Guidance for Distributed Satellite System (DSS) Architectures for Class D Missions

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1. Introduction

The availability of smaller satellites has created the opportunity to propose mission concepts with Distributed Satellite System (DSS) architectures. A DSS is a mission architecture consisting of multiple space elements that collectively accomplish the mission's objectives. Science requirements flow down to the distributed architecture and then to the individual flight elements. DSS architectures may be categorized by a variety of names including constellations, trains, clusters, swarms, etc.

The requirements and evaluation criteria for proposals and Phase A Concept Study Reports (CSRs) are the same for DSS mission concepts as they are for non-DSS missions. However, these DSS missions offer both opportunities and challenges that must be considered in the development approach. This document provides additional guidance for proposal teams to create stronger proposals and CSRs when DSS missions are proposed. Proposal teams are advised to consider the guidance in this document during the proposal process. This document is supplemental; it does not create new requirements, nor does it remove any existing requirements in the Announcement of Opportunity (AO) or Guidelines and Criteria for the Phase A Study. Guidance related to deferred material is included in this document so that proposal teams may consider it as the mission concepts are defined. Deferred material should not be included in proposals.

Additional guidance for DSS missions is provided for the following six topics.

- Consistent Terminology
- Instrument System Calibration
- Systems Engineering Approach
- Multiple Unit Development
- Operations and Ground Systems
- Mission Level Reliability

2. Consistent Terminology

2.1 Background

To avoid miscommunication between the proposing team and Technical, Management and Cost (TMC) evaluation team, a consistent set of terminology is necessary for DSS proposals.

2.2 Potential Issues for DSS Missions

Given a DSS mission consisting of multiple flight elements (e.g., satellites) needed to meet the full science objectives of the mission, combined with a plan to launch more flight elements than is needed to meet those full science objectives in order to support reliability expectations through redundancy, the proposal or CSR could assume one of two definitions of the "Baseline Science Mission:"

- the number of satellites to be launched to support both the full science objectives and redundancy
- only the number of satellites needed to meet the full science objectives.

2.3 Additional Guidance for DSS Missions

To avoid ambiguous terminology, the following definitions are provided:

- **Baseline Science Mission:** The mission that, if fully implemented, would fulfill the Baseline Science Requirements, which are the performance requirements necessary to achieve the full science objectives of the mission. A DSS Baseline Science Mission consists of multiple satellites operating as an integrated system to fulfill the Baseline Science Requirements. Multiple DSS scenarios may achieve the Baseline Science Mission.
- **DSS Launched Mission:** The planned number and configuration of satellites to be launched and the associated science measurements obtained if these satellites operated for their nominal lifetime.
- **Baseline Science DSS Resiliency:** The ability of the mission to tolerate flight system and instrument failures while still meeting the Baseline Science Mission. This resiliency may include the ability to collect the science measurements with less than the DSS Launched Mission or reconfiguration and other changes to the concept of operations that can be accomplished within the proposed resources.

3. Instrument System Calibration

3.1 Background

Most NASA observations from space require stringent and well-defined ground and on-orbit calibration and validation plans. NASA expects each proposal to fully describe the requirements for calibration and validation.

3.2 Potential Issues for DSS Missions

DSS instrument calibration for individual instruments as well as across an expanded architecture of many distributed instruments creates additional complexities compared to instruments on non-DSS missions. Non-DSS missions typically do not need to intercalibrate among multiple identical instruments.

A DSS instrument system is any group of multiple instruments that must be operated together to produce science data analysis products. An instrument system is designed to achieve measurement requirements flowed down from Level 1 Requirements and can only achieve them as a system. Examples of DSS instrument systems include:

1. A set of identical instruments on multiple satellites. For example, a DSS mission may use three-axis magnetometers on all satellites to map the magnetic field of the Coronal Mass Ejection (CME) as it passes the DSS. The final product could be a time-dependent, three-dimensional "movie" of the CME magnetic field. The same mission may use Faraday Cups on each satellite to measure the in-situ plasma density. The final product is a time-dependent three-dimensional "movie" of the CME plasma density.
2. Instruments that use different techniques that produce overlapping physical measurements. For example, a DSS mission may use Magneto-Resistant Magnetometers (MRMs) to measure low frequency magnetic fields, and Superconducting QUantum Interference Device (SQUID) Magnetometers to measure high frequency magnetic fields. The two instruments overlap at mid-frequencies, and both instrument types are required to generate the final three-dimensional, three-axis CME magnetic field movie.
3. Instruments whose components are distributed across multiple satellites and/or ground assets. A DSS mission may utilize radio frequency transceivers at two frequencies to measure line of sight plasma rotation measure between all possible pairs of satellites using polarization direction. These measurements are used along with the plasma density measurements and in-situ magnetic field measurements to tomographically derive three-dimensional maps of the time-dependent magnetic field as the CME passes the DSS.

3.3 Additional Guidance for DSS Missions

DSS mission proposals should fully describe the requirements and approach for calibration and validation of the instrument system distributed over the mission architecture. To clarify the full range of requirements, the following DSS-specific terminology is helpful:

1. **Inter-calibration**: When multiple "copies" of the same instrument are flown on multiple spacecraft, the proposal should describe the approach to ensure that individual instrument

raw measurements can be converted accurately to physically meaningful quantities by all elements of the group. For example, consider a mission where each satellite employs an MRM to measure the low-frequency three-axis magnetic field. Uncalibrated sensitivity variations between MRMs will imprint spatio-temporal artifacts in the three-dimensional, three-axis magnetic field movies. The inter-calibration plan that allows science requirements to be met by sufficiently mitigating these artifacts should be described.

2. **Cross-calibration**: When measurements from two different instrument types are being combined to produce a higher order physically meaningful quantity, the proposal should describe the instrument calibration and cross-calibration approach to ensure the required data is produced at the required performance metrics. For example, consider a mission where each satellite employs an MRM and a SQUID Magnetometer to measure intermediate frequency magnetic fields. Proposals should indicate how the two instrument types are cross-calibrated consistently in the overlapping frequency range.
3. **Distributed calibration**: When an instrument consists of components that are distributed across multiple satellites and/or ground assets, the ground and flight calibration plans should address the unique challenges of validating and calibrating distributed instruments. For example, consider a mission where a Radio Frequency (RF) transmitter on satellite A illuminates an RF receiver on satellite B at two frequencies. The polarization difference is a measure of the density-weighted line-of-site magnetic field. The transmitter polarization accuracy and the receiver sensitivity together determine the final accuracy of the measured rotation measure and derived magnetic field maps. Distributed calibration may be achieved by separately calibrating the transmitter and the receiver or more ideally, by calibrating the transmitter and receiver simultaneously in a flight-like fashion. In practice the latter may only be possible in-flight. Note that the derived magnetic field maps also depend on the plasma density and in situ magnetic field measurements, so that the final map quality depends on the calibration of the complete transmitter/receiver/plasma density/magnetometer measurement system.

4. Systems Engineering Approach

4.1 Background

All proposals are expected to describe the unique aspects of systems engineering that apply to the proposed mission. All proposals are expected to provide traceability matrices showing the instrument and mission requirements that the science goals and objectives impose on the mission design elements.

4.2 Potential Issues for DSS Missions

A DSS mission architecture may have additional complexity that is caused by the required geometric configuration of flight elements and the dynamic evolution of the configuration. DSS-related features of this complexity should be included in the definition, decomposition, and flow-down of science and mission requirements for the proposed mission.

4.3 Additional Guidance for DSS Missions

The systems engineering approach should address the unique challenges of the DSS mission consisting of multiple space elements that interact, cooperate, and communicate with each other. This systems engineering approach should address configuration and interoperability of multiple flight elements.

The proposal should address the requirements decomposition and flow-down from science goals to top-level science and mission requirements to DSS configuration, architecture, number of flight units, and observation strategy.

Sufficient technical and operational margins should be available to manage development of individual flight systems and provide resiliency at the DSS or constellation level.

Identification of requirements for any mission unique launch services pertaining to the accommodation and deployment of multiple space elements is expected.

5. Multiple Unit Development

5.1 Background

All missions must provide plans for developing the instrument and flight system hardware. DSS missions by nature require development of multiple units of various systems and subsystems. Development of multiple similar units offers both opportunities and challenges that must be considered in the development approach.

5.2 Potential Issues for DSS Missions

Manufacturing and Assembly, Integration, Test, and Verification (AITV) of DSS missions have additional challenges compared to single space vehicle missions. The proposal must address the logistics management challenges of planning, developing, integrating, and testing many similar flight elements on a time scale similar to single spacecraft missions.

Specifically, the greater number and relative development timing and delivery schedules of multiple copies of systems or subsystems can place unique requirements on items such as the AITV approach, vendor capabilities, facilities, and Ground Support Equipment (GSE).

5.3 Additional Guidance for DSS Missions

The DSS mission proposal should demonstrate the ability to build, test, and integrate the required number of flight elements (spacecraft buses, instruments, etc.) from various government, contractor, academic, and foreign organizations with repeatable quality and performance standards on the required schedule.

Planning should demonstrate resiliency to the discovery of single unit anomalies and the associated impact on various AITV approaches. This resiliency might include unique sparing plans, serial versus parallel assembly and test flows, schedule margins at critical processing steps, GSE, and unique test chamber contingency planning.

The overall unit test philosophy should be described. If different build units have different test requirements, the proposal should fully justify the differences.

The DSS mission proposal should include the impact of the flight element’s design on the repeat manufacturability, the quality assurance program implementation, the proposer’s management of any subcontracted manufacturer, and the ability to capture and apply lessons learned for the effective production of subsequent units.

6. Operations and Ground Systems

6.1 Background

All missions must be operated in a manner that enables science requirements to be met. Proposals are expected to fully describe the operational approach, capabilities, and ground systems (including software) that will be used in all phases of deployment, commissioning, commanding, monitoring, fault/anomaly response and resolution, decommissioning, and end of life operations. Some aspects of these expectations are deferred until the CSR for a two-step evaluation.

6.2 Potential Issues for DSS Missions

Operations of DSS missions have additional challenges compared to single space vehicle missions. These missions must fully consider the mission operations approach, capabilities, and resources to execute the deployment commissioning, commanding, and monitoring of all satellites in the DSS launched mission.

Specifically, the greater number and relative timing of total operational events can place a greater strain on the mission operational approach, capabilities, and facilities than simple linear scaling may predict. For example, multiple launches, “simultaneous” deployments, critical events, or faults on multiple spacecraft may require more resources (ground contacts, operator, and Subject Matter Expert (SME) support) to resolve than a non-DSS mission. Plans to address failures of individual space vehicles or instruments through reconfiguration of the remaining vehicles must be accounted for in delta-V budgets and overall mission schedule margins.

6.3 Additional Guidance for DSS Missions

The DSS mission proposal should provide a description of the plan for mission and science operations for all satellites in the DSS launched mission.

The DSS mission proposal should clearly demonstrate the ground systems and mission operations approach/capabilities/resources to accommodate all satellites in the DSS launched mission during deployment, commissioning, commanding, monitoring, fault/anomaly response and resolution (including any reconfiguration), decommissioning, and end of life operations.

7. Mission Level Reliability

7.1 Background

All missions are required to comply with NASA Procedural Requirements (NPR) 8705.4A. NPR 8705.4A defines expectations for risk tolerance for each class of mission. The objectives for each class are specified in Appendix D of NPR 8705.4A. Step 1 proposals and Step 2 CSRs are expected to demonstrate that the proposed missions have a reasonable probability of successfully meeting the risk tolerance expectations in NPR 8705.4A during Phases B-D.

Deviations in the recommended requirements in Science Mission Directorate (SMD) Policy Document (SPD)-39, *Science Mission Directorate Policy: SMD Standard Mission Assurance Requirements For Payload Classification D* and in Appendix C of NPR 8705.4A must not result in tailoring below SPD-39, even for individual flight elements within a constellation.

7.2 Potential Issues for DSS Missions

The approach to demonstrating appropriate risk tolerance with a DSS mission requires a more rigorous approach than non-DSS missions, due to the increased number of space vehicles. Proposed DSS missions may become infeasible when mission assurance and system reliability are considered. Even when all required flight elements individually meet the defined risk tolerance, the overall mission may not meet the system reliability expectations. For example, a mission that requires numerous space vehicles to all survive over the mission lifetime in order to meet the science observation requirements may not meet the system reliability expectations even if each flight element meets reliability expectations.

Furthermore, the total number of space vehicles expected to survive over the mission lifetime may well exceed the overall number required, but the configuration of the surviving space vehicles may not meet the science observation requirements.

7.3 Additional Guidance for DSS Missions

Performing a thorough mission assurance analysis is beyond the scope of both Step 1 proposals and Step 2 CSRs. However, all proposals are expected to show that the proposed approach to systemic and random errors meets the mission level reliability expectations for the specified mission class.

Systemic errors are common across all space vehicles and can result from defects in workmanship and testing standards, parts control processes, environmental effects, and relevant component heritage, among other causes. The evaluation of these areas is the same for both DSS and non-DSS proposals. Strengths and weaknesses are evaluated by SMEs in the appropriate factor areas (e.g., instruments, flight systems, systems engineering, etc.)

Random errors are all other stochastic failure modes of an individual space vehicle that impact the mission. Although the probability of these random errors may be low for an individual space vehicle, the combined probability across the total number of space vehicles in a DSS mission may prevent the DSS mission requirements from being satisfied.

Recognizing that this effect of random errors both has a potentially greater negative effect on DSS missions and that providing detailed analysis to prove resiliency against these effects is a burden on organizations that propose DSS missions, a Preliminary Mission Reliability Estimate may be provided to demonstrate that the DSS mission has a reasonable probability of successfully meeting the risk tolerance expectations in Phases B-D. Projects that do not provide a Preliminary Mission Reliability Estimate in the proposal must use other methods to demonstrate that the DSS mission will meet mission level reliability expectations. This preliminary estimate is not a replacement or supplement for SMA oversight of missions during formulation and implementation.

The Preliminary Mission Reliability Estimate only focuses on estimating the likelihood that the proposed mission assets will survive for sufficient time to achieve the science objectives. Survivability typically depends on individual space vehicle reliability, mission duration, and mission/orbit design. Proposers may use any methodology to demonstrate sufficient survivability.

To reduce the burden on organizations that propose DSS missions, projects may assume a 0.8% monthly failure rate for individual satellites without further justification in the proposal. Projects are free to use a different value for individual satellite reliability, but any deviations must be justified and well-supported in the proposal.

DSS proposals that utilize the 0.8% monthly failure rate in the Preliminary Mission Reliability Estimate are eligible for “safe-harbor” treatment. DSS proposals for missions with a Class D risk tolerance class that demonstrate Preliminary Mission Reliability Estimates greater than

- 60% for a Step 1 proposal
- 75% for a Step 2 CSR

will not have TMC/Form C weaknesses written against the impact of random errors on mission level reliability. DSS proposals that have Preliminary Mission Reliability Estimates below these values, or that use a different monthly failure rate, may or may not have weaknesses written against the impact of random errors on mission level reliability depending on the information provided in the proposal.

Note that the impact of systemic errors on mission level reliability is not covered by the Preliminary Mission Reliability Estimate and is not eligible for “safe-harbor” treatment. Systemic issues are evaluated by SMEs in the appropriate factor areas and can generate strengths or weaknesses independent of the Preliminary Mission Reliability Estimate presented in the proposal.

7.4 Preliminary Mission Reliability Estimate Examples

Two examples, one analytical and one numerical, for calculating the Preliminary Mission Reliability Estimate are presented. These examples are representative of the types of analyses that are expected, but individual proposal teams may utilize alternative methods.

For both examples, the space vehicles are 12 kg satellites with a single instrument. The individual space vehicle (CubeSat plus instrument) reliability uses the "safe-harbor" monthly failure rate of 0.8%.

7.4.1 Analytical Example

7.4.1.1 Mission Design

The DSS launched mission consists of 60 satellites split evenly between five planes. All mission requirements can be met as long as at least eight satellites are fully operational over the 21-month science period in each of the five orbital planes.

Mission design has accounted for individual satellite failure within an orbit plane. The time required for reconfiguration after a satellite failure is accounted for in the estimated instrument duty cycle. However, satellites do not have sufficient propellant to move between planes.

Launch and Early OPerations (LEOP) requires three months before science operations can begin.

7.4.1.2 Preliminary Mission Reliability Estimate

The mission requires eight of 12 satellites to survive in each orbital plane for 24 months (three months of LEOP plus 21 months of science operations). A 0.8% monthly failure rate, results in an individual satellite reliability of ~82.5% at the end of the science mission.

For a single plane, the mission assumes a binomial distribution with 12 events that requires eight successes where each probability of success is ~82.5%.

For a single plane, the binomial distribution has an ~95.6% likelihood of having at least eight of 12 satellites survive for 24 months.

Since all five planes must have eight operational satellites, the Preliminary Mission Reliability Estimate is $(95.6\%)^5$ or ~79.8%.

This mission design meets the "safe-harbor" requirements for both a Step 1 proposal and a Step 2 CSR of a Class D mission.

7.4.2 Numerical Example

7.4.2.1 Mission Design

The DSS launched mission consists of 20 type A satellites and 12 type B satellites. All science requirements can be met with at least 3500 measurement units. The number of measurement units in a given month is nA*nB where nA is the number of operational type A satellites and nB is the number of operational type B satellites.

LEOP requires three months before science operations can begin. Science operations are planned for 24 months after LEOP.

7.4.2.2 Preliminary Mission Reliability Estimate

The mission does a Monte Carlo analysis with 100,000 runs to determine the probability of achieving 3500 measurements. The number of runs should be selected to ensure that statistical sampling is not significantly impacting the results.

For each mission run, the simulation loops through the 27 months of mission operations.

Monte Carlo Details

The number of type A satellites available at the end of the first science month (nA1) is obtained by sampling one discrete event for each of the 20 type A satellites. The probability that a satellite is alive at the end of first month of science operations is $(100\%-0.8\%)^4$. The probability is raised to the fourth power because there are three months of LEOP in addition to the single month of science operations.

The number of surviving type B satellites at the end of science month 1 (nB1) is determined in the same manner.

The number of collected observations in the first science month is the product of nA1 and nB1.

The number of type A satellites available at the end of the second month (nA2) is obtained by sampling one discrete event for each of the nA1 type A satellites that were alive at the end of the first month. The probability that a satellite is alive at the end of second month of science operations given that it was alive at the end of the first month is (100%-0.8%).

The number of surviving type B satellites at the end of science month 2 (nB2) is determined in the same manner.

The number of collected observations in the second science month is the product of nA2 and nB2.

The process is repeated for all 24 months of science operations.

The total number of observations for the single run is the summation over i of nAi x nBi for all values of i from one to 24.

If the total number of observations for the run exceeds the required number of observations, increment the number of successes by one.

The Preliminary Mission Reliability Estimate is the number of successes divided by the total number of runs. The Preliminary Mission Reliability Estimate is ~97.3% for this scenario.

This mission design meets the “safe-harbor” requirements for both a Step 1 proposal and a Step 2 CSR of a Class D mission.