

Standard

Mass Properties Control for Space Systems

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Standard

Mass Properties Control for Space Systems

Sponsored by

American Institute of Aeronautics and Astronautics

Approved

1 December 2006

Abstract

This standard defines terminology and establishes uniform processes, procedures, and systematic 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 standard applies to space vehicles, upper stage vehicles, injection stages, satellite payloads, reentry vehicles, launch vehicles, and ballistic vehicles. This standard is intended to be used as a reference for the development of a project-specific, contractually required mass properties control plan.

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Foreword

This document is intended as a guide for developing mass properties control plans, and may also be used to establish requirements during preparation of acquisition contract and program specific documents.

This standard combines MIL-STD-1811, MIL-HDBK-1811 Handbook for Mass Properties Control for Space systems, and MIL-M-38310B Mass Properties Control Requirements for Missile and Space systems. It contains proven methods and lessons learned for effective mass properties control, combines tools necessary for timely evaluation of program mass properties, and enables early decision making regarding possible design changes.

The primary objective of this standard is to provide effective and uniform processes for space system mass properties control, analysis, verification, data management, and documentation. It is intended to be as comprehensive as practical and will be periodically updated to incorporate advances and innovations.

The individuals that participated in the consensus development process with greater than 20% attendance are listed below. Members of the Technical Editing Subcommittee are indicated with an asterisk. Special recognition is given to William Kruse, Richard Sugiyama, and Louis Yang, who wrote the Technical Operating Report that formed the basis of this document.

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The above consensus body approved this document in November 2006.

The AIAA Standards Executive Council (Mr. Amr ElSawy, Chairman) accepted the document for publication in December 2006.

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1 Scope

This standard defines terminology and establishes uniform processes, procedures, and systematic 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 standard applies to space vehicles, upper stage vehicles, injection stages, satellite payloads, reentry vehicles, launch vehicles, and ballistic vehicles. This standard is intended to be used as a reference for the development of a project-specific, contractually required mass properties control plan.

2 Tailoring

When viewed from the perspective of a specific program or project context, the requirements defined in this Standard may be tailored to match the actual requirements of the particular program or project. Tailoring of requirements shall be undertaken in consultation with the procuring authority where applicable.

NOTE Tailoring is a process by which individual requirements or specifications, standards, and related documents are evaluated and made applicable to a specific program or project by selection, and in some exceptional cases, modification and addition of requirements in the standards.

3 Vocabulary

3.1 Acronyms and Abbreviated Terms

AIAA	American Institute of Aeronautics and Astronautics
ANSI	American National Standards Institute
ATP	Authorization to Proceed
CAD	Computer Aided Design
CDR	Critical Design Review
CDRL	Contract Data Requirements List
CFE	Customer Furnished Equipment
CM	Center of Mass
CR	Customer Reserve
DID	Data Item Description
ECLSS	Environmental Control and Life Support System
FEM	Finite Element Model
GSE	Ground Support Equipment
I&T	Integration and Test
LV	Launch Vehicle
MGA	Mass Growth Allowance
MIL-STD	Military Standard

MOI	Moment of Inertia
MPE	Mass Properties Engineer
MPCB	Mass Properties Control Board
MPCP	Mass Properties Control Plan
NASA	National Aeronautics and Space Administration
NTE	Not to Exceed
ORD	Operational Requirements Document
PDR	Preliminary Design Review
POI	Product of Inertia
PSRR	Pre-shipment Readiness Review
SAWE	Society of Allied Weight Engineers, Inc.
SC	Spacecraft
SHEA	Safety, Health and Environmental Affairs
SV	Space Vehicle
SWI	Standard Work Instruction
TP	Test Procedure
TPM	Technical Performance Measurement
TRL	Technology Readiness Level
TRD	Technical Requirements Document
TRR	Test Readiness Review
VDL	Variance Discrepancy Log
WBS	Work Breakdown Structure

3.2 Terms and Definitions

For the purposes of this document, the following terms and definitions apply. Figure 1 provides a graphical summary of the relationships between key definitions below. Annex A provides mathematical representations of a number of the terms defined below as well as vehicle-specific graphical summaries of the relationships between key definitions.

Allowable Mass

the limit against which margins are calculated after accounting for basic masses of flight hardware, MGA, and uncertainties

NOTE Derived from the requirements early in the program, the allowable mass is intended to remain constant for the duration of the program.

Bus

the part of a space system which supports payloads

Basic Mass

the current mass data 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 (MGA) and uncertainties are not included in the basic mass.

Center of Mass (CM)

the point at which the distributed mass of a composite body can be acted upon by a force without inducing any rotation of the composite body

Critical Mass Properties

those mass properties parameters that have limits which would jeopardize mission performance if exceeded

Customer Reserve (CR)

the mass budget reserved by the customer for out-of-scope changes

NOTE Customer reserve includes the dry mass for the added items plus the additional propellant mass required for the CR items.

In-Scope Changes

design modifications implemented by the contractor to meet contractual requirements

Mass

the measure of the quantity of matter in a body

Mass Growth Allowance (MGA)

the predicted change to the basic mass of an item based on an assessment of the design maturity and fabrication status of the item, and an estimate of the in-scope design changes that may still occur

Mass Margin

the difference between the space system allowable mass and predicted mass

Mass Properties Control Board (MPCB)

a body tasked 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

Moment of Inertia (MOI)

the rotational inertia or resistance to change in direction or speed of rotation about a defined axis

Out-of-Scope Changes

design modifications that are not consistent with the current contract baseline

Overages

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

Payload

a mission-related subsystem or subsystems which perform a function or functions not directly related to a space system's basic operation or maintenance

Predicted Mass

the basic mass plus the mass growth allowance

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

Product of Inertia (POI)

a measure of a body's dynamic (or coupled) imbalance resulting in a precession when rotating about an axis other than the body's principal axis

Shortages

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

Space System

a system designed to exist in space including space vehicles (SVs), upper-stage vehicles, injection stages, satellite payloads, reentry vehicles, launch vehicles (LVs), ballistic vehicles

NOTE Space systems do not include Ground Support Equipment.

Tare

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

Uncertainty

variation in predicted mass properties due to lack of definition, manufacturing variations, environment effects, or accuracy limitation of measuring devices

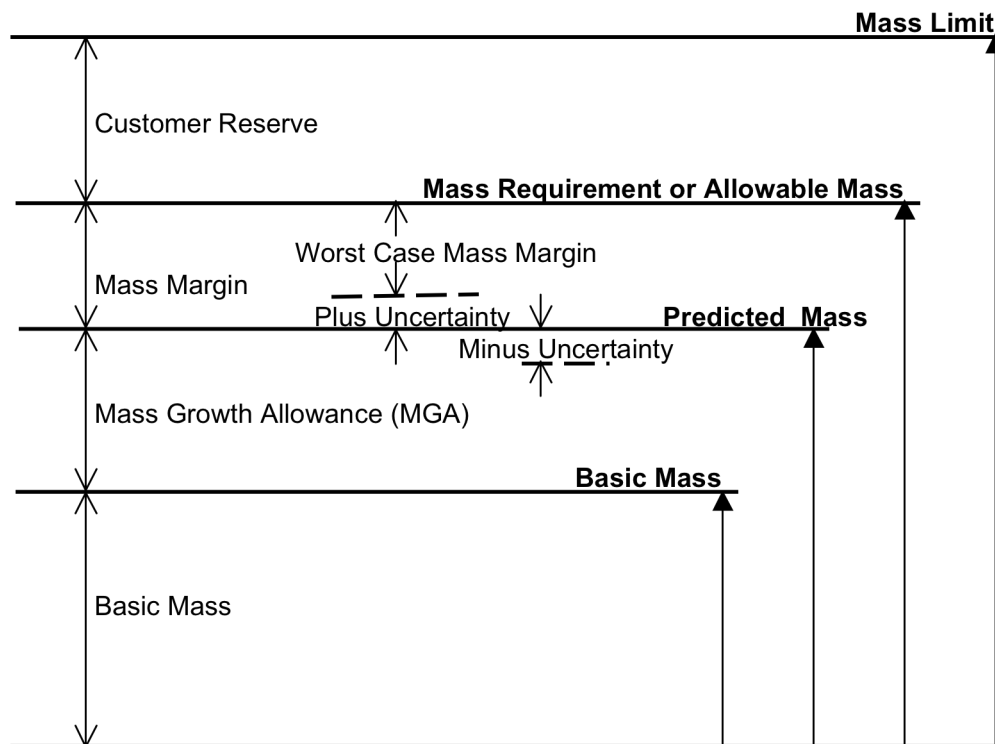


Figure 1 — General Mass Definitions

4 Requirements

4.1 Mass Properties Control

4.1.1 Scope

The mass properties control program for space systems shall be used to determine, control, and document the mass properties of the space system, including subsystems and components. The mass properties control program includes all subcontractor items, associate contractor items, and Customer Furnished Equipment (CFE) items.

4.1.2 Mass Properties Control Plan

The contractor shall develop and document a mass properties control plan (MPCP) for the space system to state the management plan and the procedures for mass properties control and verification during the various procurement phases. The MPCP describes in detail the formal process for controlling mass within the Program/Project organizational structure and includes the applicable requirements specified in Section 4 of this standard. The objective of this plan shall be to formulate an organized mass properties control program to meet the space system mass properties requirements.

4.1.2.1 Subcontractor Mass Properties Control Plan

The contractor shall be responsible for the mass properties control of each subcontractor and supplier. In each procurement document, items which affect the space system mass properties to a significant extent (as determined by the responsible MPE) shall include a mass properties control section to impose the applicable requirements of this document on the subcontractor or supplier.

NOTE Mass properties control may be tailored as appropriate for items with known mass properties.

4.1.2.2 Supplier Interface

The contractor shall structure its subcontracts to ensure suppliers provide sufficient information to support integration of subunit mass properties into complete unit mass properties and to ensure timely responses to information requests. The procuring authority shall be responsible for providing sufficient and timely mass properties information to the contractor on CFE items.

4.1.3 Mass Properties Control Process

The mass properties control process begins with a clear understanding of the mass properties requirements and an estimate of predicted performance to assess compliance to requirements. The contractor shall develop achievable mass properties objectives and shall assist the procuring authority in specifying general system mass properties requirements and their proper allocation to the configuration element requirements. During the initial development of, or any subsequent change to, mass properties objectives, the contractor shall give particular attention to substantiating data, mass properties dependent design performance information, and the critical mass properties uncertainties analysis.

4.1.3.1 Requirements Flow-down and Traceability

The contractor shall perform a comprehensive review of all program system requirements and identify all the major mass properties requirements that affect space system performance. The source of the requirements 1) starts with the (external) contractual Technical Requirements Document (TRD) or Operational Requirements Document (ORD), which provides the flow-down of requirements to the space system subsystems and components; and 2) includes internally derived requirements imposed on the space system by specialty engineering functions such as Attitude Control, Mission Engineering and Ground Handling and Transportation. The contractor shall show the traceability to its source for each requirement. The contractor shall prepare a verification cross-reference matrix showing the mapping between each requirement and the method(s) to be used for verification of the requirement.

4.1.3.2 Assessment of Predicted Mass Properties Against Requirements

The contractor shall perform an analysis to show predicted performance for each identified critical mass properties requirement and verify compliance. The mass properties shall include the basic value plus the predicted growth based on an assessment of design maturity. The contractor shall initiate a recovery plan when negative margins are predicted.

4.1.3.2.1 Basis for Mass Properties Confidence

The percent of the space system mass that is based on each of the categories in Table 1 is an indication of the confidence that shall be placed in the mass properties data.

4.1.3.2.2 Mass Properties Categorization Guidelines

Table 1 prescribes maturity codes that shall accompany each component's mass property assessment. As many categories as are necessary to accurately define the status of the mass properties may be used. Totals of each of these categories shall be recorded to provide an indication of the mass properties confidence at the subsystem level for the major subsystems and the complete system.

4.1.3.2.3 Mass Growth Allowance and Depletion Schedule

The contractor shall include in the mass data an allowance for the expected mass growth resulting from lack of maturity in the current design data. Mass growth varies as a function of hardware and its design maturity. The mass growth allowance shall be applied at the lowest design detail level reported in the mass properties database. Depletion of the mass growth allowance follows the design process; as the design and analyses of the hardware matures, the mass growth allowance depletes to reflect increased confidence in the predicted final mass. If the contractor does not have its own mass growth and depletion schedule, the contractor shall use Table 1 (Mass Growth Allowance and Depletion Schedule) to determine MGA.

Table 1 — Mass Growth Allowance and Depletion Schedule

Major Category	Maturity Code	Design Maturity (Basis for Mass Determination)	Mass Growth Allowance (%)												
			Electrical/Electronic Components			Structure	Brackets, Clips, Hardware	Battery	Solar Array	Thermal Control	Mechanisms	Propulsion	Wire Harness	Instrumentation	ECLSS, Crew Systems
			0-5 kg	5-15 kg	>15 kg										
E	1	Estimated 1) an approximation based on rough sketches, parametric analysis, or undefined requirements, 2) a guess based on experience, 3) a value with unknown basis or pedigree.	30	25	20	25	30	25	30	25	25	25	55	55	23
	2	Layout 1) a calculation or approximation based on conceptual designs (equivalent to layout drawings), 2) major modifications to existing hardware	25	20	15	15	20	15	20	20	15	15	30	30	15
C	3	Preliminary Design 1) calculations based on a new design after initial sizing but prior to final structural or thermal analysis, 2) minor modification of existing hardware	20	15	10	10	15	10	10	15	10	10	25	25	10
	4	Released Design 1) calculations based on a design after final signoff and release for procurement or production, 2) very minor modification of existing hardware, 3) catalog value	10	5	5	5	6	5	5	5	5	5	10	10	6
A	5	Existing Hardware 1) actual mass from another program, assuming that hardware will satisfy the requirements of the current program with no changes, 2) values based on measured masses of qualification hardware	3	3	3	3	3	3	3	2	3	3	5	5	4
	6	Actual Mass measured hardware	No mass growth allowance – use appropriate measurement uncertainty values												
	7	Customer Furnished Equipment or Specification Value	Typically a “not-to-exceed” value is provided; however, contractor has the option to include MGA if justified												

4.1.3.2.4 Mass Threats and Opportunities and Probability of Occurrence

The assessment of mass properties predicted performance must also consider potential changes to the design that may adversely impact predicted mass properties margin against requirements. The contractor shall evaluate the magnitude of, and document the status for, each design change that could potentially impact compliance with requirements. The evaluation of mass threats and opportunities shall include an assessment of the impact to predicted space system mass properties. Each potential change shall be evaluated and assigned a percent probability of occurrence as either: "High" (H) (above 75%), "Medium" (M) (between 25% and 75%), or "Low" (L) (less than 25%).

4.1.3.2.5 Mass Margin

The mass margin is meant to mitigate potential mass increases from omissions or refinement of existing design requirements. Mass margin must cover the upper limit of the sum of the predicted mass and the mass uncertainty.

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. Based on historical mass growth and the MGA schedule in Table 1, Table 2 can be used as a guideline for dry mass margin. The method used to calculate the percent mass margin shall be defined by mutual agreement of the procuring authority and the contractor. The mass margin shall be expressed as either a percentage of allowable mass, or as a percentage of predicted mass. For the purpose of relating Table 2 values to historical mass growth, the percent of dry mass margin is calculated as a percent of predicted dry mass.

4.1.3.2.6 Technical Performance Measurement (TPM)

The contractor shall track and status all critical mass properties parameters (including mass, CM, MOI, and POI) using TPM charts that show basic and predicted performance against derived limits and contractual requirements. An example of a TPM for assessing mass compliance by program phase is exhibited in Table 2. A graphical representation of basic dry mass, MGA, and dry mass margin versus time is presented in Figure 2. Other examples of TPM metrics include percent of hardware in the estimated, calculated and actual categories, and a summary of pending and potential changes.

4.1.3.2.6.1 Determination of Limits

Throughout the contract period the contractor shall determine and document the mass properties limits for each critical requirement. The mass properties limits shall include those established by system, subsystem, and component performance as well as by design and contract requirements. These control limits shall be applied to the appropriate TPM charts to show predicted performance margin against the requirement. Table 2 uses historical dry mass data gathered from programs consisting of new payloads or major block changes. The dispersion of the data has been coalesced into an "average" program. For programs with a preponderance of new hardware, or conversely, those using mainly existing hardware, the contractor would need to adjust the percentages in Table 2 upwards for the former, and downwards for the latter.

4.1.3.2.6.2 Trend Analysis Monitoring

Trend analysis of TPM charts may help identify potential problems early in the design cycle. This trend analysis is particularly critical prior to the program preliminary design review (PDR), when designs are still evolving, in order to minimize cost and schedule impacts for changing the design to fix non-compliant parameters. Figure 2 is a classic example of MGA and margin trends, plotting over time how the basic dry mass approaches the allowable dry mass as the program matures. The percentages from the average program of Table 2 have been inserted at the appropriate milestones in Figure 2.

4.1.3.2.6.3 Explanation of Table 2 Color Coding

Table 2 presents the mass risk assessment of the Mass Growth Allowance (MGA) and dry mass margin by program phase. The MGA is derived in Table 1, and is shown for reference in this table. The sum of the MGA and dry mass margin, however, is historically based, and deviations from this baseline are allowed if there is justification (e.g., extensive use of off-the-shelf hardware would significantly lower MGA in the early phases of a program).

Color code definitions:

- 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 handling plan should be prepared, with particular attention paid to potential design changes that would adversely affect 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 should begin.

Table 2 — TPM - Guidelines for Mass Assessment

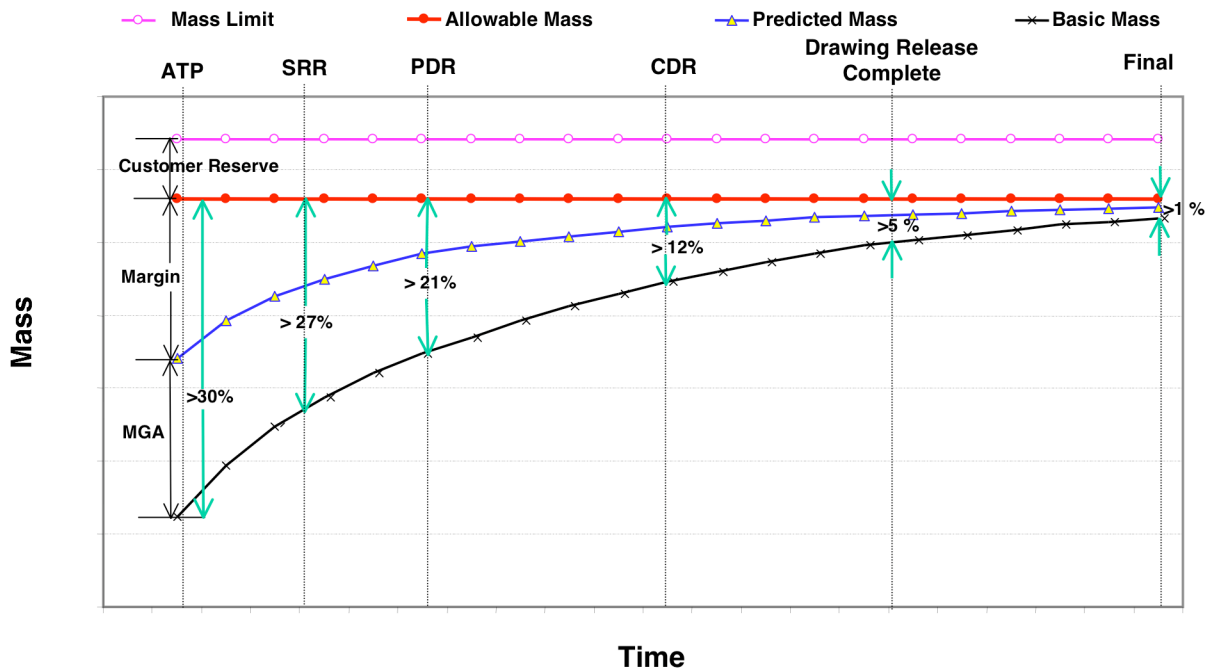
Program Milestone	MGA		Recommended Dry Mass Margin	
	% ¹	Grade	% ¹	Grade
ATP	> 15	Green	> 15	Green
	9 < MGA ≤ 15	Yellow	10 < Mass Margin ≤ 15	Yellow
	≤ 9	Red	≤ 10	Red
SRR	> 15	Green	> 12	Green
	9 < MGA ≤ 15	Yellow	6 < Mass Margin ≤ 12	Yellow
	≤ 9	Red	≤ 6	Red
PDR	> 12	Green	> 9	Green
	8 < MGA ≤ 12	Yellow	5 < Mass Margin ≤ 9	Yellow
	≤ 8	Red	≤ 5	Red
CDR	> 7	Green	> 5	Green
	4 < MGA ≤ 7	Yellow	3 < Mass Margin ≤ 5	Yellow
	≤ 4	Red	≤ 3	Red
Drawing Release Complete	> 3	Green	> 2	Green
	2 < MGA ≤ 3	Yellow	1 < Mass Margin ≤ 2	Yellow
	≤ 2	Red	≤ 1	Red
Final	0	Green	> 1	Green

¹ The percentages of MGA and Margin in the above chart are defined as follows:

MGA = predicted dry mass - basic dry mass

MGA % = (MGA/basic dry mass) * 100

Mass Margin % = [(allowable dry mass – predicted dry mass)/predicted dry mass] * 100



Note: The Figure above represents the percentage of mass growth to the "Basic Dry Mass".

$$\begin{aligned} \text{MGA} + \text{Margin} \% &= [(\text{MGA} + \text{Margin}) / \text{Basic Mass}] \times 100 \\ &= [(\text{Allowable Mass} - \text{Basic Mass}) / \text{Basic Mass}] \times 100 \end{aligned}$$

Figure 2 — Example Plot of Mass Versus Time

4.1.3.3 Mass Properties Control Board (MPCB)

A Mass Properties Control Board (MPCB) or an existing Change Control Board shall assume the responsibility for effecting a minimum mass design consistent with mission requirements, and for identifying risks to the program for any non-compliance to mass properties requirements. An example of the MPCB composition and process is shown in Figure 3.

4.1.3.3.1 Program Management Responsibility

The MPCB, under program management leadership, is the key mass properties management decision making authority on the program, and shall administer and manage all mass properties control activities directly affecting the space system design. The program management, or designee, shall provide direction to the space system teams to fully support the functions of the MPCB.

4.1.3.3.2 Key Functions of the Board

The key MPCB functions shall include, but are not limited to, the following.

- Approving the mass properties control plan and subsequent revisions.
- Establishing not-to-exceed (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.