NASA
SPACE VEHICLE
DESIGN CRITERIA
(GUIDANCE AND CONTROL)

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TUBULAR SPACECRAFT BOOMS (EXTENDIBLE, REEL STORED)

FEBRUARY 1971

NATIONAL AERONAUTICS AND SPACE ADMINISTRATION

GUIDE TO THE USE OF THIS MONOGRAPH

The purpose of this monograph is to organize and present, for effective use in spacecraft development, the significant experience and knowledge accumulated in development and operational programs to date. It reviews and assesses current design practices, and from them establishes firm guidance for achieving greater consistency in design, increased reliability in the end product, and greater efficiency in the design effort. The monograph is organized into three major sections that are preceded by a brief *Introduction* and complemented by a set of *References.*

The *State of the Art*, section 2, reviews and discusses the total design problem, and identifies *which* design elements are involved in successful designs. It describes succinctly the current technology pertaining to these elements. When detailed information is required, the best available references are cited. This section serves as a survey of the subject that provides background material and prepares a proper technological base for the *Design Criteria* and *Recommended Practices.*

The *Design Criteria*, shown in section 3, state clearly and briefly what rule, guide, limitation, or standard must be imposed on each essential design element to insure successful design. The *Design Criteria* can serve effectively as a checklist for the project manager to use in guiding a design or in assessing its adequacy.

The *Recommended Practices*, as shown in section 4, state how to satisfy each of the criteria. Whenever possible, the best procedure is described; when this cannot be done concisely, appropriate references are provided. The *Recommended Practices*, in conjunction with the *Design Criteria*, provide positive guidance to the practicing designer on how to achieve successful design.

Both sections have been organized into decimally numbered subsections so that the subjects within similarly numbered subsections correspond from section to section. The format for the Contents displays this continuity of subject in such a way that a particular aspect of design can be followed through both sections as a discrete subject.

The design criteria monograph is not intended to be a design handbook, a set of specifications, or a design manual. It is a summary and a systematic ordering of the large and loosely organized body of existing successful design techniques and practices. Its value and its merit should be judged on how effectively it makes that material available to and useful to the user.

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FOREWORD

NASA experience has indicated a need for uniform criteria for the design of space vehicles. Accordingly, criteria are being developed in the following areas of technology:

Environment

Structures

Guidance and Control

Chemical Propulsion

Individual components of this work will be issued as separate monographs as soon as they are completed. This document, *Tubular Spacecraft Booms (Extendible, Reel Stored)*, is one such monograph.

A list of all previously issued monographs in this series can be found at the back of this publication.

These monographs serve as guides to NASA design and mission planning. They are used to develop requirements for specific projects and also are cited as the applicable references in mission studies and in contracts for design and development of space vehicle systems.

This monograph was prepared under the cognizance of NASA and published by JPL. The principal contributor was Dr. George G. Herzl, assisted by William W. Walker, both of Lockheed Missiles and Space Company. Contributions were also made by John D. Ferrera of JPL.

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Comments concerning the technical content of this monograph will be welcomed by the National Aeronautics and Space Administration, Office of Advanced Research and Technology (Code RE), Washington, D.C. 20546.

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CONTENTS

TUBULAR SPACECRAFT BOOMS (EXTENDIBLE, REEL STORED)

1. INTRODUCTION

Extendible spacecraft booms deploy spacecraft subsystems including sensitive instruments, provide inertial configurations required for gravity-gradient (GG) attitude control, and serve as lightweight antennas in orbit and during recovery for both spacecraft and sounding rocket type applications.

Solar-radiation, magnetic, gravitational, and atmospheric-drag forces have a significant effect upon the design of spacecraft booms because of the extreme length-to-mass ratios required in most applications. Launch and centrifugal accelerations affect in particular the design of boom extension and retraction mechanisms.

The most common problem area resulting from the above environments, that of bending and twisting of spacecraft booms, may degrade communication system performance, attitude control accuracy and stability, and instrument experimental data. In GG-stabilized spacecraft, large boom oscillations may cause gross departures from desired spacecraft orientation, or even cause a spacecraft to overturn.

Therefore, spacecraft boom systems should be designed to minimize extension and retraction failures and torsional and bending deformations, insofar as permitted by the constraints imposed by the mission and spacecraft interfaces.

This monograph has been restricted to the design of extendible booms that are stored on reels, excluding telescopic, articulated, inflatable, and "jack-in-the-box" type booms. The design of various objects which could be used as tip masses is considered outside the scope of this monograph. Particular emphasis has been given to booms for GG-stabilization systems because this application places the greatest demands on extension mechanisms and is the most sensitive to poor boom performance subsequent to extension. Other pertinent NASA monographs are (1) Effects of Structural Flexibility on Spacecraft Control Systems (SP-8016), (2) Spacecraft Magnetic Torques (SP-8018), (3) Spacecraft Gravitational Torques (SP-8024), (4) Spacecraft Radiation Torques (SP-8027), and (5) Spacecraft Aerodynamic Torques (SP-8058).

2. STATE OF THE ART

Four extendible booms served as spacecraft antennas on Sputnik 1, the first artificial earth-orbiting satellite which was launched in 1957. Since that time, nearly every spacecraft has contained at least one boom, and it has usually been the longest object on board. There is no accurate count of the number of booms that have been flown to date, but it is estimated that more than 1000 booms have been flown on U.S. spacecraft alone. As many as 10 booms were flown on a single spacecraft, the Department of Defense gravity experiment (DODGE). The largest man-made object in space, the Radio Astronomy Explorer (RAE) spacecraft, contains booms which form a structure which measures 457 m tip to tip. The majority of booms have been made of 0.05-mm BeCu tape ranging in weight (including the extension mechanism) from a fraction of a kg to 4.4 kg each. Booms that are used as antennas do not have tip masses, while past GG booms used tip masses weighing up to 5.0 kg. The appendix (table A-1) lists numerous GG booms which have been flown, along with their principal characteristics.

2.1 Design Experience

The requirement for extreme length-to-mass ratios governs the design of most spacecraft booms. The principle of operation of extendible, reel-stored booms is similar to that of the carpenter's steel tape measure. The boom element is formed from a strip of thin prestressed metal that assumes a tubular shape on deployment. The strip is flattened and rolled on a reel for compact storage as illustrated in figure 1. When the boom is extended, the extension mechanism assures an orderly transition from the flattened strip to a tubular structure. Design and flight experience have disclosed numerous problems associated with the application of this simple principle. Techniques which have been developed to minimize the adverse effects of these problems are described. The boom systems (booms) described in this monograph consist of three principal components: the boom element, the extension mechanism, and the tip mass (object extended by the boom).

2.1.1 Boom Element

Table 1 provides a convenient tabulation of tubular extendible boom-element types that are stored on reels. As can be seen from this table, the boom element is classified according to the section and the number of tapes that are employed. The structural properties of the boom element are primarily determined by the boom length, diameter, thickness, perforations, material properties, the number of tapes, and whether the edges of tapes are open, overlapped, interlocked, or welded. Photographs of several types of booms that have been developed are shown in figure 2. The selection of the proper boom element is based principally on the axial and torsional stiffness required (see Sec. 4.2.1).

The variety of types of boom elements, which have been developed thus far, has primarily been the result of attempts to minimize boom deformations due to the thermal environment in space since this is the dominant cause of boom distortions. Highly reflective coatings on the external boom surface have been used to reduce the absorbed thermal energy and thereby diminish the temperature gradient on the perimeter of the boom. Most booms that are presently used in spacecraft (with the exception of sounding rockets) have highly reflective coatings, even though this method cannot by itself completely eliminate thermal deformations. Perforated booms have been developed to permit the solar radiation to strike the inner surface of the boom on the side facing away from the Sun to equalize the boom temperature. The pattern and size of the perforations

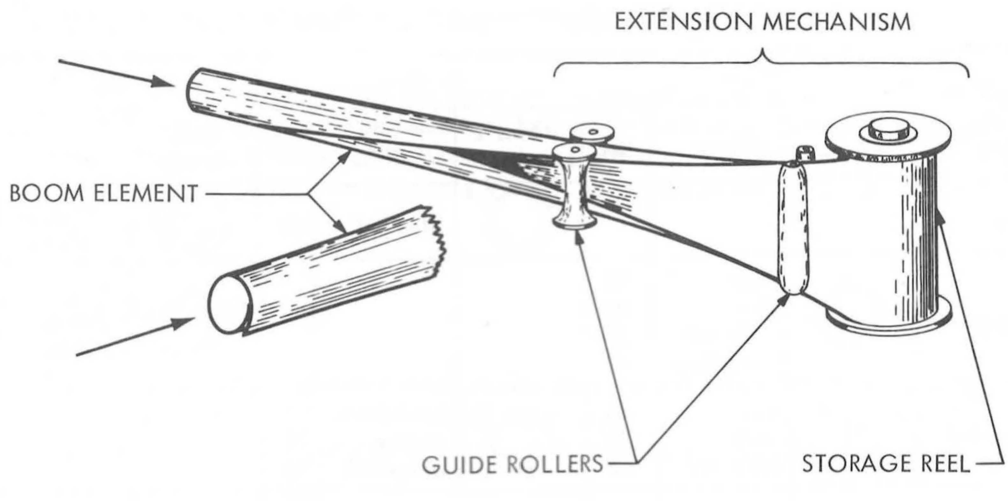


Figure 1.–Boom-system principle of operation (ref. 9).

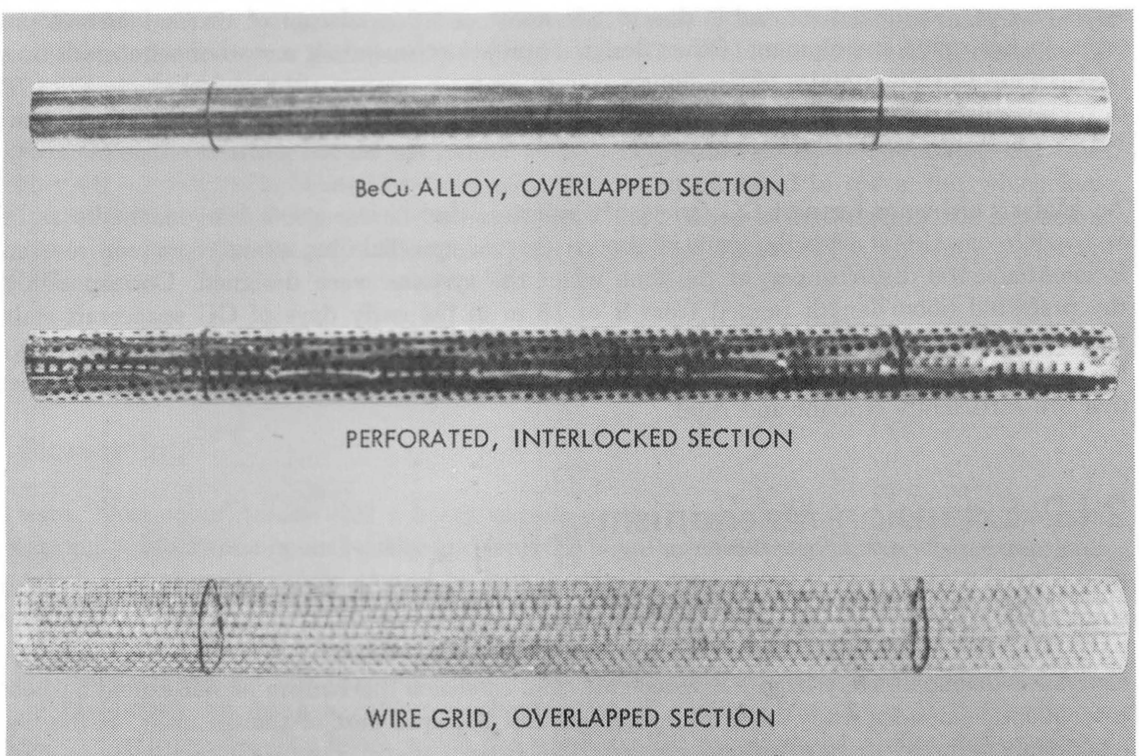
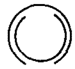
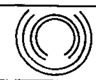
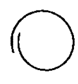
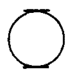
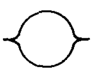


Figure 2.–Typical single-tape boom-element configurations (ref. 35).

TABLE 1.–Classification of Boom Elements

Tape / Section	Single			Double			Nested		
	Cross section	Name	Ref.	Cross section	Name	Ref.	Cross section	Name	Ref.
Open					BISTEM	34		Nested bistem	34
Overlapped		Stem Tee Moly rod Screen boom	31 22 32 33					Nested stem	31
Interlocked		Tee Trats Moly rod	22 29 32		Interlocked bistem Hinge-lock	34 22			
Welded					Welded seam Mast	35 36			

and the coatings on the inner and outer surfaces are selected to balance the thermal input for all boom orientations. Theoretically, this method can completely eliminate thermal bending, but some residual bending is inevitable due to tolerances and degradation of thermal surface properties in the space environment. Other design approaches, including screen or wire mesh booms (Ref. 1), are in various states of development in attempts to improve thermal characteristics. The developmental program of the "wire mesh" boom design was concluded with the completion of NASA Contract NAS 5-10376, February 1, 1968.

An analysis of booms for past GG spacecraft indicates that booms were designed to be as long as possible, consistent with the state of the art (regarding reliability, straightness, and resistance to environmental disturbances) at the time when the systems were designed. Correspondingly, the preferred boom length ranged from 9 to 18 m in the early days of GG spacecraft stabilization and was subsequently increased to range from 30 to 37 m. Recent developments in boom technology have clearly demonstrated that it is now feasible to extend 229-m-long booms that are sufficiently straight and rigid.

2.1.2 Extension Mechanism

Booms have been extended in orbit by a motorized mechanism or have been self-extended by the spring energy stored in the tape. The self-extending units require power only to uncage the boom. The motorized extension mechanism is attached to the main spacecraft body, and the boom element is extended away from the spacecraft. The extension mechanism of self-extending booms is frequently extended away from the spacecraft and becomes part of the tip mass off the boom (commonly referred to as a tip-reel system). This is particularly true for GG applications. Extension speeds have varied from 0.012 to 0.46 m/sec for motorized units and from 0.15 to 4.57 m/sec for self-extended units.

2.1.3 Object Extended by the Boom (Tip Mass)

The third portion of the boom system, the tip mass, is usually either a simple weight for GG applications (most common) or an experiment package. The area of concern with tip masses in this monograph will be limited to problems associated with the interface of the boom element with the tip mass and is covered in section 4.3.1 (3). More detail on tip masses themselves is covered in Reference 2.

2.2 Flight Experience

The overall performance of spacecraft booms to date has been most impressive, considering that booms cannot be adequately tested in the earth environment (ref. 3). However, problems have been encountered which can be described by the following numbered categories:

(1) Boom extension failures

(2) Instability due to space environment

(3) Straightness degradation

(4) Adverse effects of boom dynamics

Boom extension failures, category (1), have caused total failure of the mission or of that part of the mission that depended upon the operation of the boom. The problems described in category (2) have rendered the spacecraft to be temporarily inoperable, but in contrast to category (1) have not caused catastrophic failures of the spacecraft mission. Category (3) problems degrade the effectiveness of the mission, but do not render the spacecraft completely inoperable at any time. Category (4) applies to problems that have not yet been encountered in space, but which have been avoided by careful design. A phenomenological study aimed at investigating the anomolous behavior of Gravity Gradient Satellites involving navigational spacecraft is currently underway at RIAS.

2.2.1 Boom Extension Failures

(1) Blossoming

The term "blossoming" means that a boom uncoils on the storage reel like a partially unwound clock spring. A blossomed boom buckles and jams the boom extension mechanism when extension is attempted. This effect is usually caused by launch vibrations.

The DODGE satellite had eight GG booms and two damper booms to provide a variety of inertial characteristics for GG experiments (ref. 4). It was possible to remove blossoming from nine of the booms by using a caging mechanism which required retraction of the boom for release prior to extension. The boom which did not have this retraction capability stalled after a few inches of extension. This failure, which aborted part of the GG experiment, was attributed to blossoming and resulted from higher than expected launch vibrations.

(2) Mechanical Interference

The failure of the boom on the transit research and attitude control (TRAAC) satellite was attributed to payload fairing damage, although the evidence is inconclusive. The boom extension motor drew a stall current for about 5 min; however, extension did not occur (ref. 4).

(3) Boom Snarling

The orbiting vehicle (OV1-86) satellite had three damper booms mounted on an arm which was to place the booms a short distance away from the spacecraft after the flight fairing was jettisoned. A telemetry signal was received which indicated the start of the positioning operation, but no second signal was received. This indicated that the arm had not locked in position. Boom extension was nevertheless attempted, but the booms apparently snarled because of mechanical interference with the spacecraft.

(4) Motor Failure

The silver-impregnated graphite brushes of the unsealed dc motor, used to extend the gravity-gradient stabilization experiment spacecraft (GGSE-5) primary booms, caused a reduction in the extension velocity, but the boom did eventually fully extend. The exact failure mechanism is not known; however, the electrical noise generated by the brushes caused damage to several electrical components on the spacecraft.

(5) Power Failure

The single boom of the 1964-63A satellite did not extend, since no extension command was received due to a spacecraft systems power failure.

2.2.2 Instability Due to Space Environment

(1) Thermal Shock

Thermal shock is an expression used to describe an abrupt change in temperature which occurs every time the orbiting spacecraft passes the boundary between sunlight and shadow. Thermal shock causes an impulsive excitation, resulting in free oscillations of the boom-satellite system.

Spacecraft boom oscillations due to thermal shock were first observed on the TRANSIT-5A (1963-22A) satellite. Triggered by thermal shock, the 30.5-m unplated overlapped boom on this satellite had free oscillations at an amplitude of 0.2 rad. These oscillations were reduced to less than 0.004 rad for the 30.5-m boom of the same type on the 1963-49B satellite by the effect of silverplating the exterior boom surface (ref. 5). Further reduction in boom deflections due to thermal shock has been achieved by perforating the surface of the booms (ref. 6).

The use of thermal shock dampers is another promising method for reducing oscillations due to thermal shock. A thermal shock damper consisting of a cylinder partially filled with damping fluid was flown on the DODGE satellite, but test data are not available at this date. It is anticipated that the sloshing of the fluid will dissipate the undesirable oscillatory energy.

(2) Thermally Induced Oscillations

The operation of the active control system of the Orbiting Geophysical Observatory satellite (OGO-4) was severely compromised by thermally induced oscillations of an 18-m-long boom deployed as an antenna. The cross section of the boom was the single overlapped type. Evidence that the oscillations were thermal in origin was given by the fact that they were lower in magnitude while the satellite was in the shadow of the earth and increased while the satellite was in sunlight. Thermally induced oscillations of single, overlapped, cross-section booms are also believed to have caused anomalous behavior of several three-axis GG-stabilized satellites, including GGSE-5 and OV1-10 satellites (ref. 7). However, thermally induced oscillations are not certain to occur. For instance, a boom on OGO-3 that was similar to the boom on OGO-4, except that it was only 9 m long, did not exhibit the thermal instability (Ref. 8).

The flight experience indicating the presence of thermally induced oscillations prompted both experimental and theoretical investigations of the phenomenon (e.g., refs. 9–13). The physical concept (from ref. 9) behind the theory is that when a cylinder of open section is deployed in direct sunlight, thermal gradients are built up around and along it, at a rate determined by the thermal characteristics of the boom material. The boom would experience thermal stresses if it were rigidly held; as it is free, it relieves the thermal stresses by bending and twisting toward its instantaneous thermal equilibrium shape. Because of the boom's mass inertia, this response takes time. As it twists in the directional thermal field established by the Sun, a change in the heat flow around the perimeter occurs. This causes a change in the over-all temperature distribution and hence a change in the position of thermal equilibrium toward which the boom is moving. It is shown that under a broad range of conditions, the position of thermal equilibrium can change with a strong component at the first natural bending frequency of the boom. The system is then in effect driven at resonance and large-amplitude thermally induced bending motion can occur. This effect is enhanced by low ratios of torsional-to-bending stiffness. Several spacecraft have been flown using a boom specifically designed to minimize thermally induced oscillations. The boom had both an interlocked seam to increase the torsional rigidity (most significant) and perforations designed to eliminate thermal gradients. The effectiveness of this boom is mixed. In one instance (ref. 14), the thermally induced oscillations have been completely eliminated; however, several navigational satellites employing the same type of booms have behaved erratically. Further investigations of this problem are in progress.

(3) Micrometeorites

In November 1967, the DODGE satellite abruptly changed from a well-established state of GG stabilization to a tumbling mode. No boom commands had been given and the damping system was not even operational. It has been theorized that tumbling could have been caused by the impingement of a micrometeorite on the boom or on the extended object since the event occurred during the intense Leonid micrometeorite shower activity (ref. 4).

(4) Subliming Solids

The satellite 1963-38B experienced large oscillations and tumbling during a period of 14 days following the initial boom extension. The problem was traced to the sublimation of biphenyl material used to encapsule GG-libration damper components located at the end of the boom, and the manner in which biphenyl left its canister. The frequency of tumbling was reduced in the subsequent satellite 1963-49B, which had a cylindrical shroud around the tip mass to deflect the sublimating biphenyl along the boom axis. Tumbling was completely eliminated in another satellite in the same series by using an encapsulating material which sublimates at a slower rate (ref. 5).

2.2.3 Straightness Degradation

(1) Thermal Bending

Thermal bending occurs because of differential expansion of the boom caused by the uneven temperature distribution around the circumference when it is exposed to solar radiation in space. Thermal bending is the main cause of *static* straightness degradation of spacecraft booms that were launched to date; it causes pointing errors in GG-stabilized spacecraft and positioning errors of instruments extended away from the spacecraft. Differential thermal expansion of both open and overlapped booms tends not only to bend but also to twist the boom (important if tip twist constraints are placed on the boom system). Twisting can be minimized by use of a tightly interlocked boom. Steady-state temperature distribution takes place when the heat received is equal to the amount reradiated into space with differing amounts of heat received at different circumferential locations. The temperature profile can be assessed at a particular location by various analogue and digital techniques (refs. 15–17) by considering the heat balance of each small element of the boom.

Thermal deflections as high as 0.17 rad were first observed for the 30.5-m 1963-22A satellite boom which was unplated and unperforated. The deflection was significantly reduced in the subsequent 1963-49B satellite boom by silverplating the outer boom surface such that more solar radiation hitting the side of the boom facing the Sun is reflected, resulting in a more uniform circumferential temperature distribution (ref. 5). Further progress has been made by perforating the boom surface which permits the solar energy to strike directly the side of the boom facing away from the Sun (refs. 6 and 18).

(2) Atmospheric Drag

Atmospheric drag is the largest source of boom bending at orbital heights below 644 km. The booms of the applications technology satellite (ATS-1) experienced large, coupled, bending, and torsional oscillations due to atmospheric drag in the lower portions of the unplanned, highly elliptic orbit (213 by 12 779 km). After more than 1 yr in orbit, three of the four booms broke off.

(3) Gravity-Gradient (GG) Torque

The so-called GG torque is a misnomer for the combined effect of the gravitational and centrifugal gradients of the spacecraft booms. The magnitude of the torque changes continuously because of orbit eccentricity and the variations in boom orientation. Boom bending caused by a GG torque becomes significant only for very long booms, as in the case of the 229-m booms on the RAE satellite.

(4) Manufacturing Tolerances

Poor control of straightness during manufacturing of the boom was a contributing factor to the erratic behavior of the GG stabilization system of the OV1-10 satellite. Straightness degradation arises from a multitude of manufacturing effects, such as nonhomogeneous material properties, uneven heat treatment, dimensional variations, surface treatment, and aging of materials.

2.2.4 Boom Dynamics

(1) Stresses Induced by Extension Mechanism

The crackling sound that can be heard during the extension and retraction of the boom is indicative of the induced stresses. The associated boom bending is initially small, but after an undetermined number of extensions (less than 100) the boom straightness starts degrading rapidly. It is considered that no appreciable damaging effect should be observed for at least 20 to 25 extensions.

(2) Buckling Loads

The spacecraft boom is a long slender column that is very susceptible to buckling (ref. 19). The dynamic forces that can cause buckling of the boom are

- Inertial forces causing a compressive loading due to acceleration of the tip mass and of the boom itself when extension is initiated and when retraction is terminated.
- Rebound forces, again causing compressive loadings, due to moving parts when extension is terminated.
- Inertial forces causing a bending-type loading due to despin of the spacecraft when the boom is extended, and due to spinup when the boom is retracted.
- Coriolis forces, again causing a bending-type loading, due to the extension and retraction of the boom from a rotating spacecraft.
- Static compression loads such as result from using booms to extend solar arrays (anticipated future use).
- Flexural-torsional buckling caused by bending loads on a non-symmetrical cross-section.

(3) Centrifugal Loads

The centrifugal loads that act on the boom and the extended object of the spinning spacecraft or sounding rocket tend to pull out the boom from the extension mechanism. Failure to control the back winding of the mechanism may result in unacceptably high extension rates and cause boom failure (ref. 20).

3. DESIGN CRITERIA

Spacecraft boom systems (booms and associated extension mechanisms) should be designed to perform the prescribed mission functions with a high level of confidence under all anticipated flight conditions. The design of the boom system should be validated through a series of analytical studies, component tests, system tests, and reliability assessments. Also, since there is still much to learn about the dynamic interactions of extremely flexible spacecraft, a complete linearized thermoelastic analysis should be made for each new application. The design should be as simple, direct, and foolproof as practicable, consistent with the imposed requirements.

3.1 Spacecraft System Performance

The boom system should not degrade the stabilization systems of the spacecraft or the operation of spacecraft communication system and experiments, or in any other way adversely affect the mission. In developing the boom system to satisfy the requirements of a specific mission application, there are two major areas of concern, in addition to the performance requirements, which essentially dictate the design requirements for the boom system. The two areas are the interaction of the boom system with the space environment and with the spacecraft. Analytical and/or experimental assessment of the boom system should be made relative to these two areas.

3.1.1 Interaction With Space Environment

Since many of the causes of failure of the spacecraft boom systems to date have been traced to problems associated with the integration of the boom with the space environment, the following environmental effects should be considered early in the design phase:

(1) Atmospheric drag
(2) Thermally induced static bending-twisting
(3) Heating due to earth albedo
(4) Thermal shock
(5) Thermally induced oscillations
(6) Gravity gradients (GG)
(7) Variation of GG due to orbit eccentricity
(8) Solar pressure
(9) Micrometeorites impact
(10) Erosion of surface finishes
(11) Electromagnetic effects
(12) Subliming material in tip mass
(13) Radiation erosion

3.1.2 Interaction With Spacecraft Systems

Physical and functional integration of the boom system with the spacecraft and any objects attached to the boom should be achieved by considering the following interface factors as a minimum:

(1) Permissible weight and size
(2) Required location on the spacecraft

(3) Electromagnetic interference with radiofrequency (rf) signals and experiments

(4) Electrical coupling of the boom element with the spacecraft

(5) Electrical isolation of the boom from the spacecraft

(6) Utilization of the GG tip mass to contribute to the spacecraft capability

(7) Interface with object extended by boom

3.2 Boom System Tradeoffs

Once the performance requirements have been established and the effects of the interface of the boom system with the spacecraft and space environment understood, the best boom system type to meet the application can be selected. This essentially consists of selecting the desired boom element and extension mechanism and should be based on an evaluation of the following tradeoffs:

(1) Boom element type vs axial and torsional stiffness

(2) Boom length for best overall performance

(3) Self-extending vs motorized booms

(4) Fast vs slow extension and retraction velocities

(5) Multiple boom deployers vs several single deployers

3.3 Boom System Detailed Design

Once the selection of the most applicable boom system type is made, the attention paid to detailed design and testing will ultimately determine the success or failure of the system in flight. As a result of the large numbers of booms which have been flown to date (more than 1000), there is a substantial amount of detailed design information available. In fact, in many applications, boom systems can almost be supplied "off the shelf."

3.3.1 Mechanism Design

In this monograph, only those design practices unique to boom systems will be considered. Of the three components of the boom system, the boom element, the extension mechanism, and the object extended by the boom (tip mass), only the first two will be discussed in detail. The third, the tip mass, will be discussed only in terms of its interface with the boom element since, if a tip mass is used, it could consist of a variety of objects (e.g., GG mass, science equipment, antenna, etc.), which are outside the scope of this monograph. The following items should be considered relative to each of the boom system components.

(1) Boom Element

The major concern in the detailed design of the boom element is to maintain the straightness of the element within prescribed limits over the temperature environment extremes. To do this, the following items should be considered:

- Material selection
- Surface finishes
- Perforations
- Interlocking

(2) Extension Mechanism

The extension mechanism must reliably extend and retract the boom element a prescribed number of times within allowable stress limits and protect the boom element in the launch environment. To do this, the following items should be considered:

- Guidance in the transition region
- Storage reel
- Selection of suitable electric motor
- Regulation of extension velocity

(3) Object Extended by Boom

In order to insure both the proper functioning of the tip mass and that the tip mass will not cause intolerable loads on the boom element and disturbances to the spacecraft, oscillations of the boom element, the interface between the two must be well defined. To insure this, the following items should be considered:

- Inertial loads
- Attachment
- Sublimation

3.3.2 Operational and Test Considerations

The boom system shall not fail under any operating conditions including prelaunch, ascent flight, stage separation, and boom extension and retraction. The shock, vibration, and dynamic loads (resulting from the operational conditions) affecting the boom system should be investigated. Failure modes should be analyzed and ground and in-flight test plans developed.

(1) Analysis of Failure Modes

Failure modes should be studied, as well as their relationship to mission success, to determine (1) whether component and/or system redundancy is required, and (2) what type of component evaluation tests, to insure reliable operation, is called for. Typical flight failures are discussed in detail in section 2.2.

(2) Launch Environment

In protecting the boom element from the loads associated with the launch environment, two areas are of concern. The first area is the *caging* requirements. The second area is the method used to prevent *blossoming* of the boom on the storage reel. Definition of the caging requirements depends primarily on whether

- The boom is a motorized or self-extended mechanism.
- The self-extending mechanism is a part of the extended object (tip reel) or attached to spacecraft.
- An active (pyrotechnic) or passive (mechanical) mechanism is required.

The method used to prevent blossoming of the boom on the storage reel depends primarily on whether

- The extension motor is coupled directly to the storage reel.
- The boom is extended by means of a pinch roller drive system.

(3) Buckling

In preventing the buckling of the extended boom element, acceptable limits for boom compression/bending loadings must be insured and the required boom stiffness and support in the transition region must be provided. In determining acceptable limits for boom compression/bending loads, consider the following:

- Compressive loads due to inertial effects from acceleration/deceleration during extension/retraction
- Compressive loads due to rebound upon termination of extension
- Bending loads due to combined inertial and Coriolis forces (such as during spinup/despin)

To provide the required boom stiffness and support in the transition region, consider

- Nesting (see table 1)
- Doublers (localized boom stiffener)
- Increased stiffness in the transition region

TABLE 2.–Boom Bending and Disturbance Torques Due to Interaction With Space Environment

Cause	Predictable[a]	Preventable[b]	Importance[c]	Recommended practices
Atmospheric drag	Yes	Yes	1	Select higher orbit; effect is negligible above 400 n. mi. (if consistent with mission objectives). Centers of pressure and gravity to coincide to minimize effect on attitude-control system.
Thermal bending	Yes	No	2	Minimize thermal gradient on boom periphery by appropriate selection of thermal conductivity of material, absorptivity, emissivity, and reflectivity of surfaces, and boom thickness, diameter, and amount of tape overlap. Apply highly reflective coatings on outside boom surface to minimize amount of absorbed solar energy. Perforate boom tape to equalize absorption of energy on all boom surfaces. Prevent tarnishing of surfaces due to air, gases, humidity, etc. Estimate amount of deflection by using analytical boom bending models such as given in refs. 13 to 15.
Thermally induced twist	No	No	2	Same as for thermal bending (twist measured experimentally).
Heating due to earth albedo	Yes	No	3	Same as for thermal bending.
Thermal shock	Yes	No	1-2	Same as for thermal bending. Increase material hysteresis to damp oscillations. Select orbit entirely in sunlight; possible only for missions of short duration. Use a thermal shock damper (sec. 2.2.2 (1)).
Thermally induced oscillations	Yes	Yes	1-2	Same as for thermal bending. Interlock edges of boom to increase torsional rigidity. Ascertain stability using analytical models such as given in refs. 9 to 11.
Gravity gradient (GG)	Yes	No	3	Minimize boom weight and length; significant only for very long booms.

TABLE 2.– (concluded)

Cause	Predictable[a]	Preventable[b]	Importance[c]	Recommended practices
Variation of GG due to orbit eccentricity	Yes	No	3	Minimize eccentricity of orbit (if consistent with mission objectives).
Solar pressure	Yes	No	3	Minimize projected area and boom length. Centers of pressure and gravity to coincide to minimize effect on attitude-control system. Minimize length of boom to reduce effective moment arm. Analytical assessment of torque produced to determine whether torque balancing is required. Balance torque by using symmetrical boom configuration.
Micrometeorites Impact	No	No	3	Avoid predictable micrometeorite showers. Provide means of inverting spacecraft if it tips over.
Erosion of surface finishes	No	No	3	Not known whether effect is beneficial or deleterious.
Electromagnetic effects	Yes	Yes	3	Use materials and coatings that are nonmagnetic. Avoid localized magnetization of materials due to manufacturing processes.
Subliming material in tip mass	No	No	3	None satisfactory. Provide means of inverting spacecraft if it tips over.
Radiation erosion	No	No	3	Avoid orbits through radiation belts.

[a]Whether bending direction is predictable.

[b]Whether bending can be eliminated (yes) or only minimized (no).

[c]Relative worst-case boom system performance, if cause is not eliminated: 1–total failure; 2—performance degradation; 3—acceptable.

(4) In-Flight Performance Monitoring

In order to be informed of proper functioning of the boom system in space and/or to be able to trace a mission failure to a malfunction of the boom system, the essential boom performances should be monitored in flight (see listing in sec. 4.3.2 (4)).

(5) Ground Testing

Ground testing should be performed to insure proper functioning of the boom system. Extensive testing of the boom systems is frequently prohibited either by cost or because the extended boom element will not support itself in a "1-g" field. A realistic set of both *qualification* and *functional* tests should be developed and carried out, based principally on past experience and a failure-mode analysis.

4. RECOMMENDED PRACTICES

The following recommendations should serve as guidelines for the selection and physical characterization of the optimum boom systems needed to meet specified and implied requirements. These recommendations are based on the experience gained through prior design experience and flight operation. Reference 2 contains an extensive bibliography on booms, in general. The implementation of the recommended practices should be supported by analytical studies and appropriate experiments.

4.1 Spacecraft System Performance

4.1.1 Interaction With Space Environment

Interactions of the boom system with the space environment, the principal causes of boom bending and disturbance torques, and the recommended practices for minimizing these interactions are summarized in table 2 (ref. 21).

4.1.2 Interaction With Spacecraft Systems

Equally important to the boom system interaction with the space environment are the interfaces of the boom with other spacecraft systems. This essentially determines the location, mating, and functional requirements of the boom system. The following items should be considered.

(1) Permissible Weight and Size

Weight and size of the boom system should be kept at a minimum. The determining factors are type of boom, diameter, thickness, length, tightness of boom winding, interface with the spacecraft, auxiliary equipment (e.g., switches and monitoring equipment), and the restrictions due to the required orientation and location in the spacecraft. The appendix (table A-1) lists representative weights and sizes.

(2) Required Location on the Spacecraft

The required boom system location and orientation within the spacecraft should be determined in the preliminary design. The determining factors include the following:

- The required configuration of the boom-spacecraft system
- Minimizing of antenna pattern distortion
- Operation of experiments
- Boom interference with field of view of optical devices
- The use of multiple deployers to extend several booms (as discussed in sec. 4.2.5), which requires that the mechanism be centrally located in the spacecraft.

(3) Electromagnetic Interference With Radiofrequency Signals and Experiments

The spacecraft antenna pattern should not be distorted beyond acceptable limits because of the presence of the boom. The ideal solution to this problem would be development of a nonmetallic boom that is rf transparent, but to date no satisfactory nonmetallic boom has been developed. The following solutions should be considered to minimize the rf distortion problem:

- Whenever possible, orient the boom to point away from the earth so that it is not in the field of view of the transmitter. This method was used on the TRANSIT 5A, GGSE 1, and GEOS 1 satellites.
- Use a X (or V) boom configuration, as was done on the DODGE, ATS, and RAE satellites.
- Place boom on spacecraft laterally as far as possible from transmitter when both boom and communication system must point in the same direction.

(4) Electrical Coupling of the Boom Element With the Spacecraft

Reliable electrical connection between the boom element and the spacecraft should be provided when required for operation of experiments or communication systems. The design of the electrical connection depends primarily on the type of boom.

Electrical connection by means of a hard wire attached directly to the boom element should be employed for the tip-reel self-extending boom systems. When a second hard-wire connection from the spacecraft to the tip-reel extension mechanism is required, a device of the type used for length monitoring of tip-reel booms described in section 4.3.2 (4) should be considered.

Electrical coupling of the boom element of the motorized boom should be provided by means of redundant sliding contacts. Examples of contact designs that were successfully used are: (1) spring-loaded, gold-plated, rotating wheel contact in the pinch roller drive assembly; and (2) spring-loaded clip that connects the boom with the storage reel (ref. 22).

(5) Electrical Isolation of the Boom From the Spacecraft

When electrical isolation of the boom system from the spacecraft is required, it should be accomplished by breaking all electrical paths with isolating materials. Polycarbonate and Delrin were used for this purpose on the ATS spacecraft.

Electrical isolation of perforated booms should be achieved by using bushings made of a dielectric material to isolate the shafts of the guide rollers from the extension mechanism. This method is preferable to making the entire roller from an insulating material because of the abrasive action due to the boom perforations.

Isolating longitudinal boom sections from each other should be accomplished by inserting an adhesively bonded plastic film splice at the desired point in the boom. The joint should form a high-resistance, low-inductance splice while maintaining the structural integrity of the boom. An isolation joint of this type was inserted 57 m from the outer tip of each 229-m GG boom on the RAE spacecraft to minimize the antenna side lobes.

(6) Utilization of the GG Tip Mass to Contribute to the Spacecraft Capability

Reference 2 gives recommendations for the design of extended objects which are used as tip masses in GG stabilized spacecraft.

(7) Interface With the Object Extended by Booms

The object extended by the boom (tip mass) usually takes the form of either a mass for GG applications or objects such as science experiment, antenna, etc. These objects are considered to be outside the scope of this monograph. The interface is discussed in greater detail in section 4.3.1 (3) under "Boom System Detailed Design."

4.2 Boom System Tradeoffs

4.2.1 Boom Element Type vs Axial and Torsional Stiffness

The classification of boom elements was detailed in table 1. The selection of the proper boom element is based principally on the axial and torsional stiffness required. Single tapes with overlapped edges are of the simplest construction and are used when low torsional rigidity is consistent with the spacecraft mission. Booms with interlocked (also called "zippered") edges consisting of either one or two tapes have higher torsional rigidity and are used principally to maintain the angular position of payloads located at the tip of the boom. The welded-edge booms have the highest torsional rigidity. Nested booms have been developed to withstand higher bending loads such as those experienced by recovery antennas. Perforated booms have slightly less axial and torsional stiffness than does the equivalent nonperforated boom element.

4.2.2 Boom Length for Best Overall Performance

The optimal boom length should be determined considering the specific mission requirements. The following should be considered when selecting, or adjusting, the boom length:

(1) The lowest natural frequency of the boom should be made at least an order of magnitude above the design bandpass of an active control system frequency or the libration frequency of a gravity-gradient-stabilized spacecraft.

(2) The minimum length by which a motorized boom can be "tweaked" should be considered when precise length adjustment is required. The minimum extension step is typically about 0.32 cm when the extension rate is slow (on the order of 1.3 cm/sec) and the extended object weighs less than 2.3 kg. The associated time delay of the command system for each boom length adjustment depends on the orbital altitude and is typically on the order of 5 sec.

(3) For GG applications the boom should be as long as possible, consistent with straightness constraints.

4.2.3 Self-Extending vs Motorized Booms

The decision as to whether to use a self-extending or a motorized boom for a particular satellite should be based on (1) spacecraft mission requirements, such as those relating to the need to retract the boom; (2) specific requirements imposed by satellite experiments; and (3) spacecraft system configuration and number of booms. A comparison of the principal extension mechanism types discussed in this monograph is made in table 3.

TABLE 3.–Comparison of Self-Extending and Motorized Booms

Parameter	Type of boom		
	Self-extending tip reel	Self-extending stationary reel	Motorized
Multiple extension	No	No	Yes
Length adjustment in space	No	No	Yes
Use of extension mechanism for GG tip mass	Yes	No	No
Interlocking	No	No	Possible
Length monitoring	Difficult	Easy	Easiest
Extension velocity regulation	Sometimes	Yes	Yes
Requirement for electric power for extension	No	No	Yes
Reliability	Highest	Comparable	
Parts count	Fewest	Comparable	
Weight and volume	Least	Comparable	
Ground testing	Comparable		Easiest
Relative cost of extension mechanism	¾	½	1

4.2.4 Fast vs Slow Extension and Retraction Velocities

Extension and retraction velocity should be carefully selected considering the mission requirements and the type of boom that is used. A speed that is too fast or too slow can degrade the performance of the satellite or may even cause a catastrophic failure. Also, sufficient tests should be run to insure against an irregular extension velocity.

(1) The reasons for selecting fast extension and retraction velocities are

- To reduce the running time of the motor.
- To overcome temporary friction due to uneven surface rubbing or contamination in the mechanism.
- To facilitate GG capture of the spacecraft.

(2) The reasons for selecting slow extension and retraction velocities are

- To reduce the starting and stopping inertial loads and thus reduce the danger of buckling of the boom.
- To reduce the required electrical power level, since most spacecraft are power limited.
- To reduce the stresses during forming of the boom.
- To increase precision of boom length adjustment.

4.2.5 Multiple Boom Deployers vs Several Single Deployers

The use of multiple boom deployers should be considered in the preliminary design of all spacecraft which employs more than one boom.

(1) The advantages of using a common deployer to extend several booms over using several single deployers are

- Weight and space savings, since fewer components are required.
- Assurance that all booms are extending and retracting simultaneously, maintaining a symmetrical satellite configuration at all times.

(2) The disadvantages of using a common deployer are

- Multiple boom assemblies are not generally available "off the shelf" and consequently require special design and development, and expensive flight qualification and testing.
- Elaborate test setups are required to test several booms simultaneously.
- There is less flexibility in locating the booms on the spacecraft.
- The individual booms cannot be independently extended and retracted.

(3) The following are two methods that have been flown which use a common deployer with a single motor to extend several booms:

- *Storage of all the booms on a common storage reel.* The three damper booms on the OV1-86 satellite and the two damper booms on the RAE satellite were stored in this manner.
- *Storage of each boom on a separate reel.* The primary booms on the ATS-1 and -4 satellites were wound on individual storage reels which were geared together by a common spur gear drive train. This arrangement allowed scissoring (adjustment of the angle between the booms) of the boom units as was required by the spacecraft mission (ref. 23).

4.3 Boom System Detailed Design

4.3.1 Mechanism Design

This section contains only those design recommendations that are peculiar to spacecraft boom systems. Recommendations relative to the three components of the boom system, i.e., the boom element, the extension mechanism, and the extended object, will be discussed.

(1) Boom Element

The main concern in the design of the boom element is to maintain the straightness of the element within prescribed limits over the imposed temperature extremes. The major causes of boom straightness degradation due to the mechanical and material properties of the boom, and the recommended practices for minimizing degradation are shown in table 4 (refs. 14 and 21). All the described effects cause permanent degradation except for the elastic deformations which occur in the transition region. Four major design considerations of the boom element are as follows. Reference 37 contains a summary of the mechanical properties and *design equations* of various booms.

- *Material Selection.* Although most booms that have been flown to date were made of beryllium copper (BeCu), alternative materials should be considered for any new application to check whether BeCu is the best material. A convenient candidate material rating factor (ref. 24) is given by the quantity

$$kF/eaE$$

where:

k = thermal conductivity

F = allowable flattening stress

e = coefficient of linear expansion

a = outer surface absorptivity

E = Young's modulus of elasticity

TABLE 4.–Boom Straightness Degradation Due to Mechanical and Material Properties

Type of bending	Cause	Predictable[a]	Preventable[b]	Importance[c]	Recommended practices
Permanent	Nonhomogeneous material properties	No	No	2	Careful selection of materials and metallurgical processes. Quality control of all boom manufacturing processes. Localized treatment after boom straightness profile is known. Spiraling of boom to avoid cumulative deformations.
Permanent	Boom manufacturing tolerances (dimensional, heat treatment, etc.)	No	No	2	Same as nonhomogenous material properties.
Permanent	Induced by extension mechanism	No	No	2	Careful shaping and close tolerances of parts of extension mechanism that come in contact with boom. Minimize the number of extension/retraction cycles during testing.
Elastic	Transition region deflection	Yes	No	2–3	Make installation adjustment to assure that boom points in desired direction. Use double, face-to-face, boom configuration.
Elastic	Transition region tolerances	No	No	2	Quality control. Use double, face-to-face, boom configuration.
Permanent	Ground testing and handling	No	Yes	2	Careful support of boom during ground testing to prevent localized bending, buckling, nicking, etc., of boom. Minimize number of extension/retraction cycles during testing.

[a]Whether the bending direction is predictable.

[b]Whether the bending can be eliminated (yes) or only minimized (no).

[c]Relative worst-case boom-system performance, if cause is not eliminated: 1—total failure; 2—performance degradation; 3—acceptable.

Molybdenum and tungsten are promising boom materials (ref. 25). Both the ATS-E (launched in Aug. 1969) and the Apollo 15 mission (to be launched in July 1971) contain stainless steel booms. In addition to having a high rating factor, any material should have structural characteristics that are compatible with boom operation. The material should also be nonmagnetic, and should be easily processed, i.e., machined, heat treated, etc.

- *Surface Finishes.* Surface finishes are important to the thermal design of the boom element. The following design and flight experience should be considered in selecting surface finishes for spacecraft booms:

  (a) Most spacecraft booms used to date have highly reflective silver-plated outside surfaces. An aluminum outside surface finish that is less reflective, but is resistive to tarnishing, has been developed for the ATS-5 satellite. Conservative values of the coefficient of absorptivity for these boom surfaces are $\alpha_s = 0.1$ and 0.15, respectively.

  (b) The inside surface of perforated booms should be coated with a highly absorptive black coating ($\alpha_s = 0.85$) to absorb solar heat that passes through the perforations.

  (c) The inside surface of unperforated booms that are larger than 1.3 cm in diameter should be coated with a material that has both a high emissivity and a high absorptivity to enhance the radiative heat transfer within the boom.

  (d) Goldplating of the boom element should be avoided, since it can cause localized cold-welding between adjacent layers of the stowed boom. This was experienced on the boom that served as antenna on a USAF research satellite. It is surmised from the telemetry data that, as the satellite went from hot areas to cold, the thermal shock shook loose one weld after another, and the boom did eventually fully extend. The progressive increase in signal strength and decrease in spin rate were found to correlate with such a process, and the data were verified in laboratory tests (ref. 26).

  (e) Special precautions should be taken to prevent tarnishing of the boom due to exposure to air, gases, humidity, etc. The current practices are to seal the stowed boom in an inert gas before launch. The use of aluminum plating is another attempt to decrease the tendency of the boom to tarnish.

  Experiments with silver-plated booms conducted at the NASA Goddard Space Flight Center indicate that ultraviolet radiation reduces tarnishing. It was also observed that the exposure to such an environment increased the boom surface resistance to additional sulfide contamination (ref. 27). A report on spacecraft instrumentation for measuring surface degradation is given in reference 28.

  The phenomenon of erosion of surface finishes due to micrometeorite impacts is not well understood. One theory is that the impinging micrometeorites in space polish the surface of the boom and thereby actually have a beneficial effect on thermal bending of the boom. An opposite theory is that they degrade the surface finish and thereby increase thermal bending.

  (f) GSFC data accumulated on over 30 boom specimens representing a variety of materials, sizes, and configurations, suggest that optical (highly reflective) coatings per se *may* not play as important a role in alleviating thermal bend behavior as perhaps such factors as torsional rigidity, end-fixity conditions, and degree of perforations.

- *Perforations.* Perforated booms are used to eliminate the thermal gradients which could cause severe oscillations. The following practices should be considered in designing perforated booms.

  (a) The percentage of the hole area should be determined so that the temperature on the side of the boom facing the Sun will be equal to the temperature on the side facing away from the Sun. The parameters that should be considered in the analysis are the reflectivity and absorptivity of the outer and inner surfaces of the boom, and the thermal, structural, and mechanical characteristics of the boom material. Two typical types of perforated booms are (1) the silver-plated RAE satellite booms with an 8% hole area (ref. 22), and (2) the aluminum-coated booms for the ATS-5 satellite, which have a 15% hole area (ref. 29).

  (b) The arrangement of the holes should be such that uniform temperature on all sides of the boom will be maintained for all incident angles of sunlight. The holes on the RAE booms are randomly arranged, and the holes on the ATS-5 booms are arranged in a double helix pattern.

  (c) The abrasive effect of the extension mechanism on guide rollers should be taken into account in the design. The amount of abrasion depends primarily on the smoothness of the edges of the holes. This problem is important for very long booms and for booms that are often extended and retracted.

- *Interlocking.* Booms with an interlocking feature are designed to increase torsional rigidity since low torsional rigidity in combination with thermal gradients can cause induced oscillation of the end of the boom, resulting in spacecraft instability (ref. 9). Booms of 1¼-cm-diameter and of lengths greater than 6–7½ m should be zippered as a matter of general practice. The following practices should be considered in the design of interlocked booms:

  (a) The shape and the spacing of the interlocking tabs should assure that the boom will not fail under any operating conditions. In particular, any torsional load acting on the boom induces a severe longitudinal shearing action (ref. 22).

  (b) The free diameter of the boom should be smaller than the interlocked boom diameter. The resulting elastic compression at the seam provides increased torsional rigidity of the boom.

  (c) Precautions should be taken to insure that the boom interlocks repeatedly. Attention should be paid to the removal of all burrs from the interlocking tabs.

(2) Extension Mechanism

The four areas of major concern in the design of the extension mechanism so that it will repeatedly extend and retract the boom element are discussed below.

- *Guidance in Transition Region.* The boom extension mechanism should guide the boom element to assure a smooth transition from the tape on the storage reel to the fully formed boom. This should be accomplished by

  (a) Using either a series of guide rollers or a molded hub at the end of the extension mechanism.

  (b) Selecting the length of the guidance in accordance with the required bending stiffness of the boom in the transition region.

  (c) Using wear-resistant finishes on guide rollers where they come in contact with the boom to prevent abrasion.

- *Storage Reel.* The following design experience should be considered in the design of the reel on which the boom is wound prior to extension:

  (a) The diameter of the storage reel should be large enough to prevent permanent deformation of the stored boom because of excessive bending stresses at the innermost winding. A good "rule-of-thumb" is to select the inside diameter of the storage reel to be twice the width of the overlapped boom.

  (b) Long booms wound on storage reels develop flat spots on the outside nominally cylindrical surface. This effect becomes pronounced typically for a 1.3-cm-diameter BeCu overlapped boom when it reaches a 10-cm stored diameter. This effect causes some irregularity of the extension velocity, which should be considered from a reliability standpoint, particularly in the case of the self-extending boom.

  (c) The typical stacking factor (the ratio of the diameter of the reel assuming spaces between layers of tape and the diameter assuming no spaces) for unperforated booms is 1.1; the stacking factor for perforated booms is larger and depends on the method used to perforate the boom tape. Wire mesh booms have a stacking factor of only 0.75 because the longitudinal wires of one winding lie partially within the transverse layers of the next winding.

  (d) The inside diameter of the storage reel should be large enough to accommodate an extension velocity regulator, if required.

- *Selection of a Suitable Electric Motor.* Factors that should be examined in selecting electric motors for spacecraft booms include

  (a) Susceptibility to cold-welding of bearings and brushes, which depends on (1) the length of time since the last boom extension and retraction, (2) orbital parameters and mission requirements, and (3) protection afforded by the skin of the spacecraft.

  (b) Wear, which is determined by total running time, and the extension and retraction velocities.

  (c) Weight and size, which depend on the construction of the motor and on the required auxiliary equipment, such as electric converters and hermetic enclosures.

(d) Spacecraft-systems restrictions, such as available electrical power and the considerations that are imposed by the thermal design and boom dynamics.

Recommendations for selection of electric motors for spacecraft booms (ref. 30) are presented in the following paragraphs.

The unsealed precision dc motor has been used most frequently in spacecraft booms to date. These applications required less than a 1-yr exposure to the hard vacuum of space. This motor operates efficiently, has a favorable torque characteristic, and is the lightest of all boom motors. Its principal limitation is that it cannot be used over an extended period of time in space because of either (1) a buildup of an electrically insulating layer between the brush and the armature, or (2) a very high brush wear rate which causes high electrical noise. Brush wear of the boom motor caused a severe noise problem on the GGSE-5 spacecraft. Recent developments of new brush materials should result in more reliable dc boom motors.

The hermetically sealed dc motor can be used repeatedly for extended periods of time in orbit and has all the advantages of the unsealed dc motor. The disadvantages of this motor are the added weight and size of the hermetic enclosure and seals. ATS-1 and -4 satellites have successfully used hermetically sealed dc motors to extend the 39.6-m booms.

The "semihermetically" sealed dc motor should be considered for applications in which the boom is first extended after a long time in orbit. This type of motor is enclosed in a canister and is sealed with an O-ring around the shaft. The motor should operate only a short time since the simple seal is effective only until the motor has been operated for the first time in space. This motor is lighter and simpler than the permanently sealed motor but to date has not been used for spacecraft boom actuation.

The unsealed brushless ac motor is suitable for repeated operation for long periods of time in space. The total weight of the brushless ac motor and the associated electrical dc-to-ac converter is about the same as the weight of the hermetically sealed dc motor. The long lifetime of this motor in space was demonstrated by the nine DODGE satellite booms, which have been operated more than 200 times in the course of the first year in orbit.

The unsealed brushless servomotor is also suitable for spacecraft booms for repeated operation over a long period in space. This dc motor employs a permanent magnet rotor and thus requires no brushes. Like the ac motor, however, it requires supporting electronics. It has been used to date only for other spacecraft applications, e.g., on OSO-H (Orbiting Solar Observatory) and Surveyor spacecraft.

- *Regulation of Extension Velocity.* The following paragraphs describe the principal methods of the extension velocity regulation which have been used in spacecraft booms.

The electric motor itself regulates the extension velocity of the motorized boom. The motor extends the boom either by (1) torquing the storage reel in which case the extension velocity decreases as the boom is extended since the velocity depends on the amount of boom remaining on the storage reel, or (2) driving a pinch roller assembly in combination with a drag clutch which extends the boom at constant velocity. All motorized booms are retracted by torquing the storage reel.

Most self-extending booms have a governor which is located inside the storage reel. The governor keeps the velocity within safe limits throughout the extension. The centrifugal governor used for the ATS-1 and -4 damper booms typically provides a $\pm$0.24-m/sec tolerance for a 0.55-m/sec nominal extension velocity. Ratchet-type governors have also been used, e.g., on the OV1-5 and OV1-10 satellites.

The extension velocity of a self-extending tip-reel boom without a governor is determined by the energy stored in the boom and the drag in the extension mechanism. The velocity continues to increase during the extension, since the stored energy per unit length remains the same while the extending mass decreases. The maximum boom length is, therefore, limited by the stress in the boom due to sudden stopping and rebound of the remaining tip mass.

(3) Object Extended by Boom

The following practices are recommended in the design of objects to be extended by the boom:

- The extended object should be as light and as compact as possible and should be symmetrical to minimize undesirable *inertial loads* acting on the boom during extension and retraction.
- The extended object is commonly attached to the boom by means of a plug that fits inside the boom. The following methods of *attachment* have been used:

  (a) *Soft-soldering the plug to the boom.* This method imparts added torsional rigidity to the boom.

  (b) *Using two rivets in a line parallel to the boom axis.* This method allows the boom tape to be flattened while remaining attached to the plug.

  (c) *Employing a pivot arrangement normal to the boom axis.* The pivot penetrates both edges at the overlap preventing translation of the edges at the attachment point.

- The extended object should not contain any sublimating material, since even small residual *sublimation* causes large disturbance torques because of the large moment arm. This effect caused the 1963-38B spacecraft to tumble. A solution to this tumbling problem is discussed in section 2.2.2 (4).

4.3.2 Operational and Test Considerations

The boom system should not fail under any operational condition imposed by the mission. This section contains recommended practices relative to operation during the launch environment phase and during extension and retraction of the boom element. This section also contains recommendations relative to the failure mode analysis, the in-flight performance monitoring, and the ground testing necessary to maximize the chances of failure free operation.

(1) Analysis of Failure Modes

A failure analysis of the boom system should be performed to determine failure modes and the effect which each failure mode has on the performance of other spacecraft systems. The most common failure modes are discussed in detail in section 2.2. Protective measures or redundant means of operation should be provided whenever practical. There is only one known example of complete redundancy by using two entire boom systems. However, there are many instances of boom component redundancy.

A failure mode analysis not only indicates areas where component redundancy can be beneficially provided but also helps determine ground testing and in-flight performance monitoring requirements.

(2) Launch Environment

The boom system should be protected from damage during launch environment by caging and prevention of blossoming of the stowed boom element.

- *Boom Caging Requirements.* The design of the caging mechanism is influenced by whether (1) the boom is motorized or self-extending, (2) the self-extending mechanism is part of the extended object or remains attached to the spacecraft after boom extension, and (3) the caging mechanism employs active pyrotechnic devices or is operated by means of passive mechanical sequencing. Representative flight-proven caging devices that illustrate the principal design practices are described in the following paragraphs.

  The caging mechanism of the RAE spacecraft illustrates the caging of a very long motorized boom. This design incorporates a ball mechanism for caging the GG tip mass. The reel caging consists of a spring-loaded plunger which engages with one of the slots in the periphery of the storage reel (ref. 22).

  The caging device that was used for the self-extending booms in about 20 of the Navy navigation satellites where the reel becomes part of the tip mass was a mechanism which employs a double-bellows motor to extend and rotate a latch when actuated by earth command. Uncaging is accomplished when the latch withdraws two pins from the side of the extendible part. The bellows motor exerts a 4.5-kg force over 1.3 cm of travel. This system eliminates the danger of contamination of the optical surfaces on the spacecraft, since all gases generated by the explosion are contained within the bellows.

Another means of caging the self-extendible boom where the reel becomes part of the tip mass is the caging mechanism of the ATS-1 satellite. In this mechanism, two receptacles at the ends of a ball lock device couple the tip mass to the stationary parts. The plunger motion of a pyrotechnic actuator permits the balls to depress inside a housing and thus release the receptacles mounted on the tip mass. A liftoff spring provides the initial separation force, and guide pins insure coaxial separation (ref. 23).

The caging mechanism of the DODGE spacecraft is an illustration of a passive caging mechanism in which the boom motion itself unlocks the extendible object. The object is held by BeCu spring fingers which are forced into corresponding annular grooves. Releasing of the extendible object is accomplished by first retracting the boom to pull a plunger from within the spring fingers and, thus, letting them collapse. The mechanism requires that the boom exert a 2.3- to 3.2-kg force for uncaging. This system has the advantage of simplicity of a purely mechanical system without the need of pyrotechnic and associated components. However, careful adjustment is required so that the force required for uncaging is large enough to hold the extendible object securely during launch vibrations, but is not so large as to cause buckling of the boom when it is initially extended.

- *Methods for Prevention of Blossoming of Boom on the Storage Reel.* As defined in section 2.2.1 (1), blossoming means that a boom uncoils on the storage reel like a partially unwound clock spring. A blossomed boom should not be subjected to compression loading particularly during launch since it is certain to cause jamming of the extension mechanism. The method of prevention of failure due to blossoming of the stowed boom on the storage reel depends primarily on whether (1) the extension motor is directly coupled to the storage reel, or (2) the boom is extended by means of a pinch roller drive system.

  Blossoming of the boom which has the extension motor directly coupled to the storage reel should be either (1) prevented in the initial design or (2) eliminated just prior to boom extension. One means of preventing blossoming in the design is by the use of a high gear ratio between the torque motor and the storage reel to provide an irreversible torquing path. Blossoming can be eliminated prior to boom extension by first torquing the storage reel for boom retraction to take out any blossoming that may be present.

  The pinch roller drive system pulls the boom off the storage reel and eliminates compression loads on the boom between the storage reel and the pinch rollers during extension. The pinch rollers should be placed as close as possible to the exit of the boom from the extension mechanism. The storage reel should be destrained by a slip clutch during boom extension. These booms are retracted by torquing the storage reel to eliminate compression loads during boom retraction.

(3) Buckling

The magnitude of buckling loads in the boom should be kept within safe limits for all operating conditions. The principal sources of buckling loads are (1) inertial forces causing compression and bending loads due to changes in spacecraft attitude, orientation and spin rate, and (2) compression loads induced by extension and retraction of the boom. The loads listed under (1) are determined in the spacecraft mission analysis and serve as input parameters for dimensioning of the boom, while those listed under (2) are a result of the specific boom design.

Buckling of a spacecraft boom due to loads associated with boom extension or retraction should be prevented by (1) limiting the compression loads due to the dynamics of boom operation and (2) increasing boom stiffness to resist these loads. The recommended practices for these means of preventing buckling are discussed in the following paragraphs. The ever-increasing demand for longer spacecraft booms will place even greater emphasis on this aspect of boom design.

- *Acceptable Limits for Boom Compression Loading.* The three principal sources of compression loads acting on the boom and the measures that should be taken for keeping these loads within safe limits (ref. 19) are discussed in the following paragraphs.

  Inertial loads due to acceleration of the boom and of the extended object should be determined for the most severe case such as when a long partially extended boom is again extended after it has been stopped. The resulting maximum pure compression loads upon termination of extension should be kept within safe limits by

  (a) Using low extension velocity.

  (b) Minimizing the weight extended by the boom.

  (c) Using a special extension-velocity programming device for the gradual increase and decrease of extension velocity, as was considered for the ATS-1 and -4 spacecraft.

  A corollary to (a), (b), and (c) is the inertial loads due to deceleration of the boom and the extended object when the retraction is terminated. Similar analytical and hardware considerations are applicable.

  Pure compression loads due to rebound of the extended object and the boom should be kept within safe limits by

  (a) Limiting the velocity at the end of the extension.

  (b) Limiting the effective coefficient of restitution of the boom extension velocity.

  (c) Providing means for dissipation of the kinetic energy of the extended object when extension is terminated.

  (d) Making the object and the boom as light and as compact as possible.

  The compressive stresses on the top or bottom surface of the boom element (tension stresses on the opposite side) due to boom bending caused by the combined inertial and Coriolis forces during boom extension occur shortly after extension is initiated. Some of the means of assuring that this total load remains within a safe range are

  (a) Limiting the initial spin rate of the spacecraft.

(b) Limiting the extension velocity, thereby reducing the rate of despin of spacecraft

(c) Minimizing the weight of the object extended by the boom

Another pure compressive load that might exist on future applications is the use of a boom to extend the solar panels.

- *Required Boom Stiffness and Boom Support in Transition Region.* The boom should have adequate stiffness to prevent buckling due to the compression loads under all operating conditions. Although any required boom stiffness can be theoretically obtained by selecting a sufficiently large boom diameter and wall thickness the associated volume and weight of the extension mechanism may become prohibitive. The following paragraphs describe alternate means for providing increased boom stiffness.

  By extending several booms together so that one or more booms are inside the outer boom (called "nesting"), the bending stiffness can be increased nearly proportional to the number of nested elements. This method was used on the Gemini recovery antenna boom. Nesting is often preferable to increasing the boom thickness since it does not require increasing the storage-reel diameter to keep the maximum bending stress of the flattened boom below the elastic limit.

  By locally increasing boom stiffness through interlacing an additional short boom, called a "doubler," additional boom stiffness can be obtained. This method is preferable to increasing the thickness along the entire length of the boom, since added stiffening is obtained at the expense of only a fraction of added weight and volume. Doublers were used on the ATS-1 and -4, the DODGE, and the OV1-5, -10, and -86 satellites.

  Better support of the boom in the transition region where the boom is formed from a flattened tape into a circular cross section can provide increased stiffness. The stiffness of the boom in the transition region is not equal in all directions and in some directions is even stiffer than in the region of the fully formed circular shape. Whenever practical, the plane of maximum boom stiffness should be placed in the direction of the maximum anticipated bending load.

- *Flexural-torsional buckling.* Flexural-torsional buckling occurs when a boom with nonsymmetrical cross section (such as a slit, overlapped tube) is subjected to bending loads. The boom will buckle laterally out of the plane of the bending loads and also twist, which induces torsional loading. Such deflections occur because the nonsymmetrical cross section tends to rotate as the loading is applied to align the cross section principal axis of minimum inertia with the applied bending moment vector. To avoid this phenomenon, booms should be designed with symmetric cross-section shapes.

(4) In-Flight Performance Monitoring

Means of monitoring spacecraft boom performance should be considered whenever lack of experience, analytical studies, or the inability to test the boom in the 1-g environment on the ground indicates a performance-information void. Monitoring of boom events and performance during operation in space should provide sufficient information to enable the user of the spacecraft (1) to correlate boom performance with experiments, radio signal characteristics, etc., (2) to diagnose the cause of malfunctioning if it occurs, and (3) to improve future boom designs. A listing of events which are frequently monitored include length, straightness, uncaging, start deployment, deployed length vs time, time required for full deployment, and motor voltage and current during boom operation. The type and the amount of instrumentation to monitor boom performance in space should be determined on the basis of the satellite mission requirements as well as whether a particular satellite is identical or similar to a previously flown satellite. Based on past flight experiences, the consensus of opinion has been the desire for more instrumentation on board. The first two of the above events (length and straightness) have been of primary concern in past flight programs and are described in detail below.

- *Length Monitoring Instrumentation.* The design of the spacecraft boom-length monitoring devices should take into consideration (1) whether the boom is motorized or self-extending, and (2) how precisely the boom length must be known. Representative length monitoring devices that have been used successfully on spacecraft and should be considered for future applications are described in the following paragraphs.

  (a) *Motorized Boom.* The motorized boom used on the DODGE satellite has three different length-monitoring devices. One is a 10-turn potentiometer, which is driven by the storage reel shaft through a worm gear. The other is a magnetic reel switch, which counts the revolutions of the storage reel. The method for determination of boom length required for satellite inversion and of maximum extension consists of a spring-loaded follower arm and a corresponding slot in the boom; the motion of the follower arm cuts the power to the drive motor and simultaneously activates a switch that short-circuits the armature of the motor, causing a braking action.

  (b) *Self-Extending Boom.* The self-extending booms that require length monitoring are commonly of the tip-reel boom type; i.e., the storage reel becomes part of the extended object. Length monitoring of these booms is difficult because the extension mechanism, which is the source of boom length data, moves away from the satellite body as the boom deploys. On the TRANSIT-5A satellite, a fine wire, which was pulled from a bobbin in a long helix as the boom extended to its operational length, furnished the communication link between the extended object and satellite telemetry. During boom extension, a counter located in the extended object produced signals at the rate of one per revolution of the tape storage reel. This information was fed through the wire link to the telemetry system and transmitted to the earth. Although effective, this method carries with it the hazards of wire entanglement and/or fracture during boom extension.

  Another method of length monitoring of the tip-reel boom uses the end shock that normally accompanies the termination of boom extension. Here, the boom tape is attached to a sliding tail stock mounted on the main body of the satellite. This tail stock is set to move at a predetermined load level. When the extended object reaches the limit of its travel, its sudden deceleration causes the tail stock to slide and trip a microswitch in the boom monitor circuitry. The resulting signal is telemetered to earth. This method is extremely simple but has a number of shortcomings. For example, the extended object must stop suddenly enough to generate a force of sufficient magnitude to actuate the microswitch. Partial extensions will take on the appearance of full extensions, and therefore a time history must be recorded as the boom extends. This is compared with the data obtained from ground tests. A difference in friction levels will give a slightly different performance. Experience and judgment are required to evaluate the orbital data correctly.

- *Straightness Monitoring Instrumentation.* TV cameras have been used to date on all satellites that monitored boom straightness in orbit, e.g., DODGE, RAE, and ATS experimental satellites. The DODGE satellite has a narrow-angle and a wide-angle camera which have a 0.38- and 1.05-rad field of view, respectively. These cameras are also used for attitude sensing of the spacecraft. The RAE satellite carries four TV cameras, one for each primary boom. TV pictures from the ATS-1 satellites show the boom highly deflected by the aerodynamic drag in the unplanned elliptic orbit. If it is feasible to use a TV camera, the following recommendations based on the experience that was gained from the above applications should be considered:

  (a) The visibility of the boom element should be enhanced by taking the TV pictures when the boom is illuminated by the Sun from behind the camera and the background is the darkness of space.

  (b) The length of the boom at the time when the pictures are taken should be known.

  (c) The visibility of the tip of the boom should be enhanced by using a TV target. The TV targets that have been flown to date are described in the following paragraphs.

  ATS-1 and -4 satellites used a 22.9-cm-diameter disc-shaped target at the ends of the primary booms. It is made of a translucent polycarbonate so that edge and back lighting illuminate the front side of the disc. The back side of the disc is coated with a thin aluminum film to both transmit and reflect light. The front surface of the disc is covered with glass beads, a few mils in diameter, imbedded in the polycarbonate to diffuse the light that strikes the target at any angle. This target was very successful for any angle of incident sunlight and most types of background. The earth's clouds were the worst target background encountered.

  The RAE satellite used a spherical target made of a translucent polycarbonate material on the end of each 229-m boom (ref. 22). The targets on the ends of the booms facing toward the earth are 15.2 cm in diameter, and the targets on the booms facing away from the earth are 11.4 cm in diameter.

  The object extended by the boom facing toward the earth on the DODGE satellite is also a spherical TV target, 22.9 cm in diameter, and is painted in a colored beachball pattern for color TV calibration (ref. 4).

Although TV cameras have been used extensively and successfully to date to monitor boom straightness, they have the disadvantages of perhaps being costly, heavy, and power-consuming. Cameras can usually be justified only if the TV is necessary for some mission-oriented purpose. The Naval Research Laboratories are considering an alternate system which might be feasible. In this system, the boom tip is illuminated by an intermittent high-intensity light and the tip position measured by a modified solar aspect sensor. This system appears to have adequate resolution, minimizes the above-mentioned disadvantages of the TV system, does not impose excessive demands on the telemetry system, and is light enough to permit monitoring of many booms.

(5) Ground Testing

Although there has been extensive ground testing both to flight qualify specific booms and to characterize the mechanical and thermal properties of various boom types, few of the specific results have been published. Reference 37 contains an excellent summary of equations for the mechanical properties of booms and a substantial amount of test data and test descriptions on a number of specific booms which support the analytical data. Reference 38, which will soon be published, contains a large amount of test data on thermal profiles and resulting bending and twisting deflections. This work was done in the thermal chamber facility at GSFC.

All ground tests should be performed in accordance with the detailed test specifications for the particular spacecraft on which the boom is used. Extreme care should be taken in handling the boom system and in particular the boom element during testing to prevent damage. The boom element can be repeatedly extended and retracted as required by test specifications, but should not be "overtested."

The spacecraft mission requirements are the governing factors in determining which tests should be performed, to what specifications, and the relative importance of each required test. The following are listings of measurements and checks for qualification and functional tests.

- *Qualification Testing.* At least one boom system for each new spacecraft boom design should undergo qualification testing. This series of tests should be repeated each time significant design changes are introduced. Qualification testing should include tests for the following effects:

  (a) Vibration and shock

  (b) Combined thermal and vacuum

  (c) Electromagnetic interference

  (d) Unbalanced magnetic moment

  (e) Storage capability

  (f) Humidity resistance of exposed boom system

- *Functional Testing.* This type of testing, in contrast to qualification testing, should be performed on each deliverable spacecraft boom. Functional testing is performed at room temperature, except when indicated. The following checks and measurements are suggested:

  (a) Extended boom length

  (b) Boom element straightness

  (c) Deflection in transition region

  (d) Combined thermal and vacuum (for manned spacecraft applications)

  (e) Weight and size

  (f) Workmanship

  (g) Extended length vs time

  (h) Repeatability of tip position for linear and angular displacement

  (i) Measurement of current and voltage of deployment motor

  (j) Functioning of auxiliary equipment, such as microswitches, potentiometers, etc.

  (k) Dielectric insulation resistance

  (l) Shielding for radiation environment

  (m) Prelaunch checkout including short extension on launch pad

APPENDIX

RESUME OF GG BOOMS FLOWN PRIOR TO 1969

TABLE A-1.–Resume of GG Booms Flown Prior to 1969 (from Ref. 2)

Satellite designation	Quantity	Type	Boom element					Extension mechanism				Tip mass, kg	Cognizance (manufacturer)
			External finish	Length, m	Diam, cm	Thickness, mm	Weight, kg	Electric motor	Velocity, m/sec	Dimensions, cm	Weight, kg[a]		
1961-AH2 (TRAAC)	1	Motorized stem	None	18.288	1.143	0.0508	0.39	dc	0.152	25.4 × 10.16 × 10.16	2.133	1.589	USN/APL (SPAR)
1963-22A (TRANSIT 5A-3)	1	Self-extending stem (tip reel)	None	30.48	1.422		0.653	None	0.3048-1.371	12.446 diam × 15.24	1.589		USN/APL (SPAR)
1963-38B	1	Self-extending stem (tip reel)	Silver-plated					None					USN/APL (SPAR)
1963-49B	1	Self-extending stem (tip reel)	Silver-plated					None					USN/APL (SPAR)
1964-01B (GGSE-1)	1	Motorized stem	Silver-plated	8.534	1.295		0.181	dc	0.012	14.224 × 7.112 × 7.62	0.726	4.812	NRL(SPAR)
1964-26A	1	Self-extending stem (tip reel)	Silver-plated	30.48	1.422		0.653	None	0.3048-1.371	12.446 diam × 15.24	1.589	1.589	USN/APL (SPAR)
1964-63A	1	Self-extending stem (tip reel)	Silver-plated					None				2.724	USN/APL (SPAR)
1964-83D	1	Self-extending stem (tip reel)	Silver-plated					None					USN/APL (SPAR)
1965-16B (GGSE-2)	1	Motorized stem	Silver-plated	12.496	1.295		0.267	dc	0.012	14.224 × 7.112 × 7.62	0.726	2.565	NRL(SPAR)
1965-16C (GGSE-3)	3	Motorized stem	Silver-plated	18.288			0.390	dc	0.024		1.135	1.362 1.362 3.132	NRL(SPAR)
1965-17A	1	Self-extending stem (tip reel)	Silver-plated	30.48	1.422		0.653	None	0.3048-1.371	12.446 diam × 15.24	1.589	2.724	USN/APL (SPAR)
1965-48A	1	Self-extending stem (tip reel)	Silver-plated					None					USN/APL (SPAR)
1965-65F	1	Self-extending stem (tip reel)	Silver-plated					None					USN/APL (SPAR)

TABLE A-1.– (continued)

Satellite designation	Quantity	Type	Boom element					Extension mechanism				Tip mass, kg	Cognizance (manufacturer)
			External finish	Length, m	Diam, cm	Thickness, mm	Weight, kg	Electric motor	Velocity, m/sec	Dimensions, cm	Weight, kg[a]		
1965-89A (GEOS-1)	1	Motorized stem	Silver-plated	15.24	1.27		0.326	dc	0.024	14.224 × 7.112 × 7.62	1.135	2.951	APL(SPAR)
1965-109A	1	Self-extending stem (tip reel)	Silver-plated	30.48	1.422		0.653	None	0.3048-1.371	17.018 diam × 17.78	1.589	1.225	USN/APL (SPAR)
1966-05A	1	Self-extending stem (tip reel)	Silver-plated					None					USN/APL (SPAR)
1966-24A	1	Self-extending stem (tip reel)	Silver-plated					None					USN/APL (SPAR)
1966-25B (OV1-5)	2	Self-extending stem (tip reel)	None	6.096	1.27		0.127	None		10.16 diam × 5.08	0.681	0.454	USAF (SPAR)
	2	Self-extending stem (tip reel)	None	4.267			0.090	None					
	2	Self-extending	None	10.668			0.227	None			0.908	0.681	
1966-41A	1	Self-extending stem (tip reel)	Silver-plated	30.48	1.422	0.0508	0.653	None	0.3048-1.371	17.018 diam × 17.78	1.589	1.589	USN/APL (SPAR)
1966-53A (GGTS-1)	2	Motorized stem	Silver-plated	16.068	1.925		0.335	dc	0.182	17.018 × 7.336 × 10.414	1.225	4.994 4.994	USAF (SPAR)
1966-76A	1	Self-extending stem (tip reel)	Silver-plated	30.48	1.422		0.653	None	0.3048-1.371	17.018 diam × 17.78	1.589	1.225	USN/APL (SPAR)
7/13/66 (OV1-7)	2	Self-extending stem (tip reel)	None	9.753	1.27		0.227	None		10.16 diam × 5.08	0.681	0.681 0.681	USAF (GD/SPAR)
	2	Self-extending stem (tip reel)	None	5.791			0.127	None					
	2	Self-extending stem (tip reel)	None	15.24			0.326	None				1.407 1.407	

TABLE A-1.– (continued)

Satellite designation	Quantity	Type	Boom element: External finish	Boom element: Length, m	Boom element: Diam, cm	Boom element: Thickness, mm	Boom element: Weight, kg	Extension mechanism: Electric motor	Extension mechanism: Velocity, m/sec	Extension mechanism: Dimensions, cm	Extension mechanism: Weight, kg[a]	Tip mass, kg	Cognizance (manufacturer)
1966-111B (OV1-10)	2	Self-extending stem (tip reel)	None	9.753			0.227	None				0.681 0.681	USAF (GD/SPAR)
	2	Self-extending stem (tip reel)	None	5.791			0.127	None					
	2	Self-extending stem (tip reel)	None	15.24			0.326	None				1.407 1.407	
1967-31A (ATS-1)	4	Motorized stem	Silver-plated	40.233			0.871	Hermetically sealed dc	0.457	21.336 × 7.62 × 11.684	2.179	1.135 1.135	NASA (GE/SPAR)
	2	Self-extending stem (tip reel)	Silver-plated	13.716			0.295	None	0.548	23.368 × 12.192 × 8.128[b]	2.043[b]	0.726 0.726	
1967-34A	1	Self-extending stem (tip reel)	Silver-plated	30.48	1.422		0.653	None	0.3048-1.371	17.018 diam × 17.78	1.589	1.225	USN/APL (SPAR)
1967-48A	1	Self-extending stem (tip reel)	Silver-plated					None					USN/APL (SPAR)
1967-53C (GGSE-4)	1	Motorized stem	Silver-plated	18.288	1.27		0.390	–	0.012	14.224 × 7.62 × 7.366	1.044	2.724	NRL(SPAR)
	2	Self-extending stem (tip reel)	Silver-plated	12.192	1.422		0.258	None	1.219	9.144 × 7.874 × 18.034	1.589	1.362 1.362	
1967-53D (GGSE-5)	3	Motorized stem	Silver-plated	18.288	1.925		0.390	dc	0.024	14.224 × 7.112 × 7.62	1.135	1.362 1.362 3.132	NRL(SPAR)
1967-53F	1	Motorized stem	Silver-plated	12.496			0.454	dc	0.012		0.726	2.565	NRL(SPAR)
1967-53G	1	Motorized stem	Silver-plated					dc					NRL(SPAR)
1967-53H	1	Motorized stem	Silver-plated					dc					NRL(SPAR)

TABLE A-1.– (continued)

Satellite designation	Quantity	Type	Boom element					Extension mechanism				Tip mass, kg	Cognizance (manufacturer)
			External finish	Length, m	Diam, cm	Thickness, mm	Weight, kg	Electric motor	Velocity, m/sec	Dimensions, cm	Weight, kg[a]		
1967-66F (DODGE)	4	Motorized stem	Silver-plated	45.72	1.27		0.980	ac	0.076	20.066 × 7.62 × 11.176	2.497	3.745 3.745 2.224 2.224	APL(SPAR)
	4	Motorized stem	Silver-plated	15.24			0.653	ac			2.179	1.257 1.257	
	2	Motorized stem	Silver-plated	30.48			0.326	ac			1.861	2.242 2.242	
7/27/67 (OV1-11)	2	Motorized stem	None	16.76	1.27	0.0508	0.358	Hermetically sealed dc	0.076	15.24 diam × 20.32 and 7.62 diam × 15.24[b]	4.313[b]	0.908 0.908	USAF (GD/SPAR)
	3	Motorized stem	None	15.24			0.326	Hermetically sealed dc			3.859[b]	0.181 0.0758 0.0758	
1967-72A (OV1-86)	2	Motorized stem	None	16.67			0.326	Hermetically sealed dc			4.313[b]	0.908 0.908	USAF (GD/SPAR)
	3	Motorized stem	None	15.24			0.326	Hermetically sealed dc			3.859[b]	0.181 0.0758 0.0758	
1967-92A	1	Self-extending stem (tip reel)	Silver-plated	30.48			0.653	None	0.304-1.371	17.018 diam × 17.78	1.589	1.225	USN/APL (SPAR)
1968-02A (GEOS-2)	1	Motorized stem	Silver-plated	18.288			0.390	dc	0.024	14.224 × 7.112 × 7.62	1.135	2.951	APL(SPAR)
1968-12A	1	Self-extending stem (tip reel)	Silver-plated	30.48	1.422		0.653	None	0.304-1.371	17.018 diam × 17.78	1.589	1.225	USN/APL (SPAR)

TABLE A-1.–(concluded)

Satellite designation	Quantity	Type	Boom element					Extension mechanism				Tip mass, kg	Cognizance (manufacturer)
			External finish	Length, m	Diam, cm	Thickness, mm	Weight, kg	Electric motor	Velocity, m/sec	Dimensions, cm	Weight, kg[a]		
1968-055A (RAE)	4	Motorized TEE[c]	Silver-plated	228.6	1.447		4.426	dc	0.152	15.24 × 20.32 × 41.91	8.172	Light-weight targets	NASA(FH)
	2	Motorized TEE[d]	Silver-plated	96.012			2.006	dc	0.06	20.32 × 25.4 × 35.56[b]	8.308[b]	None	
1968-068A (ATS-4)	4	Motorized stem	Silver-plated	37.49	1.27		0.817	Hermetically sealed dc	0.457	21.336 × 7.62 × 11.684	2.179	3.362 3.362	NASA (GE/SPAR)
	2	Self-extending stem (tip reel)	Silver-plated	13.716			0.295	None	0.548	23.368 × 12.192 × 8.128[b]	2.043[b]	1.861 1.861	

[a]Including boom element.

[b]Dimensions and weight of the multiple deployer.

[c]Perforated booms with internal surfaces painted black.

[d]Interlocked edges.

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