CCSDS Concept Paper: Delta-DOR

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Abstract

This Concept Paper proposes the development of Consultative Committee for Space Data Systems (CCSDS) standards for the deep space navigation technique known as "delta-DOR" (Delta Differential One-Way Ranging). Delta-DOR is a VLBI technique that can be used to improve spacecraft navigation by more efficiently determining spacecraft angular position in the plane of sky. The proposed Recommendations 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 raw measurement data; parameters that will be necessary in order to correlate and process the data at one of the agencies; and interagency transfer of the computed observables. A recommendation as to how the proposed work might be allocated to the CCSDS Areas is offered.

Contents

Introduction

This document is a Concept Paper for the Consultative Committee for Space Data Systems (CCSDS). CCSDS Concept Papers are working documents of the CCSDS, its Areas, and its Working Groups. They have no official status, and are simply the vehicle by which technical suggestions are made visible to the CCSDS. They are valid for a maximum of nine months and may be updated, replaced, or rendered obsolete by other documents at any time. This Concept Paper is intended for presentation at the upcoming CCSDS Fall Meetings which are to be held 09/12/2005 through 09/16/2005 in Atlanta, Georgia, USA.

Specifically, this concept paper will argue that development of CCSDS standard(s) is desirable for interagency execution of the deep space navigation technique known as "delta-DOR", or Delta Differential One-Way Ranging. The paper will discuss what could be standardized, who the users of such a standard might be, and then makes a recommendation as to how the proposed work might be allocated to the CCSDS Areas. The paper does not dwell on the technical particulars, nor does it seek to justify in detail the benefits of using delta-DOR. Rather, the benefits are briefly discussed but largely assumed in this paper based on the detailed exposition in Reference 2 and Reference 3.

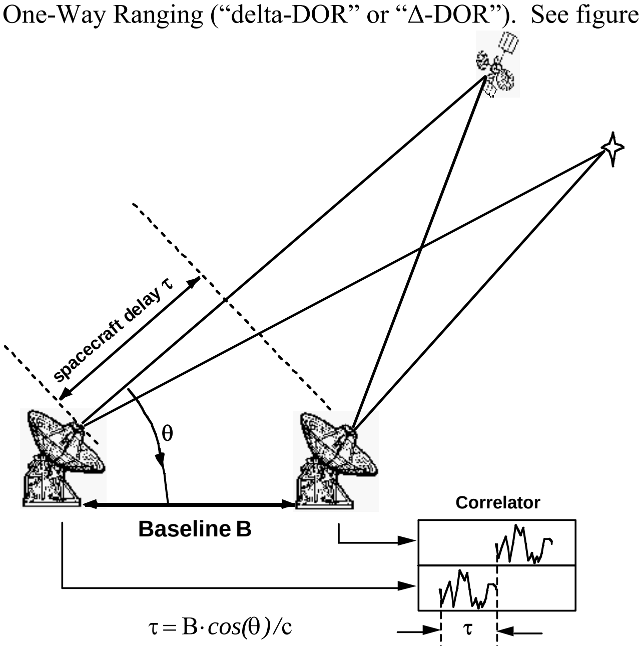
There are essentially two parts to providing such services, one being the definition of the RF domain signals and reception, the second being definition of the ground processing and data exchange. The first of these is best done in a Working Group within the CCSDS Space Link Service Area (SLS), the second is best done within a Working Group in the Mission Operations and Information Management Services (MOIMS) Area. There is a need for future work to develop SLE Service Request extensions which will naturally be done in the Service Management Working Group within the Cross Support Services (CSS) Area.

The technical aspects of the delta-DOR technique will need to be discussed and agreed to by the Working Group(s) that actually create the Recommendations, assuming the CESG elects to proceed with the chartering process.

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 “Δ-DOR”). See figure below.



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 technique requires that the same quasar and spacecraft be tracked essentially simultaneously during the same tracking pass. Thus, an “overlap” between the 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 "scans" of data recording, each of a few minutes duration. A “scan” consists of pointing the antenna to one radio source, slewing to the second source, and back to the first source. 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 delta-DOR observable is generated from one-way range measurements 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; this eliminates linear temporal errors. The observed quantity in a delta-DOR observation is time delay.

For a spacecraft, the one-way range is determined locally at each station by extracting the phases of two or more tones emitted by the spacecraft. The DOR tones are generated by modulating a pure sine wave or pure square wave onto the downlink carrier at S-band, X-band, or Ka-band. 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.

To generate the delta-DOR observable, the quasar delay observable and the spacecraft range DOR observable are differenced (the quasar delay is subtracted from the spacecraft DOR).

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. 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, Magellan, Vega, Mars Observer, Galileo, Mars Exploration Rovers, Muses-C, Mars Express, and Deep Impact. The technique is planned for missions such as Venus Express (ESA); Mars Reconnaissance Orbiter, Phoenix, and Mars Science Laboratory (NASA); and it seems reasonably likely that its use will become a standard part of many mission navigation plans. CCSDS standardization could help expand the use of the technique by allowing interagency cross-supports (e.g., JAXA spacecraft with NASA/ESA baseline), and by the addition of new baselines (ESA southern hemisphere ground stations, JAXA ground stations, etc.).

Advantages/Disadvantages of Delta-DOR

Earth-based radio metric tracking is the primary source of navigational data 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.

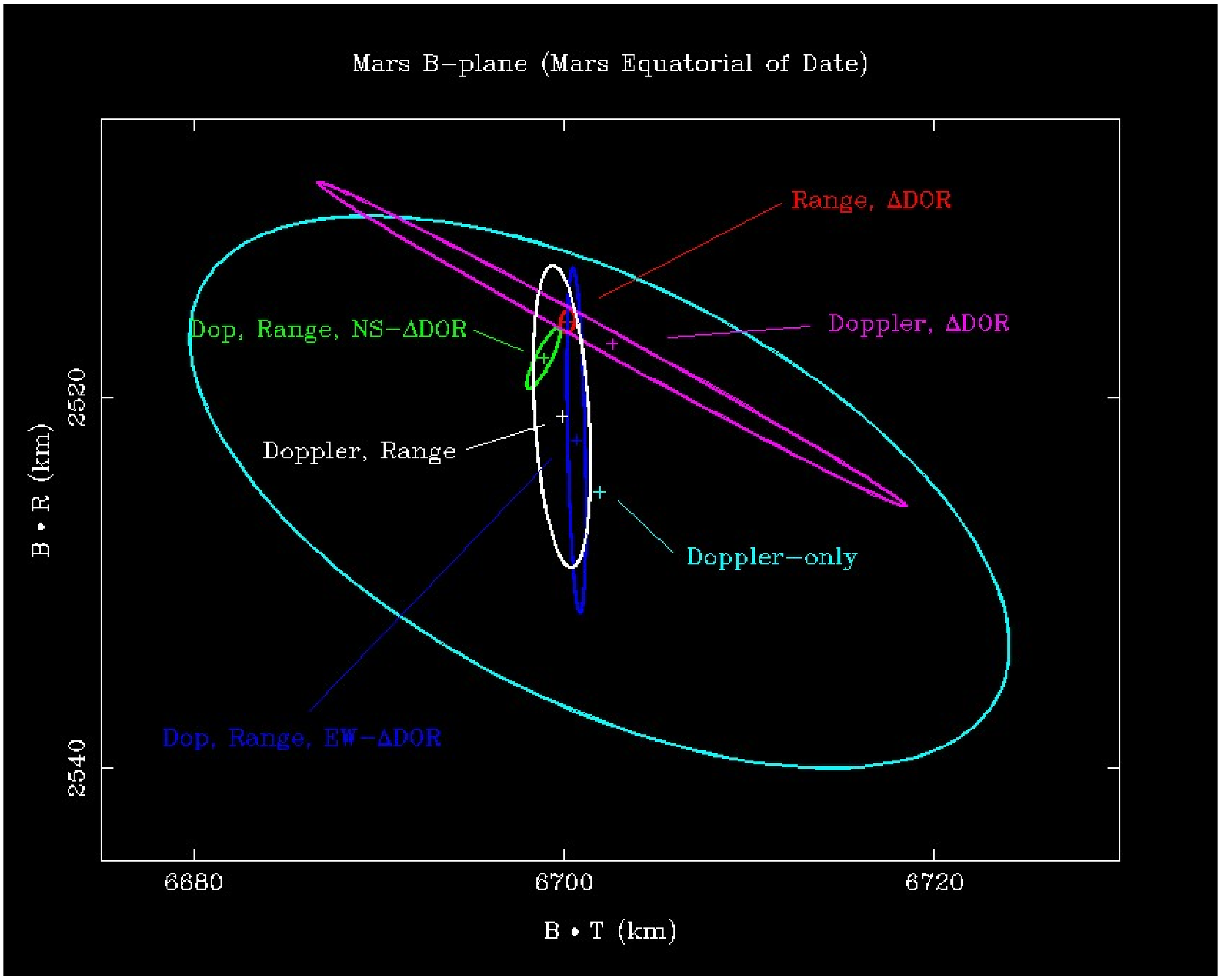
- Orbit solutions based on line-of-sight and delta-DOR data show less sensitivity to system errors, as compared to orbit solutions based on only line-of-sight measurements, due to the cancellation of errors by differencing. (See “Mars B-Plane” below from Mars Exploration Rover data, reference [5]. “B-Plane” 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.

- 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



Courtesy of JPL/Caltech

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

- Due to 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.

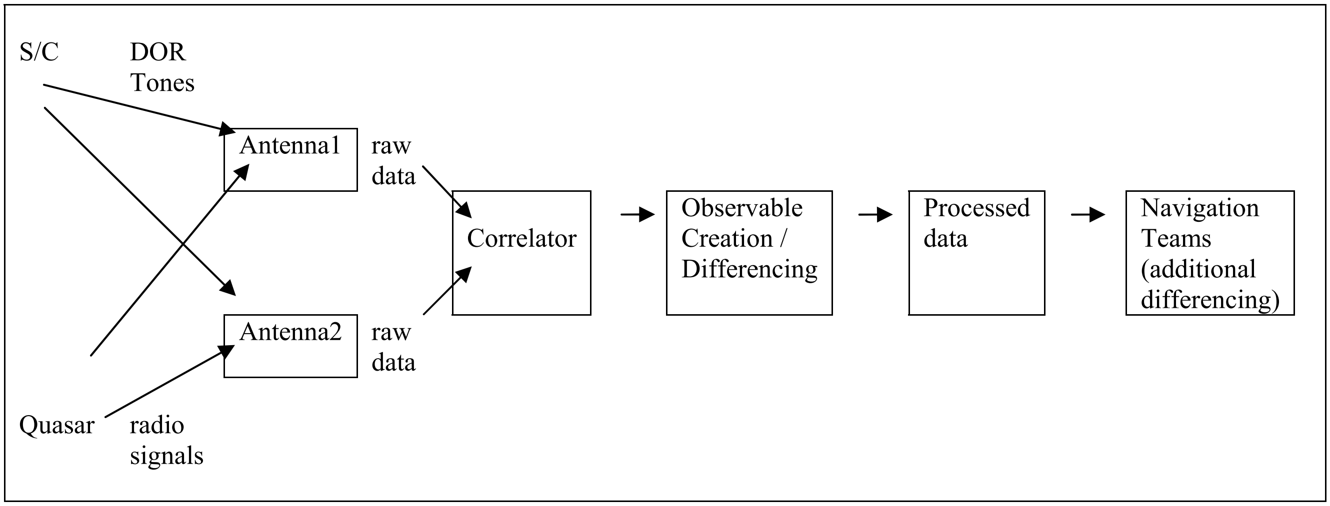
- It is usually not possible to collect telemetry data during the time that the delta-DOR measurement is in progress.

Proposed Document Set

There are many conceivable ways of organizing a set of standards for interagency delta-DOR operation. It will be necessary for the CESG to charter a Working Group (or set of Working Groups) which will discuss and agree upon many aspects of the technique (see “High Level delta-DOR Data Flow” below). The following proposed document list provides a starting point for potential items to be standardized by the proposed Working Group(s) as they relate to delta-DOR activities. The Working Group(s) must define the delta-DOR requirements, functionality, processes, contents, and implementation approach for interoperability, and prioritize which elements need to be addressed in the developed Recommendations.

The purpose of the proposed delta-DOR Working Group(s) is to produce a set of CCSDS Recommendations for coordinating delta-DOR measurements interagency. It is believed that standards that enable interoperability will significantly reduce development and operations costs while improving spacecraft navigation capabilities.

High Level delta-DOR Data Flow



The High Level delta-DOR Data Flow above shows various points where standardization would be beneficial in terms of establishing interoperability. The following proposed document list suggests attributes of a delta-DOR measurement session which could be standardized, however, it is not presumed to be a complete list. The actual set of attributes which must be negotiated for inclusion in the Recommendations may be greater or lesser in number, at the discretion of the Working Group(s). In general, the Working Group will need to consider 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), transmission mechanisms. Determination of the full set of attributes and documents is deferred to the Working Group(s).

1. <u>Service Request Specification Update</u>

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. At the very minimum, there will need to be an exchange of the setup/configuration information for the data collection session between the two agencies. Aspects of the configuration that will need to be determined will include:

- requirements for antenna pointing predicts (e.g., coordinate frame (topocentric, geocentric)
- predict point intervals and time formats
- angle formats (degrees, radians, direction cosines, etc.)
- frequency predict conventions
- required calibration activities
- receiver configuration requirements
- the scan sequence (SQS or QSQ)
- the number and timing of the scans
- possibility that multiple spacecraft may be sharing one of the ground stations ("multiple spacecraft per antenna", or MSPA)

2. Spacecraft DOR Tones Specification (Generation and Detection)

As noted previously, spacecraft transponder must emit several tones (referred to as DOR tones) spanning some bandwidth to enable a DOR measurement. The Spacecraft DOR Tones specification document will describe the DOR tones, characterize the spacecraft generation of the tones, and discuss how they may be detected/received at the ground stations. Applicable specifications for the transponder will be required. Factors that could be considered in the development of a standard for DOR tones include:

- Mission navigation accuracy requirements
- Waveform and modulation type: The DOR tones are generated by modulating a pure sine wave or pure square wave onto the downlink carrier (however under some scenarios they are simulated with ranging or telemetry). Sine waves are normally used in multi-tone systems based on efficiency considerations. Modulation type options include: use of two sinusoidal tones phase modulated on the downlink carrier signal, one square wave phase modulated on the downlink carrier, presence of telemetry on the subcarrier, and consideration of modulation indices.
- Supported downlink band and frequency: Whether the DOR tones will be at S-band, X-band, or Ka-band
- Tone power to noise spectral density ratios: The SNR influences the duration of the 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* knowledge of spacecraft angular position, while a wide spanned bandwidth is needed for high measurement accuracy. (Note: need same bandwidth span for both the spacecraft and the quasar). The bandwidth span is a very important factor in terms of controlling errors due to spacecraft SNR, quasar SNR, and instrumental phase ripple.
- Number of DOR tones (1, 2, or 3): 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.
- Tone frequencies and polarizations
- Number of data channels to be multiplexed.
- Whether or not the DOR tones will be frequency coherent with the downlink carrier.
- Whether only open loop tracking is supported (both quasar and spacecraft signals), or whether closed loop tracking of the spacecraft is allowed
- The degree to which the standard is equipment independent
- Specific tracking scenarios that will be supported (e.g., single spacecraft in cruise, spacecraft-spacecraft, orbiter-orbiter, lander-rover, etc.)
- 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 may also be in order.
- Requirements for receivers: specification on the receiver performance characteristics will be required (e.g., common sample rate, number of bits per sample, number of frequency channels, etc). Some tracking scenarios closely related to delta-DOR (SBI) may place requirements on the phase-linearity performance of ground receivers.

Note that Reference [6] already addresses a number of these factors and more, so a separate DOR tones specification may not be necessary. However, for interoperability, agencies will at least need to consider these items in and ICD or memorandum of understanding. The Working Group(s) will need to decide.

3. Quasar Catalog

There will likely be a need to select a small set of quasar catalogs that constitute a standardized set for interagency delta-DOR. This should facilitate consistency in radio source selection, pointing, and correlating. The standard quasar catalog could be an existing catalog such as the Sloan Digital Sky Survey Quasar Catalog (SDSS), International Celestial Reference Frame (ICRF), JPL Section 335 catalog (optimized for DSN delta-DOR), Large Bright Quasar Survey (LBQS), or other mutually agreed catalog of radio sources. The quasar catalog could be packaged as a separate Recommendation (Blue Book), or Informational Report (Green Book), or the Working Group(s) could simply agree to adopt an external standard specification without modification. Additional alternatives include determining a small set of quasars in an Interface Control Document (ICD), or in the service request message.

4. Raw Data Transfer/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 which may be located at another agency. The Working Group will need to determine the raw data exchange standard, which must include specifications on a number of operational parameters including:

- supported data rates
- desired structure and composition of the raw data file (e.g., time ordering issues, source interleaving issues, etc.)
- complementary ancillary data that will be required in order to correlate the data (e.g., spacecraft frequency, sampling rate, baseline identification, number of scans, spacecraft and quasar identification, ratio of DOR tones to the transmit frequency, subcarrier fundamental tone, and DOR tone harmonics).
- meanings of status flags in the data (if any)
- syntax of the message format
- time order of the packed bits (i.e., LSB or MSB)
- “Endianness” of the data (i.e., must the data be represented in “big-endian”, “little-endian”, or either)
- conventions for number formats (integer and floating point number representations)
- conventions for character data formats
- transfer record layouts
- specific transfer protocols that will be supported (e.g., FTP, SFTP, real time stream, etc.)

5. Data Correlation & Observables Generation

The Data Correlation and Observables Generation Specification will discuss the correlation and signal combining algorithms employed to produce the observables. The uplink frequency history and frequency rate history are required for use in constructing the frequency models used in the VLBI correlation process. Also necessary are the spacecraft Doppler mode (1, 2, or 3-way), and the spacecraft round trip light time. Note that the frequencies and frequency rate could be transferred via the CCSDS Tracking Data Message (TDM) currently under development; the RTLT could be transferred via a TDM COMMENT if desired. The ancillary information provided in the Raw Data Transfer/Exchange specification will be used in the processing.

If the predicted delta-DOR measurement accuracy is desired, there are a number of quantities that must be made available to the agency performing the correlation, based on the equations and error budget that should be 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
- 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
- ionospheric error (or spacecraft/quasar angular separation and the signal frequency)
- solar plasma error (or signal frequencies, sun-radio source angles, and solar wind velocity)
- antenna system noise temperatures
- antenna efficiency ratings
- antenna radii
- spacecraft elevation angle
- quasar elevation angle
- signal radio frequency
- the quasar correlated flux (a function of aperture combination (e.g., 70/70, 34/70, 34/34), which affects the accuracy of the delta-DOR measurement)
- number of quasar data samples per second
- correlated quasar flux
- number of time-multiplexed frequency channels

6. Observable Transfer/Exchange

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. 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 White Book, is supposed to be designed to transfer the delta-DOR observables, so this would be a candidate for the observable exchange. Alternatively, if the Working Group decides not to endorse use of the TDM, there will be a need to determine at least the following items, and perhaps more (including required units, precision, range of values, data formats, etc.):

- how to identify the applicable participants in the delta-DOR session: spacecraft, quasar, and the 2 downlink ground antennas, uplink band, uplink antenna.
- start time/stop time boundaries of the data: year, day of year (or month, day), hour, minute, second, fractional second
- how the timetags will be formatted
- uplink and downlink frequency bands used
- tracking mode (1-way, 2-way, 3-way)
- clock bias/offsets
- delays associated with antenna architecture, arraying configuration, etc.
- applicable calibrations
- data quality / data correction indicators
- range modulus
- compression times
- format of the DOR/DOD observables

7. Delta-DOR “Green Book”

The delta-DOR “Green Book” will be a CCSDS Informational Report as described in Reference [1]. It will provide a detailed description of the delta-DOR technique, including guidelines for DOR tone spectra, 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 technical specifications presented in the preceding Recommendation documents. The Green Book could also include the quasar catalog depending on the Working Group preference.

Note that the material in references [2], [3] and [4] provides an excellent start towards the future Green Book content.

Recommendation

There are currently two existing Working Groups in the CCSDS to which this work may be applicable; the Ranging Working Group in the Space Link Services Area and the Navigation Working Group in the MOIMS Area. The respective charters of these two working groups could be expanded to include this work, or alternatively, two new draft charters could be generated to cover this work. However, it is proposed that the best end path is likely to be to just update the charters of the existing Ranging and Navigation Working Groups to accommodate these new efforts. Some reviewers of this Concept Paper have suggested that a BOF for the raw data correlation may be a third group, though partitioning the effort over too many working groups could present a management challenge. Given the fairly common problem of acquiring resources to work on CCSDS activities, the charter extension prospect seems most reasonable and effective. On the other hand, if it turns out that resources are not an issue, partitioning the work over a larger number of working groups could achieve the end result sooner because the groups will be able to work in parallel, though of necessity in a coordinated fashion. This will, in the normal course of things, be resolved within the CCSDS WG structure by the CCSDS Engineering Steering group (CESG).

Goals, Objectives, and Deliverables

The proposed Working Group(s) will have several conceivable goals, objectives, and deliverables. The following are suggested:

1. Goal: Enable delta-DOR interoperability between agencies via a set of CCSDS Recommendations
2. Goal: Improve deep space navigation by increasing the number of intercontinental ground station baselines and enabling interagency delta-DOR
3. Objective: Identify and describe/define requirements for current and future delta-DOR operations.
4. Objective: Integrate and update current delta-DOR processes and operations into a single unified standardized framework which any authorized organization or individual can utilize.
5. Objective: Provide a fluid, systematic approach for delta-DOR operations
6. Objective: Transition interagency delta-DOR into operational status
7. Deliverables: Charter(s), Resource Allocation(s), Schedule(s) from the chartered Working Group(s) (TBD based on CMC/CESG allocation of the work across Areas, Working Groups, and BOFs)
8. Deliverables: some or all of the Recommendations (Blue Books) and Informational Reports (Green Books) as documented in the above "Proposed Documentation Set".

Risk Management Strategy

Technical risks:
Risks: Technical risks may be low since this process is not currently shared interagency, yet the technology is well defined and in the public domain. It is anticipated that for the most part existing hardware and software resources may be useable at participating agencies, assuming specific implementations that are sufficiently broad with respect to the delta-DOR theoretical capabilities. Full implementations exist at least at NASA/DSN. Thus technical issues should be manageable. Another challenge is to design a standard that can be easily updated in the future, as necessary, while not disturbing the on-going delivery of services. There is some risk that current agency practices may not be compatible, and may not be conducive to sharing.

Mitigation: Determine as early as possible any technical impediments to interoperability, and develop action plans.

Management risks:
Risks: Managing and integrating the efforts of several Working Groups could be a challenge. It may be necessary to partition the work described in this Concept Paper over at least 2 Areas and perhaps 2 or 3 Working Groups.

Mitigation: In order to make coordinated progress, the number of Working Groups should probably be kept to the minimum possible.

Conclusion

The prospect of interagency delta-DOR, and concomitant improvements in spacecraft navigation, seem feasible given the development of an appropriate set of CCSDS standards that address the end-to-end flow of control, data collection, data processing, and data exchange.

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Abbreviations & Acronyms

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
BOF	“Birds of a Feather”
CCSDS	Consultative Committee for Space Data Systems
CESG	CCSDS Engineering Steering Group
CMC	CCSDS Management Council
CSS	Cross Support Services
delta-DOR	delta differential one-way range
DOD	differenced one-way Doppler
DOR	differenced one-way range
DSN	Deep Space Network
ESA	European Space Agency
FTP	File Transfer Protocol
FTS	frequency and timing system
Hz	Hertz
ICRF	International Celestial Reference Frame
ID	identifier
JAXA	Japan Aerospace Exploration Agency
JPL	Jet Propulsion Laboratory
LAN	Local Area Network
LBQS	Large, Bright Quasar Survey
LSB	Least Significant Bit
MOIMS	Mission Operations and Information Management Services
MSB	Most Significant Bit
MSPA	Multiple Spacecraft per Antenna (or Aperture)
NASA	National Aeronautics and Space Administration
OS	operating system
QSQ	Quasar-Spacecraft-Quasar
RF	radio frequency
RTLT	round trip light time
SBI	Same Beam Interferometry
SDSS	Sloan Digital Sky Survey
SFDU	standard formatted data unit
SFTP	Secure File Transfer Protocol
SLE	Space Link Extensions
SLS	Space Link Services
SNR	signal-to-noise ratio
SQS	Spacecraft-Quasar-Spacecraft
TDM	Tracking Data Message (CCSDS)
UTC	universal time coordinated
VLBI	very-long-baseline interferometry

WG	CCSDS Working Group

References

[1] 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.

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[3] Thornton, Catherine L., and Border, James S.; Radiometric Tracking Techniques for Deep-Space Navigation, Deep Space Communications and Navigation Systems Center of Excellence (DESCANSO), Jet Propulsion Laboratory, California Institute of Technology, October 2000.

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[6] CCSDS 401.0-B-14, "Radio Frequency and Modulation Systems—Part 1: Earth Stations and Spacecraft". Blue Book. Issue 14. December 2003.