Special Features of the CLUSTER Antenna and Radial Booms Design, Development and Verification

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Abstract

CLUSTER is a scientific space mission to in-situ investigate the Earth's plasma environment by means of four identical spin-stabilized spacecraft. Each spacecraft is provided with a set of four rigid booms: two Antenna Booms and two Radial Booms. This paper presents a summary of the boom development and verification phases addressing the key aspects of the Radial Boom design. In particular, it concentrates on the difficulties encountered in fulfilling simultaneously the requirements of minimum torque ratio and maximum allowed shock loads at boom latching for this two degree of freedom boom. The paper also provides an overview of the analysis campaign and testing program performed to achieve sufficient confidence in the boom performance and operation.

1. Introduction

The CLUSTER mission is part of a cooperative scientific research program between ESA and NASA for the investigation of the plasma interactions in the Sun-Earth system. The mission relies on four identical spin-stabilized spacecraft being placed in nearly identical high eccentric polar orbits. CLUSTER will observe in unprecedented detail magnetic and electric interactions between the Earth and the Sun by performing in-situ spatial and temporal plasma particle and electromagnetic field measurements. Each spacecraft is provided with a set of four booms: two Antenna Booms (AB's), each carrying a S-Band Antenna, and two Radial Booms (RB's), to place the two Flux Gate Magnetometers on one boom and the WEC 6 experiment on the other far enough from the spacecraft body to allow for undisturbed scientific measurements. The two RB's and one AB, are located on the +X side of the satellite. The other AB is accommodated on the -X side of the satellite (Figure 1). Both the RB's deploy in a plane perpendicular to the spacecraft spin axis, and each AB deploys in a plane parallel to the spacecraft spin axis. The CLUSTER mission is a "first" for ESA in that it requires the delivery of four identical spacecraft for simultaneous launch (in a double stack configuration) on the first qualification flight of the ARIANE 5 launcher. For the boom mechanisms, this has meant a series manufacturing, assembling, integrating and testing of 20 booms: 2 Structural Models (SM), 2 Qualification Models (QM) and 16 Flight Models (FM).

Because of the limited resources available to the CLUSTER program, at the start of system definition phase it was investigated whether the required functional performance of the boom mechanisms could have been achieved by utilizing hardware of proven design with existing space qualification. The outcome of this investigation resulted in the CLUSTER boom mechanism design baseline being derived from the radial boom flown on ULYSSES and to assume the CLUSTER booms were qualified by similarity with ULYSSES. Based on these assumptions, the

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subsystem design phase was eventually started, though different and more stringent (than ULYSSES) requirements were specified to the boom mechanisms. Unfortunately, at the end of the subsystem design phase, the results of the first development tests revealed that the specific CLUSTER requirements could not be fulfilled with the assumed boom baseline design. Consequently, several design improvements were developed and implemented with the aim to recover this unexpected and critical situation. However, the introduction of these changes imposed the need for requalification and, therefore, a dedicated verification program encompassing both analysis and test was established and urgently commenced to acquire sufficient confidence in the CLUSTER booms' performance and operation.

2. Mechanism Requirements and Design Description

2.1. Mechanism Requirements
Among the CLUSTER requirements applicable to the booms, those which have significantly affected and driven the mechanism design are the:
- Electro Magnetic Cleanliness (EMC) requirements;
- Mission environmental and operational requirements;
- Static Torque Ratio (STR) requirement;
- Strength requirements;
- Structural frequency/stiffness requirements;
- Thermal requirements;
- Allocated resources.

EMC requirements. Due to the CLUSTER specific mission objectives the booms must be clean from both the electrical and magnetic point of view. Therefore, all boom external surfaces (including the thermal insulation) have to be electrically conductive and eventually grounded. In addition, the use of magnetic material is forbidden.

Mission environmental and operational requirements. During launch, the booms have to withstand the mechanical loads induced by the ARIANE 5 launcher in its first qualification flight. Upon separation from the launcher, a 45 day transfer orbit phase is foreseen, during which the booms will be subjected to a severe thermal environment induced by the wide range of expected Solar Aspect Angle (SAA). Once in their mission operation orbit, long eclipses (more than 4 hours) will be experienced. From an operational point of view, it is envisaged to release the +X AB immediately after launch and the other three booms once the Mission Operation Phase is reached. Both RB's are released after the -X AB is deployed.

Static Torque Ratio (STR) requirement. During boom deployment, available actuator forces/torques shall exceed by a factor of 2 the worst case predicted resistive forces/torques. No kinetic energy is to be taken into account. The following design factors have to be furthermore applied to the component of resistive forces/torques:

- Friction: 3.0^a
- Hysteresis: 3.0^a
- Harness: 3.0^a
- Inertia: 1.1

• Spring Stiffness: 1.2

^a These design factors can be reduced to 1.5 if relevant data for resistive contribution are obtained from test measurements.

Strength requirements. The booms must withstand the worst case combination of both mechanical and thermal loads that can be experienced during the required lifetime. Two worst cases are identified as the mechanical loads induced by the launcher and the combination of thermal and mechanical shock loads at boom release, deployment and latching. Stress analysis has to demonstrate that a positive Margin of Safety exists even after the application of a design factor of 1.5 for yield and 2.0 for ultimate. In addition, mechanical testing must demonstrate that neither structural failure nor boom performance degradation occurs when the flight loads are factored by 1.1 for acceptance and 1.25 for qualification. The launcher induced loads were derived from the coupled load analysis with the ARIANE 5 launcher. However, due to the experimental nature of the first ARIANE 5 launch, large uncertainty factors were applied leading to a Quasi-Static-Load factor of 33 g applicable for both the Radial and Antenna booms. The derivation of the shock loads at the moment of latching was performed by means of deployment analysis (see paragraph 3.1).

Structural frequency / stiffness requirements. To avoid dynamic coupling with the launcher, minimum natural frequencies of 75 Hz and 100 Hz are established for the RB and AB structures, respectively, in the stowed configuration. These frequencies were used to design the boom tubes, hinges and hold down brackets.

Thermal requirements. The booms must operate without any performance degradation within the specified acceptance temperature limits (the qualification temperature range is 20° C wider):

AB	-130°C / +115 °C -15°C / +65 °C	Non Operating[1] Operating[2]
RB	-130°C / +115 °C -20°C / +80 °C	Non Operating[1] Operating[2]

[1] Non Operating = pre-deployment and deployed.
[2] Operating = release, deployment and latching.

These limits were derived by means of flight temperature predictions employing the CLUSTER Comprehensive Thermal Mathematical Model and after application of temperature uncertainty margins. The required temperature range for the deployment operation will be achieved, if necessary, by an appropriate attitude maneuver.

Allocated resources.
A total mass of 30 kg is allowed for all the four booms. There is no power available except at boom release for the pyro actuators, and only a limited amount of telemetry channels are available to monitor boom temperatures (thermistors) and final deployment status (end-switches).

2.2. Mechanism Description

The RB is a two Degree of Freedom (DoF) system consisting of two tubes (each about 2300 mm long), two hinges, two hold-downs, their support brackets and one Inner Hinge (IH) support bracket (see RB stowed configuration in Figure 2). Additional features are:

- IH bracket interfacing with the IH support and holding the male side of the latch device;
- IH fitting holding the female side (redundant spring) of the latching device;
- Inner boom CFRP tube, 50.2 mm diameter and 1.1 mm thick;
- Two inner sleeves, properly shaped, nesting on the hold-down device and mating with the corresponding ones of the outer boom;
- Outer Hinge (OH) inner boom fitting with latch device (male side);
- OH outer boom fitting with redundant latch springs (female side);
- Redundant kick spring in the OH;
- Outer boom CFRP tube, 50.2 mm diameter and 1.1 mm thick;
- Two outer sleeves, properly shaped, nesting on the hold-down device and mating the corresponding ones of the inner boom;
- Fittings to accommodate the supported experiment sensors;
- Redundant AMPEP bearings (self-lubricated bushes) at the IH and OH;
- Single layer thermal protection of aluminized Kapton (Nomex scrim reinforced) striped with Kapton ITO tape.

Boom fittings, hinges, bearings, hold-down and hinge supports are made from Titanium alloy. In launch configuration, the two boom elements (inner and outer arm) are kept in position by two hold down clamps, which at deployment are pyrotechnically released. The clamps are subsequently driven into a latch position by a redundant spring drive system. Boom separation, deployment and latching in orbit is driven by the centrifugal forces generated by the spacecraft spin. Once both RB's are deployed, their tip to tip distance amounts to about 13 m.

The AB design is similar to the RB, except the single hinge/tube mechanism is about 1600 mm in length. During launch, each AB is clamped in position by a simple hold down mechanism (pre-loaded bolt pressing two V-shaped brackets together) located at the tip of the boom. Upon firing the pyro-nut device, the boom is released and driven by a redundant spring actuator, which rotates the tube by 90° and aligns the S-Band Antenna with the spacecraft X axis. In this position, the AB is positively latched by a redundant latch spring system which provides the required stiffness and positional accuracy. In order to comply with the CLUSTER-specified requirements, the original ULYSSES baseline design had to be changed. The design improvements implemented in the CLUSTER boom mechanisms are described in Table 1. They were mainly dictated by the mass/volume minimization constraint imposed by the CLUSTER mission and the need to:

- Increase the structural frequencies/stiffness of the booms in their stowed configuration;
- Decrease the components of the boom resistive torque contributions (e. g. hinge friction and harness) and increase the available actuator force/torque, such that sufficient STR can be achieved during the boom deployment;

- Increase the boom strength capability at the moment of latching.

As the RB is deployed by the centrifugal forces, the STR increases with the spacecraft spin rate. In order to fulfill the CLUSTER STR requirement, a spacecraft spin rate of about 20 rpm is needed. However, this would induce a shock load of about 10000 N•m at the RB IH. Obviously, the booms are not able to withstand such shock load. Critical items are the Titanium fitting/CFRP tube bonded joints. Therefore, the initial spacecraft spin rate must be decreased, thus impacting on the compliance with the STR especially at the end of the deployment. At this point, a large drive torque is required to engage the latch mechanism. However, due to the geometry and the mass distribution of the RB segments only a modest centrifugal force is available for latching.

To solve this problem and avoid a major re-design of the booms, a complex and unusual approach has been followed. First, a comprehensive analysis has been performed to determine the maximum allowable spacecraft spin rate at deployment start. Afterwards, for the determined spin rate, the available STR has been calculated. The aim was to demonstrate the baseline requirement was fulfilled at least in the first part of the deployment and at all possible stop positions. At these stop positions, which are function of the friction profiles assumed for each boom hinge, a spin-up maneuver is allowed to achieve the required STR. All analysis inputs have been verified and confirmed by test. However, the quasi-static measured torque profiles have been modified to take into account viscous effects, which have been also determined by test measurements. Finally, a special thermal conditioning phase has been planned prior to the deployment of the -X AB and the two RB's. As far as practical, a more benign thermal environment to the mechanism critical areas (hinges, harness and joints) after the rather long and severe transfer orbit phase will be provided. This will be achieved by tilting the spacecraft spin axis towards sun thus adjusting the SAA to the required value (presently predicted between 80° and 85°).

3. Verification Program

The verification of the Radial and Antenna Booms has been achieved by a combination of analysis and test. The rationale for this approach is the substantial difficulty to simulate, on ground, the in-orbit environment. Because of the RB size, it would be impractical and very expensive to release and fully deploy the booms under simulated space conditions in a thermal vacuum chamber. However, whenever possible, certain requirements have also been verified simply by test. To this purpose, specific acceptance criteria have been defined, in terms of overall resistive contribution and drive spring characteristics, to check the adequacy of the boom hardware at relevant stages of the assembly, integration and test program, both at subsystem and system level. These acceptance criteria have been also used as input for the deployment analysis in order to achieve a consistent verification.

3.1. Deployment Analysis
An extensive analysis campaign has been carried out in order to verify the boom deployment performance with respect to the applicable design requirements and check the effectiveness of potential changes and parameter sensitivity on the mechanism design. It encompasses:

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- Shock load analysis (i. e. determination of boom bending moments at latching);
- Calculation of the STR during the boom deployment;
- Contingency analysis (i. e. definition of spin-up maneuvers);
- Sensitivity analysis with respect to deployment parameter variation.

The analysis has been performed by means of multi-body dynamic simulation. An appropriate software package has been used. The spacecraft and one RB have been modelled as rigid bodies connected by revolute joints, thus obtaining a two DoF deployment system representing the inner and outer arm of one boom. The related kinematic input has been derived by flight predictions, FE analysis or estimated on the basis on the data of the ULYSSES satellite. These data have been updated as soon as test data from the physical hardware were available. The resistive torque contributors have been factored according to the design requirements.

3.1.1. Shock Load Analysis
The centrifugal field of the spinning spacecraft provides the actuating forces / torques for the boom deployment. The initial spin rate is, apart from the friction in the hinges, the main driver for the shock loads induced in the booms during latch. The goal of the shock load analysis is therefore to define an appropriate initial spin rate for the boom deployment that is consistent with the allowable shock loads of the booms and other operational requirements. During latching, the arms of the booms are mainly stressed by a bending torque around the hinge axes. The latching loads are mainly function of the latching velocity, eigenfrequencies of the latched system and system inertia.

It is required to assume best case (minimum) friction in the hinges in order to calculate worst case shock loads. The lower the friction in the hinges, the higher the latching velocity of the booms. However, for a two DoF system like the CLUSTER booms, the eigenfrequency of the system changes depending on the order of latching of the various arms. Hence, assuming zero friction in the hinges does not always provide worst case shock loads. For the CLUSTER satellite, the highest eigenfrequencies have been found to occur when the inner arm latches first and the outer arm is close to the latch position. This latching configuration does not result when both hinges are frictionless, which is the case for a single DoF system.

Instead, the worst case has been found by varying the friction factors in each hinge independently. Figure 3 shows the IH shock loads as a function of hinge friction factor and initial spin rate for +Y RB for two cases. The target shock level (290 N•m), derived from the ultimate strength of the boom including safety factors, is shown as well. In, evaluating Figure 3, the following conclusions are drawn:
1.) The latching shock in the booms is linearly increasing with the initial spin rate for one particular latching sequence.
2.) The latching sequence changes from OH latches first to IH latches first when the initial spin rate is increased.
3.) The latching sequence changes at different spin rates depending on the assumed friction values.
4.) Assuming zero friction in both hinges does not provide worst case shock loads for all initial spin rates.

5.) The maximum allowable initial spin rate for the + Y RB has been found to be 4.1 rpm. For the -Y RB, 4.5 rpm is allowed.

3.1.2. Calculation of STR
The STR is calculated for both the inner and outer arm separately. STR>2 demonstrates the capability to continue the deployment in case of a boom stop position accounting for all unknown in-orbit conditions. The spin rate used to calculate the STR is based on the maximum allowable bending torque of the booms (see par. 3.1.1.). The STR has been calculated for the complete deployment range for both the inner and outer arm. It is shown for the +Y RB IH and OH in Figure 4 and 5, respectively. Figure 4 and 5 indicate clearly that the STR requirement is not fulfilled over the full range of deployment angle (grey shaded area). The values for the OH STR are higher due to the presence of the kick spring.

3.1.3. Contingency Analysis
In order to resolve the non compliance of the boom design with respect to the STR requirement, a contingency analysis has been performed with the aim to increase the spin rate and increase the deployment torque, thus to eliminate the original non compliance. An analysis for both the +Y RB and -Y RB has been run following the steps listed below:
- Identification of non compliance areas in the boom deployment range (see Figure 4 and Figure 5).
- Definition of possible stop positions, considering that either arm of the boom may have latched.
- Calculation of the spin rate necessary to increase the STR to 2.
- Consideration of the spin rate accuracy in the calculated spin rate (±0.1 rpm).
- Calculation of the latching shock for best case friction values.

In cases where the latching shock for the increased spin rate is below the target shock level, a spin up maneuver is considered acceptable. It has been demonstrated by analysis that the boom can be recovered and successfully deployed from a stationary position by increasing the spin rate without exceeding the target shock level.

3.1.4. Sensitivity Analysis
The resistive torque profiles as well as the actuating torques of the outer hinge kick spring have been measured for all QM and FM booms. The variation of the individual profiles has been subject of a sensitivity analysis. The goal of the investigation was to demonstrate that any variation of friction up to a factor of 6 in both hinges will not affect the successful deployment of both arms and not exceed the target shock level. The results are compiled in Table 2. The data in the fields indicate:
- The deployment sequence (O/I Outer hinge lathes first; I/O inner hinge latches first);
- The first number gives the inner hinge shock load in N•m;
- The second number gives the outer hinge shock load in N•m.

It can be seen that except for the friction factor of 6 in both hinges, one go release, deployment and latching is always accomplished. An investigation of the inertia uncertainty of the spacecraft at the time of deployment has also been performed. It has

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been found that a 10% variation does not significantly influence the boom deployment behavior and latching shock magnitudes.

3.2. Testing Program
3.2.1. Subsystem-Level Testing
The boom testing program at subsystem level is based on Development tests, Qualification tests and Acceptance tests. The deployment tests were performed mainly at boom component and SM levels. turned out that with a mechanism design derived from the ULYSSES boom it was not possible to fulfill the CLUSTER specific requirements (see paragraph 2.2) and specific hardware acceptance criteria were also established (see paragraph 3.0). The Qualification and Acceptance test flow is in principle the same and, for the Radial Boom, is shown in Figure 6. Special attention was paid to the bonded joint sample testing, the thermal vacuum test and the functional performance test.

Bonded Joint Sample Testing. To adequately verify the strength capability of the CFRP tube/Titanium fitting bonded joints, a destructive sample testing campaign has been performed. Representative samples of both the 60 mm and 45 mm bonded joints have been first subjected to thermal cycling at more extreme temperature than those actually predicted and subsequently subjected to mechanical failure under representative temperature conditions expected at the moment of boom release. Based on the results of this sample testing program, a statistical evaluation has been performed to derive the allowable load for ultimate bending of the joints ("A Value" approach to achieve a probability of 99% with a confidence level of 95%). The results of this evaluation are summarized in Table 3.

Thermal Vacuum Test. The RB thermal vacuum test set-up is shown in Figure 7. Due to the limited space available in the test chamber, it was only possible to measure the friction of the IH. For the AB, full deployment and retraction has been tested. The tests for both the RB and AB confirmed the worst-case friction occurs at low temperatures and there is no significant difference between friction values measured at ambient and vacuum conditions.

Functional Performance Test. Because of adding the boom thermal conditioning phase (see paragraph 2.2.) and the thermal vacuum test results, the test verification of the basic performance of the mechanism has been performed at ambient conditions. Figure 8 shows a typical friction profile measured for the FM 3 RB. The simulation of the latching shock load has been also achieved in the frame of the functional performance test. All RB and AB QM and FM have successfully passed this test.

3.2.2. System Level Testing
The boom testing program at system level encompasses the following tests:
- Mass properties verification (prior to integration onto the satellite);
- Alignment checks in both stowed and deployed configurations (booms integrated onto the satellite) prior and after system environmental tests;
- Boom release, deployment and friction checks and latch spring proof load test, prior and after to system-level environmental tests.

- System environmental tests: mechanical (sine vibration and acoustic) and thermal vacuum tests.

In the frame of the boom release and deployment test, both the RB's and the AB's are checked with respect to the function of release and deployment. Pyro release is, however, performed, only after the environmental tests. Relevant measurements are carried out at ambient conditions.

Concerning the RB, gravity effects are compensated by means of two meteorological balloons filled with Helium (Figure 9). One of the balloons is fixed to the inner boom segment and the other to the outer boom segment at their respective mass center. The deployment of the booms is achieved by means of a small electrical motor propeller.

4. Conclusions

The key aspects of the design evolution of the CLUSTER booms have been presented. One of the major problems was caused by the assumption made during the system definition phase that the required mechanism design was of already existing qualification status. The design improvements implemented to fulfill the specific CLUSTER requirements have also been described.

The difficulties encountered to fulfill simultaneously the design requirements of the minimum STR and maximum allowed shock loads and the comprehensive analysis performed to determine the highest allowable spacecraft spin rate at the moment of boom release has been discussed.

To the authors knowledge, such combined extensive verification approach has never been applied to a conceptually simple two DoF system like the CLUSTER RB mechanism. Despite the problems encountered, the CLUSTER boom qualification has been successfully achieved at subsystem level (October 94) and confirmed at system level (December 94). All 16 flight booms have been delivered and integrated onto the CLUSTER satellites. The CLUSTER System AIV program is almost over since the FM 1, 2 and 3 satellites system environmental testing has been successfully completed and only the Thermal Balance/Vacuum test of the FM 4 satellite is still due. The CLUSTER launch is presently planned for end November, 1995.

5. Acknowledgments

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Table 1 Summary of AB/RB major design changes from ULYSSES design

Item	Design modification description	Purpose
RB	Hold–down (HD) and HD Support Bracket • rope element/pyro cutter device changed to Ti clamp/pyro nut device • support bracket cylindrical shape changed to conical shape	• increase eigenfrequency in stowed configuration • increase strength capability with respect to shock loads
AB/ RB	CFRP Tube • CFRP Tube lay–up optimized	• increase eigenfrequency in stowed configuration • increase strength capability with respect to thermal and shock loads
RB	CFRP Tube/Fitting joint • additional liner introduced inside the fitting in the glued zone	• increase strength capability with respect to thermal and shock loads
AB/ RB	Latch mechanism • latch mechanism stiffened / strengthened	• increase strength capability with respect to shock loads
AB/ RB	Hinge Bushings • clearance between shaft and bushing increased	• reduce overall friction profiles (increase STR)
AB/ RB	Harness • harness routing around hinges optimised by development test • AB harness shielding (Al tape) changed to mesh construction	• reduce overall friction profiles (increase STR)
RB	OH Drive Spring • short stroke spring (ca. 20 deg) introduced at OH	• change latching sequence (OH latches first) thus decreasing shock loads • increase STR at IH (OB help effect)
AB	Drive spring • pretension and stroke increased respecting the volume and shock load minimisation constraints	• increase confidence into succes- fully deployment start
RB	Contact surfaces • Ti/Ti contact sprayed with Everlube changed to Ti/Al Bronze (IB/OB) sprayed with Everlube	• avoid risk of cold welding

Table 2 Friction sesitivity analysis for +Y RB at 4.0 rpm

		Outer hinge friction factor						
		0	1	2	3	4	5	6
Inner hinge friction factor	0	O I 224 155	I O 278 125	I/O 275 38	I/O 261 22	I/O 237 20	I/O 210 25	I/O 176 28
	1	O/I 217 149	O/I 218 116	I/O 252 34	I/O 244 22	I/O 223 18	I/O 191 24	I/O 154 28
	2	O/I 210 143	O/I 209 111	I/O 233 35	I/O 224 22	I/O 207 17	I/O 172 23	I/O 126 26
	3	O/I 202 138	O/I 200 105	I/O 210 35	I/O 206 22	I/O 170 15	I/O 151 21	I/O 94 29
	4	O/I 193 133	O/I 192 98	I O 183 37	I/O 181 22	I/O 167 14	I O 127 20	I O 44 29
	5	O/I 183 127	O/I 181 91	I/O 138 40	I/O 152 22	I/O 141 12	I/O 96 20	I/O 32 61
	6	O/I 173 123	O/I 171 84	I/O 90 43	I/O 118 24	I/O 111 13	I/O 62 18	–

Table 3 Summary of statistical evaluation from bonded joint sample testing

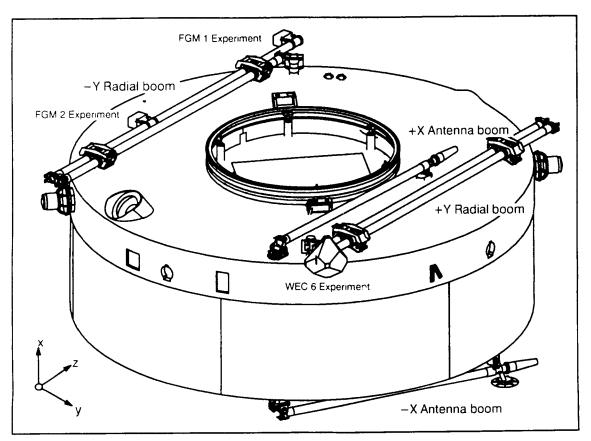| Ultimate Bending Moment [Nm]	60 mm joint 7 samples	45 mm joint 8 samples
Min	978.1	741.5
Max	1355.8	1177.3
Average	1140	973
Standard Deviation	132.8	141.8
K_A	4.64	4.35
K_B	2.75	2.58
"A" value	523	356
"B" value	774	606

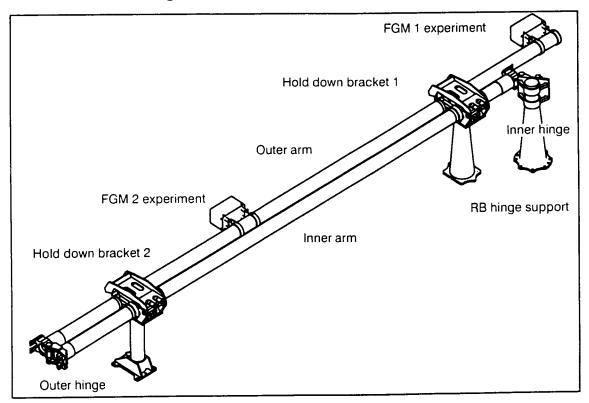**Figure 1** CLUSTER Satellite Configuration

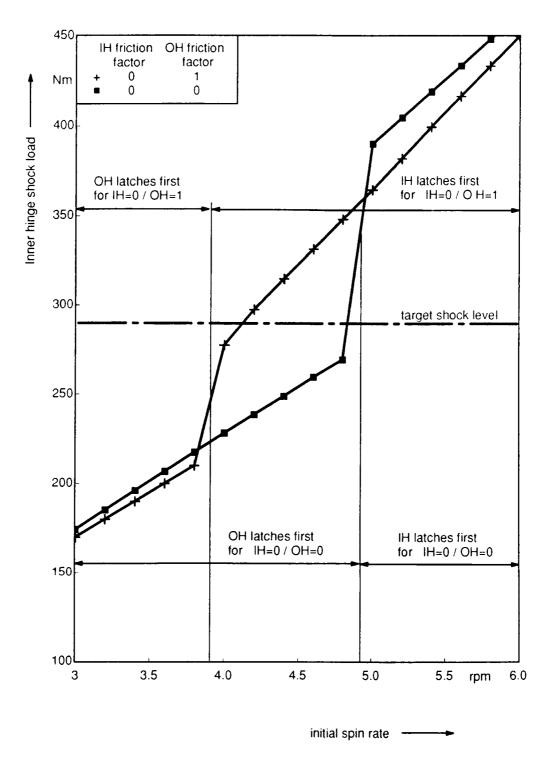**Figure 2** −Y RB Mechanical Arrangement

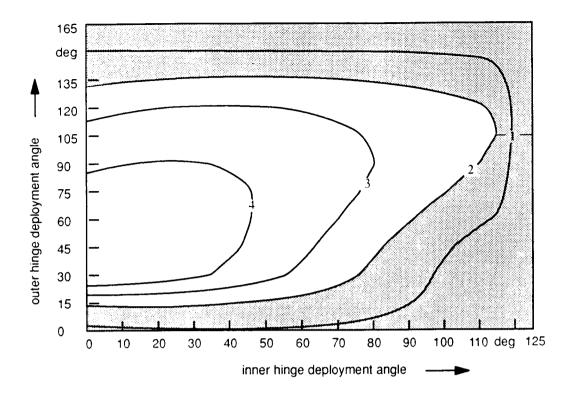**Figure 3** +Y RB Inner hinge shock load vs friction factor and initial spin rate
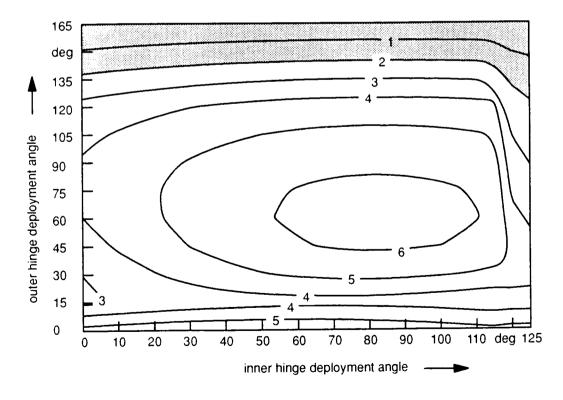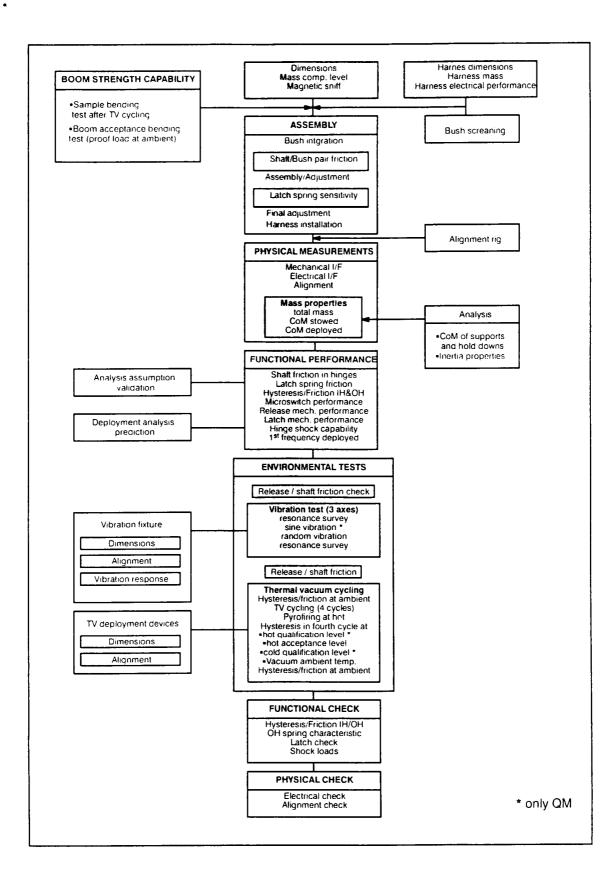
Figure 4 +Y Inner hinge torque ratio at 4 rpm

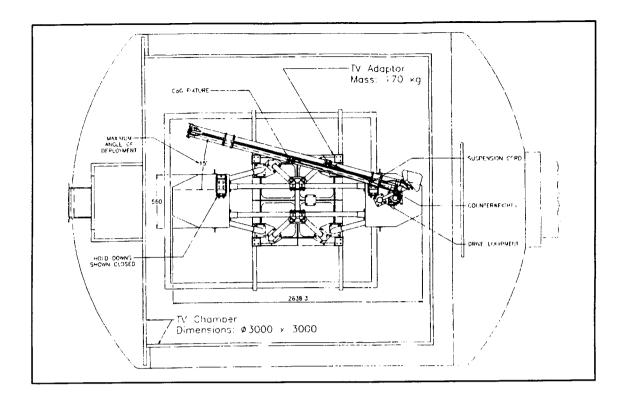**Figure 5** +Y Outer hinge torque ratio at 4 rpm

Figure 6 RB Test flow

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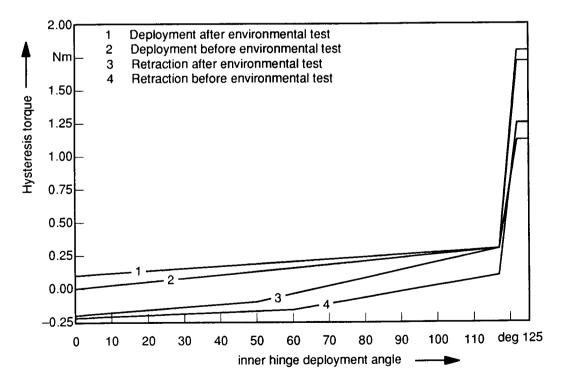**Figure 7** TV test set up for RB
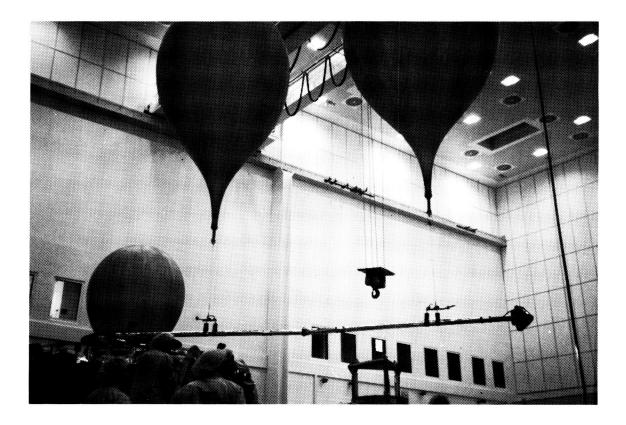

Figure 8 FM3 +Y RB Inner Hinge Friction Profiles

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Figure 9 RB System level deployment test set up