The Consultative Committee for Space Data Systems

Draft Recommendation for
Space Data System Practices

DELTA-DOR QUASAR CATALOGUE UPDATE PROCEDURE

DRAFT RECOMMENDED PRACTICE

CCSDS 506.3-R-1

RED BOOK
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(WHEN THIS RECOMMENDED PRACTICE IS FINALIZED, IT WILL CONTAIN THE FOLLOWING STATEMENT OF AUTHORITY:)

This document has been approved for publication by the Management Council of the Consultative Committee for Space Data Systems (CCSDS) and represents the consensus technical agreement of the participating CCSDS Member Agencies. The procedure for review and authorization of CCSDS documents is detailed in *Organization and Processes for the Consultative Committee for Space Data Systems* (CCSDS A02.1-Y-4), and the record of Agency participation in the authorization of this document can be obtained from the CCSDS Secretariat at the e-mail address below.

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CCSDS Recommendations take two forms: **Recommended Standards** that are prescriptive and are the formal vehicles by which CCSDS Agencies create the standards that specify how elements of their space mission support infrastructure shall operate and interoperate with others; and **Recommended Practices** that are more descriptive in nature and are intended to provide general guidance about how to approach a particular problem associated with space mission support. This **Recommended Practice** is issued by, and represents the consensus of, the CCSDS members. Endorsement of this **Recommended Practice** is entirely voluntary and does not imply a commitment by any Agency or organization to implement its recommendations in a prescriptive sense.

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FOREWORD

Through the process of normal evolution, it is expected that expansion, deletion, or modification of this document may occur. This Recommended Practice is therefore subject to CCSDS document management and change control procedures, which are defined in the *Organization and Processes for the Consultative Committee for Space Data Systems* (CCSDS A02.1-Y-4). Current versions of CCSDS documents are maintained at the CCSDS Web site:

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PREFACE

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

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

DOCUMENT CONTROL

Document	Title	Date	Status
CCSDS 506.3-R-1	Delta-DOR Quasar Catalogue Update Procedure, Draft Recommended Practice, Issue 1	July 2016	Current draft

CONTENTS

CONTENTS (continued)

1 INTRODUCTION

1.1 PURPOSE

Delta Differential One-Way Ranging (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. It involves the simultaneous use of multiple ground stations, possibly belonging to different agencies, for acquisition of both spacecraft and quasar signals.

The quasar sources required for Delta-DOR measurements have to be known a priori. The quality of a Delta-DOR measurement depends on the availability of compact and strong quasars, together with the knowledge of their precise positions.

Delta-DOR operations requires a quasar catalogue, geared to Delta-DOR measurements.

Historically, quasar catalogues are populated by astronomers, via VLBI campaigns. This is highly valuable information for Delta-DOR measurements and established reference catalogues exist today.

The X-band catalogue adopted as a starting point for this book is the one reported in reference [1]. This catalogue has been adopted because it has been developed and used, over the years, to perform Delta-DOR measurements.

This catalogue is now available as a SANA registry (reference [5]):

http://sanaregistry.org/r/radio_sources/

A Ka-band quasar catalogue is also under preparation.

The purpose of this Recommended Practice is to provide:

– specifications for a quasar catalogue to be used in Delta-DOR measurements;

– description of the catalogue update process;

– procedures and qualitative criteria to evaluate whether the updates of such catalogues are acceptable;

– description of the registries to be included in a quasar catalogue;

– rules to update SANA entries.

1.2 APPLICABILITY

This CCSDS Quasar Catalogue Update Procedure applies to agencies doing Delta-DOR operations and to all requests to create and manage the quasar catalogue registered in the SANA. It shall be binding on the DDOR WG and on all CCSDS member, affiliate, and service provider organizations that supply and manage information for these quasar registries.

1.3 STRUCTURE OF THIS DOCUMENT

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

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

– Section 3 addresses the specifications for a radio source catalogue.

– Section 4 describes the criteria for accepting a catalogue update to be submitted to SANA.

– Section 5 provides the description of the registry structure.

– Annex A is the procedure to update the SANA registry.

– Annex B addresses security considerations.

– Annex C illustrates the procedure to update the catalogue.

– Annex D provides an extract of the current catalogue.

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

– Annex F is a list of informative references.

1.4 NOMENCLATURE

1.4.1 NORMATIVE TEXT

The following conventions apply for the normative specifications in this Recommended Practice:

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

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

c) the word ‘may’ implies an optional specification;

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

NOTE – These conventions do not imply constraints on diction in text that is clearly informative in nature.

1.4.2 INFORMATIVE TEXT

In the normative sections of this document, informative text is set off from the normative specifications either in notes or under one of the following subsection headings:

– Overview;

– Background;

– Rationale;

– Discussion.

1.5 DEFINITIONS

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

B1950 Name: Source name based on its position at the Besselian epoch B1950.0.

Common Name: Source name in common usage in astronomical community.

very long baseline interferometry, VLBI: 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 antennas.

1.6 REFERENCES

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

[1] *X-Band Radio Source Catalog*. Module 107, Rev. D, October 22, 2015 in *DSN Telecommunications Link Design Handbook*. DSN No. 810-005, Rev. E. Pasadena California: JPL, April 8, 2013.

[2] Alan L. Fey, David Gordon, and Christopher S. Jacobs, eds. *The Second Realization of the International Celestial Reference Frame by Very Long Baseline Interferometry*. IERS Technical Note No. 35. Frankfurt am Main, Germany: IERS, 2009.

[3] M. J. L. Kesteven and A. H. Bridle. "Index of Extragalactic Radio-Source Catalogues." *Journal of the Royal Astronomical Society of Canada* 71, no. 1 (February 1977): 21–39.

[4] Ojars J. Sovers, John L. Fanselow, and Christopher S. Jacobs. "Astrometry and Geodesy with Radio Interferometry: Experiments, Models, Results." *Reviews of Modern Physics* 70, no. 4 (October 1998): 1393.

[5] "DDOR X-Band Radio Sources." Space Assigned Numbers Authority. http://sanaregistry.org/r/radio_sources/.

[6] J.B. Thomas. *Interferometry Theory for the Block II Processor*. JPL Publication 87-29. Pasadena, California: JPL, October 15, 1987.

2 OVERVIEW OF THE DELTA-DOR TECHNIQUE

2.1 SPACECRAFT AND QUASAR OBSERVATIONS

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

An application of VLBI is spacecraft navigation in 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. The observation geometry is illustrated in figure 2-1. Even though data acquisition and processing are not identical for the spacecraft and quasar, both types of measurements can be interpreted as delay measurements and they have similar information content and similar sensitivity to sources of error. The data produced in such a measurement session are complementary to Doppler and ranging data.

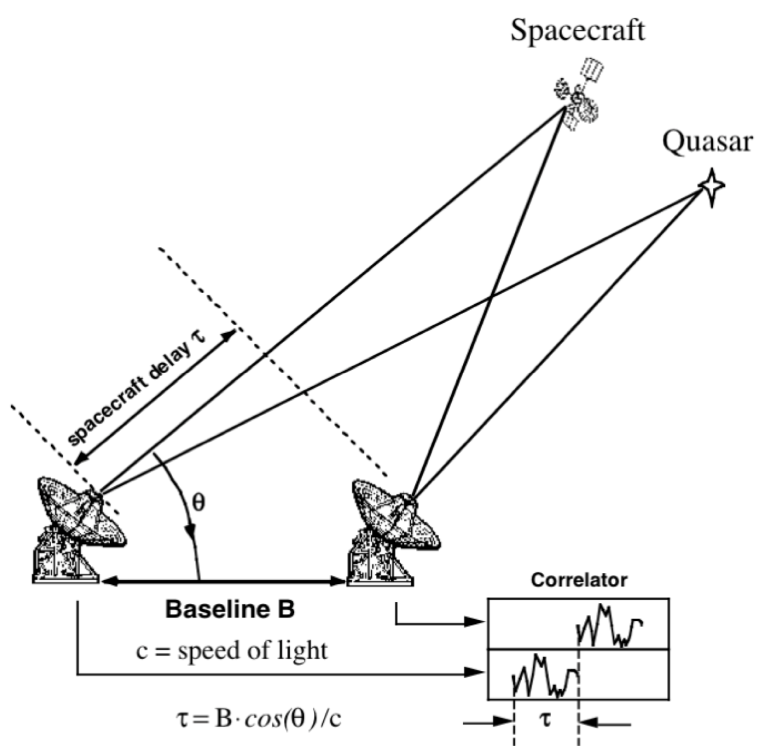

Figure 2-1: Delta-DOR Observation Geometry

2.2 RATIONALE

Quasar sources needed for Delta-DOR measurements have to be known a priori.

– Quasars define a celestial reference frame which is used in the Orbit Determination (OD) process, which makes use of the Delta-DOR measurements.

– In Delta-DOR, the instrument consisting of two or more stations used as an interferometer to measure spacecraft position must be calibrated by observing quasars.

– Up to a few quasars can be used as calibrators of the single SpaceCraft (S/C) DOR measurement.

The quality of a Delta-DOR measurement depends on the availability of:

– Compact sources: This kind of source (e.g., point-like) allows a better identification of a defined source position in the plane-of-sky, thus enabling better determination of the calibrator position to be used in the measurement.

– Knowledge of their precise positions and related uncertainty: This knowledge is needed since the quasar delay is used to calibrate the Delta-DOR measurement. Ideally, a perfectly known quasar position would lead to better determination of spacecraft position in the celestial reference frame.

– Strong quasars (correlated flux density): A strong correlated flux is a desirable property, since it allows better jitter performance in the quasar delay computation with a limited integration time. Unfortunately, correlated flux can be highly variable and therefore there is little control on this parameter and often a trade-off is necessary between different quasars near the tracked S/C to identify the best source(s) to be used as calibrators,

– Sources angularly close to the target S/C: Such property is important to ensure spatial coherency between the S/C and the quasar delay measurement, thus enabling better calibration performance.

These properties are required in a quasar catalogue that is geared to Delta-DOR measurements. The catalogue must specifically address the four properties cited above and cover the frequencies that are normally used in deep space operations: X-band (8.4 – 8.5 GHz) and Ka-band (31.8 – 32.3 GHz).

Quasar measurements made for Delta-DOR use tend to be limited in sensitivity as compared to measurements made for astrometric and geodetic purposes. Also, since most of the deep space missions are flown in the solar system ecliptic plane, there is a particular interest in having a higher number of sources near the ecliptic plane.

For the actual planning of a DDOR measurement, the catalogue is searched to find candidate sources that are angularly close to the spacecraft position at the measurement time, compact, and of sufficient flux.

Specific sources are selected for observation based on the criteria of minimizing measurement error. This process is further described in *Delta-DOR—Technical Characteristics and Performance*, reference [F2].

3 RADIO SOURCE CATALOGUE SPECIFICATION

3.1 A common radio source catalogue shall be used by all space agencies to facilitate consistency in radio source selection, pointing, and correlating.

3.2 The catalogue shall provide:

a) a unique name for each radio source (see section 5);

b) coordinates and coordinate uncertainties for each radio source;

c) an estimate of flux and structure (i.e., apparent coordinate variability) for at least the radio sources that are likely to be used for Delta-DOR observations;

d) the number of observation per source; and

e) the epoch of observation.

3.3 The catalogue may contain a full or partial correlation matrix for source coordinate uncertainty.

3.4 The SANA radio source catalogue (reference [5]) should be used as the standard Delta-DOR catalogue for X-band observations.

NOTE – The SANA registry is based on the JPL catalogue (reference [1]). It 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.

3.5 All space agencies should support the extension of the existing catalogue as follows:

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

b) develop a Ka-band catalogue;

c) provide separate correlated source flux estimates for each agency or interagency baseline;

d) provide information on flux variation versus time on each baseline of interest.

4 CRITERIA FOR ACCEPTING CATALOGUE UPDATE

4.1 The proposed new quasar catalogue, to be submitted to SANA, shall contain at least the information as specified in 3.2.

NOTES

1 A catalogue update is always presented as a new catalogue (see A2.1).

2 The DDOR WG will consult with the world astrometric community and the space navigation community to keep informed of new candidate quasar catalogues that might become available.

4.2 The proposed new catalogue shall be presented with related documentation that can be used to judge the suitability of such catalogue for Delta-DOR applications.

4.3 The accompanying documentation should include, as a minimum:

a) description/reference to models used for

   1) tropospheric/ionospheric calibrations,

   2) terrestrial reference frame,

   3) Earth orientation parameters,

   4) uncertainty of the coordinates noise floor;

b) number of observations and related information on timespan over which such observations have been taken;

c) number and distribution of sources;

d) comparison of the proposed catalogue with the ICRF-2 reference frame, reference [2].

4.4 The proposed new catalogue shall be reviewed by the DDOR WG.

NOTE – The DDOR WG may decide, in order to evaluate the suitability of the proposed new catalogue, to consult with external entities (e.g., radioastronomy community, flight dynamics group at CCSDS, etc.).

5 STRUCTURE OF THE REGISTRY (PARAMETERS DESCRIPTION/ LEGAL VALUES)

5.1 OVERVIEW

Structure of the registry and parameter description are given hereafter (an example of the catalogue is in annex D):

5.2 B1950 NAME

The B1950 Name field contains the source name based on its position at the Besselian epoch B1950.0, which is one of the two standard epochs that have been used in the last 30 years for reporting source positions (the other being the Julian epoch J2000.0). The name is related to the position of the source but is most useful for searching historical databases for information about the source. The name is constructed as follows. The first two digits represent hours of right RA, the next two digits minutes of RA, the fifth place is used to specify the sign of the declination, places 6−7 give degrees of declination, and the last digit gives the first digit of the fractional part of degrees of declination. Thus the first name entry in the catalogue, 2357-326, is interpreted as a right ascension of 23 hours and 57 (time) minutes and a declination of negative 32.6 degrees at the B1950.0 epoch. It should be noted that, because the catalogue positions are given for epoch J2000 and many of the names (e.g., 2357-326) are based on a B1950 position, the catalogue names do not start at zero right ascension, whereas the actual positions do.

5.3 COMMON NAME

The Common Name field contains the name most commonly used in the literature for the source and is also the name used by the DSN for Delta−DOR measurement scheduling. Often there is a short prefix that indicates the organization or radio observatory that first documented the source in a survey. The remainder of the name may be related to the source position or an arbitrary sequence number. Some of the prefixes and naming conventions include (see reference [3]):

a) 3C *nnn* – From the Third Cambridge Catalogue. The *nnn* is the numerical designation assigned by the catalogue. This survey, originally conducted at 159 MHz, identified many of the stronger sources used in VLBI. Unfortunately, many of these stronger sources are also less point-like, making them less desirable for the highest accuracy astrometric measurements.

b) 4C *zz.nn* – From the Fourth Cambridge Catalogue. The *zz* corresponds to the declination ‘zone’. The *nn* is a sequential number within the zone. There are no sequential numbers greater than 99.

c) B2 *RRrrSDDa* – Most likely from the Second Bologna Survey. The *RRrr* is hours and minutes of right ascension, *S* is the sign of declination and *DD* is degrees of declination. The meaning of a (an alpha character) is unknown.

d) CTA *nn* and CTD *nn* – From the California Institute of Technology 'A' or 'D' surveys where *nn* is the numerical designation assigned by the catalogue.

e) DW *RRrrSDDd* – From the Dwingelo Radio Observatory (Netherlands) catalogue. The *RRrr* is hours and minutes of right ascension, *S* is the sign of declination, *DD* is degrees of declination, and *d* (if present) is the first digit of the fractional part of declination.

f) GC *RRrrSDDd* – Most likely names taken from the 'General Catalog of 33342 (optical) Stars'. The *RRrrSDDd* are as described before.

g) HR *nnnn* – Most likely names taken from the 'Harvard Revised (optical) Catalog', where *nnn* is the numerical designation assigned by the catalogue.

h) M *nn* – Most likely names taken from the 'Messier Catalog of Galaxies', where *nn* is the numerical designation assigned by the catalogue.

i) NRAO *nnn* – From the National Radio Observatory catalog, where *nnn* is the numerical designation assigned by the catalogue.

j) O_ *nnn* – From the Ohio State Survey where the second letter indicates the hour of right ascension (two letters are skipped from the alphabet) and *nnn* is a numerical designation assigned by the catalogue.

k) P *RRrrSDDd* – From the Parkes Radio Observatory (southern Australia) survey. The *R RrrSDDd* are as described before.

l) V RO *DD.RR.rr* – From the Vermillion River Observatory (University of Illinois) catalogue. The *DD* is degrees declination and *RR* is hours right ascension. The *rr* is unknown but may be either minutes or fractional hours of right ascension.

5.4 IDENTIFIER

The Identifier field contains a unique number, presently in the range of 1 to 4044, assigned to each radio source for use by programs that identify sources by number instead of name. The correspondence between source name and number will not change when the catalogue is updated. This catalogue can be used to establish a unique correspondence between the B1950 or Common Name and ID number. If a source in this catalogue is deleted from future revisions of the catalogue delivery, its number will be retired. When new sources are added, they will be assigned unique numbers starting with 4045.

5.5 ANGULAR POSITIONS

5.5.1 GENERAL

The Angular positions are specified by a pair of angular coordinates: RA and DEC. It should be noted that while right ascension used to be defined as the angular distance along the celestial equator from the intersection of the equator and the ecliptic, this is no longer true once one becomes concerned with accuracy levels < 100 milliarcseconds (500 nrad).

Since 1 January 1998, right ascension, and most importantly the origin of RA, have been defined by conventional agreement as to the value of the RA of extragalactic radio sources. In practice this means that the axes implicitly defined by a set of source positions must agree with the ICRF2 (reference [2]) to within the formal uncertainty of the ICRF2 axes, or approximately 10 µas (1 standard deviation). Thus the orientation of the celestial frame axes may vary in future realizations by roughly that amount.

5.5.2 RIGHT ASCENSION

Right Ascension is presented in the form '*hh mm SS.ssssssss*' where the first subfield gives hours of RA followed by (time) minutes of RA and (time) seconds of RA to eight decimal places.

5.5.3 DECLINATION

Declination is presented in the form '*Sdd mm SS.sssssss*' where

– the first subfield, *S*, gives the sign of declination (a blank is allowed and should be interpreted as a positive declination);

– the remaining subfields give angular declination in degrees, minutes, and seconds to seven decimal places.

NOTE – A minus sign applies to the whole declination (*dd mm SS.sssssss*). For example, a declination of –00 00 00.*sssssss* should be read as minus 0.*sssssss* arcseconds of declination. This means that users desiring decimal representations of declination must first convert from degrees, minutes, seconds format to decimal format before applying the relevant sign.

5.6 RIGHT ASCENSION ERROR

Right Ascension Error (RA Error) provides the formal one standard deviation right ascension uncertainty in units of seconds of time.

5.7 DECLINATION ERROR

Declination Error (DEC Error) provides the formal one standard deviation declination uncertainty in units of arcseconds of angle.

5.8 CORRELATION OF RIGHT ASCENSION AND DECLINATION

The Correlation of Right Ascension and Declination (RA DEC Corr) provides the formal correlation of right ascension and declination. The quantity may range from –1.0 to +1.0 and a blank in front of the value should be interpreted as indicating a positive correlation. Values near zero indicate that the principal axes of the error ellipse are close to the RA−Dec axes. The large number of negative correlations results, in part, from the large influence of the California to Australia baseline on determination of declination.

5.9 OBSERVATION EPOCHS

5.9.1 GENERAL

Epochs are referred to Modified Julian Day (MJD) and are typically on the order of 50000 days.

5.9.2 OBS EPOCHS FIRST

OBS Epochs First is the earliest epoch of the first observation.

5.9.3 OBS EPOCHS LAST

OBS Epochs Last is the termination epoch of the most recent observation.

5.10 NUMBER OF SESSIONS

The Number of Sessions (OBS Number), where a session is defined as a continuous data collection period, may be used as a rough indicator of the robustness of the position determination. Any position based on less than three sessions should be considered provisional.

5.11 CORRELATED FLUX DENSITY

5.11.1 GENERAL

The Correlated Flux Density is an estimate of the average correlated flux density for observations of the radio source using DSN baselines Goldstone-Madrid and Goldstone-Canberra. Average correlated flux density values are reported for each baseline when available. This value, in Janskys (Jy), is computed from the measured signal-to-noise ratio (SNR), based on a normalized sampling rate, using the formula:

$$S(\text{Jy}) \approx \text{SNR}/150$$

The SNR is determined during the cross-correlation and fringe-fitting of actual radio source observations. If no recent observations of a radio source on DSN baselines are available, no value is provided for correlated flux. Independent values for the correlated flux density are reported for the California-Madrid and the California-Canberra DSN baselines.

NOTE – Correlated flux densities are only given for the Goldstone-Madrid and Goldstone-Canberra baselines. A new catalogue may contain more flux information from other baselines.

5.11.2 CORRELATED FLUX DENSITY GOLDSTONE-MADRID BASELINE

The Correlated Flux Density Goldstone-Madrid Baseline is the correlated flux density for quasars observed on the Goldstone-Madrid baseline. Flux densities on this baseline are available for 643 of the sources.

The values shall be inserted only when reliable information on such quantity are available; otherwise the field shall be left blank.

5.11.3 CORRELATED FLUX DENSITY GOLDSTONE-CANBERRA BASELINE

The Correlated Flux Density Goldstone-Canberra Baseline is the correlated flux density for quasars observed using the Goldstone-Canberra baseline. Flux densities on this baseline are available for 608 of the sources.

The values shall be inserted only when reliable information on such quantity are available; otherwise the field shall be left blank.

5.12 STRUCTURE INDEX

The Structure Index is determined through the following relationship between the radio source structure index and the median value of the VLBI structure delay corrections (reference [2]):

$$SI = 1+ 2 \log(\tau_{median})$$

Here SI is the structure index, and τ_{median} is the median value of the structure delay corrections (ps). A value for τ_{median} in the range of 0 to 40 ps is typical for a source that is point-like. A value in the range of 40 to 60 ps is typical for a source that has significant structure. The source structure itself may contribute an error of this magnitude to the delay error budget. Values of the delay scatter greater than 60 ps are typical for sources with large, extended, and possibly variable structure. Estimates of the structure index are available for 693 of the sources.

The values shall be inserted only when reliable information on such quantity are available; otherwise the field shall be left blank.

ANNEX A

PROCEDURE TO UPDATE SANA REGISTRY

(NORMATIVE)

A1 OVERVIEW

The Procedure to update the SANA quasar catalogue is defined here.

A2 PROCEDURE

A2.1 The submitter shall produce an updated catalogue. The update shall be of the whole catalogue; 'deltas' with respect to an existing catalogues will not be accepted.

A2.2 The submitter shall submit the catalogue update to the CCSDS Delta-DOR Working Group.

A2.3 The Delta-DOR Working Group shall apply the following criteria to determine whether to authorize the new catalogue:

NOTE – The Delta-DOR Working Group is in charge of assessing any new candidate catalogue and deciding when and if the SANA registry will be updated.

a) completeness of the proposed catalogue in terms of information given within the catalogue description, as defined in section 3;

b) applicability of the catalogue to Delta-DOR operations (e.g., relevance of the frequency band of the proposed catalogue);

c) applicability of the minimum acceptance criteria illustrated in section 4.

A2.4 Once accepted by the Delta-DOR Working Group, the catalogue will be submitted by the Working Group to SANA for Registry update.

NOTE – SANA registry update rules are:

– Registration Policy: Update requires Expert Review

– Review authority: SEA-D-DOR

ANNEX B

SECURITY CONSIDERATIONS

(INFORMATIVE)

B1 INTRODUCTION

This annex 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.

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.

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

There are no explicitly known consequences of not applying security to the specific information-security interoperability provisions specified in this Recommended Practice.

ANNEX C

PROCEDURE TO UPDATE THE CATALOGUE

(INFORMATIVE)

C1 INTRODUCTION

The following is a description of the process used to update the catalogue.

C2 ORGANIZING A CAMPAIGN

The radio catalogue engineer organizes an observing campaign.

a) Goals: First the goals of the campaign are set. These goals may include improving the overall accuracy of the radio frame, updating the fluxes to account for variable sources, and making the catalogue more dense in a region of interest such as the area near a planetary encounter with compact and strong sources.

b) Source selection: Based on the goals defined in the previous step, candidate sources are selected from assorted radio surveys. These candidates are to be added to the existing list of proven sources.

c) General considerations of observation configuration: Next, a specific set of observations are planned. This includes applying for observing time on various sets of antennas, designing the placement of channels, and finally designing the sequence of observations: source, RA, Dec, start time, and source integration time.

d) Input data description (example): Inputs to the scheduling of the sequence include the list of sources, a catalogue of RA, Dec in J2000, a catalogue of station positions, scanning mode(s), slew rates, Azimuth/Elevation limits.

C3 PERFORMING A CAMPAIGN TO ACQUIRE DATA

General description (VLBI data): At this stage a set of antenna pointing predicts are first generated and then delivered to the stations and a set of channel frequencies and other configuration information are provided for the VLBI backend and data recorder. This will also include the start/stop times for each observations of a source. This information is used to acquire data from multiple stations that are then transferred to a central location for correlation purposes.

NOTE – RDEF format (reference [F3]) can be used for the purpose of exchanging raw data, but is not mandatory.

C4 PROCESSING DATA

C4.1 Correlation processing: Correlation processing is done for each baseline connecting two antennas that provided observations. A days worth of radio catalogue observations can produce several TBytes of data recorded at rates from 128 to 4096 Mb/s. As a result, it is necessary to run an initial stage of signal processing which cross-correlates (multiply with a set of lags) the data samples from each pair of stations and averages the cross correlation sums to a moderate rate, typically about one normal point per second.

C4.2 Fringe fitting: The correlation output for a set of time and frequency points is then sent to the fringe fitting stage (reference [6]), where it is Fourier transformed in order to produce a priori estimates of delay and phase rate which are used to correct cycle slips and then to bootstrap least squares final estimate of group delay and phase rate.

C4.3 Preliminary observable modeling and parameter adjustment: The group delays and phase rates are then sent to a sophisticated model which accounts for geometry, relativity, geophysical effects, atmospheric effects, instrumental drifts, etc. After modeling the residual group delays and phase rates, a least-squares parameter adjustment is entered to refine parameters of interest, such as source RA, Dec, station locations, as well as ‘nuisance parameters’ to account for the instrumentation, and troposphere (reference [4]).

C4.4 Data editing: Once the preliminary modeling and parameter adjustment is done, the resulting residuals are examined for outliers. Outliers are then either removed or, if resources allow, the fringe fitting stage is revisited to look for the cause of the outlier from antennas being late on source, dead channels, RFI, etc. If a cause is found then the data processing can be iterated to produce a corrected data set.

C4.5 Run global solution: The corrected data set from a day’s observing is then merged into the cumulative database of all radio catalogue observations. Then the modeling and parameter estimation stages are run on the merged data set to produce the RA, Dec, and other parameters. The set of RA and Dec parameters and the related error estimations are the raw catalogue (see reference [4]).

C5 VALIDATING RESULTS

In order to validate the global solution, two types of verification are done: internal and external.

a) Internal verification: This tasks examines the RMS scatter of delay residuals, station locations, nutation parameters, clocks, tropospheres and compares them against expected values and/or known standard models.

b) External verification: This task compares the candidate catalogue against the International Astronomical Union’s (IAU) International Celestial Reference Frame (e.g., ICRF-2) and other high quality radio catalogues. At this stage, the analyst verifies that the candidate catalogue is rotationally aligned with the ICRF, that zonal trends are within required limits, and RA/Dec scatter versus other catalogues is at the expected levels. Once these checks are done the catalogue is ready to be formatted into an updated version of it and formally delivered.

ANNEX D

EXTRACT AND SAMPLE CATALOGUE

(INFORMATIVE)

Figure D-1 is a page, provided for reference, from the current quasar catalogue (reference [1]).

Source Name		ID No.	Right Ascension			Declination			RA Error (s)	Dec. Error (arcsec)	RA–Dec Corr.	Observation Epoch MJD		No. Obs.	Source Flux (Jy)		Str Index
B1950	Common		H	M	S	D	M	S				First	Last		10-60	10-40	
2357-326	2357-326	2274	00	00	20.39995646	-32	21	1.2341485	.00003605	.0010074	-0.1568	52305.9	52306.0	1			
2358+406	2358+406	2275	00	00	53.08158877	+40	54	1.7931619	.00015359	.0020370	-0.1702	50242.6	50242.7	1			
2358-161	2358-161	2276	00	01	5.32873051	-15	51	7.0756294	.00003475	.0009841	-0.7390	50631.3	50631.5	1			
2358+605	2358+605	2277	00	01	7.09962657	+60	51	22.8028338	.00030531	.0034085	-0.0996	52306.1	52306.1	1			
2358+189	2358+189	984	00	01	8.62156972	+19	14	33.8016881	.00000403	.0000745	-0.0439	50085.0	56664.1	97			
2359-221	2359-221	2278	00	02	11.98151630	-21	53	9.8647879	.00013558	.0033386	0.7251	54818.1	55483.3	2			
0000-199	0000-199	2279	00	03	15.94944558	-19	41	50.4043557	.00017952	.0071919	-0.8263	54088.0	54088.0	1			
0000-197	0000-197	2280	00	03	18.67501429	-19	27	22.3553356	.00003463	.0009540	-0.2104	50631.3	50687.5	2			
0000+212	0000+212	2281	00	03	19.35001932	+21	29	44.5078137	.00003320	.0009546	-0.4215	50085.0	50155.9	2			
0001+478	0001+478	2282	00	03	46.03098500	+48	07	4.2008098	.02167613	.1323638	-0.9936	50305.5	50305.5	1			
0001-120	0001-120	1309	00	04	4.91500315	-11	48	58.3857125	.00001196	.0004032	0.0268	50575.6	53133.7	3			
0001+459	0001+459	2283	00	04	16.12765771	+46	15	17.9701176	.00002779	.0005847	0.1118	50305.4	50305.5	1			
0002-478	0002-478	706	00	04	35.65549073	-47	36	19.6040785	.00001147	.0002013	0.4295	49330.5	56504.1	33			
0002+200	0002+200	985	00	04	35.75829598	+20	19	42.3173063	.00001456	.0002752	0.0946	52408.7	52983.4	3			
0002+541	0002+541	2284	00	05	4.36339833	+54	28	24.9248304	.00004002	.0003804	0.1936	49576.3	56393.6	2	0.22		
0002-170	0002-170	2285	00	05	17.93378034	-16	48	4.6787946	.00002823	.0009044	-0.5072	50631.3	50631.5	1			
0002+051	0002+051	2286	00	05	20.21554656	+05	24	10.8005007	.00013213	.0021387	-0.1058	49914.4	49914.5	1			
0003+380	GC 0003+38	1	00	05	57.17538923	+38	20	15.1490655	.00000525	.0000755	-0.1421	48719.9	56766.4	43	0.30	0.40	3.4
0003-302	0003-302	2287	00	06	1.12320481	-29	55	50.0966280	.00020176	.0056806	0.8648	52408.7	52409.6	1			
0003+340	0003+340	2275	00	06	7.38258280	+34	22	20.4058169	.00001848	.0004735	0.1091	55915.9	55916.2	1			
0003-066	0003-066	696	00	06	13.89288879	-06	23	35.3354137	.00000340	.0000537	-0.0569	48196.3	56776.1	1143	1.07	1.01	3.1
0003+123	0003+123	2288	00	06	23.05611993	+12	35	53.0973123	.00005770	.0010507	0.2592	54111.9	54112.1	1			
0004+240	0004+240	2289	00	06	48.78939742	+24	22	36.3929012	.00007456	.0013617	0.2432	50085.0	50155.9	2			
0005+568	0005+568	2290	00	07	48.46855993	+57	06	10.4391862	.00030458	.0032354	0.4617	49576.3	49576.5	1			
0005-239	0005-239	2291	00	08	0.36965705	-23	39	18.1508447	.00002570	.0007460	-0.7253	50631.3	54643.3	3			
0005+114	0005+114	2292	00	08	0.83833663	+11	44	0.7746711	.00005794	.0010698	-0.1352	52408.8	52409.7	1			
0005-262	0005-262	2293	00	08	26.25253369	-25	59	11.5391634	.00003832	.0012580	0.4295	50631.3	50687.5	2			
0005+683	0005+683	2294	00	08	33.47270295	+68	37	22.0480250	.00039129	.0014544	-0.2464	49826.7	54112.1	2			
0006-363	0006-363	2295	00	08	33.66108528	-36	01	25.0414158	.00012222	.0056954	0.4183	53552.5	55656.8	2			
0006+061	0006+061	2296	00	09	3.93184876	+06	28	21.2400688	.00000950	.0002627	0.0784	52408.7	56701.0	2	0.12	0.12	
0006+397	0006+397	2297	00	09	4.17357962	+40	01	46.7048409	.00003069	.0006426	-0.3266	50242.6	50242.7	1			
0007-325	0007-325	1310	00	09	35.55782459	-32	16	36.9309139	.00004656	.0011018	-0.7501	54965.6	54965.6	1			
0007+439	0007+439	2298	00	10	30.04645093	+44	12	42.5044093	.00002932	.0008687	0.2691	54087.1	54088.0	1			
0007+106	III ZW 2	986	00	10	31.00591022	+10	58	29.5041940	.00000382	.0000623	-0.0981	51427.3	56633.0	77			0.9
0007+171	GC 0007+17	6	00	10	33.99061349	+17	24	18.7612505	.00000534	.0000946	-0.1808	44203.1	55244.5	48	0.17	0.11	3.7
0008-311	0008-311	4046	00	10	34.90967756	-30	54	15.3008586	.00004795	.0017185	0.5297	55965.9	55965.9	1			
0008-307	0008-307	2299	00	10	35.74237629	-30	27	47.4164553	.00014542	.0043050	0.7871	52305.9	52306.0	1			
0008-300	0008-300	2300	00	10	45.17732291	-29	45	13.1769533	.00005091	.0027023	-0.3993	54087.1	55783.9	2			
0008-421	P 0008-42	707	00	10	52.51757282	-41	53	10.7751151	.00024803	.0084664	0.1635	49329.5	52408.7	4			
0008-222	0008-222	2301	00	10	53.64998229	-21	57	4.2198778	.00001116	.0003758	-0.2445	50631.3	50687.5	2			
0008-264	P 0008-264	7	00	11	1.24673888	-26	12	33.3771100	.00000503	.0000782	-0.1116	44227.2	56772.3	101	0.27	0.43	1.6
0008+704	0008+704	2302	00	11	31.90286621	+70	45	31.6257354	.00004723	.0003901	0.0561	49826.7	49826.8	1			
0009+081	0009+081	1253	00	11	35.26963568	+08	23	55.5859353	.00001015	.0003003	-0.5144	49914.4	53946.3	5	0.30	0.20	
0009-148	0009-148	2303	00	11	40.45587914	-14	34	4.6337440	.00005171	.0014628	0.2835	54111.9	54112.0	1			
0009+467	0009+467	1311	00	12	29.30290370	+47	04	34.7396084	.00004557	.0009570	-0.3786	53572.4	53572.5	1			
0009+655	0009+655	1312	00	12	37.67098190	+65	51	10.8235107	.00060065	.0039228	0.0430	53152.5	53152.6	1			
0010+336	0010+336	2304	00	12	47.38219160	+33	53	38.4715703	.00002447	.0005676	-0.3647	53502.7	53503.6	1			

Figure D-1: Page from X-Band Radio Source Catalog

ANNEX E

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.

Term	Meaning
CCSDS	Consultative Committee for Space Data Systems
Dec	Declination
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
IAU	International Astronomical Union
ICRF	International Celestial Reference Frame
ID	Identifier
IF	Interface
JAXA	Japan Aerospace Exploration Agency
JPL	Jet Propulsion Laboratory
Jy	Jansky
NASA	National Aeronautics and Space Administration
OD	Orbit Determination
RA	Right Ascension
RF	Radio Frequency
SANA	Space Assigned Number Authority
S/C	Spacecraft
SNR	Signal-to-Noise Ratio
VLBI	Very Long Baseline Interferometry

ANNEX F

INFORMATIVE REFERENCES

(INFORMATIVE)

[F1] *Delta-Differential One Way Ranging (Delta-DOR) Operations*. Issue 1.0. Proposed Draft Recommendation for Space Data System Practices (Proposed Pink Book), CCSDS 506.0-P-1.0. Washington, D.C.: CCSDS, February 2016.

[F2] *Delta-DOR—Technical Characteristics and Performance*. Issue 1. Report Concerning Space Data System Standards (Green Book), CCSDS 500.1-G-1. Washington, D.C.: CCSDS, May 2013.

[F3] *Delta-DOR Raw Data Exchange Format*. Issue 1. Recommendation for Space Data System Standards (Blue Book), CCSDS 506.1-B-1. Washington, D.C.: CCSDS, June 2013.