International Rendezvous System Interoperability Standards (IRSIS)

Baseline – March 2019

REVISION AND HISTORY

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PREFACE

INTERNATIONAL RENDEZVOUS SYSTEM INTEROPERABILITY STANDARDS (IRSIS)

This International Rendezvous System Interoperability Standards (IRSIS) is to establish standards to enable on-orbit crew operations, rendezvous and docking/berthing and collaborative endeavors utilizing different spacecraft in deep space.

Configuration control of this document is the responsibility of the Multilateral Coordination Board (MCB). The National Aeronautics and Space Administration (NASA) will maintain the IRSIS under Human Exploration and Operations Mission Directorate (HEOMD) Configuration Management. Any revisions to this document will be approved by the MCB.

INTERNATIONAL RENDEZVOUS SYSTEM INTEROPERABILITY STANDARDS (IRSIS)

CONCURRENCE

MARCH 2019

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1.0 INTRODUCTION

This International Rendezvous System Interoperability Standards (IRSIS) is the result of collaboration by the International Space Station (ISS) membership to establish interoperable interfaces, terminology, techniques, and environments to facilitate collaborative endeavors of space exploration in cislunar and deep space environments. These standards are available for international and commercial partnerships.

To date, only nation states have conducted successful human rendezvous and docking, an indication both of the costs and complexity involved. Rendezvous systems have also been highly customized and optimized as an integrated system for each mission. Examples exist throughout human spaceflight of rendezvous problems, starting in the 1960s with both Soviet and United States (U.S) programs, and continued through the ISS Program. All examples to date have relied on the implementing nation state controlling both sides of the interface, namely the passive and active vehicle rendezvous systems. In the case of an international standard, each interface must be adequately defined to assure full compatibility and cooperation between the rendezvous systems from many different providers.

Standards that are established and internationally recognized have been selected where possible to enable a variety of providers. Increasing commonality among providers while decreasing unique configurations has the potential to reduce the traditional barriers in space exploration: overall mass and volume required to execute a mission. Standardizing interfaces reduces the scope of the development.

The information within this document represents a set of parameters, which if accommodated in the system architecture support greater efficiencies, promote cost savings, and increase the probability of mission success. These standards are not intended to specify system details needed for implementation nor do they dictate design features behind the interface. Specific requirements will be defined in unique documents.

1.1 PURPOSE AND SCOPE

The purpose of the IRSIS is to provide basic common design parameters to allow developers to independently design compatible rendezvous operations that will enable the interoperability of different spacecraft in cislunar and deep space environments for human exploration missions and associated interfaces. The focus of this document version is on cislunar space missions and provides a starting point for future deep space missions. Implementation of the Rendezvous Standards should lower development cost, decrease operational complexity, and improve safety and mission success within the Rendezvous, Proximity Operations and Capture/Docking phases in spaceflight missions. Standardizing operational philosophy, flight phases, and terminology helps to enable international partnerships and other collaborations.

The scope of the IRSIS covers the following:

- Rendezvous: From an initial relative maneuver, up to first mechanical contact. This phase begins when the visiting vehicle (an active, or chase vehicle) is confirmed to be in an orbit established relative to the target vehicle's state/orbit. In this scenario, the crew transportation vehicles, crew transportation vehicles with co-manifested payload, logistics modules, sample return vehicles or lander ascent modules are the visiting vehicle, performing rendezvous operations with a target vehicle.

  - Departure operations are also included within the rendezvous concepts, and commence at vehicle separation.
  - The scope will also include nominal and off-nominal scenarios.
  - Rendezvous shall include all operations in close proximity to the target vehicle. These include docking port relocation and fly-around.

- Docking: Commences at nominal first mechanical contact, up through mating. An international standard docking interface has been defined in the International Docking System Standard (IDSS) Interface Definition Document (IDD) to ensure physical mating compatibility and keep out zones. Operations associated with docking are covered in the IDSS IDD.
- Berthing: Commences at nominal first mechanical grapple/grasp with robotic arm, up through mating. All robotic operations associated with berthing shall be covered by robotic operations documentation, starting after grapple.

1.2 RESPONSIBILITY AND CHANGE AUTHORITY

Any proposed changes to this standard by the participating partners of this agreement will be brought forward to the IRSIS working group for review.

Configuration control of this document is the responsibility of the Multilateral Coordination Board (MCB). The National Aeronautics and Space Administration (NASA) will maintain the IRSIS under Human Exploration and Operations Mission Directorate (HEOMD) Configuration Management. Any revisions to this document will be approved by the MCB.

2.0 DOCUMENTS

2.1 APPLICABLE DOCUMENTS

The following documents include specifications, models, standards, guidelines, handbooks, or other special publications. The documents listed in this paragraph are applicable to the extent specified herein.

None

2.2 REFERENCE DOCUMENTS

The following documents contain supplemental information to guide the user in the application of this document. These reference documents may or may not be specifically cited within the text of this document.

DSG-16-32	Rendezvous and Docking Standards Recommendation, ISS Exploration Capabilities Study Team – Rendezvous Standards Team, January 2017
IDSS-GUIDE-001	Navigation and Alignment Aids Concept of Operations and Supplemental Design Information, Revision A
IDSS IDD	International Docking System Standard (IDSS) Interface Definition Document (IDD), Revision E, October 2016
SSP 50808	International Space Station (ISS) to Commercial Orbital Transportation Services (COTS) Interface Requirements Document (IRD), Revision F, September 2014
SSP 50313	Display and Graphics Commonality Standard

3.0 INTERNATIONAL RENDEZVOUS SYSTEM INTEROPERABILITY STANDARDS

3.1 GENERAL

The goal of establishing standards and agreeing on other assumptions is to maximize the success of future human spaceflight missions conducted as international partnerships. The ability of components, systems, or vehicles delivered from multiple sources to work together as an effective system is important to the success of actual missions. Good collaboration can make technology development and system maturation more efficient, by sharing the lessons learned and failures that drive standards. Using standard assumptions can also make development more efficient by making tests conducted by one partner relevant and valid to multiple partners.

This document is focused on issues that drive system performance and on issues that most directly affect interoperability between systems.

3.1.1 DESCRIPTION

The following subsections describe the system interfaces for the IRSIS.

Rendezvous, regardless of whether it is automated or conducted by crew, is among the most challenging operations during a spaceflight mission. Failure to rendezvous and dock has implications for mission success and crew survival.

Terminology has also been traditionally customized to each Program. This results in reduced operational carry over between Programs, and lost opportunity. Even within a Program, the terminology can be different from vehicle to vehicle. Intent of this standard is to ensure all participants are communicating the same message, thereby reducing risk to the Program(s).

Rendezvous techniques are limited by orbital mechanics and vehicle characteristics, however there are still large variations between the techniques across current users.

3.1.2 ENGINEERING UNITS OF MEASURE

All dimensions are in International System of Units (SI units) (metric).

All linear dimensions are in meters. All angular dimensions are in degrees. Unless otherwise specified, the dimensional tolerances shall be as follows:

- xx implies xx ± # m,
- xx.x implies xx.x ± 0.1 m,
- xx° implies xx° ±30’.

3.1.3 RENDEZVOUS DEFINITIONS

The following subsections describe the definitions of the terms to be used in the context of spacecraft rendezvous.

3.1.3.1 PHASES

Explanation of the different flight phases as part of a standard assures both consistent application of terms but also assures common operations for joint missions. The phases pair fairly close with the decision points. Objective is to clarify the high-level phases to avoid confusion when discussing these terms.

- **Launch and Insertion** – This phase begins at ignition for launch and ends when the visiting vehicle (VV), also referred to as the chaser, is confirmed to be ready for trans-lunar injection (TLI) burn. The goal of this phase is to deliver the visiting vehicle into a TLI point. During this phase, the visiting vehicle control teams typically operate independently with some basic planning and data coordination being performed with the target spacecraft's control team (e.g. state vector and maneuver plan exchange, communication coverage planning, timeline planning).
- **Transfer** – This phase begins when the visiting vehicle is confirmed to be ready for TLI and ends when it is confirmed to be in an orbit established in cislunar space. The goal of this phase is to move the visiting vehicle from Earth orbit to cislunar orbit, or from a cislunar orbit to Earth orbit. During this phase, the visiting vehicle control team typically operates independently with some basic planning and data coordination being performed with the mission control team (e.g. state vector and maneuver plan exchange, communication coverage planning, timeline planning). For transit to the cislunar orbit, the target vehicle and visiting vehicle control teams will begin integrated operations toward the end of this phase to support the "GO for Rendezvous Orbit Entry" decision.
- **Rendezvous** – This phase begins when the visiting vehicle is confirmed to be in an orbit established in cislunar space relative to the target vehicle and ends at docking/berthing start.
  - **Far Rendezvous** – This phase brings the visiting vehicle closer to the target vehicle, while still protecting the ability to passively abort the approach on a trajectory that is operationally safe. Space-to-space communications has been confirmed and that the visiting vehicle has transitioned to relative navigation. The decision to NO-GO the Approach Initiation (AI) burn would result in committing to either visiting vehicle disposal, visiting vehicle return to Earth, or visiting vehicle re-rendezvous.
  - **Close Rendezvous** – Includes the operations within the approach sphere (reference Figure 3.1.3.2-1, Notional Concept of Zones and Corridors):
    - **Approach** - During this phase the visiting vehicle transitions to the approach axis while staying outside the Keep-Out Sphere (KOS). Once the visiting vehicle has reached the approach axis, it then enters the KOS while staying within the pre-analyzed approach corridor.
    - **Fly-around** – Consists of a visiting vehicle maneuver during approach or departure in which the visiting vehicle transitions to another approach axis, or circumnavigates the target vehicle and returns to an approach axis.
- **Proximity Operations** (Prox Ops) – This phase encompasses multiple phases defined above: final approach, fly-around, and undocking and departure. This is

used extensively within the NASA ISS community to cover all maneuvers performed within the Approach Sphere (AS).

- **Docking** – Defined as the docking mechanism contact, capture and hard-mate. Docking begins at the time of initial contact of the vehicles' docking mechanisms and concludes when hard-mating hooks/latches have been fully engaged. After first contact, rendezvous phase is complete. This phase is owned by the docking mechanism.
- **Berthing Capture** - Defined as the physical robotic capture of the visiting vehicle. Rendezvous phase is completed at first contact. This phase is owned by the robotics operations.
- **Undocking** – Defined as the physical separation of the two vehicles.
- **Release** – Defined as the physical release by the robotic arm of the visiting vehicle.
- **Departure** - For release and departure, the phase commences upon physical separation, either docking mechanism push-off or grapple release, from the target spacecraft (host platform). This phase is complete when the visiting vehicle is confirmed to be departing on a trajectory that is operationally safe and the visiting vehicle is outside the AS.
- **Retreat** – Defined as the visiting vehicle increasing its relative range with respect to the target spacecraft, aiming at a predefined hold point.
- **Hold** – In this phase, the visiting vehicle maintains its relative position with respect to the target spacecraft such that it neither approaches nor retreats from the target.
- **Free Drift** – In this phase, the target vehicle’s and the visiting vehicle’s translational and rotational control are inhibited. This phase is initiated at first contact for docking, or at visiting vehicle command for berthing.
- **Abort** – This phase is initiated automatically or by crew (chaser or target) for the visiting vehicle to perform a separation sequence (thruster firing), which places the visiting vehicle on a safe trajectory departing from the target.

3.1.3.2 OPERATIONAL REGIONS AND ZONES

The visiting vehicle will not enter the following regions prior to a predefined maneuver that takes the visiting vehicle inside those regions. To manage the risk associated with rendezvous operations, four regions have been defined. These regions are used as references to determine when critical events will occur. The items below provide an initial design point for developing the operational regions and zones for rendezvous and docking. The regions are as follows, and are depicted in Figure 3.1.3.2-1, Notional Concept of Zones and Corridors. The exact implementation will be dictated by the visiting vehicle’s capabilities and mission objectives. The results of the changes to these zones will be included in programmatic documents.

1. Rendezvous Sphere (RS) – The RS is a 10 kilometer (km) **<TBC 3-1>** radius sphere around the target spacecraft’s center of mass and is used to govern the Rendezvous Entry (RE) decision. A shape larger than the AS is needed to balance the risk

associated with the large dispersions expected from the RE burn, to ensure target vehicle safety.

2. Approach Sphere (AS) – The AS is a 1 km **<TBC 3-2>** radius sphere centered at the target vehicle center of mass.

3. Keep-out Sphere (KOS) – The KOS is 200 meter (m) **<TBC 3-3>** radius sphere centered at the target vehicle center of mass.

4. Approach/Departure Corridors – The Approach and Departure corridors are ±10° **<TBC 3-4>** centered to the docking port axis within the KOS.

Rationale: For the cislunar orbits (Near Rectilinear Halo Orbit (NRHO), Distant Retrograde Orbit (DRO), Earth-Moon LaGrange Orbit 2 (E-M L2) Halo, etc.), safety regions will be defined based on relative dynamics, configuration of the spacecraft, and navigation accuracy (both target vehicle and visiting vehicle). Safety regions are critical to contributing to mission safety and success, and have an impact of expected performance of Guidance, Navigation, and Control (GN&C). The intent is to have common zones/regions for all vehicles performing Rendezvous, Proximity Operations and Docking (RPOD) with a target vehicle.

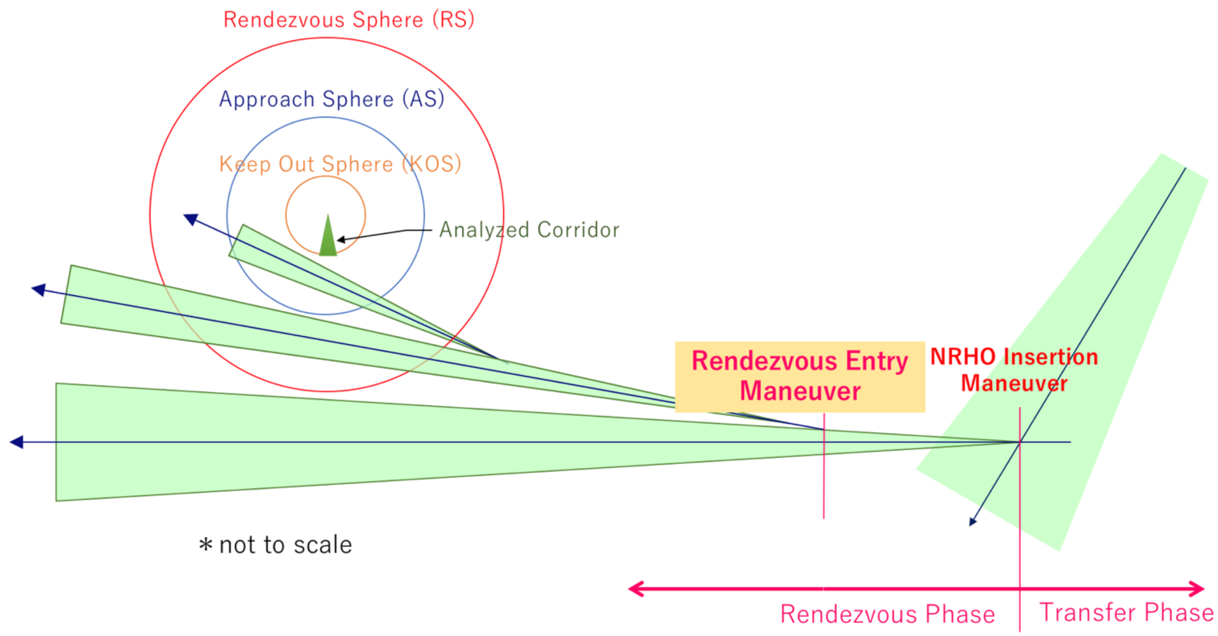

FIGURE 3.1.3.2-1 NOTIONAL CONCEPT OF ZONES AND CORRIDORS

3.1.3.3 INTEGRATED OPERATIONS

Integrated operations refers to the mode of authority structure used by the operations team, in which all commanding is approved through the lead control center. Integrated operations begin before the visiting vehicle is on a trajectory that will enter the AS, and terminate when the visiting vehicle is outside the AS and confirmed to be on a safe free drift trajectory.

3.1.3.4 DECISION POINTS

To execute a visiting vehicle mission to or from the target vehicle, there will be a series of decisions that start with the mission management team and then will be handed off to the operations team and the visiting vehicle. Time delay considerations need to be accounted for in the decision process. Decision points are vehicle specific, defined by trajectory design and visiting vehicle's performance. Decision points are common across all participants:

1. **Element Readiness** (Program Level Decision)
2. **GO for Rendezvous Entry** – The visiting vehicle will transition to an orbit established in cislunar space before beginning the rendezvous operation. "Go" enables visiting vehicle to continue operations into the RS.
3. **GO for Approach Initiation** – The AI burn is the first burn that is allowed to target into the AS.
4. **GO for Final Approach** – This decision allows the vehicle to proceed inside the KOS, but requires that the vehicle stay within a predefined approach corridor.
5. **GO for Docking/Capture** – This is the final decision to allow the vehicles to have contact. For cis-Martian operations this decision may ultimately be combined with the GO for Final Approach (to accommodate communication delay if decision is Earth/Mission Control Center (MCC) based).
6. **GO for Undock/Release** – This decision will result in the visiting vehicle returning to free flight.
7. **GO for Return** – This decision implies that the vehicle has implemented a hold point or abort compliant with the KOS/AS/RS constraints. Returning to the target vehicle shall be compliant with nominal approach constraints, as defined above.

3.1.3.5 CHECK POINTS

The visiting vehicle approach trajectory will include predefined points where the visiting vehicle will not proceed on the approach if it has not received "GO" command from the associated ground operator, target vehicle crew or the visiting vehicle crew. The visiting vehicle may have additional non-mandatory checkpoints, where an approaching or separating vehicle may perform additional actions such as station-keeping, wait for additional "go/no-go" decisions, or perform trouble-shooting in contingency situations.

Note:

- Check points are vehicle specific, defined by trajectory design and visiting vehicle's performance.
- Check points may be added at the discretion of each visiting vehicle.

Rationale: In order not to limit the development of each visiting vehicle, design of check points should not be standardized as is the case of ISS rendezvous. However, the guidelines for designing check points should be standardized to increase the mission safety.

3.2 INTERFACES

Unless otherwise stated, the features called out in this section and its subsections shall be implemented on IRSIS systems. These are standards to ensure IRSIS compatibility between systems of different origin. Each standard is specified only once with its required value and tolerance (if applicable).

3.2.1 OPERATIONAL PRINCIPLES/PROCEDURES

3.2.1.1 COORDINATE SYSTEMS

Coordinate systems are required to convey spacecraft location and properly exchange information.

3.2.1.1.1 CELESTIAL COORDINATE SYSTEMS

Inertial reference frames are required to understand the location and pointing of each spacecraft, in absolute and relative states. This Standard will utilize the International Celestial Reference Frame (ICRF), which is in itself a recognized international standard, and maintained by the International Earth Rotation and Reference Systems service.

International Celestial Reference System (ICRS): This system is intended to serve as the inertial reference system and its location is determined with respect to hundreds of celestial quasar sources.

- *Origin*: The origin is at the barycenter of the solar system, at a chosen epoch (usually J2000).
- *X-axis*: Points to the vernal equinox at epoch,
- *Y-axis*: In the Earth-Sun equatorial plane completed by Y = Z x X,
- *Z-axis*: Points to the Earth's celestial North Pole at epoch.

Earth Centered Inertial Frame (J2000): This frame is practically aligned with the ICRS with axis deviation in the range of 5.1 milli-arc second. Figure 3.2.1.1.1-1, J2000, Mean of 2000, Cartesian, displays the Earth centered inertial frame.

- *Origin*: Earth's center,
- *X-axis*: Pointing to the vernal equinox at Epoch J2000,
- *Y-axis*: In the Earth-Sun equatorial plane completed by Y = Z x X,
- *Z-axis*: Points to the celestial north pole at Epoch J2000.

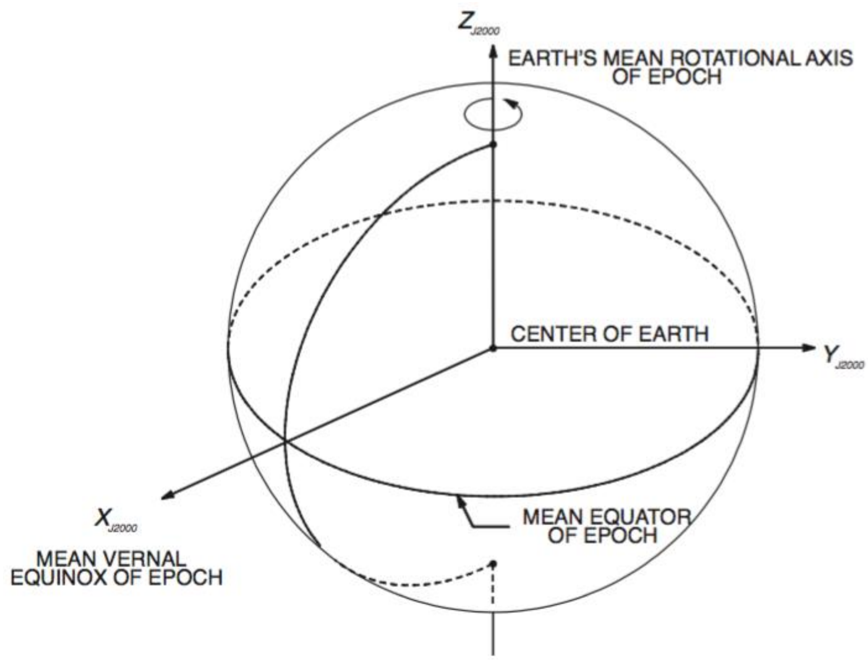

FIGURE 3.2.1.1.1-1 J2000, MEAN OF 2000, CARTESIAN

Lunar Centered Inertial (LCI) Frame: This frame is inertial with the X and Y axes in the Moon orbital plane around the Earth. It must be defined at a particular epoch, since the moon's orbit plane precesses in the ecliptic.

- *Origin*: Center of the Moon,
- *X-axis*: At the ascending node of the lunar orbital plane to the earth's equatorial plane at epoch,
- *Y-axis*: In the Moon orbital plane completed by Y = Z x X,
- *Z-axis*: Normal to the moon's orbital plane at epoch.

Synodic Rotating Frame (SRF): This is a rotating frame located along the Earth-Moon line. It is used for reference and definition of other frames. (This is also known as the Earth-Moon Rotational (EM-ROT) frame.)

- *Origin*: At the Cislunar Lagrange point on the Earth-Moon line,
- *X-axis*: Along the Earth-Moon line pointing from the Earth to the Moon,
- *Y-axis*: In the Moon orbital plane completed by Y = Z x X,
- *Z-axis*: Normal to the lunar orbital plane in the celestial north direction.

Sun Referenced Local Vertical Local Horizontal (LVLH) <TBR 3-1>: This is the primary frame used to represent all the relative motion dynamics and kinematics, see Figure 3.2.1.1.1-2, Sun Referenced LVLH. It will be the same frame used for the rendezvous and docking. The definition will be valid for NRHOs whose instantaneous orbital plane can be defined with respect to the SRF.

- *Origin*: Target spacecraft center of mass,
- *Z-axis*: The Z axis lies along the heliocentric radius vector to the target vehicle and is positive toward the center of the Sun,
- *Y-axis*: The Y axis is normal to the orbit plan and points along the negative instantaneous angular momentum vector of the target vehicle,
- *X-axis*: The X axis completes the right-handed orthogonal system. It lies in the target vehicle orbital plane and is positive in the direction of vehicle motion.

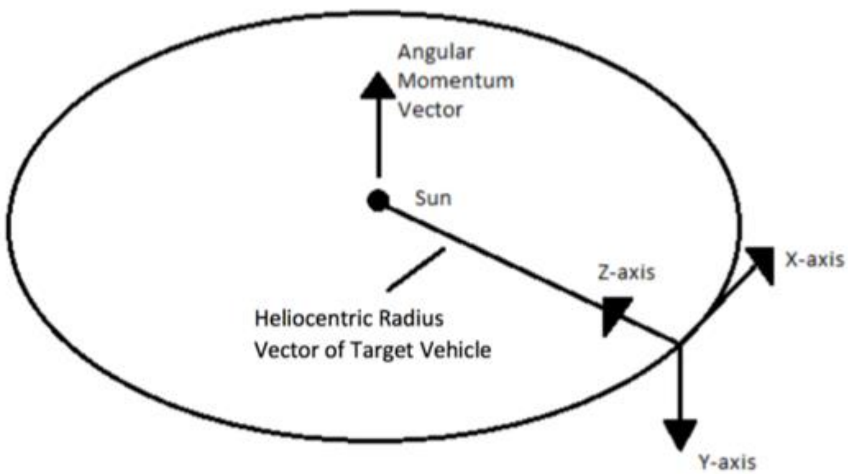

FIGURE 3.2.1.1.1-2 SUN REFERENCED LVLH

Orbital Frame (ORB): This frame is mostly used to define the position of the spacecraft on the respective orbits.

- *Origin*: The orbital focal point, Moon or Lagrange,
- *X-axis*: From the focal point in the orbital plane to the location of the spacecraft, measured at an angle from the ascending node,
- *Y-axis*: Completed by Y = Z x X,
- *Z-axis*: Same as the Z-axis of the LCI frame.

3.2.1.1.2 VEHICLE COORDINATE SYSTEMS

Spacecraft based coordinate systems will include structural, body, docking, and grapple fixtures (if applicable) at a minimum. Corridors and keep out zones are tied to vehicle reference frames.

Geometrically Fixed Frame (GFF) <TBR 3-2>: This frame is used to specify the location of equipment on the spacecraft and serves as the main mechanical reference.

- *Origin*: Located at the intersection of the longitudinal axis of the spacecraft with the docking port hard capture surface,
- *X-axis*: Parallel to the longitudinal axes of the spacecraft and forward pointing from the docking port,
- *Y-axis*: Parallel to a line orthogonal to the longitudinal axis and going through the point between the 2 Solar Array Drive Mechanisms (SADM)s on port side,
- *Z-axis*: Z = X x Y.

Spacecraft Body Frame: Used for the dynamics and kinematics of the spacecraft.

- *Origin*: Spacecraft center of mass (COM),
- *X-axis*: Parallel to the GFF_x,
- *Y-axis*: Parallel to the GFF_y,
- *Z-axis*: Parallel to the GFF_z.

Metrology Frame: This is the sensor frame in which the range and Line of Sight (LOS) is measured. The frame is ideally parallel to the GFF, but might have a rotation matrix to account for sensor orientation/pointing with respect to the docking axis.

- *Origin*: The origin is specified in the GFF and located likely at the center of the sensor’s measurement datum/reference,
- *X-axis*: Ideally parallel to the GFF_x,
- *Y-axis*: Ideally parallel to the GFF_y,
- *Z-axis*: Ideally parallel to the GFF_z.

Chaser Docking (DC) Frame <TBR 3-3>: The docking mechanism coordinate systems are defined in IDSS IDD. Refer to Section 3.3.1.1 in the IDSS. The chaser docking frame in this case is “active docking system” per the IDSS IDD.

3.2.1.1.3 TARGET VEHICLE COORDINATE SYSTEMS

Target Vehicle Analysis Coordinate System (TACS) (shown below in Figure 3.2.1.1.3-1) <TBR 3-4>:

- *Origin*: Located at center of the forward docking interface, at the center of the docking mechanism hard capture surface (HCS),
- *X-axis*: Perpendicular to the HCS, and positive in the direction of the spacecraft assembly stack,
- *Y-axis*: Parallel to the centerline normal vector of the radial docking port on Starboard side,
- *Z-axis*: Parallel the HCS, and positive between the fine alignment pin and guide on the docking mechanism.

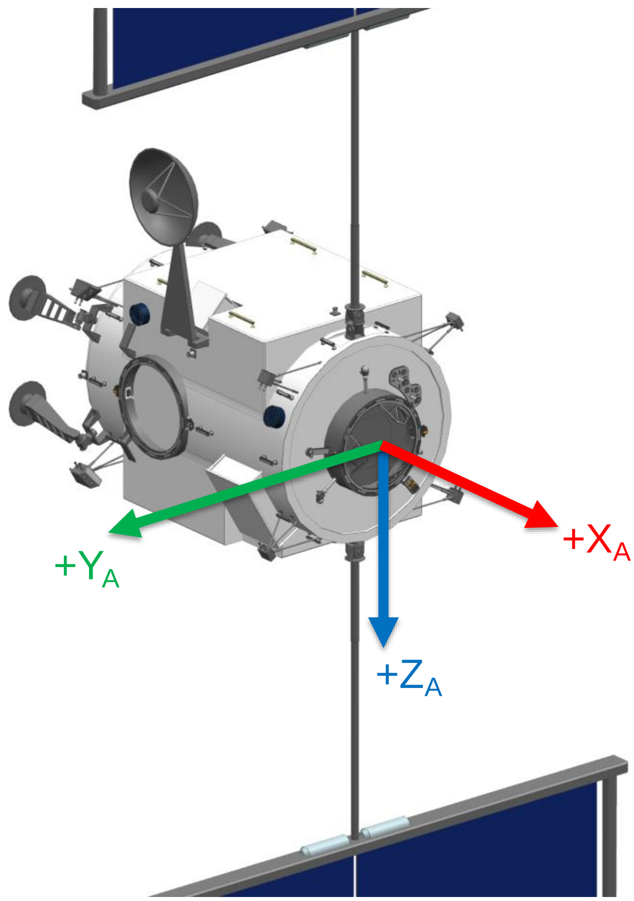

FIGURE 3.2.1.1.3-1 TARGET VEHICLE ANALYSIS COORDINATE SYSTEM

Target Vehicle Body Frame <TBR 3-5>: Used for the dynamics and kinematics of the spacecraft including its attitude with respect to the inertial or LVLH frames.

- *Origin*: Spacecraft COM,
- *X-axis*: Parallel to the $TACS_x$,
- *Y-axis*: Parallel to the $TACS_y$,
- *Z-axis*: Parallel to the $TACS_z$.

Target Docking Frame Longitudinal <TBR 3-6>: The docking mechanism coordinate systems are defined in IDSS IDD. Refer to Section 3.3.1.1 in the IDSS. The chaser docking frame in this case is “passive docking system” per the IDSS IDD. The “longitudinal” term is for a docking port that points to forward or aft along the longitudinal axis of the target spacecraft.

Target Docking Frame Radial <TBR 3-7>: The docking mechanism coordinate systems are defined in IDSS IDD. Refer to Section 3.3.1.1 in the IDSS. The chaser docking frame in this case is “passive docking system” per the IDSS IDD. The “radial” term is for a docking port that points to starboard, port, nadir or zenith with respect to the longitudinal axis of the target spacecraft.

3.2.1.2 TIME INFORMATION

RDV-001: A synchronized, unified time information shall be maintained by all vehicles in the overall architecture, including visiting vehicles as well as the target vehicle.

Note: The target vehicle maintains the orbit master clock with the Ground master clock providing synchronization pulse, and the synchronization pulse is also received by the visiting vehicle. Once vehicles are within inter-vehicle communication range, the times are exchanged and the offsets are computed. The notional concept is depicted in Figure 3.2.1.2-1, Proposed Time Distribution Architecture. It is anticipated that time synchronization is worked through a Systems Engineering and Integration (SE&I) process that includes the Communications and Tracking, Avionics, and Rendezvous teams to ensure proper time synchronization across the whole system.

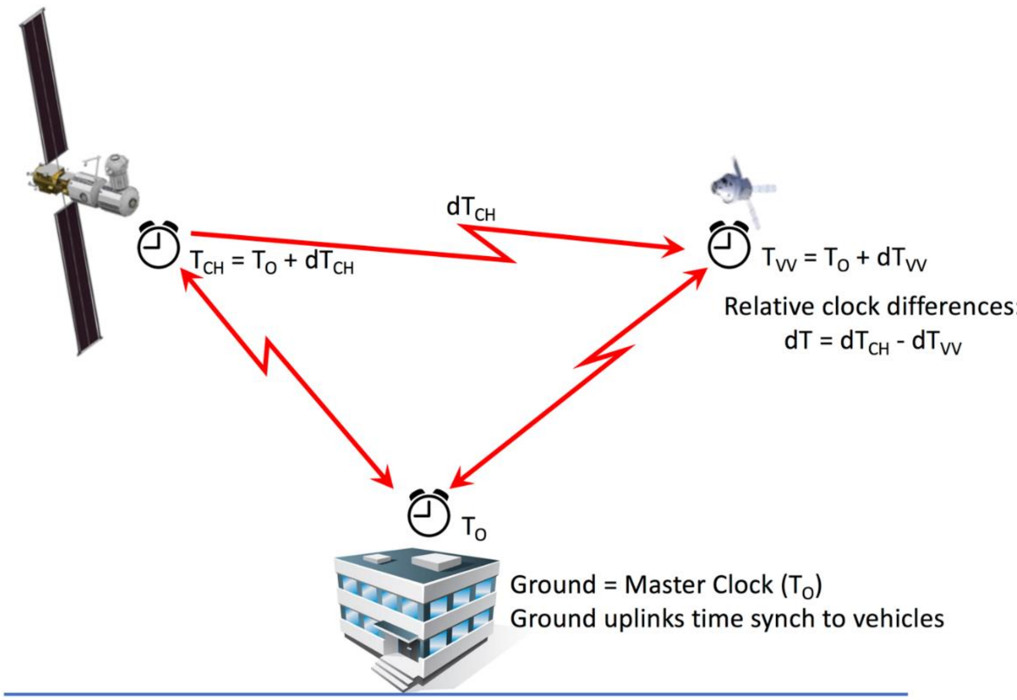

FIGURE 3.2.1.2-1 PROPOSED TIME DISTRIBUTION ARCHITECTURE

3.2.1.3 SAFETY GUIDELINES

Standard safety guidelines should be defined and agreed to amongst all partners. The visiting vehicles should have the following capabilities and/or data:

- Rendezvous sensors (e.g. cameras and light detection and ranging (LIDAR)) are single fault tolerant,
- Independent and dissimilar sensor cross-check,
  - Range and range-rate data,
  - For docking, six degrees of freedom (6-DOF) data (relative position and relative attitude) at least 15 meters prior to and through to docking,
  - For automated berthing/capture, 6-DOF data at least 15 meters prior to through arrival and maintaining state in the berthing box.
- Crew monitoring consisting of telemetry and video, and for crewed vehicles will include audio.

3.2.2 TRAJECTORY SAFETY

3.2.2.1 APPROACH SPHERE (AS)

See definition in Section 3.1.3.2.

RDV-002: Prior to the visiting vehicle's AI maneuver, all visiting vehicle coast trajectories shall not intercept the AS for a minimum of 24 hours **<TBC 3-5>**. This ensures the target vehicle is safe from a visiting vehicle's free-drift trajectory.

Rationale: In order to ensure the target vehicle safety, specifying a 24-hour safe free drift trajectory will require analysis that visiting vehicle will not collide with target vehicle if there are failures rendering the vehicle inoperable.

3.2.2.2 KEEP OUT SPHERE (KOS)

See definition in Section 3.1.3.2.

RDV-003: The KOS shall only be entered via the approach corridor after authority to proceed (ATP) has been granted.

Note: Fly-around inside KOS will be along a pre-defined corridor (that has been analyzed and authorized).

3.2.2.3 ABORT

RDV-004: The visiting vehicle shall be capable of execute abort commands issued automatically by its onboard systems, initiated by the onboard crew, or by external commands (from target vehicle crew or from ground controllers) that places the visiting vehicle on a 24-hour safe free drift trajectory **<TBC 3-6>**.

Note:

- In ISS Rendezvous, Passive Abort (PA) and Collision Avoidance Maneuver (CAM) are defined. The visiting vehicle must be able to execute a CAM at all times for all mission phases. During a CAM, the vehicle must stop closing (decreasing relative range) and then establish an opening rate (increase relative range). For ISS rendezvous, a CAM must put the vehicle on a 24-hour safe free drift trajectory. The safe free-drift trajectory duration for cislunar and deep space operations needs to be defined based on vehicle kinematics/dynamics.
- It should be considered to have a CAM capability issued from the target vehicle to the visiting vehicle (in particular when supporting rendezvous operations with a small robotic element such as the lunar ascent stage) to ensure spacecraft safety.

Rationale: In order to ensure the target vehicle safety, automatic abort functions would be necessary as is the case in ISS rendezvous. Standard rules for abort operations would increase mission safety.

3.2.2.4 CORRIDORS

RDV-005: The target vehicle shall have corridors, which will be used during rendezvous.

Rationale: Several "corridors" are defined for ISS visiting vehicles. The ISS crew has to be informed/trained of the differences in their sizes due to vehicle dynamics and capabilities. Having a standard corridor definition will minimize crew burden. Tailoring of initial corridors will be dependent on vehicles' dynamics, system capabilities and environment.

3.2.2.4.1 APPROACH CORRIDOR

See definition in Section 3.1.3.2.

RDV-006: The visiting vehicle's approach to the target vehicle within the KOS shall be within a predefined corridor, standardized for all visiting vehicles.

Corridor sizing and definition will follow guidelines, utilizing information such as docking contact conditions (IDSS requirements), mass properties, velocity profile, vehicle dynamics, vehicle keep out zones, structural clearance, etc. The initial approach corridors will be defined that apply to all incoming vehicles to minimize multiple corridor definitions, with tailoring and adjustments per the vehicle's design.

Rationale: In ISS rendezvous, all visiting vehicles are required to approach the ISS, when inside the KOS, within the approach corridor. Each visiting vehicle had a unique approach corridor, documented in the interface control document (ICD) that was based on the vehicle's capabilities and operations. The approach corridor was used by ISS crew and ground operators to monitor the vehicle performance and determine if any action was required.

3.2.2.4.2 DEPARTURE CORRIDOR

See definition in Section 3.1.3.2.

RDV-007: The visiting vehicle shall depart from the target vehicle within the predefined corridor specified for each visiting vehicle.

Rationale: In ISS departures, all visiting vehicles were/are required to depart from the ISS within agreed to corridors, which were defined mainly by the monitoring capability of the ISS and the visiting vehicle's performance. The departure corridor was used by ISS crew and ground operators to monitor the vehicle performance and determine if any action was required.

3.2.2.4.3 RELOCATION CORRIDOR

RDV-008: The visiting vehicle shall perform docking port relocation in a predefined corridor with respect to the target vehicle.

The relocation corridor is a combination of approach corridor, departure corridor and a fly-around corridor inside the KOS. Exact sizing will account for target spacecraft elements (module size/shape, and articulating appendages such as solar arrays and communications antennas) and visiting vehicle sizing and dynamics.

Note: An example of ISS docking port relocation is shown below in Figure 3.2.2.4.3-1, ISS Russian Vehicle Relocation Corridor. The Russian docking port relocation corridor is within the ISS KOS.

Rationale: Configuration of the relocation corridor(s) should be standardized to ensure spacecraft safety. These will be a function of appropriate orbit(s) and vehicle dynamics.

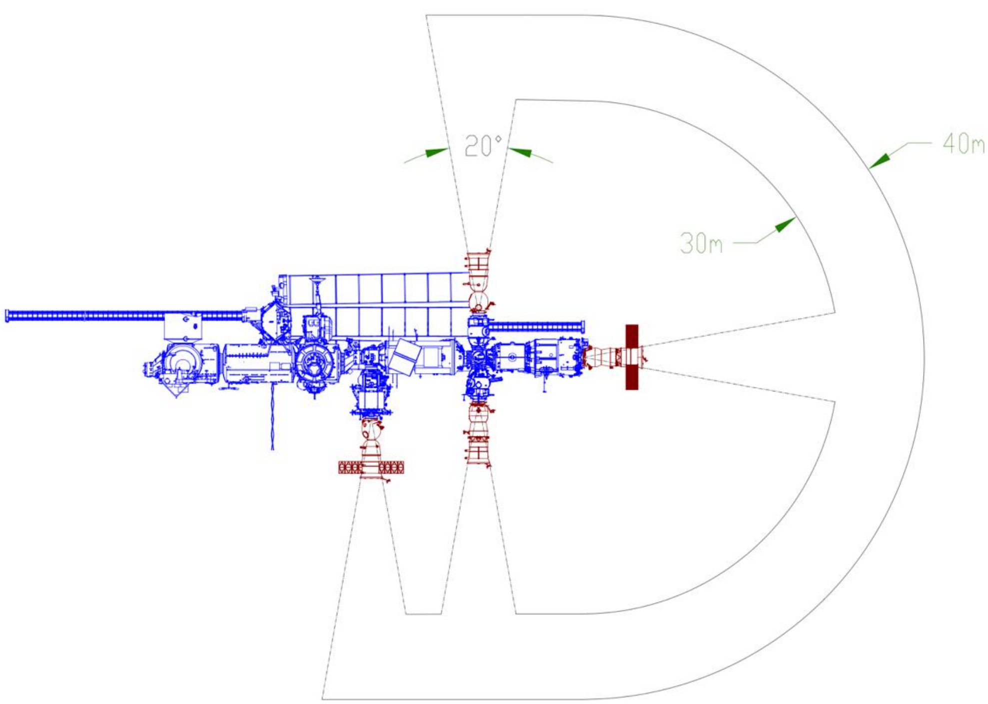

FIGURE 3.2.2.4.3-1 ISS RUSSIAN VEHICLE RELOCATION CORRIDOR

3.2.2.4.4 ABORT CORRIDOR

The following subsections describe the various abort corridors. Figure 3.2.2.4.4-1, Abort Corridor Definitions, shows the relationship between the multiple abort corridors.

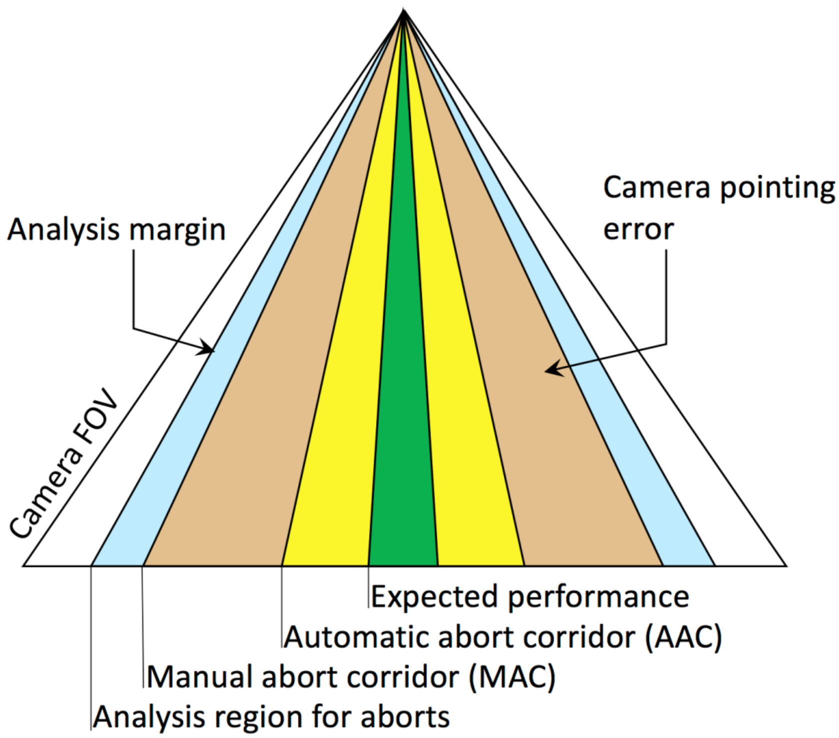

FIGURE 3.2.2.4.4-1 ABORT CORRIDOR DEFINITIONS

3.2.2.4.4.1 AUTOMATIC ABORT CORRIDOR (AAC)

RDV-009: When visiting vehicle flies in automated mode, the visiting vehicle shall monitor the predefined "Automatic Abort Corridor" and perform an abort automatically if it senses a corridor violation.

RDV-010: The initial upper limit of the AAC shall be ±7.5° **<TBC 3-7>**.

Refinement of the automatic abort corridor will be determined via Monte Carlo analysis with 3-sigma trajectory dispersions. The abort corridor represents the vehicle's analyzed space with margin to ensure target vehicle safety while aiming mission success.

3.2.2.4.4.2 MANUAL ABORT CORRIDOR (MAC)

RDV-011: Any spacecraft crew (visiting vehicle or target vehicle), or ground operator shall monitor a predefined "Manual Abort Corridor".

RDV-012: Any spacecraft crew (visiting vehicle or target vehicle), or ground operator shall execute an abort command to the visiting vehicle if they observe a violation of the manual abort corridor.

RDV-013: The initial size of the MAC shall be ±10° **<TBC 3-8>**.

Rationale: The size of MAC must be larger than the AAC, plus monitoring errors (camera pointing errors, attitude errors, etc.), yet smaller than the monitoring capability (i.e. smaller than the camera Field-of-Views (FOV)s).

3.2.2.5 MATING ENVELOPES

3.2.2.5.1 DOCKING ENVELOPE

Refer to the IDSS IDD, Table 3.3.1.1-2, Initial Contact Conditions. The docking envelope is comprised of closing rate, lateral rate, pitch/yaw rate, roll rate, lateral misalignment, pitch/yaw misalignment and roll misalignment.

3.2.2.5.2 CAPTURE ENVELOPE

RDV-014: The process for formulation of the robotic capture envelope shall be defined for robotically captured vehicles, utilizing the following items should be included when developing the capture envelope: robotic arm reach, visiting vehicle dynamics/control (station keeping, jet firing history, plume, navigation sensor, etc.), visiting vehicle grapple fixture location, and vehicle observability (visual alignment and monitoring). **<TBD 3-1>**

RDV-015: The vehicle shall remain within the following volume during a capture attempt, as presented in Figure 3.2.2.5.2-1, Notional Free Flyer Capture Volume Definition (CSA-GWY-CDD-001). **<TBD 3-2>**

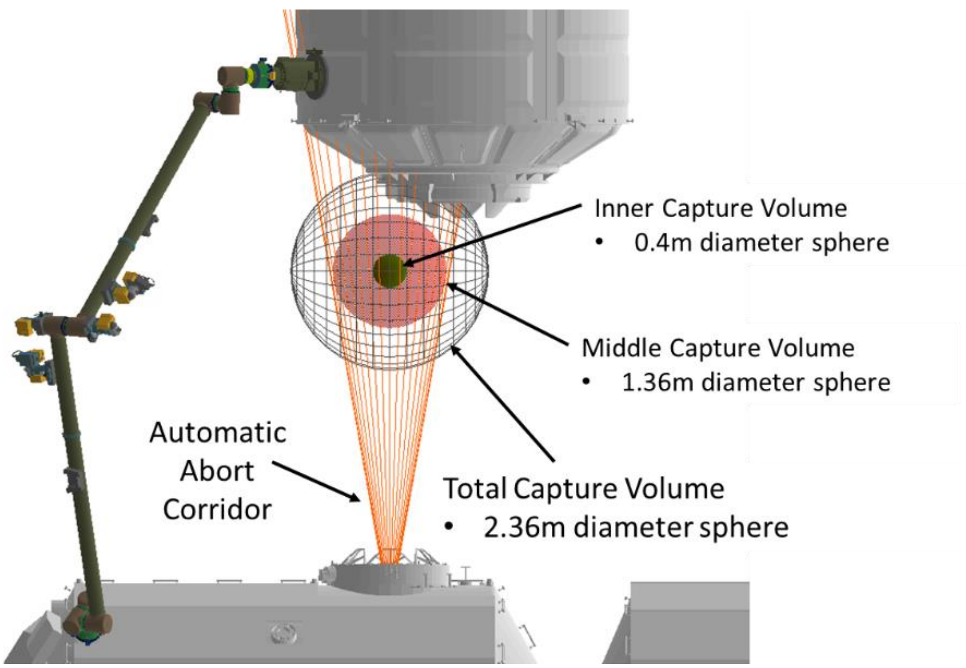

FIGURE 3.2.2.5.2-1 NOTIONAL FREE FLYER CAPTURE VOLUME DEFINITION (CSA-GWY-CDD-001)

Complete information and rationale can be found at Section 7.5.1 of CSA-GWY-CDD-001.

3.2.2.5.3 RESIDUAL DRIFT RATES FOR BERTHING OPERATIONS

RDV-016: The net velocity of the visiting vehicle shall be less than 8 millimeters per second (mm/s), root sum squared (RSS) **<TBC 3-9>**.

RDV-017: The net angular velocity shall be less than 0.04 degrees per second (deg/s) RSS **<TBC 3-10>** for the duration of the capture operation.

Note: These values are to be measured from the visiting vehicle center of mass to the docking system reference frame or the grapple fixture. These values will be used for the initial design space and analysis for robotic capture during berthing operations.

RDV-018: The visiting vehicle grapple fixture shall be 3.75 m or less from the vehicle’s center of mass.

3.2.2.5.4 DEPARTURE/RELEASE POINT

Departure/release point will be jointly developed by External Robotics and Rendezvous. The release point will utilize similar information to that used to inform the capture envelope.

3.2.2.6 SAFETY CLEARANCE

3.2.2.6.1 STRUCTURAL CLEARANCE

RDV-019: The structural safety clearance shall be 1 meter **<TBC 3-11>** specific to the particular docking port.

Note: Structural safety clearance will have static and dynamic clearances, based on the spacecraft’s configuration, docking mechanisms and attachment points.

Rationale: For collision avoidance, minimum clearance between the structure of the visiting vehicle and the target should be defined.

Structural safety clearance has an impact on the visiting vehicle’s design. Agreeing on clearances early on, contributes to reducing the development cost of the visiting vehicle.

3.2.2.6.2 PLUME IMPINGEMENT AND CONTAMINATION

Plume impingement and contamination joint analysis process should be done at System Engineering and Integration level, not at the Rendezvous Standards level. The plume impingement/contamination requires exchange of vehicle requirements, thruster models and capabilities during the project design, and are used to perform cyclical analyses, that enable design modifications to minimize impacts to the target spacecraft. Listed below are the necessary data products and analyses that will determine the impacts to the target vehicle and visiting vehicle trajectory.

1. Data: visiting vehicle thruster plume model, thruster locations and orientations.
2. Trajectory: visiting vehicle relative trajectory (Monte Carlo analysis) that includes jet firing histories (jets fired, pulse-width, etc.). Each corridor (docking port) shall be analyzed. Contingency cases shall also be included (thruster failures, sensor failures, capture failures, etc.).
3. Analyses: The trajectories with plume models are analyzed to determine the impacts on target vehicle.
    a. Objective is to determine if the loads (force and torques on the appendages, and thermal loads) are within acceptable loads on target vehicle (articulating elements such as solar arrays). If loads unacceptable, provide feedback to trajectory design for changes and repeat the cycle (steps 2 and 3).
    b. Erosion and contamination effects are analyzed for undue harm/stress to the target spacecraft.

Rationale: Since plume impingement from the visiting vehicle may impact the trajectory of the target vehicle, pressure and thermal input due to plume impingement should be restricted to the acceptable amount. Need to include impacts of target vehicle onto visiting vehicle.

3.2.2.7 SECONDARY STATE DETERMINATION

For vehicles that implement a secondary state determination system for validation and sensor cross-check, the following standards are provided. The intent of the secondary state determination system is to enable crew or vehicle systems to cross-check the primary navigation performance against an independent source.

RDV-020: Assessment of vehicle’s relative navigation correctness shall be performed, based on the independent and dissimilar navigation data computed in the secondary state determination.

RDV-021: Dissimilar, secondary state determination shall be implemented in addition to the visiting vehicle’s main navigation loop.

RDV-022: Secondary navigation data shall be used for safety assessment.

Secondary navigation data can be used for main data navigation verification.

Secondary state navigation can be used to perform automated rendezvous. In this case, the source of navigation data shall be redundant with the primary navigation data.

RDV-023: The source of secondary state navigation data shall be located on the target vehicle; however, secondary state determination can be hosted on the visiting vehicle.

RDV-024: Secondary state navigation data shall be accessible in the place of determination. This implies that it can be used where it is derived, be that on the target vehicle or on the visiting vehicle.

RDV-025: Secondary state navigation data shall be determined at hold/check/decision points and during safety critical phases according to safety guidelines defined in 3.2.1.3.

RDV-026: Secondary state navigation shall determine relative range, bearing, and range rate at longer ranges, and relative position while in the approach corridor during final approach.

RDV-027: Secondary state navigation shall determine full 6-DOF relative state during the last stage of final approach from 20 m **<TBC 3-12>** to docking or autonomous capture.

RDV-028: Secondary state navigation data delay and frequency shall not prevent fulfilling safety requirements.

RDV-029: Secondary state data shall be time tagged.

Rationale: Safe joint operations require a secondary, dissimilar relative navigation data. This data is used by crew (visiting vehicle and/or target vehicle, where applicable) to evaluate the visiting vehicle's navigation performance. Maintaining a secondary system on visiting vehicle can impact vehicle design.

3.2.3 INTER-VEHICLE TELEMETRY

RDV-030: The inter-vehicle (vehicle to vehicle) telemetry data shall be exchanged over a wireless communications interface during rendezvous. The communication interface provides the conduit for data exchange: visiting vehicle to target vehicle and target vehicle to visiting vehicle.

3.2.3.1 STANDARD TELEMETRY OVERVIEW

RDV-031: Telemetry data provided to/from the target vehicle and from/to the visiting vehicle shall contain the data specified in the standard telemetry list, described in 3.2.3.2.

RDV-032: Standard telemetry data shall be expressed in the common units and representations.

RDV-033: Standard telemetry measurement data shall have a standard definition of where/how it was measured (i.e. from what point to what point the measurement should be made, or, from what frame to what frame the attitude should be represented).

RDV-034: The definition of vehicle status in the standard telemetry, such as the visiting vehicle's flight mode (approach, retreat, hold, depart, etc.) shall conform to the spacecraft definitions.

Note that, since some parts of the data will be vehicle-specific, inter-vehicle telemetry should have some undesignated allocations for vehicle-specific data.

Rationale: Standard telemetry list will help crew-display development, reduce crew workload including training, and increase efficiency.

Standardization of systems and representations in which the telemetry data described would reduce complexity for both crews and flight software. It would contribute to not only promoting interoperability but also increasing mission safety and cost reduction.

3.2.3.2 STANDARD TELEMETRY CONTENT

RDV-035: The inter-vehicle standard telemetry content will consist of a minimum set of data defined within this section.

3.2.3.2.1 TIME

RDV-036: The visiting vehicles and the target vehicle shall utilize a unified synchronized reference time in Coordinated Universal Time (UTC) with Modified Julian Date format, as stated in section 3.2.1.2. This is the time stamp indicating when the data is obtained, not when it is transmitted.

RDV-037: Time information shall be provided for each data included in the standard telemetry, since the obtained time of individual data may differ and shall be expressed in common time reference or, if not, the additional clock drift information shall be provided.

Rationale: Any information sent should have a time stamp included for time synchronization, relative navigation and situational awareness.

3.2.3.2.2 DATA VALIDITY <TBC 3-13>

This is a validity flag indicating whether each transmitted data is valid or not.

RDV-038: Data validity shall be individually provided for each data included in the standard telemetry.

Rationale: Need to have mechanism in place to ensure that the sender and receiver properly process data and identify whether it is valid or invalid. This could be with a data validity flag, times stamps, or omitting sending invalid data (don't send bad data).

3.2.3.2.3 ABSOLUTE NAVIGATION DATA

This is absolute position, velocity, attitude, and angular rate of the host vehicle (the vehicle transmitting the data: the visiting vehicle or the target vehicle) measured by ground operation or onboard measurement.

RDV-039: The reference point of position and velocity measurements shall be the vehicle's estimated COM and expressed in ICRF inertial frame.

RDV-040: The attitude shall be expressed as a quaternion representing the rotation of vehicle's body frame with respect to ICRF inertial frame.

RDV-041: Quaternion shall be defined as having the scalar term in the first element.

RDV-042: The angular rate shall be expressed in the vehicle's body frame.

Rationale: The visiting vehicle can use this data as an option for the target vehicle state knowledge when the space-to-ground link is lost.

The target vehicle can use this data as an option for visiting vehicle state knowledge when the proximity communication is established.

The target vehicle can use this information for confirmation of the visiting vehicle's expected state by comparing it with the relative navigation data provided from the visiting vehicle.

3.2.3.2.4 RELATIVE NAVIGATION DATA (VISITING VEHICLE TO TARGET VEHICLE)

This is relative position, velocity, attitude, and angular rate of the visiting vehicle with respect to the target vehicle, based on the navigation sensor(s) and the estimation filters onboard the visiting vehicle.

RDV-043: If the visiting vehicle estimates a secondary solution, it shall also be transmitted to the target vehicle, in the same manner/form as the primary relative navigation solution.

RDV-044: Regarding relative position and velocity, the following two data sets with different reference points shall be transmitted, when available:

- Relative position/velocity between the COMs of the visiting vehicle and the target vehicle expressed in a target vehicle-centered, Sun-referenced LVLH frame (refer to Section 3.2.1.2.1).
- Relative position/velocity between mechanical interface points expressed in the target vehicle docking/berthing frame. Mechanical interface points will be as follows:
  - (for docking) the origins of the docking mechanism's Soft Capture System onboard the vehicles.
  - (for berthing) the capture point and the origin of the grapple fixture onboard the visiting vehicle.

RDV-045: Prior to and during docking, automated capture/berthing, undocking and separation operations, relative attitude shall be transmitted as a quaternion representing the rotation of the visiting vehicle docking frame with respect to the target vehicle docking frame.

RDV-046: Relative angular rate shall be expressed as the rotation rate of each axis of the visiting vehicle docking frame with respect to each axis of the target vehicle docking frame.

Rationale: The relative navigation data from the visiting vehicle will be used by the target spacecraft crew (when applicable) for monitoring, to cross check the target spacecraft's own relative navigation data, as well as used to trigger a CAM if needed.

3.2.3.2.5 RELATIVE NAVIGATION DATA (TARGET VEHICLE TO VISITING VEHICLE)

This is relative position, velocity, attitude, and angular rate of the visiting vehicle with respect to the target vehicle, based on the navigation sensor(s) and the estimation filters onboard the target vehicle.

RDV-047: When available, the range and range-rate shall be transmitted from the target vehicle to the visiting vehicle.

RDV-048: Regarding relative position and velocity, the following two data sets with different reference points shall be transmitted, when available:

- Relative position/velocity between the COMs of the visiting vehicle and the target vehicle expressed in the target vehicle-centered LVLH frame.
- Relative position/velocity between mechanical interface points expressed in the target vehicle docking/berthing frame. Mechanical interface points will be as follows:
    - (for docking) the origins of the docking mechanism’s Soft Capture System onboard the vehicles.
    - (for berthing) the capture point and the origin of the grapple fixture onboard the visiting vehicle.

RDV-049: When required during docking and berthing operations, relative attitude shall be transmitted as a quaternion representing the rotation of the visiting vehicle docking frame with respect to the target vehicle docking frame.

RDV-050: Relative angular rate shall be expressed as the rotation rate of each axis of the visiting vehicle docking frame with respect to each axis of the target vehicle docking frame.

Rationale: The relative navigation data from the target vehicle will be used by the visiting vehicle crew for monitoring and to cross check the visiting vehicle’s own relative navigation data. The data can be used as redundant data for the visiting vehicle’s own GN&C navigation.

3.2.3.2.6 VISITING VEHICLE FLIGHT MODE

RDV-051: The flight mode information of the visiting vehicle shall be transmitted from the visiting vehicle to the target vehicle. The vehicle flight mode should be in line with the phases defined in Section 3.1.3.1.

Rationale: Visiting vehicle’s flight mode will be provided to the target vehicle and used for monitoring and go/no-go decisions.

In order to avoid confusion and misunderstanding, definition of the visiting vehicle flight mode provided to the target vehicle needs to be common across all platforms/vehicles.

3.2.3.2.7 TARGET VEHICLE STATUS

This is critical health and status information on the host vehicle.

RDV-052: The target vehicle status information transmitted from the target vehicle to the visiting vehicle shall be as shown in Table 3.2.3.2.7-1.

TABLE 3.2.3.2.7-1 TARGET VEHICLE STATUS INFORMATION

Data Description	**State**
Control mode, target vehicle Health	**<TBD 3-3>**
Target vehicle from/to Ground Comm status Target vehicle Carrier Lock status Target vehicle Bit lock status Target vehicle RX Power level Target vehicle TX ON/OFF Target vehicle TX Power level	 LOCK/UNLOCK LOCK/UNLOCK ** dB ON/OFF ** dB
Target vehicle from/to visiting vehicle Comm status Target vehicle Carrier Lock status Target vehicle Bit lock status Target vehicle RX Power level Target vehicle TX ON/OFF Target vehicle TX Power level	 LOCK/UNLOCK LOCK/UNLOCK ** dB ON/OFF ** dB
Error Status (ex. Caution and Warning Message)	None/Error code (* OR, standard status flag indicating the criticality of the error)
Status of docking mechanism	(* Refer to IDSS IDD)
Relative Navigation Source Status	Status SENSORS Filter status

RDV-053: The visiting vehicle status information transmitted from the visiting vehicle to the target vehicle shall be as shown in Table 3.2.3.2.7-2

TABLE 3.2.3.2.7-2 VISITING VEHICLE STATUS INFORMATION

Data Description	**State**
Abort delta-V	Abort delta-V vector in target vehicle-centered LVLH (* Zero vector means passive abort)
Visiting vehicle from/to Ground Comm status Visiting vehicle Carrier Lock status Visiting vehicle Bit lock status Visiting vehicle RX Power level Visiting vehicle TX ON/OFF Visiting vehicle TX Power level	 LOCK/UNLOCK LOCK/UNLOCK ** dB ON/OFF ** dB
Visiting vehicle from/to target vehicle Comm status Visiting vehicle Carrier Lock status Visiting vehicle Bit lock status Visiting vehicle RX Power level Visiting vehicle TX ON/OFF Visiting vehicle TX Power level	 LOCK/UNLOCK LOCK/UNLOCK ** dB ON/OFF ** dB
Error status	None/Error code (* OR, standard status flag indicating the criticality of the error)
Maneuver Countdown Timer	±** seconds
Next maneuver delta-V	Delta-v vector in target vehicle-centered LVLH
Status of docking mechanism	(* Refer to IDSS IDD)
Primary Relative Navigation Source	Status SENSORS Filter status
Secondary Relative Navigation Source	Status SENSORS Filter status

Rationale: This information is important for the visiting vehicle crew to know if the target vehicle is ready or not for approach and docking, and vice versa (if applicable to a crewed target vehicle).

This information would be used for trouble shooting to understand the state of the vehicle when the ground communication of the vehicle is interrupted.

3.2.4 CREW CAPABILITY

RDV-054: The crew functions during rendezvous are crew monitoring and crew commanding shall be implemented and utilized either on visiting vehicle and/or on target vehicle depending where the crew is present.

Implementation of crew capabilities on target vehicle will be standardized. Crew capabilities of a crewed visiting vehicle supersedes the target vehicle crew capabilities.

3.2.4.1 TARGET VEHICLE CREW CAPABILITY

Target vehicle-based crew monitoring and commanding needs to be standardized as a nominal target vehicle crew capability. This will enable quick and easy recognition of anomalies, regardless of a crew-member's location within the target spacecraft and display being viewed.

3.2.4.1.1 TARGET VEHICLE CREW MONITORING

Target vehicle crew monitoring consists of relative motion monitoring and visiting vehicle/target vehicle status assessment.

Relative motion monitoring by crew is an obligatory function in the case of a crewed vehicle.

RDV-055: Crew monitoring shall use independent data source which is not used in the visiting vehicle navigation loop. For example, the source of independent monitoring data could be visual information or dissimilar, independent navigation sensor or combination of different sources.

RDV-056: Relative motion monitoring by crew shall span from KOS entry through the vehicle's docking/capture. The monitoring will ensure relative motion safety for all maneuvers even beyond nominally required fault tolerance.

Required set of parameters for relative motion monitoring:

- position in approach/departure/relocation corridor,
- range and range-rate,
- relative attitude.

The required parameters will be evaluated against the defined corridors, and if a violation is observed, the crew can respond/act accordingly (such as issuing abort command). Precision and measurement domain for each parameter will be sufficient to detect safety areas violation.

RDV-057: Each target vehicle docking port shall be equipped with visual camera aligned with docking port axis.

RDV-058: Location of camera shall allow visual monitoring of required motion parameters.

RDV-059: For visual monitoring, target vehicle shall use visual camera installed either on target vehicle or visiting vehicle. Utilization of visiting vehicle-based camera is desirable to ensure visual monitoring during fly around and relocation maneuvers.

Note: Target vehicle-based cameras at each docking port enables the target vehicle-based crew to visually monitor incoming visiting vehicles without reliance on visiting vehicle assets.

RDV-060: Maximum delay in visual image and telemetry data transfer shall not affect rendezvous safety.

RDV-061: Visiting vehicle and target vehicle shall have their own checklists with minimum required state of involved systems and critical equipment to proceed to next operation. These checklists will be verified by crew at decision point as part of GO criteria for docking, undocking, etc. Vehicle status assessment is an external check of equipment or systems based on telemetry data.

Sections 3.2.3 and 3.2.5 describes the standard contents/formats of telemetry data and standard for visual monitoring.

3.2.4.1.2 TARGET VEHICLE CREW COMMANDING

For the scenario where target vehicle crew is present during incoming, uncrewed visiting vehicle RPOD operations, the crew must be able to perform actions to ensure the safety of target vehicle and its crew.

RDV-062: Target vehicle crew shall be able to issue time-critical commands to initiate safety provision maneuvers. Minimum list of the required commands:

- Rendezvous suspend,
- Rendezvous resume,
- Collision Avoidance Maneuver.

Additional commands to control visiting vehicle onboard equipment may be implemented using standard communication protocol.

3.2.4.1.3 TARGET VEHICLE CREW REMOTE PILOTING

For vehicles that choose to implement a remote piloting capability, the following standards are provided. Remote manual piloting is an extension to target vehicle crew commanding capability, dedicated to perform approach, departure or relocation of visiting vehicle, when the visiting vehicle is within the AS.

Following standards shall be implemented on visiting vehicle and target vehicle for remote piloting function:

RDV-063: The target vehicle shall have unified control post for visiting vehicle monitoring and control, with video display, telemetry data overlays, crew hand controllers and control panel.

RDV-064: Bidirectional radio channel between target vehicle and visiting vehicle shall be implemented for crew commands and crew hand controller signals. A minimum bandwidth of 9.6 kilobits per second (Kbps) is recommended.

RDV-065: Video camera shall be installed on visiting vehicle.

RDV-066: The visiting vehicle camera shall be aligned with visiting vehicle docking port axis and operated using target vehicle-based targets.

RDV-067: Video imagery shall be transferred to target vehicle control post. A minimum image quality 576i@10 feet per second (fps) is recommended (minimum image quality of 720p@25fps is desired).

Maximum total delay accounting all contributors (crew hand controller signals direct link and video image return link) is 1.0 second.

RDV-068: Visiting vehicle shall perform translation maneuvers along 3 axes upon crew hand controller signals. Translational hand controller controls the visiting vehicle linear acceleration.

RDV-069: Visiting vehicle shall follow attitude rate around 3 axes based on crew hand controller signals. Attitude hand controller controls visiting vehicle attitude acceleration.

RDV-070: Visiting vehicle shall perform attitude stabilization with respect to target vehicle nominal attitude.

3.2.5 COMMON GUIS AND OPS PRODUCTS

Graphical User Interfaces (GUI)s and operational (OPS) products for crew monitoring should be common across all elements, modules and vehicles. GUIs and OPS products will consist of monitoring displays, crew commanding hardware/software, and, if appropriate, remote piloting hardware/software/displays and ground displays.

Rationale: Standardization of GUIs and OPS products promote interoperability and reduce complexity in the target spacecraft's system by reducing crew training and work-load for the various modules and elements.

Note: Existing ISS visiting vehicle monitoring display is standardized in ISS operations to the U.S. Nodes (SSP 50313, Display and Graphics Commonality Standard). Currently, it is not standardized across all of the ISS monitoring capabilities. Purpose is to provide ISS crew with consistent displays regardless of which vehicle is approaching/departing.

3.2.6 DEMONSTRATION STANDARD

RDV-071: The visiting vehicle shall demonstrate that it has the performance and functionality to perform the expected maneuvers necessary to execute the rendezvous and any safety maneuvers. Best practices include: a) chaser vehicle(s) can rendezvous and dock safely to target vehicle,
b) demonstrate that safety maneuvers (for example: holds, retreats and aborts) can be accomplished in the appropriate or suitable environment.

All rendezvous related equipment, including but not limited to: navigation sensors, propulsion system, communication system, etc., which have no flight heritage and cannot be fully exercised outside of the space environment, should receive approval for use in flight after completion of the demonstration program.

All safety maneuvers should be demonstrated before they are enabled, but does not prevent ability to perform nominal flight program. If execution of safety maneuvers impacts mission or abort availability (e.g. uses too much prop or adds unacceptable risk to timeline) or could prevent docking/berthing (e.g. Collision Avoidance Maneuver), those safety maneuvers could be demonstrated in full scale after visiting vehicle undocking/unberthing (contributes to mission success by performing abort demonstration after delivery is complete).

Rationale: The intent of any demonstration is to satisfy requirements and prove capabilities to enable mission success. This approach may not require the visiting vehicle to perform any demonstration in cislunar or deep space, provided the capabilities have been proven to meet the appropriate environment and RPOD requirements. If a demonstration in an appropriate environment is proposed, then the demonstration specifics need to be clearly defined with stated/measurable objectives. All ISS visiting vehicles performed initial demonstrations prior to capture or docking on their first flight. There were considerable resources invested (such as multiple partner negotiations, added cost and schedule) to perform the demonstrations, though the demonstrations lead to successful programs.

3.3 PERFORMANCE

3.3.1 RADIO FREQUENCY (RF) RANGING

The RF communications between the target and chaser vehicle supports radiometric tracking (ranging) and provides another “sensor” for obtaining range and range rate during RPOD between chaser and target vehicles.

Rationale: Use of RF-based range and range-rate enables ground independence during RPOD, and refines the relative navigation state at long and medium ranges (within 400 km, range at which vehicle to vehicle communication is expected to be established).

3.3.2 SECONDARY STATE DETERMINATION SYSTEM (SSDS)

Figure 3.3.2-1, General Rendezvous Sensor Availability Assumptions, shows the assumed sensor availability in the establishment of a reference. As a reference, to transition from RF communication ranging to the SSDS occurs at 750 m distance. A target extended range mode where the visiting vehicle is at 5 km of the target spacecraft will also be defined **<TBD 3-4>**.

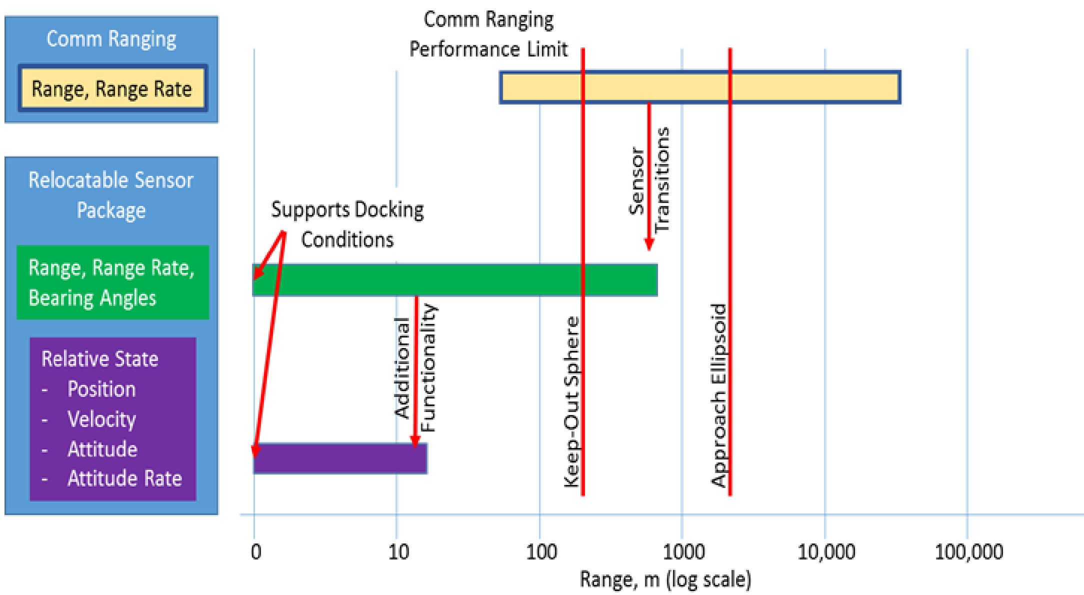

FIGURE 3.3.2-1 GENERAL RENDEZVOUS SENSOR AVAILABILITY ASSUMPTIONS

3.3.2.1 SSDS MISSION LEVEL PERFORMANCE STANDARDS

Based on the reference scenario presented in "Trajectories and Dispersions for Rendezvous in a DRO and an NRHO" (F. Clark / CS Draper Labs, 17 September 2015), the following mission level performance standards, presented in Table 3.3.2.1-1, Preliminary Performance Standards of the SSDS, were derived.

TABLE 3.3.2.1-1 PRELIMINARY PERFORMANCE STANDARDS OF THE SSDS

Standard	Title	Description	Rationale/Note
RDV-SSDS-101	Target Acquisition Time	The SSDS shall automatically perform acquisition of the visiting vehicle within 90 seconds when the target is in the operational field of view and range.	Minimize manual operation and operation time.
RDV-SSDS-102	Tracking Update Rate	The SSDS shall provide navigation data at least once per second (1Hz).	Typical GN&C requirement.
RDV-SSDS-103	Coverage Area	The SSDS FOV shall cover an area greater than 45° x 20° **<TBR 3-8>**.	Lots of motion expected in plane and little out of plane. Mounting on a robotics platform would alleviate FOV constraints (except for initial acquisition).
RDV-SSDS-104	Bearing Mode LOS Bias	The SSDS LOS (Az, El) RSS measurement bias shall be less than 0.3° (3-sigma). Intermediate values can be linearly interpolated, assuming the visiting vehicle will have a reflective target (retro-reflector) visible by the SSDS.	Draper analysis [Draper-2015] uses 0.333° at 1 sigma for LOS camera
RDV-SSDS-105	Bearing Mode LOS Noise	The SSDS LOS (Az, El) RSS measurement noise shall be less than 0.15° (3-sigma). Intermediate values can be linearly interpolated, assuming the visiting vehicle will have a reflective target (retro-reflector) visible by the SSDS.	Draper analysis [Draper-2015] uses 0.05° at 1 sigma for LOS camera.
RDV-SSDS-106	Bearing Mode Range Bias	The SSDS bearing range RSS measurement bias shall be less than 0.5% of the target range, assuming the visiting vehicle will have a reflective target (retro-reflector) visible by the SSDS.	Draper analysis [Draper-2015] uses 0.33 m to 7 m (for 1 m to 1.5 km) for 1 sigma
RDV-SSDS-107	Bearing Mode Range Noise	The SSDS bearing range RSS measurement noise shall be less than 0.5% of the target range, assuming the visiting vehicle will have a reflective target (retro-reflector) visible by the SSDS.	Draper analysis [Draper-2015] uses 0.33 m to 7 m (for 1 m to 1.5 km) for 1 sigma

TABLE 3.3.2.1-1 PRELIMINARY PERFORMANCE STANDARDS OF THE SSDS

Standard	Title	Description	Rationale/Note
RDV-SSDS-108	6-DOF Pose Bias	The SSDS LOS 6-DOF relative pose RSS measurement bias shall be less than 2 cm at the minimum docking range and less than 1 m at the maximum 6-DOF range (3-sigma). Intermediate values can be linearly interpolated.	
RDV-SSDS-109	6-DOF Pose Noise	The SSDS LOS 6-DOF relative pose RSS measurement noise shall be less than 2 cm at the minimum docking range and less than 1 m at the maximum 6-DOF range (3-sigma). Intermediate values can be linearly interpolated.	
RDV-SSDS-110	6-DOF Relative Attitude Bias	The SSDS LOS 6-DOF relative attitude RSS measurement bias shall be less than 0.5° at the minimum docking range and less than 5° at the maximum 6-DOF range (3-sigma). Intermediate values can be linearly interpolated.	IDSS can tolerate 4°.
RDV-SSDS-111	6-DOF Relative Attitude Noise	The SSDS LOS 6-DOF relative attitude RSS measurement noise shall be less than 0.5° at the minimum docking range and less than 5° at the maximum 6-DOF range (3-sigma). Intermediate values can be linearly interpolated.	IDSS can tolerate 4°.
RDV-SSDS-112	Sun in the Field of View	The SSDS shall meet its performance standards while operating with the sun in the Field of View of the sensor.	Some visiting vehicle approach / departure trajectories will impose having the sun in the field of view of the sensor.

3.4 VERIFICATION AND TESTING

It is the responsibility of the spacecraft developer to perform verification and validation. The majority of the standards will be verified using a combination of interface/compatibility testing, integrated end-to-end testing and analysis at the subsystem and system level.

4.0 FUTURE TOPICS FOR POSSIBLE STANDARDIZATION

The applicability of the rendezvous standards to deployed small satellites and free flyers needs to be evaluated, and determined if the vehicles must abide by the standards set forth in this document.

The tailoring of the zones and corridors for orbits in vicinity of celestial bodies need to be considered (i.e. low lunar orbit, Martian orbits, etc.).

APPENDIX A - ACRONYMS AND ABBREVIATIONS

6-DOF	Six Degrees of Freedom
AAC	Automatic Abort Corridor
AE	Approach Ellipsoid
AI	Approach Initiation
AS	Approach Sphere
ATP	Authority To Proceed
Az	Azimuth
CAM	Collision Avoidance Maneuver
COM	Center of Mass
Comm	Communication
COTS	Commercial Orbital Transportation Services
CSA	Canadian Space Agency
dB	decibel
DC	Chaser Docking
deg/s	degrees per second
DRO	Distant Retrograde Orbit
DSG	Deep Space Gateway
El	Elevation
E-M L2	Earth-Moon LaGrange Orbit 2
EM-ROT	Earth-Moon Rotational
FOV	Field-of-View
fps	feet per second
GFF	Geometrically Fixed Frame
GN&C	Guidance, Navigation, and Control
GUI	Graphical User Interface
HCS	Hard Capture Surface
HEOMD	Human Exploration and Operations Mission Directorate
Hz	Hertz
ICD	Interface Control Document
ICRF	International Celestial Reference Frame
ICRS	International Celestial Reference System
IDD	Interface Definition Document
IDSS	International Docking System Standard
IRD	Interface Requirements Document
IRSIS	International Rendezvous System Interoperability Standards
ISS	International Space Station
Kbps	Kilobits per second
km	kilometer

KOS	Keep-Out Sphere
LCI	Lunar Centered Inertial
LIDAR	Light detection and ranging
LOS	Line of Sight
LVLH	Local Vertical Local Horizontal
m	meter
MAC	Manual Abort Corridor
MCB	Multilateral Coordination Board
MCC	Mission Control Center
mm/s	millimeters per second
NASA	National Aeronautics and Space Administration
NRHO	Near Rectilinear Halo Orbit
OPS	Operational
ORB	Orbital Frame
PA	Passive Abort
prop	propellant
Prox Ops	Proximity Operations
RE	Rendezvous Entry
RF	Radio Frequency
RPOD	Rendezvous, Proximity Operations and Docking
RS	Rendezvous Sphere
RSS	Root Sum Squared
RX	Receive
SADM	Solar Array Drive Mechanism
SE&I	Systems Engineering and Integration
SI	International System of Units
SRF	Synodic Rotating Frame
SSDS	Secondary State Determination System
SSP	Space Station Program
TACS	Target Vehicle Analysis Coordinate System
TBC	To Be Confirmed
TBD	To Be Determined
TBR	To Be Resolved
TLI	Trans-lunar Injection
TX	Transmit
U.S.	United States
UTC	Coordinated Universal Time
V	Velocity
VV	Visiting Vehicle

APPENDIX B – GLOSSARY OF TERMS

ABORT

The chase vehicle performs a separation sequence which places it on a safe trajectory which departs from the target vehicle.

APPROACH ELLIPSOID (AE)

A 4 x 2 x 2 km ellipsoid, centered at the ISS center of mass, with the long axis aligned with the V-Bar (per SSP 50808, Appendix B).

APPROACH INITIATION (AI) BURN

The AI burn is the first burn that is allowed to target into the AS.

APPROACH SPHERE (AS)

The AS is a sphere around the center of mass of the target vehicle. It defines a region around the target vehicle that the visiting vehicle shall not enter without approval. If visiting vehicle becomes disabled during RPOD, it shall not enter the AS based on its own trajectory dynamics (free drift trajectory does not take visiting vehicle into AS).

ATTACHED

The portion of the trajectory in which the target vehicle and the chaser vehicle are physically connected.

AUTOMATED SYSTEM

A system which executes its commands as it is programmed to do and perform its closed loop control, which is predesigned and reference signals are precomputed. It needs external intervention for changes and re-planning.

AUTOMATIC CONTROL

An automatic control loop, a controller compares a measured value of a process with a desired set value, and processes the resulting error signal to change some input to the process, in such a way that the process stays at its set point despite disturbances. This closed-loop control is an application of negative feedback to a system.

Process that is executed to completion without human intervention; however, the ground or crew can observe and confirm the state/status and actions performed by the vehicle.

AUTONOMOUS SYSTEM

Autonomous control systems must perform well under significant uncertainties in the plans and the environment for extended periods of time and they must be able to compensate for system failures without external intervention. The system is able to adapt to external measured changes without external intervention and it possesses the capability to perform re-planning and self-adaptation to new situations with no external intervention.

BERTHING

The act of robotically mating two vehicles.

CAPTURE

The act of robotically capturing a vehicle, typically assumed with robotic arms/devices, or soft capture system within docking mechanisms.

CHASE OR CHASER VEHICLE

Is an active spacecraft during rendezvous with a target vehicle. The chaser vehicle targets and executes a primary set of maneuvers during rendezvous.

CHECK POINT

A predefined location on the vehicle's trajectory where the visiting vehicle will not proceed on the approach if it has not received "GO" command from the associated ground operator, target vehicle crew or the visiting vehicle crew.

CORRIDOR

A frustum (truncated pyramid or cone) portion of space with its apex located at the target docking mechanism (or capture box) and its longitudinal axis along the direction of intended approach. The chase vehicle maintains its target relative position within the corridor for approach to and possibly, separations from the target.

CREW

Humans on a space-based vehicle.

CREW INTERRUPT

A crew executed command sent to the visiting vehicle. The command may be a hold/halt, retreat, abort, or resume.

CREW MONITORING

The crew ability to observe and assess the operation, typically with telemetry and video.

[Note: In most cases there will be a blending of video and telemetry. In some cases, this capability could be used to control a formal hazard. We have general agreement that this would be used for all operations where crew is present.]

DEPARTURE

Trajectory starting with the undocking/release event, which places the visiting vehicle on a safe trajectory.

DISSIMILAR SENSOR

This term is applied to sensors being implemented on a vehicle and refers to the suite of sensors being implemented not being vulnerable to common mode failures. Addresses vulnerability to design issues, environmental sensitivity, and operational usage.

DOCKING

The act of using a docking mechanism to contact, capture and hard-mate with another vehicle.

FREE DRIFT

The vehicle (chaser/visiting vehicle or target vehicle) inhibits translational and rotational control. This includes thrusters, control moment gyros, magnetic torquers, etc. This occurs at docking contact/latching or before undocking/departure of the vehicle.

FREE FLIGHT

The portion of the trajectory in which the target vehicle and the chaser vehicle are not physically connected.

HOLD

The chase vehicle maintains its relative position with respect to the target vehicle such that it neither approaches nor departs from the target.

INDEPENDENT SENSOR

This term is applied to sensors being implemented on the vehicle and refers to sensors not relying on the same power and data connections. Addresses vehicle architecture and vulnerability to single power failure, data connections, etc.

KEEP OUT SPHERE (KOS)

The KOS is the smallest control sphere around the target spacecraft, regulating final approach to the target vehicle. Final approach to the target vehicle is not permitted inside KOS unless approval is granted.

MANUAL CONTROL

Control input provided by a human operator. This is a general term which includes Manual Piloting and Remote Piloting.

MANUAL PILOTING

Refers to action taken by a human to fly the vehicle. The ability for crew to pilot the vehicle.

PROXIMITY OPERATIONS

Vehicle maneuvers that are either within the KOS or RS. These maneuvers may include final approach, fly-around, undocking and departure. This is used extensively within the NASA ISS community to cover all maneuvers performed within the RS.

REMOTE PILOTING

The ability for crew to manually pilot a vehicle they do not occupy.

RENDEZVOUS

This phase begins when the visiting vehicle is confirmed to be in an orbit established in cislunar space relative to the target vehicle and ends at docking start.

RENDEZVOUS SPHERE (RS)

The RS is the largest control sphere around the center of mass of the target spacecraft and is used to govern the RE.

RESUME

The chase vehicle maintains its position with respect to the target vehicle such that it continues on the preplanned profile. This function is typically only used during proximity operations.

RETREAT

The chase vehicle increases its range with respect to the target vehicle such that it creates an opening rate. The retreat will proceed to a predefined HOLD point.

SEPARATION

The dynamic process of flying a chaser vehicle away from a target. It results from propulsive forces (thruster or mechanical springs) and/or effects of orbital mechanics.

TARGET VEHICLE

Is primarily a passive spacecraft during rendezvous by a chaser or visiting vehicle.

UNDOCKING

The process of a chaser / visiting vehicle unlatching and separating from a target vehicle.

APPENDIX C - OPEN WORK

Table C-1 lists the specific To Be Determined (TBD) items in the document that are not yet known. The TBD is inserted as a placeholder wherever the required data is needed and is formatted in bold type within brackets. The TBD item is numbered based on the section where the first occurrence of the item is located as the first digit and a consecutive number as the second digit (i.e., <TBD 4-1> is the first undetermined item assigned in Section 4 of the document). As each TBD is solved, the updated text is inserted in each place that the TBD appears in the document and the item is removed from this table. As new TBD items are assigned, they will be added to this list in accordance with the above described numbering scheme. Original TBDs will not be renumbered.

TABLE C-1 TO BE DETERMINED ITEMS

TBD	Section	Description
3-1	3.2.2.5.2	Capture envelope definition process (RDV-014).
3-2	3.2.2.5.2	Capture volume (RDV-015).
3-3	3.2.3.2.7	Control mode and target vehicle health/status in telemetry.
3-4	3.3.2	Target extended range mode where visiting vehicle is at 5 km of target vehicle will be defined.

Table C-2 lists the specific To Be Resolved (TBR) issues in the document that are not yet known. The TBR is inserted as a placeholder wherever the required data is needed and is formatted in bold type within brackets. The TBR issue is numbered based on the section where the first occurrence of the issue is located as the first digit and a consecutive number as the second digit (i.e., <TBR 4-1> is the first unresolved issue assigned in Section 4 of the document). As each TBR is resolved, the updated text is inserted in each place that the TBR appears in the document and the issue is removed from this table. As new TBR issues are assigned, they will be added to this list in accordance with the above described numbering scheme. Original TBRs will not be renumbered.

TABLE C-2 TO BE RESOLVED ISSUES

TBR	Section	Description
3-1	3.2.1.1.1	LVLH frame definition needs to be refined.
3-2	3.2.1.1.2	GFF definition needs to be refined.
3-3	3.2.1.1.2	DC frame definition needs to be refined.
3-4	3.2.1.1.3	Target Vehicle Analysis Coordinate System frame needs to be refined and generalized.
3-5	3.2.1.1.3	Target Vehicle Body frame.
3-6	3.2.1.1.3	Target Docking Longitudinal frame definition needs to be refined.
3-7	3.2.1.1.3	Target Docking Radial frame definition needs to be refined.
3-8	3.3.2.1	RDV-SSDS-103: Table 3-1, SSDS FOV 40° x 20°.

Table C-3 lists the specific To Be Confirmed (TBC) issues in the document that are not yet confirmed/verified. The TBC is inserted as a placeholder wherever the required data is needed and is formatted in bold type within brackets. The TBC issue is numbered based on the section where the first occurrence of the issue is located as the first digit and a consecutive number as the second digit (i.e., <TBC 4-1> is the first unresolved issue assigned in Section 4 of the document). As each TBC is resolved, the updated text is inserted in each place that the TBC appears in the document and the issue is removed from this table. As new TBC issues are assigned, they will be added to this list in accordance with the above described numbering scheme. Original TBCs will not be renumbered.

TABLE C-3 TO BE CONFIRMED ISSUES

TBC	Section	Description
3-1	3.1.3.2	Rendezvous Sphere radius is 10 km.
3-2	3.1.3.2	Approach Sphere radius is 1 km.
3-3	3.1.3.2	Keep Out Sphere radius is 200 m.
3-4	3.1.3.2	Approach/Departure Corridor is ±10°.
3-5	3.2.2.1	RDV-002: Coast trajectory shall not intercept AS for 24 hours.
3-6	3.2.2.3	RDV-004: 24-hour safe free drift after abort.
3-7	3.2.2.4.4.1	RDV-010: Automatic abort corridor is ±7.5°.
3-8	3.2.2.4.4.2	RDV-013: Manual abort corridor is ±10°.
3-9	3.2.2.5.3	RDV-016 net velocity less than 8 mm/s.
3-10	3.2.2.5.3	RDV-017 net angular rate less than 0.04 deg/s.
3-11	3.2.2.6.1	RDV-019: Structural safety clearance 1 meter.
3-12	3.2.2.7	RDV-027: Secondary State Determination from range = 20 m.
3-13	3.2.3.2.2	Data Validity section needs to be confirmed/worked with C&T and Avionics.