Mass Properties Control for Space Systems

Revision Letter

Prepared by
The AIAA Mass Properties Committee on Standards
in partnership with
The Standards and Practices Workshop of the International Society of Allied Weight Engineers, Inc.

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SAWE RECOMMENDED PRACTICE
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AMERICAN INSTITUTE OF AERONAUTICS AND ASTRONAUTICS
## Change Record

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Foreword

The International Society of Allied Weight Engineers, Inc., (SAWE), a major source of Mass Properties Engineering (MPE) Subject Matter Experts, signed a Memorandum of Understanding with the American Institute of Aeronautics and Astronautics (AIAA) to jointly develop both a revised mass properties standard and a revised recommended practice (RP). SAWE wishes to acknowledge the efforts of the AIAA Mass Properties Engineering Committee on Standards (CoS) in developing these revisions. The new revisions, designated as AIAA S-120A-2015 and SAWE RP A-3, are intended to fully replace AIAA S-120-2006 and SAWE RP-11C.

The revised standard, AIAA S-120A-2015, is intended to convey the minimally acceptable mass properties requirements for space systems, while the associated SAWE RP A-3 provides guidance for implementation of a program-specific mass properties control plan. Together, the two documents may also be used to establish requirements during preparation of acquisition contracts and program-specific documents.

These documents are useful for all companies wishing to control and manage vehicle mass properties and are especially useful for new companies, companies unfamiliar with mass properties requirements or companies without dedicated Mass Process Engineers (MPEs).

Other useful documents can be found at the website www.sawe.org.
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1 Scope
This recommended practice (RP) defines terminology and establishes uniform processes, procedures, and methods for the management, control, monitoring, determination, verification, and documentation of mass properties during the design, development, and operational phases of space systems, including their components and subsystems.

This RP contains mass properties control guidance for both space vehicles (SVs) and launch vehicles (LVs). A distinction between SVs and LVs is made because, in certain areas, mass properties analyses, control, and verification techniques can vary significantly between these two space system classes. Where significant differences in recommended practices exist between these two space system classes, the applicable space system class is specified.

2 Purpose

This document may be used as a reference to specify mass properties control for SVs (satellites, satellite payloads, interplanetary vehicles, or reentry vehicles) and LVs (launch vehicles, upper stage vehicles, injection stages, or exoatmospheric missiles). For these applications, the term space system is to be interpreted as the applicable vehicle.

Note: AIAA S-120A-2015 contains tailorable requirements, while this document contains best practices; therefore, the use of “should” in this document is appropriate unless in direct conflict with AIAA S-120A-2015. Inclusion of an SAWE RP in a document, standard, on contract by a company or agency is a voluntary act.

3 Associated Documents
This RP is used in conjunction with the following publications. When the following specifications are superseded by an approved revision, the revisions apply.

   3) SAWE RP 16. Measurement of Missile and Spacecraft Mass Properties. SAWE Recommended Practice

4 Definitions, Abbreviations, Acronyms
For the purposes of this document, the following terms and definitions apply.

4.1 Abbreviations and Acronyms

\sigma \quad \text{Sigma, deviation}

& \quad \text{Ampersand (and)}
4.2 Definitions

Actual Mass Properties
mass properties determined by measurement or by comparison of nearly identical components, for which measured mass properties are available (assessed as maturity category A5 or A6 in Table 1)

Allowable Mass
the limit against which mass margins are calculated

NOTE 1 The allowable mass is a derived requirement set early in the program and is intended to remain constant until there is a change in requirements.

NOTE 2 Examples of an allowable mass include a contractor not-to-exceed (NTE) mass limit or an informal mass allocation to a design organization.

Basic Mass
the current mass of dry or inert hardware based on an assessment of the most recent baseline design

NOTE 1 This design assessment includes the estimated, calculated, or measured (or actual) mass and includes an estimate for undefined design details like cables, multi-layer insulation, and adhesives.

NOTE 2 The mass growth allowances (MGAs) and uncertainties are not included in the basic mass.

Bulk Item
a constituent of an assembly or part that is not readily identified by an exact quantity or graphical representation and where its shape, volume, and mass may be determined upon installation or by a note only. These items generally have a quantity of “as required” in the parts list, e.g., paints, structural adhesives, fluids, tapes.

Bus
the portion of an SV that supports payloads and performs functions related to the SV’s basic operation and maintenance, such as flight control, power, and propulsion

Calculated Mass Properties
mass properties determined from preliminary or released drawings or controlled computer models (assessed as maturity category C3 or C4 in Table 1)

Center of Mass (CM)
the point at which the distributed mass of a simple or composite body can be acted upon by a linear force without inducing any rotation of the body
Critical Mass Properties
those mass properties that have limits that would jeopardize mission performance or safety if exceeded

Estimated Mass Properties
mass properties determined from preliminary data, such as sketches, analysis from preliminary layouts or models, or parametric data (assessed as maturity category E1 or E2 in Table 1)

Forecast Mass
predicted mass plus consideration for pending and potential mass changes

In-Scope Changes
design modifications implemented by the contractor to meet contractual requirements

Launch Vehicle
a space system whose purpose is to carry one or more payloads from the surface of the Earth (or other celestial body) and deliver the payload(s) into space with position and velocity meeting desired target state vectors at the desired time

Mass
the measure of the quantity of matter in a body that results in the body’s resistance to change in translational velocity

Mass Growth Allowance
the predicted change to the basic mass of an item based on an assessment of the hardware category, design maturity, fabrication status, and an estimate of the in-scope design changes that may still occur throughout life cycle

NOTE 1 MGA should be defined as part of contract negotiations.
NOTE 2 The alternate word “contingency” is vague and is no longer used to define MGA or margin.

Mass Limit
maximum mass that can satisfy all mission performance requirements

NOTE Also referred to as mission limit.

Mass Margin
the difference between the space system allowable mass and the predicted mass

Mass Properties
mass, CM, moments of inertia (MOI), and products of inertia (POI)

Mass Properties Control Board (MPCB)
a body tasked with reviewing and managing a space system’s mass properties, typically to produce a minimum mass design consistent with mission requirements and to identify risks to the overall program resulting from any non-compliance with mass properties requirements
Mass Properties Database
a data management system used to record and manage the mass properties data records of
a space system and its constituent parts

Mass Reserve
mass allowance defined and retained by the customer or program management for
potential out-of-scope changes or any other unforeseen mass impacts

Moment of Inertia
a body's resistance to change in angular velocity about a defined axis resulting from the
body's distribution of mass

Out-of-Scope Changes
design modifications that are not consistent with the current contract requirements

Overages
non-flight items on a test article when a measurement is conducted

Payload
for SVs, a mission-related subsystem or subsystems that performs a function or functions
not directly related to a space system's basic operation or maintenance; for LVs, the SV
or system, LV adapter, and other mission-unique hardware

Payload Margin
for LVs, the difference between the predicted payload capability and the required payload
capability to a specified target state vector in terms of mass

NOTE Payload partial derivatives describe the relationship between payload margin
and mass margin for hardware jettisoned before achieving the target state vector
corresponding to a particular mission trajectory design.

Payload Partial Derivative
for LVs, the rate of change in payload mass delivered to a specified target state vector
divided by the rate of change in mass (or other system parameter) of the specified LV
component, valid within small variations

NOTE The payload partial derivative is 1.0 for LV hardware that arrives at the
specified target state vector with the payload.

Pending Change
mass properties data that have been approved for incorporation into the database but,
because of timing, have not yet been incorporated

Potential Change
an unapproved design modification that, if approved, would effect a change to the system
mass properties

NOTE Changes that increase mass are called threats, and those that decrease mass are
called opportunities.
Predicted Mass
sum of the basic mass and MGA; intended to estimate the final mass at system delivery or operation

NOTE CM, MOI, and POI values are derived using the predicted mass.

Predicted Payload Capability
the analytically derived performance of a LV, expressed as payload mass to a target state vector, based on LV predicted mass, launch site, trajectory, propellant loading, and environmental conditions

NOTE LVs may relate changes in payload margin to changes in LV segment predicted mass or propellant using payload partial derivatives.

Product of Inertia
a measure of a body's mass distribution asymmetry with respect to a reference coordinate system

Propellant Margin
for LVs, the mass of usable main impulse propellant that the upper stage carries that is in excess of the propellant needed to meet all performance and flight uncertainty reserve requirements for a specific mission

NOTE 1 LV programs commonly express predicted performance risk for a specific mission in terms of propellant margin.

NOTE 2 LV programs may utilize propellant margin partial derivatives to evaluate the effects of changes in LV segment predicted mass on propellant margin and mission performance.

Satellite
an SV whose purpose is to navigate and operate in orbit around Earth or other celestial body

Shortages
flight items missing from a test article when a measurement is conducted

Space System
a system designed to function in space, including crewed and unmanned SVs, in-space propulsion vehicles, injection and upper-stage vehicles, satellite payloads, reentry vehicles, LVs, ballistic vehicles, and components thereof

NOTE For the purposes of this document, space systems do not include Ground Support Equipment (GSE).

Space Vehicle
a space system whose purpose is to navigate and operate in space, performing one or multiple functions, which may include data collection; communications; research; delivery of cargo, equipment, personnel, or weapons to or from space; reentry; or other purposes
Spacecraft
an SV

State Vector
in astrodynamics or celestial dynamics, a combination of a vehicle’s position vector and velocity vector at a specified date and time (epoch), uniquely determining the orbital parameter and/or trajectory of a vehicle or other body in space.

Tare
non-flight hardware, excluding overages, used to perform a measurement of a test article

Target State Vector
for LVs, the desired vehicle state vector to be achieved when the payload is released from the LV. For multiple payload missions, there will be multiple target state vectors.

Uncertainty
plus or minus variation in predicted mass properties because of lack of definition, manufacturing variations and tolerances, environment effects, or accuracy limitations of measuring devices or techniques

NOTE Uncertainty is calculated relative to predicted mass.

Figure 1 provides a graphical summary of the relationships between key definitions listed above, as do Figures A.1 and A.2 in Appendix A in this document. Appendix A also provides mathematical representations of a number of the terms defined above as well as vehicle-specific graphical summaries of the relationships between key definitions.
5 Recommended Practices

5.1 Mass Properties Control

5.1.1 Scope

Mass properties control is the management of a system’s mass properties to enable the system to fulfill its contractual and performance objectives. A space system and its subsystems may have explicitly defined mass properties contractual limits and/or other performance requirements that necessitate internally derived mass properties requirements and limits.

Specifying appropriate mass requirements at the start of development is of critical importance for a successful development. During space system development, mass properties control is typically implemented by organizing a mass properties control program, which is defined by contractually levied standards and in the program’s Mass Properties Control Plan (MPCP).
During operation, a space system may implement active mass properties control through onboard vehicle configuration or fluid management systems.

### 5.1.2 Mass Properties Control Plan

The level of rigor required for specific system development programs depends on the criticality of the mass properties requirements.

The contractor flows mass properties requirements and appropriate sections of the MPCP to each subcontractor through contractual requirements. For this reason, the contractor's mass properties organization defines the appropriate mass properties and MPCP flowdown requirements for each subcontractor early in the program and ensure that the subcontractors are included in contract negotiations. Use of common mass control terminology and methodology between prime contractors and subcontractors supports integrated mass properties analysis.

Mass properties control addresses requirements such as NTE limits and limits on mass and center of gravity location (stowed and deployed). These requirements are specified in the procurement documentation addressing all relevant phases of the system life cycle.

LV mass properties control methods and objectives can differ from those used on SV programs because they are focused primarily on maximizing the LV’s payload delivery capability and accuracy rather than on regulating the LV mass properties to be within certain limits. For this reason, it is important to know the primary LV performance requirements and how stage mass properties affect system performance.

### 5.1.3 Mass Properties Control Process

Space system mass is a primary concern. Without early mass properties control, there is a significant risk of performance, schedule, and/or cost problems later in the program.

The mass properties control process begins with the concept development program phase and continues through design, development, fabrication, test and evaluation, and operations. During concept development, before design selection, and preliminary design maturity, mass properties control consists primarily of understanding the basis of estimate and specification values for mass properties. Historical data are of great value at this phase of product development as estimates may be derived from similar complete or operational systems.

As the program moves into preliminary design, more rigorous mass properties control is implemented. Typically, technical management implements margin control through technical performance measurement and mass maturity tracking. Figure 2 shows an example of the mass properties control process.

The control process after authorization to proceed (ATP) may include one or more of the following elements:

- Understanding of the flowdown of requirements that affect mass properties analysis and test plans.
- A mass reduction plan.
SAWE Recommended Practice No. A-3

- Implementation of a MPCB.
- Mass allocation and trend analysis.
- Mass properties monitoring and assessment.
- Subcontractor mass control.

Application of some of the more stringent elements listed above is contingent on available mass and stability margins, cost considerations, and the planned verification (measurement versus analysis) schema.
Figure 2. Example Mass Properties Control Process
5.1.4 Requirements Flowdown and Traceability

Mass properties control begins with the identification and listing of the specific system and subsystem mass properties that should be controlled for the space system to fulfill its contractual and mission requirements. Mass properties requirements may be defined directly from external sources, such as contractually defined system requirements, or from flowdown from internally derived system requirements.

The source of the space system requirements generally starts with the system’s (external) contractual Technical Requirements Document, Operational Requirements Document, and Interface Control Documents. These and similar documents define the top-level requirements governing the system’s characteristics and performance. Some of these top-level documents may include explicitly defined mass properties limits for the space system. Other top-level requirements flow down through specialty engineering functions, such as trajectory and performance, guidance, stability and attitude control, mission engineering, loads, ground handling, and transportation, to become internally derived mass properties requirements for the space system or its subsystems and components.

Once a complete list of the program’s controlled mass properties is formed, limiting values for each controlled mass property should be defined. These limits are typically defined either in terms of high and low limiting values or nominal values with plus and minus tolerances. These lists of mass properties requirements become the focus of the MPCP.

To verify the space system’s compliance to its requirements, the contractor has to show the traceability of each requirement to its source. The contractor should also prepare a verification cross-reference matrix showing the mapping between each requirement and the method(s) to be used for verification of the requirement.

5.1.5 Mass Maturity Assessment

System mass historically has grown from initial concept to in-service flight system. Mass maturity assigns a categorical rating based on the stage of design and manufacturing; this rating is used to provide guidance in assigning MGAs to predict future mass growth.

Mass maturity assessments should be accomplished for each record in the mass properties database by reviewing the following:

1. Heritage of the component.
   a. Is this a new modified, or existing design?
   b. If modified, how extensive are the changes?
   c. Has this item been space qualified before?

2. Completeness of the component’s and system’s design and analyses.
   a. Does a design exist yet, or is this just an estimate?
   b. Have loads analyses and sizing been performed?
c. Do the component and system design close, i.e., meet all mass, strength, natural frequency, thermal, shock balance, performance, environmental requirements?

d. Is the design a layout, or is it released for manufacture?

e. Has the design been built and tested?

3. Method used to derive the mass properties data.

a. Estimation.
b. Parametric prediction.
c. Hand calculation.
d. Computer-aided-design (CAD) analyses.
e. Measurement.
   i. Of a similar unit.
   ii. Of an identical unit.
   iii. Of the exact unit.

After considering the above factors, the lower portion of Table 1 (under the heading Expanded Definitions of Maturity Categories) can be used to assign a design maturity category and maturity code to the mass properties data record.

5.1.6 Assessment of Predicted Mass Properties against Requirements

The basis of space system mass properties can be categorized by the methods used for their determination:

- Estimated (E1, E2): Mass properties determined from preliminary data, such as sketches or calculations from layout drawings or prerelease models.

- Calculated (C3, C4): Mass properties determined from released drawings or three-dimensional (3D) CAD models.

- Actual (A5, A6): Mass properties determined by measurement or by comparison of nearly identical components for which measured mass properties are available.

- Customer-furnished equipment (CFE) or Specification Value (S7): Mass properties of a customer-furnished component or defined by a specification value, typically an NTE mass.

The percentage of the space system mass that is based on each of these mass maturity categories is an indication of the confidence that can be placed in reported mass properties data. When ambiguities occur, the most representative category should be used, keeping in mind that the purpose of this categorization is to provide an indication of the confidence of the reported mass properties. The basis (estimated, calculated, measured) of each component’s mass should be included as part of the recorded component data. As many categories as are necessary to accurately define the status of the mass properties may be used. Totals of the mass in each of these categories should be
recorded to provide an indication of the mass properties confidence at the subsystem level and for the complete vehicle.

5.1.7 Mass Growth Allowance

Mass growth varies as a function of the type of hardware and its design maturity. MGA is an estimating factor that addresses hardware design maturity based on a fixed set of requirements. The MGA schedule is documented in the program-specific MPCP and is adhered to through the life of the program. For a particular program, specific MGA values in Table 1 are selected based on the contractor’s experience level. Higher, more conservative values are selected when the contractor has less experience or when the contractor’s experience indicates that more conservative values are warranted. MGA is applied at the lowest design detail level reported in the mass properties database. The ranges shown in Table 1 are percentage values indicating the recommended percentage of basic mass that should be allocated for mass growth, based on the type of component and maturity category.

Depletion of the MGA follows the design process; as the design and analyses of the hardware mature according to the categories documented in Table 1, the MGA depletes to reflect increased confidence in the predicted final mass. The contractor should use Table 1 to determine MGA, unless the contractor has supporting data that supersede the MGA values given in Table 1.
### Table 1. Mass Growth Allowance by Design Maturity

<table>
<thead>
<tr>
<th>Maturity Code</th>
<th>Design Maturity (Basis for Mass Determination)</th>
<th>Electrical/Electronic Components</th>
<th>Percentage Mass Growth Allowance</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td>Structure</td>
<td></td>
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<tr>
<td></td>
<td></td>
<td>Thermal Control</td>
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<td></td>
<td></td>
<td>Propulsion</td>
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<td></td>
<td></td>
<td>Batteries</td>
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<td></td>
<td></td>
<td>Wire Harnesses</td>
<td></td>
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<tr>
<td></td>
<td></td>
<td>Solar Array</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>ECLSS, Crew Systems</td>
<td></td>
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<tr>
<td></td>
<td></td>
<td>Brackets, Clips, and Hardware</td>
<td></td>
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<td></td>
<td></td>
<td>Mechanisms</td>
<td></td>
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<td></td>
<td></td>
<td>Instrumentation</td>
<td></td>
</tr>
<tr>
<td>E</td>
<td>Estimated</td>
<td>0-5 kg</td>
<td>20-35</td>
</tr>
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<td></td>
<td>5-15 kg</td>
<td>15-25</td>
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<td></td>
<td>&gt;15 kg</td>
<td>10-20</td>
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<td></td>
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<td>18-25</td>
<td>30-50</td>
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<td>Layout</td>
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<td></td>
<td>20-30</td>
</tr>
<tr>
<td>C</td>
<td>Preliminary Design</td>
<td>8-20</td>
<td>3-15</td>
</tr>
<tr>
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<td></td>
<td>3-12</td>
<td>4-15</td>
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<td>Released Design</td>
<td>5-10</td>
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<td></td>
<td>2-10</td>
<td>2-6</td>
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<td>3-8</td>
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<tr>
<td></td>
<td></td>
<td></td>
<td>3-5</td>
</tr>
<tr>
<td>A</td>
<td>Existing Hardware</td>
<td>1-5</td>
<td>1-3</td>
</tr>
<tr>
<td></td>
<td></td>
<td>1-3</td>
<td>1-3</td>
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<td></td>
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<tr>
<td></td>
<td></td>
<td></td>
<td>1-3</td>
</tr>
<tr>
<td>S</td>
<td>Actual Mass</td>
<td>Measured mass of specific flight hardware; no MGA; use appropriate measurement uncertainty.</td>
<td></td>
</tr>
<tr>
<td>S</td>
<td>CFE or Specification Value</td>
<td>Typically, an NTE value is provided, and no MGA is applied.</td>
<td></td>
</tr>
<tr>
<td>E1</td>
<td>Estimated</td>
<td>a. An approximation based on rough sketches, parametric analysis, or incomplete requirements</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>b. A guess based on experience</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>c. A value with unknown basis or pedigree</td>
<td></td>
</tr>
<tr>
<td>E2</td>
<td>Layout</td>
<td>a. A calculation or approximation based on conceptual designs before initial sizing (equivalent to layout drawings)</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>b. Major modifications to existing hardware</td>
<td></td>
</tr>
<tr>
<td>C3</td>
<td>Preliminary Design</td>
<td>a. Calculations based on new design after initial sizing but before final structural, thermal, or manufacturing analysis</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>b. Minor modification of existing hardware</td>
<td></td>
</tr>
<tr>
<td>C4</td>
<td>Released Design</td>
<td>a. Calculations based on a design after final signoff and release for procurement or production</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>b. Very minor modification of existing hardware</td>
<td></td>
</tr>
<tr>
<td>A5</td>
<td>Existing Hardware</td>
<td>a. Measured mass from another program, assuming that hardware will satisfy the requirements of the current program with no changes</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>b. Values substituted based on empirical production variation of same or similar hardware or measured mass of qualification hardware</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>c. Catalog values</td>
<td></td>
</tr>
</tbody>
</table>

*Note: The MGA percentage ranges in the above table are applied to the basic mass to arrive at the predicted mass.*
5.1.8 Mass Threats, Opportunities, and Probability of Occurrence

Assessment of compliance of mass properties requirements includes the use of MGA as discussed above and the tracking of pending changes and potential changes (threats and opportunities). Pending changes are approved design changes that have yet to be incorporated into the mass properties database. Potential changes should be categorized as either internal or external to the current baseline requirements, where internal potential changes are combined with the predicted mass to achieve forecast mass and external potential changes are negotiated with the customer. The contractor should evaluate the magnitude of the predicted mass and likelihood for each identified potential change and document the status regularly for compliance with requirements.

Potential changes that are mutually exclusive competing options should not be double booked when combining an aggregate threat or opportunity. External changes resulting in a change of the baseline design may fall outside the scope of design maturity and should be estimated.

Each potential change may be assigned a percent probability of occurrence; for example, High (H), above 75 percent probability; Medium (M), between 75 percent and 25 percent probability, or Low (L), below 25 percent probability or similar. The corresponding percentages may be used as weighting factors in a weighted sum approach to aggregating the combined effect of the potential changes. The aggregate sum of pending changes and potential changes when combined with the predicted mass is the basis of forecast mass.

The contractor should actively pursue mass reduction opportunities to offset documented threats when forecast mass indicates a non-compliance of requirements.

5.1.9 Mass Margin

Mass margin is the difference between the allowable mass and the predicted mass. The recommended amount of mass margin varies, depending on the complexity and the design heritage (new, modified, production) of the space system and the risk that the procuring authority and contractor are willing to accept. Guidance for mass margin and MGA at program milestones is shown in Table 2.

Margin calculations include consideration of manufacturing variations. For systems with mass specifications written as NTE, it is recommended that the predicted mass include high-side manufacturing variation of the system mass. For LV systems with payload capability specifications written as not less than, it is recommended that predicted payload capability include high-side manufacturing variation of the LV hardware mass.

Typically for LV development, the critical parameter is the payload capability rather than the mass of the system. Mass margin is calculated as the difference between the predicted capability minus the required capability. Changes to the mass of the LV’s stages affect the LV margin based on the specific mission trajectory and the LV’s staging operations. Often LV mass is only one of many critical parameters that drive system performance; other factors to be considered include engine and motor performance and aerodynamic considerations. Consideration should be given to stage mass margin philosophy and how that relates to the management of overall system margin.
5.1.10 Mass Risk Assessment

Table 2 can be used as a guideline for mass margin. Care should be taken to apply margin and MGA recommendations to space systems that contain heritage hardware. Hardware categorized as C4 (Released Design) or Actual in Table 1 may not require margin and should be separated from the hardware under development when applying the guidance from Table 2.

Color code definitions for Table 2:

Green: At each specific design phase, if MGA and margins are greater than the percentages shown in the green shaded areas of Table 2, mass risks are considered to be minimal. No action is required other than monitoring the mass status.

Yellow: If MGA and margins are in the yellow percentage ranges, there is medium mass risk. A risk mitigation plan is prepared that pays particular attention to potential design changes that would adversely remediate the margin.

Red: If MGA and margins are in the red shaded area, there is high mass risk, and an immediate mass audit, mass reduction effort, or risk mitigation process is initiated.

Table 2. Mass Risk Assessment Example

<table>
<thead>
<tr>
<th>Program Milestone</th>
<th>Recommended MGA (%)^1</th>
<th>Recommended Mass Margin (%)^1</th>
<th>MGA + Mass Margin (%)^2</th>
<th>Grade</th>
</tr>
</thead>
<tbody>
<tr>
<td>ATP</td>
<td>&gt;15</td>
<td>&gt;15</td>
<td>&gt;30</td>
<td>Green</td>
</tr>
<tr>
<td></td>
<td>9&lt;MGA≤15</td>
<td>10&lt;Mass Margin≤15</td>
<td>19&lt;MGA+Mass Margin≤30</td>
<td>Yellow</td>
</tr>
<tr>
<td></td>
<td>≤9</td>
<td>≤10</td>
<td>≤19</td>
<td>Red</td>
</tr>
<tr>
<td>PDR</td>
<td>&gt;12</td>
<td>&gt;9</td>
<td>&gt;21</td>
<td>Green</td>
</tr>
<tr>
<td></td>
<td>8&lt;MGA≤12</td>
<td>5&lt;Mass Margin≤9</td>
<td>13&lt;MGA+Mass Margin≤21</td>
<td>Yellow</td>
</tr>
<tr>
<td></td>
<td>≤8</td>
<td>≤5</td>
<td>≤13</td>
<td>Red</td>
</tr>
<tr>
<td>CDR</td>
<td>&gt;7</td>
<td>&gt;5</td>
<td>&gt;12</td>
<td>Green</td>
</tr>
<tr>
<td></td>
<td>4&lt;MGA≤7</td>
<td>3&lt;Mass Margin≤5</td>
<td>7&lt;MGA+Mass Margin≤12</td>
<td>Yellow</td>
</tr>
<tr>
<td></td>
<td>≤4</td>
<td>≤3</td>
<td>≤7</td>
<td>Red</td>
</tr>
<tr>
<td>Released Design</td>
<td>&gt;3</td>
<td>&gt;2</td>
<td>&gt;5</td>
<td>Green</td>
</tr>
<tr>
<td></td>
<td>2&lt;MGA≤3</td>
<td>1&lt;Mass Margin≤2</td>
<td>3&lt;MGA+Mass Margin≤5</td>
<td>Yellow</td>
</tr>
<tr>
<td></td>
<td>≤2</td>
<td>≤1</td>
<td>≤3</td>
<td>Red</td>
</tr>
<tr>
<td>Final</td>
<td>0</td>
<td>&gt;1</td>
<td>&gt;1</td>
<td>Green</td>
</tr>
</tbody>
</table>

1. The percentages of aggregate MGA and Mass Margin in the above chart are defined as follows:
   
   MGA = Predicted Mass – Basic Mass
   % of MGA = (MGA/Basic Mass) × 100
   % of Mass Margin = [(Allowable Mass - Predicted Mass)/Basic Mass] × 100

2. The percentage of MGA + Mass Margin is defined as:
   % of MGA + Mass Margin = [(Allowable Mass – Basic Mass)/Basic Mass] × 100

5.1.11 Technical Performance Measurement (TPM)

The contractor tracks critical mass properties using TPM charts that track basic and predicted performance against derived limits and contractual requirements. TPMs and
their associated forms and schedules are negotiated between the procuring authority and the program office and are generally reported by the program office. If a mass properties engineer (MPE) is required to support this effort, the TPMs and requirements for TPMs should be documented in the program-specific MPCP. An example of a TPM for assessing mass compliance by program phase is exhibited in Table 2 above. Trend analysis of TPM charts may help identify potential problems early in the design cycle. This trend analysis is particularly critical before the program preliminary design review (PDR), when designs are still evolving, to minimize cost and schedule impacts for changing the design to address non-compliant parameters.

An idealized graphical representation of basic mass, MGA, predicted mass, and margin versus time is depicted in Figure 3.

![Figure 3. Example Plot of Mass versus Time](image)

Other examples of TPM metrics include basic and predicted mass trending, percent by mass of hardware in the estimated, calculated, and actual categories, and a summary of pending and potential changes. CM may be a TPM or a key input to system dynamic stability TPM. As there are several related technical measurements associated with mass, a composite TPM that combines basic and predicted mass trends, significant pending and potential changes, and mass maturity assessment on a single sheet may be used to provide an overall picture of system compliance to mass requirements.

For LVs, a similar approach to TPMs may be employed. Trends of predicted capability to required capability, significant pending and potential changes, and mass maturity assessment of the component stages can provide an overall picture of system compliance to payload capability requirements.
5.1.12 Mass Properties Control Board

An MPCB, under program management leadership, is the key mass properties management decision-making authority on the program and administers and manages all mass properties control activities directly affecting the space system design.

An MPCB may be comprised of a mass properties working group in conjunction with a formal change control board (CCB), rather than a formal MPCB. This body will discuss in detail the current status of mass properties requirements compliance, related risks or issues, and recommended changes to the baseline as necessary.

Key functions of the MPCB include but are not limited to the following:

- Approving the MPCP and subsequent revisions.
- Establishing NTE mass properties control limits (allocations) at the space system, subsystem, and unit level and approving all subcontractor specification mass properties.
- Directing audits of the mass properties database to verify that the current mass properties accurately reflect the current design configuration.
- Assessing proper assignment of MGA based on design maturity.
- Assessing adequate mass properties margins and, if not sufficient, defining and initiating a recovery plan to restore margins consistent with the level of program maturity.
- Generating and maintaining a comprehensive list of opportunities to reduce mass with which the MPCB can request estimates for cost, schedule, and performance impacts to support a program decision to implement.
- Evaluating potential design changes to identify threats to increase and opportunities to decrease the system mass and assign probability of occurrence (H, M, and L) and assigning a decision-making date for implementation. Reviewing and updating the decision date at MPCB meetings.
- Forecasting mass based on predicted mass and consideration of potential changes.
- Providing risk assessments and recommended risk mitigation actions.
- During full-scale development, reviewing the following:
  - The status of action items from the previous MPCB meeting.
  - Current space system mass.
  - Changes to current mass.
  - Reasons for changes.
  - Mass maturity status.
- Mass growth trends of the subsystems, bus, payload, and space system.
- Critical mass properties requirements.
- Pending and potential changes.
- Launch vehicle performance and control limits.

5.1.12.1 MPCB Meeting Minutes
The Mass Properties Lead Engineer (or designee) documents all approved engineering mass changes, decisions, and actions in MPCB minutes for distribution to all members of the program team. The minutes for each separate MPCB meeting should be maintained throughout the program duration.

5.1.12.2 Mass Properties Monitoring
The space systems mass properties should be monitored by all program personnel and teammates responsible for delivery of flight hardware to the space system to meet system mass properties requirements. The contractor mass properties personnel should be assigned responsibility for accurate mass properties determination, monitoring of the design, and timely reporting to support the mass properties control tasks on the program and to ensure delivery of hardware compliant with all mass properties requirements. To achieve this goal, the MPCB sets internal mass properties allocations, e.g., allowable mass, at the subsystem and unit levels consistent with their respective next higher level mass properties allocation requirement and the scope of the MPCB.

Space system requirements are derived early in the program; however, the allowable mass and other mass properties may change in response to a change in performance requirements or other factors. If necessary, the MPCB performs a rebalancing across subsystems, updating allowable mass allocations until requirements are more stable. Each member of the program team should be aware of their current mass properties allocations and limits and provide compliance status to the MPE through the design release phase.

The rebalancing process may be aided by:

- Top-down mass limits.
- Bottom-up design information.
- Program reserves strategy for mass properties.
- High-level mass margin “what-if” tools.
- Stochastic mass margins tools.
- Historic data.

5.1.12.3 Design Release Sign-Off
Documents, drawings, and models controlling the design, manufacture, and procurement of items that affect the space systems mass properties are approved before release and typically reflect mass properties in the C4, Released Design, maturity category. Such approval signifies component acceptability in satisfaction of system mass properties objectives.

5.1.12.4 Trade Studies
Mass properties are often critical parameters in trading competing design solutions. Mass properties should be developed to support trade studies involving mass properties
inputs. Methodology and tools should be developed that enable scaled mass properties, including mass estimating relationships, mathematical curves, computer models, or any suitable means for relating major design parameters to significant mass properties.

A parametric assessment of inter-system and intra-system mass properties related to various inputs enables technical and program management insight during trade studies leading to design selection. The contractor should determine and maintain, in a form available for review by the procuring authority, mass properties considered in the trade studies and other screening processes for including or excluding competing designs and the net effect on mass properties if the trade study recommendations are implemented.

5.2 Analysis

5.2.1 Scope
The mass properties analysis supports the program requirements for space system mass properties for all configurations throughout the program, including subsystems and components. The mass properties analysis program includes all subcontractor items, associate contractor items, and CFE items.

System mass properties analyses provide data that support performance, stability and control, structural design, structural loads and dynamics, and simulations of dynamic events. Mass properties are also determined for the purpose of supporting program management and risk assessment.

5.2.2 Methods of Analysis
The early phases of program acquisition and development are critical because historical data indicate that a significant portion of the mass growth experienced on an average program occurs during this period.

The primary reasons for this observed mass growth are:

- Lack of design maturity information.
- Overly optimistic assessment of the hardware maturity.
- Requirements that are not fully defined or understood or are not flowed down to the subsystem or unit levels.

During concept formulation, the contractor may prepare a parametric analysis to substantiate the accuracy of the space system and components mass estimate. The parametric analysis should be based on the historical performance from previous programs using analysis techniques such as empirically derived parametric scaling of data. Before PDR, the parametric analysis should be replaced by a bottom-up analysis based on design requirements and loads analysis.

Mass maturity assessments are accomplished by defining the heritage for each space system detail using the categories provided in Table 1. MGA is applied to the developing hardware at the lowest possible detail level, and aggregate totals and percent of total by mass are compiled for each maturity category.
Mass properties software tools should have the capability of performing changes in configuration, such as deployments and fuel depletion. Analysis reporting should include clear reference to applicable coordinate axes and responsible development organizations. Guidance in selecting coordinate systems for use in space systems may be found in SAWE RP 6.

5.2.2.1 Manual Layout/Drawing Analysis
Layout reviews typically occur before formal drawing release. Care should be taken to ensure that appropriate attention to the program estimating process according to the MPCP is employed in developing and documenting of mass estimates on preliminary drawings.

For a drawing analysis, the contractor documents and maintains records of the manual calculation of mass properties data from design layouts and drawings organized by drawing or part number and show rollups from lower level details to assembly and subsystem definitions.

5.2.2.2 3D Model Analysis
Using 3D CAD models provides an efficient and highly accurate method to analyze a particular component’s mass, CM, and MOI and POI.

Such computer models have the advantage of visually representing the spatial layout of the hardware and calculating basic mass properties. Disadvantages of 3D computer models include calculation of non-homogenous hardware, such as wiring and avionics boxes, and other bulk items, such as thermal finishes (primer, paint), structural adhesives, wire harness, and fluids.

Care should be taken in calculating mass properties according to the appropriate coordinate system, application of MGA, and reporting at an appropriate functional level.

5.2.2.3 Drawing Number or Part Number
The contractor’s analysis of the space system detail components, assembly, and installation level definition should include an identifying number (model version, drawing number, or part number).

5.2.3 Flight Hardware Analysis
Flight hardware mass properties are analyzed as necessary to support the needs of the various technical and management organizations. Accounting of mass and mass properties aggregate values may require a robust data management system as discussed in section 5.4.2. Several typical analyses are discussed in the following sections.

5.2.3.1 Correlation to Work Breakdown Structure (WBS)
The WBS is a hierarchical outline of the work to be done on the program or contract, along with a dictionary defining each entry in the outline. The contractor’s flight hardware mass properties records should correlate to the program contract WBS.

5.2.3.2 Remaining Test Instrumentation
All test instrumentation or GSE that remains with the space system through launch or operation should be controlled as flight hardware and included in the mass properties model.
5.2.4 Mass Properties Uncertainty Analysis
Mass properties uncertainty analyses should be conducted as necessary when mass properties dispersions are required for other analyses or when the uncertainties may cause mass properties limits to be exceeded. The accuracy of the mass properties data used in space system performance, stability, control, and structural analyses should be documented. This is true not only for the total space system but also for elements of the space system such as fluids and deployable and independently moving parts. In some cases, the accuracy of the combination of certain mass properties may be required, such as an inertia ratio (spin to transverse moments of inertia ratio) or the inertia asymmetry, the difference of two transverse principal inertias.

The uncertainty analysis should include a detailed analysis of each uncertainty source with a description of the derivation of the uncertainties. The uncertainties include, but are not limited to, measurement uncertainties (maturity category A6), manufacturing variations (maturity category A5), environmental effects, and uncertainties derived or assumed for mass properties estimations or calculations. In most cases, the uncertainty analysis should be calculated relative to the predicted mass. If MGA is included in the analysis, an explanation of how it is combined with the other sources of uncertainty should be provided. Determine how the customer is going to use the data before assuming that predicted mass is the preferred method for applying uncertainty.

Typical methods of combining uncertainties or error sources are either by simple arithmetic addition or by root-summed-square. When determining CM uncertainties, care should be taken when applying dependent variables such as component location and fastener tolerances. Coordinate system transformations and/or rotations have an impact on the MOI and POI uncertainties and should be evaluated if mass properties transformations and/or rotations are applied.

5.2.5 Special Analyses
Special analyses are performed to support design engineering such as structural analysis, dynamics, attitude control, mission engineering, ground support and transportation operations, or payload layout design.

5.2.5.1 Balance and Ballast Mass Analysis
If required to meet the space system CM, static or dynamic balance, or MOI requirements, balance or ballast mass may be required. Equipment layout trades are performed to minimize the total amount of balance or ballast mass required. Optimum locations and configuration of balance or ballast mass are considerations in the design and integration of these masses. Analyses should be performed to define the maximum amount of mass allowed at each balance or ballast mass location.

5.2.5.2 Mission and Attitude Control Systems Analysis
Mass properties analysis in support of space system on-orbit operations should be performed as necessary, including special consideration of space system launch and on-orbit operations, such as determination of propellant location, mass properties of movable objects in the stowed and deployed configurations, and sequential mass properties of the space system configuration from launch to on-orbit operations to de-orbit.
5.2.5.2.1 Propellant

The propellant mass properties are calculated based on the system geometry of the tanks, baffles, feedlines, and components. The contractor should calculate the propellant mass properties based on the system predicted mass. The associated mass for pressurizing gases, loading uncertainties, operational uncertainties, residuals, and other inert fluids should also be calculated.

Typically, the MPE provides a predicted mass summary to the propulsion engineering organization, which then provides propellant analysis by mission phase for the MPE to complete the system mass properties analysis.

There is no MGA applied to the propellant itself. Propellant mass margin is generally calculated relative to tank capacity but, in some cases, may be restricted by other mission limits, e.g., wet mass at launch.

The contractor should have the ability to model the location of the propellant mass in the propellant tank(s) as a function of propellant fraction fill and mission condition, e.g., launch or spin field. The effective inertia of the propellant should be estimated, taking into account the effects of location in a spin field and use of bladders or baffles. For systems with large propellant mass, propellant sloshing should be assessed for contribution to overall mass properties.

5.2.5.2.2 Movable Objects

The mass properties of movable objects, e.g., solar arrays, rotating antennas, and articulating engine nozzles, greatly affect the dynamic stability and attitude and control system of the entire space system. Proper attention to pivot coordinate system location (when applicable), reported with accurate mass properties data, will support the attitude and control analysis for best performance. A best practice is to analyze the constituents of these movable objects with a bottom-up approach, which allows for a minimum of misrepresentation of the mass of the moveable object.

The storage of coordinate transformations and articulation records in the mass properties database, combined with appropriately structured assembly and component mass properties records and software, can enable the database and mass properties analysis system to compute mass properties for various vehicle configurations with simple manipulation of articulation records.

Mass properties of the moving parts separable from a space system are essential for analyzing system flight stability and other dynamic events. Mass properties of any jettisoned hardware are necessary to support re-contact analysis; mass properties of the moving parts of the system's engines are necessary for stability analysis.

5.2.5.2.3 Mission Sequential Mass Properties

The contractor should perform sequential and subsystem mass properties as necessary to support guidance navigation and control and jettison and re-contact analyses. The space system mass properties should be determined and documented as a function of time or propellant fraction fill from mission initiation through mission completion.

The changing aspects of an LV's mass properties are essential for analyzing system flight
stability and performance. Mass properties of propellants, including slosh dynamics, pressurization gases, ullage, and recirculation fluids, should be analyzed at critical times in the mission in support of propulsion system development.

5.2.5.3 Finite Element Model (FEM) Mass Distribution Analysis
Sectional mass distribution analysis, consistent with the segment definitions set by the structural and controls systems analysis group, supports the development of the space system FEM. The FEM supports analyses to determine dynamic response, loads distribution, stress analysis of structure and units, and control and stability limits for space system components.

Support includes coordination of a mass properties distribution format, i.e., geographic segmentations, raw mass properties, special groupings; required vehicle configurations, e.g., dry, at launch, beginning of life, end of life, dry deployed, limited assemblies; and data formatting, i.e., Microsoft® Excel® workbook, comma-separated values, text.

5.2.5.4 Mission Worst-Case Analysis
To guarantee space system performance throughout the mission, a worst-case mass properties analysis may be requested periodically. The contractor should have the capability to perform this analysis, which takes into account extremes of mass, CMs, and inertias, as well as MGA, mass threats/opportunities, uncertainties, and margins (both predicted mass and propellant).

5.2.5.5 Post-Flight Analysis
Actual mass properties data should be determined by analysis of post-flight data, where available, for significant mission events. If a post-flight analysis is performed, then the differences from the planned conditions should be itemized and explained.

5.2.5.6 Ground Operations Support Analysis
Adequate mass properties should be developed and documented for the support of ground handling, transportation, and launch operations. These data should be in agreement with the actual vehicle configuration and with the planned loading and utilization of fluids and propellants.

5.2.5.7 Post-Test Analysis
The contractor's records of all changes to the SV subsequent to final mass properties measurements and the resulting mass properties should be made available for review.

5.3 Verification

5.3.1 Verification Plan
The Verification Plan should include a general description of the method selected to verify each mass properties parameter that is to be used in performance analyses, stability and control analyses, or other analyses that require mass properties data as an input.

The Verification Plan should originate during the conceptual design and development stage, be updated and reviewed at PDR, and be released by Critical Design Review (CDR). The purpose of the Verification Plan is to provide a document that engineering,
management and the customer can use to review planned methods for verifying the SV mass properties.

5.3.1.1 Verification Criteria
The contractor should provide a matrix to list the parts or units, subassemblies, assemblies, bus, payload, and space system to be verified, along with mass properties parameters, verification methods, required accuracies, and schedule. This matrix may be a section of the system Verification Cross Reference Matrix.

5.3.1.2 Verification Method Selection
Verification may be accomplished by approved analytical methods, by test, or by a combination of both. The verification methods should be selected early enough in the program to provide time for the acquisition, modification, or preparation of measurement equipment (handling, fixturing, and support equipment) and test site selection. (See SAWE RP 16 for options in selecting test equipment.)

5.3.2 Test Plan
The Test Plan documents the mass properties to be verified by measurement. (See SAWE RP 16 for guidelines on performing mass properties measurements.) Significant mass properties measurements are included in the program schedule with a method established to inform the responsible MPE of imminent measurement opportunities. The test plan includes requirements for measuring mass, CM, and MOI or for performing static or dynamic balance, as necessary to meet the program’s design and operational requirements. The test plan outlines the steps to be followed during a test or, where practical, refers to the latest revision of the standard work instruction (SWI) or test procedure (TP).

5.3.2.1 Test Description
An example outline of a test description is given below:

- Description of the Test Items: List the items to be measured, e.g., electronic unit, wire harness, thermal blanket, assembly, bus, or total space system. Provide the part numbers or drawing numbers and serial numbers for the test items.
- Configuration: Verify completeness of the test items using the parts list of the current drawings. Identify and record any shortages, overages, and tare items. Note the configuration status if the items are not in final flight status, e.g., engineering model or qualification unit.
- Mass Properties Parameters, Required Tests, and Success Criteria: Identify the required mass properties tests, such as mass, CM, MOI, POI, and static or dynamic balance. Provide the test requirements and success criteria.
- Accuracy: Address how the following sources of error are being handled: buoyancy, volume of air, aerodynamic lift or drag, nutation damper fluids, and propellant fluids or gas.
- Provide a list of the measurement system and equipment to be used and the test location.
• Describe the test setup and outline the test steps to be followed by an approved SWI or TP.

• Include the pertinent dimensions, definition of the coordinate system, and reference data.

• Include the environmental and safety control provisions.

5.3.2.2 Ground Support Equipment
The GSE used for test measurements includes adapters, lifting and handling fixtures, and sling cables. Depending on the type of measurement, other GSE such as enclosures or ballast mass may be required. All potential GSE should be identified in both the test plan and the TP. The test plan also includes a schedule for GSE storage, transport to test site, and restoration to a clean and working condition. GSE typically has much wider fabrication tolerances and mass variation than flight hardware. In addition, GSE may have numerous optional pieces that may or may not be installed during weighing operations. For these reasons, GSE configuration and mass properties data must be carefully monitored and recorded during mass properties measurement operations.

Additionally, GSE may have periodic inspection and proof load requirements and unforeseen repairs and modifications for various reasons. GSE mass properties should be either:

1. Measured immediately before or after each flight hardware weighing.

2. Measured at periodic intervals, such as after proof test and refurbishment, and mass properties should be tracked by serial number of the GSE.

3. Marked so that the mass properties group is notified whenever the GSE is modified in any way.

Appropriate proof load and effective validation dates are recommended to exceed 6 months beyond the scheduled test date.

5.3.2.3 Measurement Uncertainty
Measurements are used to validate analytical models and to document final mass properties, which may differ from analyses for two reasons: insufficient modeling or failure to include some sources of mass or inertia and imprecise measurements. Since it is difficult to identify all potential sources of discrepancy between predictions and measurements, the test plan includes a measurement system error analysis that includes sources of error, the method of estimation used for each error, effects of each error source on measurement precision, and the method by which all sources of error are combined to form the overall measurement imprecision. The measurement uncertainty analysis should be initiated as part of the test plan and updated as the test configuration matures and the test equipment design and fit check are completed. A final measurement uncertainty analysis is performed upon completion of final system testing.
5.3.2.4 Measurement Schedule
The program master phase plan should contain dates for which major mass properties measurements are to occur. The contractor should also estimate the time required for each test based on previous experience and prepare and distribute a test schedule flow chart. A method should be established to inform the MPE of imminent measurement opportunities.

5.3.3 Standard Work Instruction
The SWI contains detailed instructions on how to perform a task. The SWI is usually applicable when routine mass properties measurements are to be followed, e.g., SWI for mass and CM measurements, SWI for load cell calibration, or SWI for electrostatic protection. The SWI should be referenced in the TP.

5.3.4 Test Procedure
Major mass properties measurements are conducted in accordance with approved and released detailed TPs.

5.3.4.1 Test Scope
The test scope describes the general plan for the test objective, success criteria, test methods, and operation.

5.3.4.2 Applicable Documents, Equipment, GSE, and Software
The test procedure lists all applicable documents related to the test, including Government documents, standards, specifications, a list of the associated equipment, GSE, and software, related SWI, general practices, and procedures.

5.3.4.3 Requirements
The following requirements should be included in the mass properties test procedure:

- Environmental conditions (test site cleanliness, temperature, humidity), including environmental hazards class certification (if required).
- Security level in effect during the test; entrance, escort, and guard regulations are stipulated.
- Test equipment calibration dates and stated accuracies.
- Quality assurance and safety, health, and environmental affairs provisions, including signatures before procedure release.
- A log to record test events and anomalies.
- Reference to documents that contain flowdown of requirements upon which test is based.
- A definition of the success criteria for the test.
- Reference to the uncertainty analysis for the test article.
- The acceptance criteria for each measurement; any deviation from these criteria is approved by the MPE authority before proceeding to the next step in the test.
5.3.4.4 Test Configuration
The mass properties test configuration is documented so that personnel can clearly understand that the test item is ready before starting any test. Any change during the test is recorded and evaluated to validate that the test objectives and requirements are met. Any configuration change after the test is monitored and assessed for impact on requirements to assure the mission success. The following requirements apply:

- The test article simulates the flight condition to the extent practical, excluding hazardous components or components not normally installed at the measurement site. Deviations from the flight condition are recorded and should be commensurate with test objectives so that the test results are meaningful and measurement uncertainties are within expected ranges.

- Configuration Verification: The cognizant manager or authorized designee, vehicle engineer, and responsible quality control engineer verify the test article configuration, provide a list of shortages, overages, and tare items, and sign and certify that the test configuration meets above test configuration requirements.

- The mass properties test director (mass properties lead engineer or designee) reviews the certificate and signs acceptance before starting the mass properties test.

- The use of mass simulators instead of flight items in any test is accurately documented.

- The MPE performs an appropriate analysis for the shortages and overages, and if required, test personnel formulate and install simulation and compensation weights during the appropriate test process.

- The mass properties test director or authorized designee verifies the GSE used in each mass properties test step to assure that the GSE has a valid proof load certificate.

- Illustration of the coordinate system is provided in the TP to describe the coordinate systems used for the test article, GSE, and test equipment and to provide a table to identify the relationship between the different coordinate systems if the test item coordinate system is different from that of the test equipment or GSE.

5.3.4.5 Test Sequence
A general test sequence is described in the following example:

- Test setup: Describe the step-by-step set-up procedure for the test equipment or follow the sequence from the released SWI. The SWI should be referenced and attached in the test procedure during the test. Test site cleanliness practices commensurate with the requirements should be followed.

- Install and secure the GSE in accordance with the TP.
• Align the GSE in accordance with the approved alignment procedure or SWI. Record alignment raw data for each iteration until the alignment requirements are met. The MPE should verify the alignment accuracy and analyze the effect of the residual alignment error on the test results to assure that the overall alignment is acceptable.

• Perform tare balance or mass properties measurements, e.g., MOI, in accordance with the TP.

• Verify test item test configuration. Sign acceptance if the test configuration requirements are met.

• Weigh test item in accordance with the TP or SWI before the installation on GSE and then perform test item alignment.

• Install simulation and compensation mass in accordance with the analysis for the shortages and overages, if required.

• Perform test item balance or other mass properties measurements. Install balance mass as required in accordance with the TP until the requirements are met. Take inventory of the balance mass and record on the data sheet.

• Perform data reduction.

• Compare the test results with the predicted results. Summarize results with comparisons to the predicted results and make a timely assessment.

• Remove the test item from GSE and take final mass measurement.

• Publish As-Measured Mass Properties Report.

5.3.5 Data Record
The mass properties measurement data are recorded within the appropriate TP or SWI. The data are then reduced and converted into a test report. A description of the minimum test report requirements and post-test tracking are described in the following subsections.

5.3.5.1 Records for Mass Properties Measurements
Records for each major mass properties measurement performed in accordance with approved procedures or detailed work/process instructions includes the following:

• An explanation of any deviations from approved procedures or work/process instructions.

• An evaluation of the measurement results with conclusions that state whether the mass properties measurements comply with their requirements.
• In cases where non-compliance to requirements is predicted, clearly define the technical performance impact for such and identify options to mitigate any technical performance shortfall.

• Test equipment model number, serial number, and date of last calibration or date of calibration expiration.

• Location where measurements were performed, signature of authorized individual responsible for the entries, date and time of entries, document number of the approved measuring procedures, and identification of the item measured.

• Provision for the signature of the contractor’s quality control representative on measured data.

• Tables showing scale readings: tare; net mass; moment arm; moment for longitudinal, vertical, and lateral CM; and calculations showing the derivation of the as-measured mass and CM condition from the measurements.

• Measurements taken for the determination of MOI and POI and calculations showing the derivation of the as-measured inertias from the measurements.

• Variance items: a list of items, including shortages and overages, for the mass, CM, MOI, POI, and data to be added to or subtracted from the as-measured condition to obtain the actual mass properties determination for the flight condition. If permitted by security, photographically document the as-measured configuration of the measured article with a series of high-resolution photos of the overall weighing, including weighing equipment rigging, and close-up photos of areas where complex configurations of the measured article must be verified.

• Diagrams of measuring equipment and related fixtures showing pertinent dimensions and other data required for the determination of the as-measured mass, CM, MOI, and POI.

• If the measured article includes large propellant tanks, pressurant tanks, or sealed compartments that are known to or are suspected of containing liquids or gases with densities different from the surrounding atmosphere during weighing, take measurements to compute tank buoyancy. Take gas samples of the gas in each separate tank; also measure the pressure in each tank, measure barometric pressure of the surrounding atmosphere, and measure the ambient air temperature. If the gas temperature in the tanks may differ significantly from ambient temperature, take measurements of the tank gas temperatures, if possible.

• If using force measurement devices, such as load cells or electronic platform scales, to obtain weight readings, include the measurement or computation of local gravitational acceleration at the weighing site so weight measurements can be converted to corresponding mass values. Note that some electronic weighing systems have software features that can adjust weight measurements in local gravity to standard gravity. The presence of such features should be verified, and if present, the system’s gravity adjustment settings during the weighing should be
recorded. If the weight measurement is performed using mass balance systems, such as balance beam scales, this fact should be documented, and no local gravity adjustment should be performed.

5.3.5.2 Post-Test Configuration Change Log
The contractor prepares and maintains a detailed record of all changes made post-test to the flight configuration for each critical mass properties measurement. The post-test change log includes the following items at a minimum:

- Description of the change and the mass properties affected.
- The “was” and “is” conditions for each mass properties parameter affected by the change.
- Date of the change.
- Signatures of the contractor’s quality/configuration control representative and the responsible engineering activity for each configuration change.
- Records prepared in chronological order.

5.4 Mass Properties Data Management

5.4.1 Scope
The contractor’s mass properties data management system is an essential analysis model of the space system, representing the system mass properties of all critical parameters through planned ground and control operations. The accuracies of the space system model support the program reporting requirements. The contractor’s space system mass properties database is maintained and updated to reflect the most recent information from design data, drawings, models, mass properties measurements, CFE data, associate contractors, subcontractors, and suppliers.

5.4.2 Data Management System
An analytical database, preferably relational, is maintained and accurately represents the space system’s mass properties throughout the mission, including launch, transfer orbit, on station, and return (if applicable). The database is capable of sorting mass properties by various criteria and recombining aggregate mass properties based on that sort criteria.

5.4.2.1 Database Requirements
In addition to those requirements listed in AIAA S-120A-2015, a flexible mass properties database management tool should be capable of providing the following:

- Ability to change the coordinate system used for mass properties calculations for a single entry or a group of entries.
- Ability to calculate propellant mass properties as a function of time or fill level (time independent).
• Ability to import, e.g., from CAD databases, and export, e.g., to Microsoft® Excel® spreadsheet formats, mass properties.

• Ability to store mass change, mass maturity, and material usage information in user definable fields and custom report formats.

5.4.2.2 Frequency of Database Update
The database is updated on an agreed-upon schedule to be current with the space system design activity and meet the overall program requirements for reporting.

5.4.3 Data Organization Utility
The mass properties database should have the flexibility to sort and report mass properties data in multiple formats, based on criteria from various programmatic and technical stakeholders, as described in the following sections.

5.4.3.1 Functional Breakdown Structure (FBS)
To provide a uniform basis for mass properties comparisons, the space system mass properties should be categorized on a functional basis. For example, the mass of all items that function primarily as the space system structure should be accumulated for the total mass of the space system structure. Similarly, for movable parts and jettison items, a separate accounting should be performed in support of the analysis community.

Summary mass properties reports may require first, second, third, or subsequent levels of detail. See Appendix B in this document for examples of FBS for various space systems.

5.4.3.2 Work Breakdown Structure Organization
The database should have the organization and sort capability to show correlation to the program contract WBS. This typically means a correlation of component masses to their respective development organization or by drawing numbers. This should be done at a level of detail that permits determination that the masses of all items on the space system have been included properly and within the prescribed mass allocation.

5.4.3.3 Sectional Organization
When knowledge of the section mass properties of the space system is required, the mass properties data for the sections should be developed separately. Examples of this include a propulsive vehicle having more than one stage, an independently movable section of a space system, and FEM mass distribution modeling. The functional organization is maintained within the mass properties data of each section.

5.4.3.4 Customer-Furnished Equipment
The contractor’s mass properties records should have a separate tabulation of all CFE.

5.4.4 Database Record Keeping
The contractor maintains records of the detailed mass properties, including the correlation of weights with their respective drawing numbers or model versions, at a level of detail that permits the determination that the weights of all items on the space system have been included correctly. Delivery of the electronic form of the mass properties database is provided to the customer at major milestone reviews or upon request.
5.4.5 Mass Changes
A documented accounting of all mass changes, including part name and drawing number, should be maintained throughout the contract. For all mass changes, the accounting should include the “was” and “is” value of the item, the magnitude of the change, the reasons for the changes, be gathered into the categories defined in Table 3 (contained in section 5.5.7.6 of this document), and be accumulated throughout the program.

5.5 Documentation

5.5.1 Scope
Mass properties documentation consists of plans and reports. Plans define the program management methods for controlling, reporting, and measuring mass properties. Reports provide visibility into the hardware configuration and design maturity through the development process. Documentation described in this section should be specified in the contractor statement of work and Contract Data Requirements List (CDRL). Recommended document submittal schedules are provided in Appendix D of this document.

5.5.2 Mass Properties Control Plan
An MPCP is developed and documented by the contractor and approved by the customer. The plan provides visibility into the contractual agreements for mass properties control and details tailoring of the mass control requirements. The scope of the MPCP includes management process and procedures to be used for mass properties control, verification, and documentation during the various program phases.

5.5.2.1 Terminology
The MPCP should define all mass properties terminology used on the program.

5.5.2.2 Mass Growth Allowance Schedule
The MPCP should define the MGA schedule used on the program.

5.5.2.3 Critical Mass Properties
The MPCP relies on the flowdown of requirements to identify all critical mass properties required for system analysis.

5.5.2.4 Mass Control Process
The MPCP should define the authoritative body charged with approving changes affecting mass. In some cases, this is a MPCB, while in other cases, it is a board chaired by the Chief Engineer or technical authority.

5.5.2.5 Technical Performance Measurement
The MPCP should describe the content, format, and submission frequency of program-specific TPMs as described in sections 5.1.10 and 5.1.11 in this document.

5.5.2.6 Mass Properties Reporting
The MPCP should define the content and frequency of mass properties reporting as described in section 5.5.7 in this document.
5.5.3 Verification Plan
Verification planning is incorporated in program-specific verification documentation. The planning defines the methods to be used to verify the mass properties data, detailed verification objectives, success criteria, and compliance artifacts. The planning should address the process for determining part, unit, subassembly-, and assembly-level verification. The verification methods should be formulated in the early stages of the program, with detailed planning completed by CDR.

Mass properties measurement requirements can affect the hardware design. Consequently, procurement of long-lead measurement devices, such as adapters and handling equipment, might be required. In addition, hard points on vehicles should be provided in the design to align the flight vehicle to the test equipment.

The plan should define the method of verification, analysis, or test for each mass properties parameter. If margins are small, an uncertainty analysis should be performed to verify whether analysis is sufficient. A more detailed plan, including which units, parts, subassemblies, or modules are to be weighed, may be required. A note should be placed on each detail or assembly drawing defining which items should be weighed. On programs with multiple identical space systems, it may be sufficient to weigh only the first serial number at the detail part or unit level. Such information should be transmitted to the manufacturing organization for implementation in planning documents.

5.5.4 Mass Properties Test Plans and Procedures
Formally released test plans include information on the facility and timing of tests, GSE required to perform the test, system safety and environmental requirements, alignment requirements, and coordinate system references.

For complex measurements, formally released test procedures contain detailed, step-by-step instructions to be followed in the course of system-level mass properties measurements. For simpler operations, an SWI may be developed.

5.5.5 Test Completion Reports
The records for each critical mass properties test, performed in accordance with approved and released procedures, are documented in a test completion report. As a minimum, the report should include the following:

- A concise summary of the measurement results and predicted compliance against the requirements. In cases where non-compliance is predicted, quantify the impact to space system performance, and state the plan to resolve the problem.
- A summary of the critical mass properties and their limits for which the validation measurements were executed.
- The results of uncertainty analyses that provide a worst-case bound on the measurement results to properly predict whether requirements are met with adequate margin.
- Documentation that demonstrates that all the steps in the test procedure were performed and that the recorded measurement data are correct.
• Copies of all the raw test data measurements taken, with clear annotation on the data records to indicate the date and time (in chronological sequence) when the test data were taken.

• Applicable diagrams and coordinate system definitions to indicate the spatial relationship between the test data, test equipment, and the flight test article.

• If the measured article is not in its final in-flight configuration, include documentation of the as-measured configuration of the measured article, inventory and summary of the article’s missing flight items (shortage list), inventory and summary of the non-flight items attached to the article during measurement (overage list), and derivation of the article’s in-flight mass properties from measurement data and overage and shortage item accounting.

• If the measured article includes large propellant tanks, pressurant tanks, or sealed compartments that are known to or are suspected of containing liquids or gases with densities different from the surrounding atmosphere during weighing, tank buoyancy computations and weight measurement adjustments should be performed. Include measurements of in-tank gas or fluid sample compositions, internal tank pressures, barometric pressure of the surrounding atmosphere, and applicable atmosphere and tank temperature measurements. Also include computations and results of the gas or fluid density calculations, tank or enclosure volumes, and resulting buoyancy adjustments.

• If using force measurement devices (such as load cells or electronic platform scales) to obtain weight readings, include the measurement or computation of local gravitational acceleration at the weighing site to document how weight measurements were converted to corresponding mass values. If the electronic weighing systems have software features that can be used to adjust weight measurements in local gravity to standard gravity, document that the measurement system has such features, and document the system’s gravity adjustment settings during the measurement. If the weight measurement is performed using mass balance systems, such as balance beam scales, this fact should be documented, and no local gravity adjustment should be performed.

5.5.6 Contract Change Proposals
Information necessary to evaluate and substantiate the effect on vehicle mass properties resulting from proposed changes is submitted with the change proposal.

5.5.7 Mass Properties Status Report
A report format establishes the needs of the customer, program office, and other internal customers who rely on the timely communication of mass properties information.

Periodic status reports provide insight into the space system’s mass properties throughout development. The report may consist of a full set of mass properties or a subset thereof, depending on the contractual requirement for reporting. In some cases, where margins are large and control systems robust, reporting total predicted mass is sufficient. The level of detail to be reported may also vary depending on the degree of visibility required of a particular assembly or subsystem as stated in the contract.
EXAMPLE: Typically, the details of the masses of the components within an electronic box are not required, so there might be a request to report only the predicted total mass of the unit. Conversely, at certain points in the program, the customer might want to view the entire detail mass properties database for an independent review.

The following subsections are descriptions of the various document elements.

5.5.7.1 Title Page
A title page should contain the following information, as applicable:

- Document number.
- Type of submittal.
- Vehicle flight number.
- Step, stage, or module.
- Applicable serial numbers.
- Date of issuance.
- Actual date of data reported.
- Contractor's name.
- Mission identification.

5.5.7.2 Introduction
The introduction defines the scope or purpose of the document and concisely summarizes the significant material presented in the document.

5.5.7.3 Table of Contents
The Table of Contents is a listing of the document elements and their location within the report.

5.5.7.4 Mass Properties Summary
The mass properties summary should include the following:

a. Mass Status: Current basic and predicted mass, change to basic and predicted mass from last status, NTE mass allocation (specification), and margin against requirement for the following:

- Space system functional subsystems.
- Payload or cargo subsystems.
- CFE (if required).
- Space system dry flight vehicle.
- For LVs, dry mass properties for each in-flight separable LV segment.
- Propellants and pressurant.
- Space system wet flight vehicle.
- For LVs, wet mass properties for each in-flight separable LV segment.
- LV adapters and mission-peculiar items.
- Space system launch mass.
- LV mass-to-orbit capability for the specified target state vector.
b. Design Maturity Status: Show percentage of mass categorized by maturity code (as defined in Table 1) for the following configurations:

- Space system functional subsystems.
- Payload or cargo subsystems.
- Space system (dry).

c. Mass Properties Requirements (Limit Monitoring): Present a tabulation of all the critical mass properties, and provide the following for each requirement to substantiate the predicted performance against the requirement:

- Description.
- Current basic value.
- Uncertainty.
- Current predicted parameter value.
- Specification requirement or derived limit.
- Predicted compliance to the requirement (margin).
- Indicate method to verify the requirement (analysis or test).
- List the source of the requirement.

d. SV Mass Properties Summary: Provide a tabulation of the current space system stowed configuration mass properties (mass, CM, MOI, POI) in an orderly buildup from the dry space system to the space system configuration at separation from the LV. Provide the mass properties data for the following hardware categories and conditions, as a minimum:

- Space system functional subsystems.
- Payload or cargo functional subsystems.
- CFE (if required).
- Space system (dry).
- Propellants and pressurant.
- Space system at separation from the LV.

e. LV Mass Properties Summary: Provide a tabulation of the current LV configuration mass properties (mass, CM, MOI, POI) in an orderly buildup from the dry to the loaded beginning-of-flight (such as at the end of propellant loading or at liftoff) condition for each separable LV segment. Stack the vehicle segment mass properties data to provide a mass properties summary of the entire LV, including payloads at beginning of flight. Provide the above mass properties data for each of the vehicle’s separable vehicle segments, as a minimum:

- Space system functional subsystems.
- Payload or cargo functional subsystems.
- CFE (if required).
• Space system (dry).

• Propellants and pressurant.

• Space system at liftoff, LV segment separation events, and SV separation events.

f. TPM Charts: Provide TPM charts for all critical mass properties requirements.

g. Summarize concerns and new technical issues that impact the space system mass properties.

5.5.7.5 Mass Change Analysis

Prepare a detailed tabulation of the space system mass changes that have occurred since the last status report. The changes should be grouped by functional subsystems for the bus and payload. Provide the following information, as a minimum, for each mass change:

• Date of incorporation into the database.
• Database functional code.
• Mass change code (as defined in Table 3 in section 5.5.7.6 in this document).
• Description of the change.
• Current basic mass of the item(s) changed.

For LVs, the changes should be grouped by functional subsystems for each in-flight separable LV segment.

5.5.7.6 Mass Change Summary by Change Code

Prepare a tabulated summary, at the space system level, of the total mass change coded to each change category (as defined in Table 3) for each status report and show a running total of the mass change total by change category from program ATP.

Table 3. Mass Change Codes and Definitions

<table>
<thead>
<tr>
<th>Code</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td><strong>Better definition of the design</strong></td>
</tr>
<tr>
<td></td>
<td>Changes that occur as the design progresses beyond the proposal stage and the design criteria and requirements become better defined. These changes are generally early in the program (before drawing or model release).</td>
</tr>
<tr>
<td>2</td>
<td><strong>Out-of-scope changes</strong></td>
</tr>
<tr>
<td></td>
<td>Scope changes caused by the procuring authority’s adding new or changing existing requirements.</td>
</tr>
<tr>
<td>3</td>
<td><strong>Redesign or corrective action</strong></td>
</tr>
<tr>
<td></td>
<td>Changes to the original component or subsystem design related to repackaging, failure of a component during testing, impact of other subsystem changes, or other corrective actions.</td>
</tr>
<tr>
<td></td>
<td><strong>Reference Coordinate Axes and Space System Configurations</strong></td>
</tr>
<tr>
<td>---</td>
<td>-------------------------------------------------------------</td>
</tr>
</tbody>
</table>
| 4 | **Maturing component design**  
   Updated mass analysis related to model revisions at or after original release. |
| 5 | **Safety or operational enhancements**  
   Updated mass related to an improvement of operations or safety-related measures. |
| 6 | **Error in previous estimate**  
   Changes related to errors in the mass calculations for a previous estimate. |
| 7 | **Vendor changes**  
   A change in supplier or a change in the supplier’s design (regardless of cause). |
| 8 | **Mass reduction activity**  
   Changes related to official mass reduction efforts. |
| 9 | **Measured versus calculated or weighing deviation**  
   Changes related to the measured mass of a component or unit differing from a calculated or previously measured values. |
| 10 | **Cost/schedule reduction or process improvement**  
   Mass increases that were incurred to save cost or schedule, e.g., substitution for expensive exotic materials or redesign of elaborate machined parts and cutouts to reduce machinery costs. |

### 5.5.7.7 Pending and Potential Changes

All pending or potential design changes with threats to increase and opportunities to decrease the system mass should be documented. The changes should be grouped by functional subsystem. Each potential change is evaluated and assigned a percent probability of occurrence. A closure date is assigned to each item to indicate when disposition to drop or implement the change will be made. An evaluation of impacts for each potential change is made and documented. Potential changes may be summed, or weighted average may be used; pending changes are additive. Prepare the following information, as a minimum, for each identified change:

- Description of the change.
- Functional subsystem(s) affected.
- Estimated item(s) basic mass, MGA, and predicted mass.
- Probability of occurrence: H, M, or L.
- Closure date.
- Impact to critical mass properties limits.

### 5.5.7.8 Reference Coordinate Axes and Space System Configurations

A diagram or CAD model depiction that relates the location and orientation of the reference axis system used for mass properties determination of the space system should be included in each status report. The exact location of the reference axis system origin with respect to the vehicle should be noted on the diagram. If the space system comprises more than one section and each section has a different reference axis system, each system should be similarly described. Their mutual relative locations and orientations should also be described.
Guidelines for reporting the mass properties of flight vehicles have been developed by SAWE in RP 6. It is recommended that these guidelines be used when developing a reference axis system.

5.5.7.9 Seized Mass Properties
Prepare data (mission event, mass, CM, MOI, and POI) for the space system at each significant mission event from launch (showing the dry and wet conditions) through the end of the mission. The mission events should be presented according to the mission timeline, showing the space system mass properties for pre- and post-propellant burns and deployments. Define the basis for the data, i.e., basic mass or predicted mass.

5.5.7.10 Space System Movable Objects
Prepare tabulated mass properties data for all of the space system elements that move during the mission sequence from launch to end of mission, e.g., antennas, solar arrays, or payload sensors. The information should include the following for each movable object at a minimum:

- Pivot point or translation point location in the space system coordinate axes (if applicable).
- Stowed mass properties.
- Deployed mass properties (nominal deployed position).
- Basis for data: basic mass or predicted mass.

5.5.7.11 Mission-Critical Mass Properties
Include tabulations of the significant mass properties that vary during the mission sequence and are used to derive mission performance, e.g., attitude determination, stability, and control. Examples include but are not limited to the following:

- Tabulation or plot of mass; CM; pitch, yaw, and roll MOI versus mission time.
- Tabulation or plot of spin-to-transverse inertia ratio, spin-axis tilt (wobble angle) and phase angle versus mission time.

The tabulation or plot should stipulate whether basic or predicted mass values are used.

5.5.7.12 Uncertainties
The requirements for mass properties uncertainty determination are generally specified in section 5.2.4 of this document. Mass properties uncertainties should be considered when evaluating the following:

- Assessment of mass properties predicted performance and compliance to requirements.
- Selection of mass properties verification methods, either test or analysis.
• Selection of test equipment accuracy/sensitivity.

5.5.7.13 Mass Distribution
Mass distribution models to support the analysis tasks of engineering technical specialties, such as stress/dynamics and ground systems, should be documented and correlated to defined mass properties models. Mass distribution models support the development of:

• FEMs.
• GSE designs (lifting slings, handling fixtures, etc.).

5.5.7.14 Mass Growth Allowance Schedule
The MGA schedule documented in the MPCP should be used for reporting.

5.5.7.15 Space System Design Features
These data include major dimensional factors, design criteria, and design features used in the development of the reported mass properties. Appendix C in this document presents a list that may be used as a guide for data submitted.

5.5.7.16 Detailed Mass
Prepare a tabulation of the current space system detailed mass by functional subsystem or drawing tree structure. Show the following for each line of detail:

• Functional code.
• Description.
• Basic mass.
• Predicted mass.
• Percent of basic mass in each category as coded in Table 1.
• MGA.

5.5.7.17 Detailed Mass Properties
Prepare a tabulation of the current space system detailed mass properties by functional subsystem or drawing tree structure. Show the following for each line of detail:

• Functional code.
• Description.
• Basic mass.
• Predicted mass.
• CM (X, Y, Z).
• MOI (Ixx, Iyy, Izz).
• POI (Ixy, Ixz, Iyz).

The contractor should stipulate whether the values used to derive CM, MOI, and POI are derived from basic or predicted mass.
5.5.7.18 Definitions and Acronyms
Include a list of definitions and acronyms specific to the document.

5.5.7.19 References
Include a listing of the pertinent references, such as data sources, reports correspondence, substantiating documents, and any other material germane to the document.

5.5.7.20 Evaluation of Flight
Compare the actual launch mass properties and the actual mass properties variations observed throughout the flight with the predicted mass properties flight data. An evaluation of the critical mass properties, uncertainties, and other pertinent data should be included in any final post-flight report to substantiate the contractor’s predicted mass properties and confirm either expected flight mass properties conditions or apparent anomalies.

6 References
A. Supplemental Information for Terms and Definitions

A.1 Mathematical Descriptions

The following mathematical descriptions are provided to aid understanding of certain definitions contained in section 4.2.

A.1.1 Mass

Unlike weight, mass is an intrinsic property that is independent of the gravitational field. Mass is given by $m = \int dm$ for a continuous system or $m = \sum m_i$ for a discrete system.

A.1.2 Center of Mass

The CM in the X-axis is given by $x_{cm} = \int \frac{1}{m} x dm$ for a continuous system or $x_{cm} = \frac{\sum m_i x_i}{m}$ for a discrete system relative to a defined, fixed coordinate system.

A.1.3 Moment of Inertia

MOI and POI together quantify the distribution of mass relative to a defined coordinate system. MOI are defined as the sum of the products of each element of mass by the square of the perpendicular distance from a specified axis. For example, the MOI about the X-axis is given by $I_{xx} = \int (y^2 + z^2) dm$ for a continuous system or $I_{xx} = \sum m_i (y_i^2 + z_i^2)$ for a discrete system. Typically, MOI are defined with respect to the CM.

A.1.4 Product of Inertia

POI are defined as the sum of the product of each element of mass by the perpendicular distances from two specified axes. For example, a positive integral POI about the X and Y-axes is given by $I_{xy} = \int xy dm$ for a continuous system or $I_{xy} = \sum m_i x_i y_i$ for a discrete system. Usually, POI are defined with respect to the CM.

POI are defined as a negative integral by Guidance, Navigation, & Control or Attitude Control System ($I_{xy} = \int xy dm$). Special attention should be paid to understanding whether a positive or negative integral is used in the determination of the POI. POI is expressed in the same units as MOI, but it can have either positive or negative polarity.

A.1.5 Inertia Tensor

An inertia tensor consists of MOI (diagonal terms) and POI (off-diagonal terms) in the coordinate system of interest. The eigensolution of the inertia tensor provides three principal inertias (eigenvalues) and their corresponding principal axes (eigenvectors).

For a continuous system (with xyz coordinates):

$$
\begin{bmatrix}
\int (y^2 + z^2) dm & -\int xy dm & -\int xz dm \\
-\int xy dm & \int (x^2 + z^2) dm & -\int yz dm \\
-\int xz dm & -\int yz dm & \int (x^2 + y^2) dm
\end{bmatrix}
$$
For a discrete system:

\[
I = \sum_i l_{xx} + \sum_i m_i [(y_i - \bar{y})^2 + (z_i - \bar{z})^2]
- \sum_i l_{xy} - \sum_i m_i (x_i - \bar{x})(y_i - \bar{y})
- \sum_i l_{xz} - \sum_i m_i (x_i - \bar{x})(z_i - \bar{z})
\]

\[
l = \begin{bmatrix}
- \sum_i l_{yy} - \sum_i m_i (x_i - \bar{x})(y_i - \bar{y}) & \sum_i l_{yy} + \sum_i m_i [(x_j - \bar{x})^2 + (z_j - \bar{z})^2] & - \sum_i l_{yz} - \sum_i m_i (y_j - \bar{y})(z_j - \bar{z}) \\
- \sum_i l_{xy} - \sum_i m_i (x_i - \bar{x})(y_i - \bar{y}) & \sum_i l_{xx} + \sum_i m_i [(x_j - \bar{x})^2 + (y_j - \bar{y})^2] & - \sum_i l_{xz} - \sum_i m_i (x_j - \bar{x})(z_j - \bar{z}) \\
- \sum_i l_{xz} - \sum_i m_i (x_i - \bar{x})(z_i - \bar{z}) & - \sum_i l_{yz} - \sum_i m_i (y_i - \bar{y})(z_i - \bar{z}) & \sum_i l_{zz} + \sum_i m_i [(x_i - \bar{x})^2 + (y_i - \bar{y})^2]
\end{bmatrix}
\]

If the coordinate axes of a body align with the principal axes of that body, then the inertia tensor is a diagonal matrix, i.e., POI are 0.

The inertia tensor quantifies the effects of the distribution of mass of a body on the rotational dynamics of that body. In theory, zero dynamic imbalance occurs when a rigid body spins about one of its three principal axes; however, instability may occur when not spinning about the major principal axis or dealing with flexible bodies.

### A.2 Space System Specific Mass Definitions

![Space Vehicle (SV) Allowable Wet Mass at Launch](image)

- Wet Mass Margin at Launch
- LV/SV Interface Adapter (Including MGA and Mission-Peculiar Items)
- Predicted Propellant Mass
- MGA for Payload
- MGA for Bus
- Payload Basic Dry Mass
- Bus Basic Dry Mass

**Figure A.1.** Space vehicle mass definitions
Figure A.2. Launch vehicle mass definitions

NOTE Second and higher stages should use the same mass definitions as shown for the first stage.
### A.3 Hardware Categories

#### Table A.1. Hardware Category Description

<table>
<thead>
<tr>
<th>Table 1 Hardware Category</th>
<th>Description</th>
</tr>
</thead>
</table>
| Electrical/Electronic Components | Primary purpose is to manage electronic data or power.  
- Any unit requiring electrical power, except as reserved for other categories, such as Battery, Solar Array, Thermal Control, Mechanisms, Propulsion or Instrumentation.  
- Includes but is not limited to a chassis that houses the electronic components. This includes but is not limited to communications, avionics, computers, and power conditioning, conversion or distribution. |
| Structure | Primary purpose is to provide structural support for primary and secondary loads and attachments.  
- Includes but is not limited to support panels, support tubes or trusses, doublers*, and adapters. |
| Brackets, Clips, Hardware | Primary purpose is to provide support for bracketry, attach hardware, grounding tabs, support or clamps for cables, wiring, and propellant lines. |
| Battery | Primary purpose is to provide stored electrical power.  
- Includes but is not limited to various sorts of power cells.  
- Units that support Power Conditioning should be under Electrical/Electronic Components. |
| Solar Array | Electrical device consisting of a collection (array) of connected solar (photovoltaic) cells used for converting solar energy into electricity. |
| Thermal Control | Primary purpose is to manage or control the temperature of the system.  
- Includes but is not limited to various louvers, heat pipes, blanketing, mirrors, thermal protection systems, thermal surface finishes, heaters, radiators, and phase changing materials. |
| Mechanisms | Primary purpose is to provide mechanical linkage for the reorientation or repositioning of other devices and also mechanical devices that move.  
- Includes but is not limited to various deployment mechanisms, positioners, gimbals, bearing assemblies, and momentum or reaction wheels. |
| Propulsion | Primary purpose is to provide axial or lateral thrust and/or attitude control to the system.  
- Includes but is not limited to propellant tanks (liquid and/or gas), thrusters (examples are chemical-liquid, chemical-solid, electric, nuclear), valves, manifolds, feed lines, and fittings. |
| Wire Harness | Primary purpose is to transmit signals or power to the rest of the system.  
- Includes but is not limited to flat or round conductive wiring, fiber optic lines, coaxial cabling, ordnance transfer lines. |
| Instrumentation | Primary purpose is to sense or measure the operating environment.  
- Includes but is not limited to thermocouples, strain gages, vibration transducers, accelerometers. |
| ECLSS, Crew Systems | Primary purpose is to provide a habitable environment for a flight crew in a crew compartment of a manned space system, in addition to cooling or heating various space systems or components.  
- Typically consists of an air revitalization system, water coolant loop systems, atmosphere revitalization pressure control system, active thermal control system, supply water and waste water system, waste collection system and airlock support system. |

**NOTE** These category definitions are for the purpose of assigning an MGA and not intended to be used as subsystem definitions for a specific program.

*Doubler could be either categorized under Structure or Thermal Control; suggest categorizing by primary usage.*
## B. Functional Breakdown of Mass

**Table B.1.** Example Functional Breakdown (Satellite)

<table>
<thead>
<tr>
<th>1. Payload</th>
</tr>
</thead>
<tbody>
<tr>
<td>2. Structure</td>
</tr>
<tr>
<td>2.1 Basic Structure</td>
</tr>
<tr>
<td>2.1.1 Main Truss</td>
</tr>
<tr>
<td>2.1.2 Equipment, Bulkheads, and Platforms</td>
</tr>
<tr>
<td>2.1.3 Kick Motor Support Cone</td>
</tr>
<tr>
<td>2.2 Secondary Structure</td>
</tr>
<tr>
<td>2.2.1 Reaction Control System Tank Supports</td>
</tr>
<tr>
<td>2.2.2 Momentum Wheel Supports</td>
</tr>
<tr>
<td>2.2.3 Solar Array Retention Fittings</td>
</tr>
<tr>
<td>2.3 Adapter, Separation</td>
</tr>
<tr>
<td>2.4 Mechanical Integration (hardware, clips, miscellaneous)</td>
</tr>
<tr>
<td>3. Thermal Control</td>
</tr>
<tr>
<td>3.1 Louvers</td>
</tr>
<tr>
<td>3.2 Heat Pipes</td>
</tr>
<tr>
<td>3.3 Insulation</td>
</tr>
<tr>
<td>3.4 Surface Mirrors, Paint</td>
</tr>
<tr>
<td>4. Electrical Power</td>
</tr>
<tr>
<td>4.1 Solar Array</td>
</tr>
<tr>
<td>4.1.1 Power Source</td>
</tr>
<tr>
<td>4.1.2 Substrate</td>
</tr>
<tr>
<td>4.1.3 Drives</td>
</tr>
<tr>
<td>4.2 Converters</td>
</tr>
<tr>
<td>4.3 Power Switches</td>
</tr>
<tr>
<td>4.4 Electrical Integration (harness, connectors, hardware, miscellaneous)</td>
</tr>
<tr>
<td>5. Guidance, Navigation</td>
</tr>
<tr>
<td>6. Data Management</td>
</tr>
<tr>
<td>7. Telemetry, Tracking, Command</td>
</tr>
<tr>
<td>8. Orientation Control</td>
</tr>
<tr>
<td>9. Reaction Control</td>
</tr>
<tr>
<td>10. Propulsion</td>
</tr>
<tr>
<td>11. Fluids</td>
</tr>
</tbody>
</table>
### Table B.2. Example Functional Breakdown (Liquid Propulsion Stage)

<table>
<thead>
<tr>
<th>1. Structure</th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>1.1 Fuel Tank</td>
<td></td>
</tr>
<tr>
<td>1.1.1 Domes</td>
<td></td>
</tr>
<tr>
<td>1.1.2 Cylinder</td>
<td></td>
</tr>
<tr>
<td>1.1.3 Skirts</td>
<td></td>
</tr>
<tr>
<td>1.1.4 Anti-Slosh Devices</td>
<td></td>
</tr>
<tr>
<td>1.2 Oxidizer Tank</td>
<td></td>
</tr>
<tr>
<td>1.3 Intertank Structure</td>
<td></td>
</tr>
<tr>
<td>1.4 Thrust Structure</td>
<td></td>
</tr>
<tr>
<td>1.5 Launch Supports</td>
<td></td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>2. Thermal Control</th>
<th></th>
</tr>
</thead>
</table>

<table>
<thead>
<tr>
<th>3. Main Propulsion</th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>3.1 Rocket Engine</td>
<td></td>
</tr>
<tr>
<td>3.1.1 Thrust Chambers</td>
<td></td>
</tr>
<tr>
<td>3.1.2 Pumps</td>
<td></td>
</tr>
<tr>
<td>3.1.3 Engine Systems</td>
<td></td>
</tr>
<tr>
<td>3.2 Fuel Feed</td>
<td></td>
</tr>
<tr>
<td>3.3 Oxidizer Feed</td>
<td></td>
</tr>
<tr>
<td>3.4 Pressurization</td>
<td></td>
</tr>
<tr>
<td>3.5 Fill, Drain, Vent</td>
<td></td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>4. Thrust Vector Control</th>
<th></th>
</tr>
</thead>
</table>

<table>
<thead>
<tr>
<th>5. Reaction Control System</th>
<th></th>
</tr>
</thead>
</table>

<table>
<thead>
<tr>
<th>6. Secondary Power</th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>6.1 Electrical</td>
<td></td>
</tr>
<tr>
<td>6.2 Hydraulic</td>
<td></td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>7. Avionics</th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>7.1 Guidance, Navigation, &amp; Control</td>
<td></td>
</tr>
<tr>
<td>7.2 Data Management</td>
<td></td>
</tr>
<tr>
<td>7.3 Telemetry, Tracking, and Command</td>
<td></td>
</tr>
<tr>
<td>7.4 Command and Data Handling</td>
<td></td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>8. Range Safety and Abort</th>
<th></th>
</tr>
</thead>
</table>

<table>
<thead>
<tr>
<th>9. Fluids</th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>9.1 Impulse Propellant</td>
<td></td>
</tr>
<tr>
<td>9.2 Residual Propellant</td>
<td></td>
</tr>
<tr>
<td>9.3 Reserve Propellant</td>
<td></td>
</tr>
<tr>
<td>9.4 Bias Propellant</td>
<td></td>
</tr>
<tr>
<td>9.5 Outage Propellant</td>
<td></td>
</tr>
<tr>
<td>9.6 Pressurization Gas</td>
<td></td>
</tr>
</tbody>
</table>
Table B.3. Example Functional Breakdown (Launch/Ballistic Vehicles)

<p>| | |</p>
<table>
<thead>
<tr>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>1. Stage I</td>
<td></td>
</tr>
<tr>
<td>1.1 Oxidizer tank</td>
<td></td>
</tr>
<tr>
<td>1.2 Intertank</td>
<td></td>
</tr>
<tr>
<td>1.3 Fuel Tank</td>
<td></td>
</tr>
<tr>
<td>1.4 Engine Section</td>
<td></td>
</tr>
<tr>
<td>1.5 Propulsion</td>
<td></td>
</tr>
<tr>
<td>1.6 Interstage</td>
<td></td>
</tr>
<tr>
<td></td>
<td>1.6.1 Primary Structure</td>
</tr>
<tr>
<td></td>
<td>1.6.1.1 Forward Rings</td>
</tr>
<tr>
<td></td>
<td>1.6.1.2 Aft Rings</td>
</tr>
<tr>
<td></td>
<td>1.6.1.3 Skin</td>
</tr>
<tr>
<td></td>
<td>1.6.1.4 Doors</td>
</tr>
<tr>
<td></td>
<td>1.6.1.5 Fasteners</td>
</tr>
<tr>
<td></td>
<td>1.6.2 Secondary Structure</td>
</tr>
<tr>
<td></td>
<td>1.6.3 Environmental Protection</td>
</tr>
<tr>
<td></td>
<td>1.6.4 Separation Systems</td>
</tr>
<tr>
<td></td>
<td>1.6.5 Electrical/Electronics System</td>
</tr>
<tr>
<td>2. Assist Motors</td>
<td></td>
</tr>
<tr>
<td>3. Stage II</td>
<td></td>
</tr>
<tr>
<td>4. Stage III</td>
<td></td>
</tr>
<tr>
<td>5. Payload Attach Fitting</td>
<td></td>
</tr>
<tr>
<td>6. Payload Fairing</td>
<td></td>
</tr>
<tr>
<td>7. Payload</td>
<td></td>
</tr>
</tbody>
</table>
Table B.4. Example Functional Breakdown (Manned Reentry Vehicles)

<table>
<thead>
<tr>
<th>1. Crew and Flight Crew Equipment</th>
</tr>
</thead>
<tbody>
<tr>
<td>2. Environmental Control and Life Support Systems (ECLSS)</td>
</tr>
<tr>
<td>3. Structure</td>
</tr>
<tr>
<td>3.1 Primary Structure</td>
</tr>
<tr>
<td>3.2 Secondary Structure</td>
</tr>
<tr>
<td>3.3 Ingress/Egress Hatch</td>
</tr>
<tr>
<td>3.4 Service Module Adapter, Separation System</td>
</tr>
<tr>
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<td>4.2 Insulation</td>
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<td>4.3 Surface Mirrors, Paint</td>
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<td>6.1 Batteries</td>
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<td>6.2 Converters</td>
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<tr>
<td>6.3 Power Switches</td>
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<td>6.4 Electrical Integration (harness, connectors, hardware, miscellaneous)</td>
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<td>7. Avionics</td>
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<td>7.1 Guidance, Navigation, &amp; Control</td>
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<td>7.2 Data Management</td>
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<td>7.3 Telemetry, Tracking, and Command</td>
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<td>8. Recovery Systems</td>
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<td>9. Seats</td>
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<td>13. Expendable Fluids</td>
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</tbody>
</table>
C. DESIGN DATA

C.1 Scope
This appendix is a guide for reporting design parameters that have major influences on SV subsystem weights.

C.2 Referenced Documents
(Not Applicable).

C.3 Major Reporting Parameters
The following categories of data are useful for evaluating subsystem weights during the early design phase and for the improvement of weight estimating techniques.

C.3.1 Unmanned Satellite
a. Vehicle sketch giving major dimensions and the reference coordinate system

b. Design life

c. Electrical power subsystem description (solar array, battery)
   - Solar array area, cell thickness, cover glass thickness, substrate type, and materials
   - Battery type, depth of discharge, capacity, number of battery cells
   - Bus voltage, number of buses

d. Attitude control
   - Type (momentum, magnetic, mass expulsion, etc.)
   - Pointing accuracy, slew angles, and rates

e. Propulsion subsystem - for maneuvering or orbit changes
   - Propellant type
   - Pressurization method
   - Number of tanks and tank size
   - Number of thrusters and thrust rating
   - Total velocity increment

f. Thermal control
   - Type (paint, insulation, louvers, heat pipes, refrigerators)
   - Radiator area
g. Structure
   - Material type(s)
   - Construction type(s) (monocoque, skin/stringer, etc.)

h. Payload

C.3.2 Liquid Propellant Stage
   a. Vehicle sketch giving major dimensions, tank geometry, etc., and reference coordinate system.
   b. Structural materials and types
   c. Tank design pressures and volumes
   d. Safety factor
   e. Structural design conditions, loads
   f. Engine data
      - Thrust, Specific Impulse (sea level and vacuum)
      - Expansion ratio
      - Chamber pressure
      - Throttling ratio
      - Number of engines
      - Number of starts
      - Throat area
   g. Propellant type, mixture ratio by volume or weight, densities
   h. Payload

C.3.3 Solid Propellant Stage
   a. Vehicle sketch giving major dimensions and the reference coordinate system
   b. Chamber pressure - average and maximum expected
   c. Safety factor
   d. Case structural material, number of segment joints
   e. Burn time
   f. Nozzle materials, throat area, expansion ratio(s)
   g. Thrust vector control type
   h. Propellant density, loading fraction
   i. Specific impulse - sea level, vacuum
   j. Payload

C.3.4 Reentry Vehicle
   a. Vehicle sketch giving major dimensions and the reference coordinate system
   b. Lift-to-drag ratio
   c. Thermal protection system type
   d. Wetted area (total)
e. Pressurized volume
f. Mission duration
g. Structural materials and types
h. Wing span, root chord length and thickness, plan area (define)
i. Safety factor
j. Ultimate load factor and associated weight
k. Stabilizing and control surface areas
l. Landing system type (parachute, retro-rockets, etc.)
m. Propellant type, mixture ratio, densities
n. Reaction control system type, propellant type
o. Auxiliary propulsion system type, propellant type
p. Crew size
q. Payload
D. Document Content and Submittal Schedule

D.1 Schedule of Submittals
The schedule for the documents specified by this practice is listed in the CDRL for each deliverable specified by a Data Item Description. As an example, a typical mass properties document content and submittal schedule is presented in Table D.1.

D.2 Distribution
The contractor is responsible for the distribution of these documents to the appropriate members of the space system team and should include distribution to the organizations specified by the procuring authority.
Table D.1. Example Document Content and Submittal Schedule

<table>
<thead>
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<th>Program Phase</th>
<th>Pre-Systems Acquisition</th>
<th>Systems Acquisition</th>
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<td>Monthly for studies &lt;2 months; at first of each month for studies &gt;2 months; semiannually for studies &gt;1 year; at completion of all studies; at major design reviews</td>
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<td>Test Completion Report</td>
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</table>

Table D.1. Example Document Content and Submittal Schedule (continued)
E. Understanding Customer Needs and Coordinating the Contents of Mass Properties Data Deliveries

When mass properties data are requested for a special analysis or when existing mass properties data or reports are provided to a new user of the data, it is essential that clear and precise communication of the data needed and of the data provided take place. Failure to properly communicate exactly what is needed and what was delivered can result in analytic errors, rework, performance shortfalls, and possibly mission failures.

Some of the issues commonly encountered that are the result of poorly communicated mass properties requirements and data deliveries include:

- Unspecified data units.
- Data for the wrong vehicle or hardware configuration.
- Data in the wrong or an unspecified coordinate system.
- Unspecified or incorrectly assumed POI sign convention.
- Uncertainty data without specified type of uncertainty distribution.
- Gaussian (normal) distribution uncertainty data without indication to which multiple of standard deviation or variance that the uncertainty values correspond.
- Delivery of basic instead of predicted mass properties or vice-versa.

Below is a recommended checklist of steps to minimize the chances of communication and documentation issues associated with mass properties data.

1. The MPE preparing and/or providing the data should understand precisely what the data will be used for, what data are required, and in what form the data should be provided. The MPE should ask, as applicable:
   a. For what analyses will the data be used?
   b. Are particular areas of concern being investigated?
   c. What is the exact vehicle, subsystem, or hardware configuration for which the mass properties data are requested?
      i. Stowed, deployed, or other position(s) of articulated components?
      ii. Should ballast and balance masses be included?
      iii. What jettisonable, ablable, or expendable items should be included or excluded?
d. Which mass properties data (mass, CM, MOI, POI, principal axes, growth, uncertainties, materials, volumes, densities, etc.) are required?

e. Are upper limit, lower limit, nominal, or other mass properties variations desired?

f. Should inertia data be scaled proportionately with mass growth?

g. Should the delivered data be sorted, organized, or summarized in any particular manner?

h. What level of detail is required?

i. What data formats and data delivery media are required?

j. In what data units and coordinate system(s) should the data be provided?

k. In which product of inertia sign convention (positive or negative integral definition) should the data be provided?

l. If delivering time-sequenced mass properties, for which time intervals, specific events, and configurations are the mass properties required?

2. If the tools or methods used to extract, assemble, or process the mass properties data have known limitations, built-in assumptions, inaccuracies, or specific options, these should be communicated with the parties requesting the data.

3. Besides the mass properties data itself, the MPE should provide the requesting parties a clear definition of what the data represent. As applicable, provide:

   a. Part numbers, revision letters, serial numbers, effectivities, etc.

   b. Description of what is included and of what is excluded in the mass properties provided, such as:

      i. Mass growth.
      ii. Plus or minus uncertainties or uncertainty biases.
      iii. Ballast and balance masses.
      iv. Rivets, shims, adhesive, paint, insulation.
      v. Jettisonable, ablative, or expendable items
      vi. Components or subsystems specifically requested to be included or excluded.

   c. Positions of loose or moveable components, such as ropes, wires, cables, fluids, gases.

   d. Any assumptions used in preparing or extracting the data.

   e. The applicability and limits of the data set provided.

   f. Documentation of the units, coordinate system(s), and product of inertia sign convention of the data.

   g. Description of the data source and, if relevant, how the data were acquired and assembled.
h. Figures and diagrams of the vehicle, hardware features, coordinate systems, etc.

i. Statistical information associated with any uncertainty data provided.
   
   i. The assumed distribution type (uniform, Gaussian, or other).
   
   ii. For Gaussian distributions, specify if the uncertainty values provided represent 1\(\sigma\), 2\(\sigma\), or 3\(\sigma\), etc. multiples of the standard deviation or the variance.