies (Scenario 2, 3, 4, 5, or 6 in 2.7), then the more comprehensive set of standards, as proposed in 2.6, to define the Delta-DOR service will be needed. A service request should then include the full information identified in 3.2.

3.2.6 As an example, suppose that assets of Agencies 1 and 2 are used to acquire Delta-DOR data for a spacecraft of Agency 2, and that the correlation processing will be done by Agency 2 (Scenario 3 in 2.7). Cross support for this case could be accommodated as follows:

- The two agencies agree on a nominal schedule for observations, e.g., two measurements per week for six months.
- The second agency provides information about the spacecraft downlink signal (spectral components, signal power), for the spacecraft configuration that will be used for DOR measurements, to the first agency.
- The second agency provides an ODM (Interface 6) to be used for antenna pointing predicts, frequency predicts, and correlation processing.
- The two agencies agree on compatible settings for the data acquisition hardware to be used.
– The two agencies agree upon and schedule specific stations and times for the measurements.

– The two agencies agree on radio sources and the measurement scan sequence.

– The second agency has the spacecraft configured for DOR downlink at the scheduled times.

– Each agency generates predicts, configures its station receiver, and makes the observation.

– Raw data are transferred from each station to the correlator facility of Agency 2.

– Agency 2 uses a data translator to convert the format of raw data received from Agency 1 into the data format expected by the correlator.

– Agency 2 correlates the data and makes use of the reduced data.
4 TRANSPONDER AND GROUND STATION SPECIFICATION

4.1 GENERAL

Spacecraft DOR tones are shown as ‘Interface 2’ in figure 2-1 above. Reference [3], CCSDS 401.0-B (2.5.6B), addresses the factors associated with the generation and detection of spacecraft DOR tones. Thus a separate DOR tones specification is not necessary. However, for interoperability, agencies will need to identify the specific modulation format, DOR tone frequencies, and power levels selected for each spacecraft in an ICD or memorandum of understanding.

4.2 GENERATION/DETECTION OF DOR TONES

4.2.1 GENERAL

As noted previously, a spacecraft transponder must emit several tones (referred to as DOR tones) spanning some bandwidth to enable a DOR measurement. CCSDS document 401.0-B (2.5.6B), listed as reference [3], describes the DOR tones, characterizes the spacecraft generation of the tones, and discusses how they may be detected/received at the ground stations. Specifications for the spacecraft transponder and for ground station receivers must be consistent with the DOR tone standards in order to enable Delta-DOR measurements. It should be noted that DOR tones do not need to be at one exact frequency. Rather, a range of frequencies could be used to provide a Delta-DOR capability over a range of performance values. A general description of DOR tones is presented here, along with considerations that factor into design choices. The description given here helps explain the specification given in reference [3]. Equations to support the general statements given here on performance trade-offs are provided in reference [C1].

4.2.2 DOR TONE DESIGN CONSIDERATIONS

Factors considered in design trade-offs for DOR tones include:

- Mission navigation accuracy requirements: Missions requiring more accuracy would tend toward use of higher frequency bands and wider spanned bandwidths for DOR tones. The higher frequency band, say Ka-band rather than X-band, reduces the effects of charged particles on the measurement. Several of the key Delta-DOR error sources scale inversely with spanned bandwidth, so an overall improvement in performance is obtained by increasing the spanned bandwidth.

- Waveform and modulation type: The DOR tones are generated by modulating a sine wave or square wave subcarrier onto the downlink carrier. The subcarrier waveform may itself either be modulated or unmodulated. An unmodulated subcarrier, in common use today, results in a spectrum of sinusoidal signals that are used for the Delta-DOR measurement. During a measurement session, receivers are configured to record frequency channels centered on the received DOR tones. The same frequency channels must be used for both the spacecraft and quasar in order for the quasar
measurement to provide a calibration of instrumental delay for the spacecraft measurement. The frequency channels must be wide, on the order of 2 MHz, to detect the weak signals from natural radio sources. When the spacecraft signal is narrow bandwidth the instrumental delay experienced by the spacecraft signal will not be identical to the instrumental delay experienced by the broadband quasar signal. The spacecraft sees the phase delay at one discrete frequency near the channel center while the quasar sees the average phase delay over the full channel bandwidth. This instrumental delay difference is one of the dominant measurement errors for Delta-DOR. This error source could be reduced, or nearly eliminated, if the subcarrier were modulated by a pseudo noise code that effectively spreads the spacecraft signal power over the full channel bandwidth used for recording the quasar signal.\(^1\) In this case, instrumental effects on the two signal paths would be more nearly equal.

- **Modulation parameters:** Sine waves are normally used in multi-tone systems based on efficiency considerations. Modulation options include: use of two sinusoidal waveforms phase modulated on the downlink carrier signal, one square wave phase modulated on the downlink carrier, and choice of modulation indices. When multiple tones are provided, relatively more power is preferred in the outermost tones, since these are used to develop the final observable.

- **Support for legacy missions:** At present, both telemetry sidebands and uplink range codes have been used to enable Delta-DOR measurements on spacecraft without dedicated DOR tone modulation. While these signals may be used, they generally provide less spanned bandwidth than DOR tones, and hence provide poorer performance. Delta-DOR measurement accuracy scales linearly with inverse spanned bandwidth for bandwidths below 10 to 20 MHz.

- **Supported downlink band and frequency:** The DOR tones may be at S-band (2290-2300 MHz), X-band (8400-8450 MHz), or Ka-band (31.8-32.3 GHz and 37.0-38.0 GHz). Charged particle effects in delay measurements scale as one over frequency squared, so the higher RF bands provide better accuracy when other factors are the same. Further, more spanned bandwidth has been allocated for deep space tracking at the higher RF bands. The higher bands can provide better accuracy by selecting a DOR tone frequency up to the available spectrum allocation. Note that there is no need to extend this technique to Category A missions (‘Near Earth’) or L2 or lunar missions. The Delta-DOR technique is of benefit to deep space missions.

- **Tone power to noise spectral density ratios:** The SNR influences measurement accuracy. There is a trade-off between SNR and the duration of the spacecraft scan (‘observation scan length’)

- **Bandwidth span:** The frequency separation between the two outermost DOR tones is referred to as the spanned bandwidth of the spacecraft signal. Generally, a narrow spanned bandwidth is needed for integer cycle ambiguity resolution based on a priori

\(^1\) The use of a modulated subcarrier for generation of DOR signals is not presently covered in reference [3].
knowledge of spacecraft angular position, while a wide spanned bandwidth is needed for high measurement accuracy.

NOTE – The same bandwidth span is used for both the spacecraft and the quasar to ensure instrumental error cancellation.

The bandwidth span is a very important factor in terms of controlling errors due to spacecraft SNR, quasar SNR, and instrumental phase ripple, as these errors scale inversely with spanned bandwidth.

– Number of DOR tones (one, two, or three): This is partially determined by the band of the DOR tones. To provide higher performance (i.e., a wider spanned bandwidth with more power in the outer tones), while still providing a spanned bandwidth narrow enough for integer cycle ambiguity resolution, more DOR tones are needed. But if a transponder also has capability to generate a telemetry subcarrier, then it is usually possible to use telemetry sidebands for ambiguity resolution, removing the need for low frequency DOR tones.

– Tone frequencies: There is a trade-off between
  a) choosing the widest possible bandwidth for improved measurement accuracy
  b) placing the signal within the band allocated for deep space tracking, and
  c) keeping the spectrum compact to avoid interference from or to other users.

Historically, 19 MHz has been used as the DOR tone frequency at X-band, and this sets a limit on the Delta-DOR measurement accuracy that can be achieved. The wider bandwidth allocation at Ka-band allows for the possibility of improved accuracy. But a higher frequency DOR tone would be needed to realize improved accuracy. Surveys indicate that natural radio sources have correlated flux, over longer baselines, that is typically reduced by a factor of two to three from the X-band flux. There are sources with different spectral types and exceptions, but the typical behavior is relevant for support of navigation that requires a large catalogue of quasars. Further, ground receivers have system noise temperatures that are about a factor of two higher at Ka-band when compared to X-band. The combination of these two effects implies, for the same DOR tone frequency, that the error due to system noise on the quasar measurement would be about five times higher at Ka-band as compared to X-band. Since this is typically one of the dominant Delta-DOR errors, overall Delta-DOR performance would degrade by this factor. To recover the same performance at Ka-band as for X-band, one could increase the DOR tone frequency by a factor of four and also increase the channel sample rate by a factor of two. The combination of these two effects would reduce the system noise error on the quasar measurement by a factor of 5.7, providing just slightly better performance at Ka-band than X-band. But to realize substantially better performance at Ka-band, it would be necessary to increase the DOR tone frequency further.
– Coherency: The DOR tones may be a coherent submultiple of the downlink carrier, or they may be generated from an independent oscillator onboard the spacecraft. Either method provides comparable performance when DOR tone SNR is high enough for standalone tracking, say 10 dB•Hz or greater. If the DOR tone is weaker than this, and if carrier aiding is used to detect the DOR tones, then performance is better if the DOR tone is coherent with the carrier. There is no advantage in having the downlink carrier coherent with an uplink signal as long as the one-way downlink carrier can itself be detected and tracked.

4.2.3 GROUND STATION RECEIVER DESIGN CONSIDERATIONS

Factors that could be considered in design trade-offs for ground station receivers and recorders include:

– Hardware compatibility: A standard set of nominal sample rates and quantization levels should be agreed to. However, it is likely that each agency will develop its own hardware for receiving and recording the signals from spacecraft and quasars. It will be necessary for each station to offer the option of recording in channels at or near the same frequency locations and at or near a standard sample rate. Given this, it would be possible to convert data files recorded by one agency into the format of data files recorded by the other agency.

– Configuration flexibility: The specific tracking scenarios that will be supported (e.g., single spacecraft in cruise, spacecraft-spacecraft, orbiter-orbiter, lander-rover, etc.) have implications for the number of frequency channels and the functionality of prediction generation that will be needed.

– Precision and accuracy: The precision of a spacecraft DOR measurement depends on the received tone power to noise power ratio and on the spanned bandwidth of the DOR tones. But the accuracy of a Delta-DOR measurement also depends on the precision of the quasar delay measurement, on knowledge of the quasar position, on clock stability, on instrumental phase response, and on uncertainties in earth platform models and transmission media delays. Requirements or guidelines for interagency Delta-DOR accuracy and precision should be specified in an ICD or memorandum of understanding. Then, a strategy to provide the required accuracy for model parameters (quasar coordinate, station location, transmission media delay, earth orientation) should be developed.

– Requirements for receivers: Specification of the receiver performance characteristics will be required (e.g., linearity of the phase-frequency response over each frequency channel, center frequency, sample rate, number of bits per sample, number of frequency channels, etc.). Several levels of instrumental performance could be specified that would correspond to different levels of Delta-DOR accuracy.
– Instrumental delay: The instrumental delay must be kept the same over the duration of the measurement session, and the same for both spacecraft and quasar, within the limits imposed by variations in analog components. If different channel sampling rates are used for the spacecraft and the quasar, then the filter delay should be compensated so that both spacecraft and quasar will experience the same signal delay.
5 RADIO SOURCE CATALOGUE SPECIFICATION

Natural radio source (quasar) input is shown as ‘Interface 3’ in figure 2-1 above. There is no current CCSDS Standard Radio Source Catalogue. It will be necessary to select a standardized catalogue of radio sources in order to perform interagency Delta-DOR effectively. This will facilitate consistency in radio source selection, pointing, and correlating. There are a number of factors to consider when specifying a catalogue.

– The radio source catalogue shall be freely available.

– The standard quasar catalogue should be an existing catalogue such as the Sloan Digital Sky Survey Quasar Catalogue (SDSS), International Celestial Reference Frame (ICRF), JPL Radio Source catalogue (optimized for DSN Delta-DOR) published in JPL Document 810-005, Large Bright Quasar Survey (LBQS), or other mutually agreed catalogue of radio sources.

– A separate catalogue shall be designated for each radio band to be observed.

– The radio source catalogue shall contain a name identifier for each radio source.

– The radio source catalogue shall contain direction coordinates and formal coordinate error for each radio source.

NOTE – The radio source catalogue should include flux information and structure information. Flux and structure information are not readily available or up-to-date for all sources and all radio bands.

– The CCSDS recognized quasar catalogue may be packaged as a separate Recommended Standard (Blue Book), or Informational Report (Green Book), or simply an agreement to adopt an external standard specification without modification.

– For any given Delta-DOR measurement session, the participating agencies shall agree on a common definition of the radio sources that will be used.

– The radio source catalogue for X-band shall be updated on a regular basis, as new data on radio sources are available.

– A radio source catalogue shall be developed for Ka-band.
6 RAW DATA TRANSFER/EXCHANGE SPECIFICATION

6.1 GENERAL

Raw data exchanges are shown as ‘Interface 4’ and ‘Interface 5’ in figure 2-1 above. There is no current CCSDS Recommended Standard for raw Delta-DOR data exchange. For an interagency Delta-DOR session, it will be necessary to transfer at least half of the raw data, and perhaps all of the raw data, from the collection sites to the processing site. The processing site may be located at another agency. In order to exchange raw Delta-DOR measurement data, there must be specifications relating to a number of operational parameters.

6.2 RAW DELTA-DOR MEASUREMENT DATA EXCHANGE

6.2.1 When antennas of two agencies are used in a Delta-DOR recording session, transfer of the raw data from both sites to the chosen correlator facility is necessary. When different hardware are used by two agencies, the sampling format for raw data may not be identical. However, if similar channel placement and sampling rates are used, then it would be possible to re-sample one data stream to make it fully compatible with the second stream. Raw data could be transferred as is and then re-sampling could be done as needed at the correlator facility. This is one approach to achieve interagency compatibility at the raw data level. Alternatively, a standard format for raw data could be defined. Each agency would take the responsibility to convert data from its own internal format into the standard format. In this case each correlator facility would need to be able to process data files in the standard format.

6.2.2 For raw data exchange, each agency will need to provide an Interface Control Document (ICD) that completely describes the content and format of their raw data. The data file (or files) must contain ancillary information to describe the recording session completely, as well as the primitive samples of the spacecraft and quasar signals. Based on the ICD’s, software translators may be developed to read, re-sample, and re-format the data files received from one agency into the format of another agency. The responsibility will rest at the correlator facility to run the software translators, as necessary. Once the translation has been completed, standard correlation processing should be routine.

6.2.3 The information to be transferred as part of the ‘raw data file’ should include the following:

- station ID;
- for each scan:
  - source ID;
  - start time;
  - stop time;
– for each spacecraft scan:
  • if signal is derived from onboard oscillator:
    nominal carrier frequency;
  • if signal is coherent with an uplink:
    a) ID of uplink station;
    b) time history of uplink frequency;
    c) spacecraft transponder turnaround ratio;
– for each frequency channel:
  • flag to indicate whether DOR tone is coherent with downlink carrier or derived
    from an independent oscillator;
  • nominal DOR tone offset (e.g., submultiple factor of carrier or subcarrier
    frequency and harmonic number);
  • data samples and time-tags;
  • downconverter frequency;
  • sampling rate;
  • number of bits per sample;
  • type of samples (e.g., real Upper Sideband (USB) or real Lower Sideband (LSB)
    or complex in-phase and quadrature phase (I/Q);
  • flag to indicate whether the downconversion was at a fixed frequency or driven by
    predicts:
    if driven by predicts, then need the downconverter model phase for the center
    of each data frame.

6.3 DATA TRANSFER REQUIREMENTS

6.3.1 A method for transfer of a large volume of data will be needed to support raw data
exchange. Historically, VLBI experimenters have exchanged data by shipping tapes from
one site to another. But measurement systems developed for Delta-DOR have relied on
electronic file transfer. Data lines such as an internet connection are needed from each
station to the correlator facility. Because of the large data volume expected, indirect routes
such as first transferring the data to one location and then to the correlator, should be
avoided. The necessary transfer rate that must be provided will depend on the data volume
and the allowed latency for delivery of the data.
6.3.2 As an example, 12 Gbytes of data may be transferred in 9 hours at a rate of 3 Mbits/sec. This typical data volume and latency can be supported by two T1 lines.

6.3.3 For each measurement session, the required data volume and the required latency should be specified.

6.3.4 A data path and overall strategy will need to be developed, to make data available outside the firewall of each agency, and between the tracking stations and the correlator facilities.
7 DATA CORRELATION & OBSERVABLES GENERATION SPECIFICATION

7.1 GENERAL

7.1.1 Data correlation is performed at a central processing location, as shown in figure 2-1. Time delay observables, as discussed in a general way in 2.2, are derived from the correlator output. Conventions must be followed so that the navigation observables derived from the correlator output are consistent with the definitions of observables as given in reference [4].

7.1.2 As well as producing observed time delays (the DOR observable), the data processing also provides the observed change in time delay over the scan duration. This observable is based on change in phase delay rather than group delay. It is generally referred to as a VLBI phase delay rate observable, but in the case of spacecraft tracking it is often referred to as a Differential One-way Doppler (DOD) observable. Similar to ΔDOR terminology, the ΔDOD observable is the difference between delay-rate measurements of the spacecraft and quasar. The ΔDOD observable is far less sensitive to angular position than ΔDOR, but it can be useful since, for a single baseline, it provides sensitivity to angular position in the component normal to that provided by ΔDOR over the same baseline, and the measurement is unambiguous.

7.1.3 Models for measurement geometry and signal path delay are used during processing. The correlation process always needs the spacecraft ephemeris or quasar catalogue, the station locations, and the spacecraft Doppler mode (one-, two-, or three-way). For one-way mode a nominal value is needed for the spacecraft downlink carrier frequency. In the case that the DOR tones are coherent with an uplinked signal, the uplink frequency history and frequency rate history are required for use in constructing the frequency models used in the VLBI correlation process. Nominal values are also needed for earth orientation (UT1 and polar motion), for transmission media delays, and for inter-station clock offsets. Note that the spacecraft ephemeris is provided via the Orbit Data Message (ODM) ('Interface 6' in figure 2-1). The ancillary information provided in the Raw Data Transfer/Exchange specification ('Interface 4 and 5' in figure 2-1) is also used in the processing. The reduced data are provided via the Tracking Data Message (TDM) ('Interface 7' in figure 2-1).

7.2 DELTA-DOR MEASUREMENT ACCURACY

To estimate Delta-DOR measurement accuracy, there are a number of quantities that must be made available to the agency performing the correlation. Equations providing sensitivity of measured delay to factors that effect the measurement geometry or path delay are published in the Green Book. For example, the predicted Delta-DOR measurement accuracy can be computed as the RSS of terms derived from the following factors:

- observation geometry (e.g., spacecraft and quasar elevation angles, spacecraft-quasar separation angle, baseline projection, scan sequence and duration);
- signal radio frequency;
- signal spanned bandwidth;
– spacecraft DOR tone SNR (or spacecraft delay measurement error);
– quasar SNR (or quasar delay measurement error);
– uncertainty in the quasar position coordinates;
– clock instability;
– instrumental phase ripple;
– uncertainty in station location coordinates;
– uncertainty in the orientation of the earth in inertial space;
– uncertainty in the zenith tropospheric delay;
– uncertainty in the ionospheric delay;
– solar plasma error (or signal frequencies, sun-radio source angles, and solar wind velocity).
8 OBSERVABLE TRANSFER/EXCHANGE SPECIFICATION

8.1 GENERAL

Observable data exchanges are shown as ‘Interface 7’ in figure 2-1 above. Once the raw data has been collected, transferred, and correlated, the Delta-DOR observables are delivered to the spacecraft navigation team for second differencing and use in the process of orbit determination.

8.2 DELTA-DOR OBSERVABLE EXCHANGE

8.2.1 It may be necessary to transfer the Delta-DOR observables from one agency to another, depending on the association of the processing agency with respect to the agency or location of the Navigation Team. The Tracking Data Message (TDM) specification, currently a CCSDS Red Book (reference [5]), is designed to transfer the Delta-DOR observables. There will be a need to transfer at least the following items:

– identification of the applicable participants in the Delta-DOR session: spacecraft, quasar, the two downlink ground antennas, and uplink antenna;
– data time-tags and DOR/DOD observables;
– uplink and downlink frequency bands;
– reference frequencies;
– tracking mode (one-way, two-way, three-way);
– clock bias/offsets;
– delays associated with antenna architecture, arraying configuration, etc.;
– media delay calibrations;
– data quality / data correction indicators;
– compression times for differenced Doppler.

8.2.2 The means of data transfer should be agreed by the specific exchange participants and documented in the ICD.
9 SECURITY

9.1 INTRODUCTION

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

9.2 SECURITY CONCERNS WITH RESPECT TO THIS RECOMMENDED STANDARD

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

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

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

9.2.4 Data Transfer Between Communicating Entities: The transfer of data formatted in compliance with this Recommended Standard between communicating entities should be accomplished via secure mechanisms approved by the IT Security functionaries of exchange participants.

9.2.5 Control of Access to Resources: This Recommended Standard assumes that control of access to resources will be managed by the systems upon which provider formatting and recipient processing are performed.

9.3 POTENTIAL THREATS AND ATTACK SCENARIOS

There are no known potential threats or attack scenarios that apply specifically to the technologies specified in this Recommended Standard. Potential threats or attack scenarios applicable to the systems and networks on which this Recommended Standard 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 Standard.
9.4 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 Standard. The consequences of not applying security to the systems and networks on which this Recommended Standard is implemented could include potential loss, corruption, and theft of data.

9.5 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 Standard should be specified in an ICD.
ANNEX A

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.

- **ASCII** - American Standard Code for Information Interchange
- **CCSDS** - Consultative Committee for Space Data Systems
- **CSS** - Cross Support Services
- **Delta-DOR** - delta differential one-way range
- **DOD** - differential one-way Doppler
- **DOR** - differential one-way range
- **DSN** - Deep Space Network
- **ESA** - European Space Agency
- **Hz** - Hertz
- **ICRF** - International Celestial Reference Frame
- **ID** - identifier
- **JAXA** - Japan Aerospace Exploration Agency
- **JPL** - Jet Propulsion Laboratory
- **LBQS** - Large, Bright Quasar Survey
- **LSB** - Lower Sideband
- **MOIMS** - Mission Operations and Information Management Services
- **NASA** - National Aeronautics and Space Administration
- **QSQ** - Quasar-Spacecraft-Quasar
- **RF** - radio frequency
- **SDSS** - Sloan Digital Sky Survey
- **SLE** - Space Link Extensions
- **SLS** - Space Link Services
- **SNR** - signal-to-noise ratio
- **SQS** - Spacecraft-Quasar-Spacecraft
- **TDM** - Tracking Data Message (CCSDS)
- **VLBI** - very-long-baseline interferometry
ANNEX B

ITEMS FOR AN INTERFACE CONTROL DOCUMENT

(INFORMATIVE)

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

It might be feasible for participating agencies to have a generic baseline ICD (‘standard service provider ICD’) 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 ICDs could be used for the mission/spacecraft specific arrangements.

The following table lists the items that should be covered in an ICD, along with where they are discussed in the text:

<table>
<thead>
<tr>
<th>Item</th>
<th>Section</th>
</tr>
</thead>
<tbody>
<tr>
<td>1. Spacecraft downlink signal structure and nominal frequency</td>
<td></td>
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<tr>
<td>2. Delta-DOR observable accuracy</td>
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<tr>
<td>3. Delta-DOR data delivery time</td>
<td></td>
</tr>
<tr>
<td>4. Specific modulation format, DOR tone frequencies, and power levels selected for each spacecraft</td>
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</tr>
<tr>
<td>5. For raw data exchange, each agency will need to provide an Interface Control Document (ICD) that completely describes the content and format of their raw data.</td>
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</tr>
<tr>
<td>6. Transfer protocols</td>
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</tr>
<tr>
<td>7. Specific information-security interoperability provisions that may apply between agencies involved in an exchange</td>
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<tr>
<td>8.</td>
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ANNEX C

INFORMATIVE REFERENCES

(INFORMATIVE)

NOTE – Normative references are provided in 1.6.


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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, the end-to-end flow, applicable foundation equations, operational considerations, and a discussion of error sources and measurement accuracy that are not germane to the standards proposed in the White Book.
ANNEX D

WORKING GROUP ITEMS

(TO BE DELETED)

1. Should the Green Book be the first book produced by the SIG?

2. Messages in XML format or ASCII text?

3. Question: should the catalogue of natural radio sources be called a ‘quasar catalogue’ or ‘radio source catalogue’? Usage should probably be consistent throughout.

4. Define common terminology in Green Book instead of the Operations Standard?

5. Suggested interface layout (see below)

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<th>Format</th>
<th>Units/Precision</th>
<th>Range</th>
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