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New Antenna Deployment, Pointing and Supporting Mechanism

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Abstract

On ITALSAT Flight 2, the Italian telecommunications satellite, the two L-Ka antennas (Tx and Rx) use two large deployable reflectors (2000-mm diameter), whose deployment and fine pointing functions are accomplished by means of an innovative mechanism concept. The Antenna Deployment & Pointing Mechanism and Supporting Structure (ADPMSS) is based on a new configuration solution, where the reflector and mechanisms are conceived as an integrated, self-contained assembly. This approach is different from the traditional configuration solution. Typically, a rigid arm is used to deploy and then support the reflector in the operating position, and an Antenna Pointing Mechanism (APM) is normally interposed between the reflector and the arm for steering operation. The main characteristics of the ADPMSS are:

- combined implementation of deployment, pointing, and reflector support;
- optimum integration of active components and interface matching with the satellite platform;
- structural link distribution to avoid hyperstatic connections;
- very light weight;
- high performance in terms of deployment torque margin and pointing range/accuracy.

After having successfully been subjected to all component-level qualification and system-level acceptance tests, two flight ADPMSS mechanisms (one for each antenna) are now integrated on ITALSAT F2 and are ready for launch. This paper deals with the design concept, development, and testing program performed to qualify the ADPMSS mechanism.

Introduction

The deployment mechanisms for large antenna reflectors on satellites must bring the reflector from its stowed launch configuration up to the operative, in-orbit deployed one. A three-axis stabilized spacecraft, once in orbit, has to continuously adjust the fine pointing (relative to the ground stations) of its reflectors when high pointing accuracy is required.

The ITALSAT F2, an Italian satellite for domestic telecommunications service, was commissioned by the Italian Space Agency (ASI) to Alenia Spazio as follow-up to the previous ITALSAT flight unit 1. It is scheduled for launch in mid-1996. It was conceived, such that a higher payload mass (with respect to F1) was introduced; therefore, a particular effort was made to reduce the overall satellite weight as much as

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Design Criteria

The ADPMSS has been developed according to the following design criteria:

- a) use an integrated system to cover the antenna deployment, pointing, and support functions with an optimum function/hardware allocation;
- b) ensure a "load-free" condition for the ADPMSS hardware during the launch phase, such that its basic dimensioning is only enabled for the on-orbit stiffness requirement. In other words, the mechanism is not a part of the launch load path between the S/C structure and the antenna reflector when in the stowed condition (launch configuration); therefore, the ADPM parts do not carry any significant load (except for that of the masses when subjected to flight accelerations). As a positive consequence of this criterion, the use of beam elements became feasible, thus leading to the achievement of the maximum structural efficiency;
- c) tailor the structural links architecture for supporting the reflector on the spacecraft body to avoid hyperstatic connections, which could result in dangerous preloads acting on the mechanism;
- d) achieve an accurate definition of specific loads on structural elements and on kinematic couplings to get maximum strength/mass ratio;

Although all the previously described design criteria are very important for the ADPMSS functionality/efficiency, (b) represents a key design point. To meet this requirement, special I/Fs have been designed to connect the ADPM parts to the reflector. In fact, when the antenna is held down by the Pyro Release System, each ADPM-reflector I/F allows for large relative motion (several millimeters) without inducing significant loads on the matching parts. After the antenna release, the ADPM internal springs immediately restrain all the reflector degrees of freedom to the S/C body. The same springs provide the internal forces necessary to preload the I/F matching parts to avoid backlash. Therefore, this approach provides both a simple passive switching of structural links from large compliance to large stiffness and a backlash-restraining capability of the kinematic couplings.

Mechanisms Description

Antenna Deployment Mechanism

The ADM is an articulated frame, composed of a "trapezium" and an "upper beam" that are linked together by a metallic/plastic hinged joint. All the rods are CFRP-made. The upper beam interfaces to the reflector center by a suitable gimbal, and the assembly is preloaded by a compliant spring, mounted on the terminal part of the upper beam. On the S/C side, the trapezium is fitted on two metallic, hinged supports: each consists of one propulsive rotational spring and one oil damper device. The assembly, consisting of the two rotational springs and the one mounted on the upper beam, is able to provide the motor torque necessary for the antenna deployment motion. Specifically, just after the reflector release, the upper beam spring acts as a kick-off spring. The deployment motion is made very smooth by the two dampers. Due to the deployment kinetics, the motor torque value is maximum at both the beginning and the end of the deployment run (theoretically, it tends to infinity in this case!), when the torque needs are greater. Over the entire ADM run, the minimum torque margin

value is 8. When the antenna is in the stowed configuration, the ADM is folded in the allowable volume between the reflector and the S/C side wall.

Antenna Pointing Mechanism

The APM is a linear actuator, essentially composed of a rotating stepper motor and a screw gear, connected to the motor shaft by a lead screw coupled to the screw gear to obtain the linear motion. These components are integrated on a compact aluminum frame, which also provides the support guides for the lead screw and the housing for the electrical end-stroke limits. The linear motion of the lead screw is directly applied to the reflector arm pin-jointed I/F. The kinematic couplings, in which only sliding motion between parts is foreseen, are made of hard materials in contact with soft, self-lubricating materials. The coupling, between the screw gear and the lead screw, is made of steel (screw gear) in contact with Teflon, which constitutes an insert that is mounted inside the lead screw titanium case. This assembly has been carefully designed to ensure the maximum dimensional stability of the Teflon insert under both mechanical loads and thermal environment. This is to avoid stress concentration inside the Teflon-made part from asymmetrical contact between the matching parties. The prismatic coupling between the supporting case and the lead screw body is based on Vespel parts, which ensure a low friction coefficient. The driving unit is a dual-wound, four-phase hybrid stepping motor with a step angle of 1.8° and a minimum dynamic torque value of 170 N-mm. Due to the geometric characteristics of the screw gear-lead screw kinematic coupling, a single motor step provides a displacement of 0.01 mm at the reflector arm I/F level. The overall APM kinematic chain axial play is continuously recovered by the Spring Restraining System, which acts on the motor with a constant force over the entire linear actuator stroke.

Reflector Supporting Structure

The RSS sub-assembly is a truss-shaped structure, firmly mounted on the reflector back side, and is composed of two short "arms," made of sandwich material (CFRP skins and Al core), in conjunction with six CFRP-made rods. In addition, a special rod, coincident with the actual antenna deployment axis, is interposed between the dish (bottom edge) and one actuator to prevent in-plane reflector rotations. The RSS arms are designed to provide high stiffness along the in-plane directions and low stiffness in the orthogonal one. This solution, in conjunction with a suitable gap at the APM interface, avoids induced stresses on the APM-RSS composite. The ADPMSS features are summarized in Table 1.

Development and Qualification Program

The ADPMSS development and qualification phase included manufacturing and testing of three models:

- The bread-board model was used to validate the design concept and to provide high confidence of the conceptual approach. It mainly consisted of preliminary testing on critical parts — the coupling between the lead screw and screw gear of the APM — to verify ADM kinematics for accomplishing correct reflector deployment function.

- The engineering model (EM) was mainly used for development purposes, to define the main design choices, and to detect, in advance, any major criticality before starting the subsequent formal qualification test program. It was built, as close as possible, to flight standards to be quite representative of the final Flight Model. At the end of the activity on the EM, a high level of design maturity was obtained.
- The qualification model (QM) was the hardware built at full flight standard and used to formally qualify the ADPMSS. It was submitted to a complete test campaign. After successful completion of the first testing phase at the component level (i.e., the APM and ADM were tested alone as single components), the QM underwent a sub-system level (i.e., at antenna level) test program.

Component Level Test Program

Due to the differences in the functional aims, the duty cycle characteristics, and the design of each component, the ADM, APM, and RSS qualification models were qualified according to different test plans and modalities to cover all the environmental, functional, and reliability aspects.

The ADM alone was submitted to the following component-level qualification test program:

- Deployment functional check at ambient conditions (torque margin, deployment time, deployment angle repeatability);
- Vibration along three axes (sine, random, quasi-static loads applied on each axis);
- Deployment functional check at ambient conditions (torque margin, deployment time, deployment angle repeatability);
- Deployment functional check at extreme temperatures (deployment time at +55°C hot and at -25°C cold conditions).

Furthermore, before starting the test on the ADM, a special test program was performed to qualify the damper alone, whose design was based on the fluid viscosity effect principle. The damper test sequence included:

- Reference functional test at ambient conditions (50 mechanical cycles of extension/retraction, followed by fluid leak check)
- Thermal vacuum (4 thermal cycles, -26°C/+50°C range, including 6 cycles of extension/retraction at cold and 20 cycles of extension/retraction at hot)
- Final functional test at ambient conditions (50 mechanical cycles of extension/retraction, followed by fluid leak check).

Similarly to the ADM tests, the APM alone was also submitted to a dedicated component-level qualification test program. It included the following:

- Performance test:
 - motor pull-in minimum voltage measurement
 - electrical/mechanical stops check
 - step size check and its reproducibility
 - step response
 - actuator torque margin
 - backlash verification
- Vibration along three axes
(sine, random, quasi-static loads applied on each axis)
- Performance test
(short form);
- Thermal vacuum with short form performance test
(temperature range: -21°C/+58°C, four cycles);
- Life test
(5 x10⁶ triangle wave cycles with 50 steps peak-to-peak; i.e., 100 steps each cycle).

All the measured parameters fulfilled the requirements, and an excellent repeatability, both before and after environmental exposure, of the main functional parameters were found.

The RSS was not submitted to a dedicated test campaign because it was not a "stand-alone component"; but by a mechanical point of view, it could be considered a part of the reflector structure. Therefore, its qualification was achieved in the frame of the subsequent ADPMSS sub-system level test program.

Sub-system Level Testing

The sub-system testing was carried out at the antenna level using a complete QM ADPMSS integrated on a QM reflector and mounted on a satellite structural panel simulator. The purpose of the antenna-level test program was to validate the integration procedure of the "reflector-ADPMSS" composite on the satellite and to verify that the mechanisms meet the performance requirements after exposure to the qualification load. To perform this test program, a typical off-loading set-up was used: the reflector was placed with the hinge line vertical and suspended on swing-arm test equipment ("opening door" concept).

The test plan, at the sub-system level, included the following verifications:

- functional deployment with reflector manual release in ambient conditions
- deployment angle repeatability
- deployment time
- ADM torque margin
- environmental exposure: vibration (sine and acoustic), thermal vacuum cycling

- functional deployment with reflector pyro release in ambient conditions
- deployment angle repeatability
- deployment time
- ADM torque margin
- antenna steering test (APM stepping)
- first mode frequency of deployed reflector (dynamic response).

The tests were successfully performed, and all the obtained results met the requirements. In particular, the torque margin, measured by applying a zero kinetic energy test methodology, was always 8, at the minimum, and the deployment time was 22 seconds average, with a maximum delta variation of ± 0.5 second. These values were produced very consistently when the same parameters were measured during the ADM component qualification.

During the test program, two anomalies occurred and resulted in design changes, as described later.

Radio Frequency Compatibility Check

The qualification activity at subsystem level also included a radio frequency compatibility check to verify and quantify any effect of the ADM on the antenna electrical performance, since the mechanism is located between the antenna feed cluster and the reflector.

The test was performed throughout the antenna test range with two antenna configurations: one without the ADM (i.e. "clean" area between feeds and reflector), and one with the mounted ADM (corresponding to the antenna on-orbit configuration). For both conditions, the radiation patterns in azimuth and elevation were measured and then compared, also taking into account the test range measurement errors and repeatability.

The test results showed a negligible influence of the ADM on the first side lobe level of co-polar radiation patterns along the azimuth plane. This degradation corresponds to a worst-case interference contribution on communication channels of -34 dB in transmit and -30 dB in receive. These values were largely acceptable because the impact on the antenna performance along the azimuth plane was always well within electrical requirements.

On the other hand, the test demonstrated that the ADM did not degrade on the first side lobe along the orthogonal plane (i.e., elevation plane). Furthermore, all the other antenna parameters (e.g., beam pointing, gain slope, first null shift) were not significantly influenced by the presence of the mechanism.

Finally, mutual coupling verifications were performed between the Ka and L-band functions by transmitting a Ka signal and measuring the received level in L-band. In this case, the impact of the ADM was also quite negligible because the measured values were well within the antenna noise behavior requirements (i.e., about -55/-60 dB).

Satellite Level Testing

After the successful completion of ADPMSS qualification , the mechanism was declared ready for space application. Therefore, the ADPMSS was selected for use on the ITALSAT Flight Model 2 satellite for on-orbit deployment and steering of the two large L-Ka antenna reflectors. To optimize the Assembly, Integration and Test (AIT) operations sequence at satellite level, testing of antenna reflector integration/alignment and deployment/pointing was planned to occur just after the satellite alignment phase. Instead of using the traditional test set-up approach (based on testing configuration with spacecraft z-axis parallel to the floor and reflector hinge line vertical), as previously used during the sub-system test campaign, the spacecraft is in a vertical position (alignment set-up), with the satellite z-axis orthogonal to the floor. To perform the AIT operations on the "reflector-ADPMSS" assembly in this condition, an innovative test set-up concept was developed because the reflector had to be deployed with the hinge line horizontal ("lowering draw bridges" concept).

The AIT operations were performed by special off-loading test equipment, aimed to compensate for the gravity effect on the "reflector-ADPMSS" assembly during both the integration and testing phases. This equipment is based on a counterweight concept with the reflector suspended on a steel wire at its center of gravity.

The test plan, at satellite level, included the same verifications previously performed during the antenna-level testing and aimed to verify that the "reflector-ADPMSS" assembly integration on the satellite was correctly done.

All the test results at satellite level were well within performance requirements and always consistent with the same parameters that were previously measured during the qualification test programs at both component and sub-system level. No anomalies or problems occurred.

Development Problems and Solutions

During the development/qualification program, some problems were encountered and then solved. Among them, the most significant anomalies (by engineering point of view) occurred during the APM life test and during the sine vibration testing, performed at sub-system (antenna) level. Two major anomalies were detected:

- Modest pollution of Teflon particles was generated due to wear phenomenon in the kinematic coupling between the steel gear screw and the Teflon-made internal insert of the lead screw. This fact created concern, not for the APM integrity risk, since the thread thickness was large enough to guarantee a long lifetime, but because the Teflon particles escaping from the mechanism could pollute the satellite components (e.g., mechanisms, optical sensors). The problem was solved by modifying the internal thread profile of the Teflon insert (i.e., a sort of race, placed at base of the thread, was added to act as a "reservoir" for Teflon particles). Furthermore, tighter manufacturing tolerances of the gear/lead screw assembly and improved surface finishing of the gear screw thread were also introduced;

- Friction torque of the electric motor ball bearing increased due to a lubrication fault, induced by a sum of causes. The bearing is fitted with a Duroid cage (PTFE/MoS₂/glass fiber composite). After a thorough investigation, involving the bearing supplier and the European Space Tribology Laboratory, the findings were:
 - Due to the limited motor shaft rotation (90°), each ball path did not overlap the adjacent ones;
 - The high peak friction torque was caused by an accumulation (on the raceways) of heavily compacted Duroid debris from the cage at the ends of ball motion profile. No steel wear was found;
 - The relatively high peak contact Hertzian stress (about 1.4 GPa) due to the motor internal preload (45 N) and the air humidity (life test in a thermal chamber at ambient pressure) caused the cage anomalous wearing phenomena and the Duroid cage debris compression in the raceway "dead zones."

To overcome this problem, a series of improvements have been introduced in the motor design: internal preload reduction and more accurate evaluation of its actual value after motor assembly, tighter tolerances applied to the bearing-shaft fitting, etc.

The lessons learned were that, except for the specific design optimization need, this problem mainly occurred as consequence of attempting to carry out a very accelerated life test aimed at saving testing time. This led to unrealistic worst-case mechanical cycling. Therefore, a subsequent, more realistic, life test program was performed on the APM, and the qualification was then fulfilled.

Two other anomalies occurred in the frame of the sub-system level testing. The first problem, concerning the APM, was the breakage of one internal joint between the motor and the gear screw. The subsequent investigation showed that an operator mistake, during the APM integration phase, caused pre-stress conditions in the joint. Therefore, a more accurate step-by-step integration procedure was generated. In addition, improvements on the joint design, such as material change (from Vespel to aluminum) and tighter manufacturing tolerances, were also introduced.

The second anomaly occurred during the dynamic response test. The first resonance frequency (10.13 Hz) of the reflector in the deployed configuration was too close to the first sub-harmonic of the antenna closed-loop tracking system (i.e., 9.125 Hz). This could create instability of the control loop system during antenna pointing operation, thus leading to a long steering operation time. Therefore, the RSS design was improved by adding two additional struts, so that the structural stiffness improved and the deployed reflector frequency increased up to 11.1 Hz.

Conclusions

The extensive development program and subsequent testing campaign — at component, sub-system, and system level — demonstrated the validity of the ADPMSS innovative design concept and its suitability for space application. All the problems during the qualification process were solved by suitable changes that definitively eliminated the malfunctions and improved the mechanism performance.

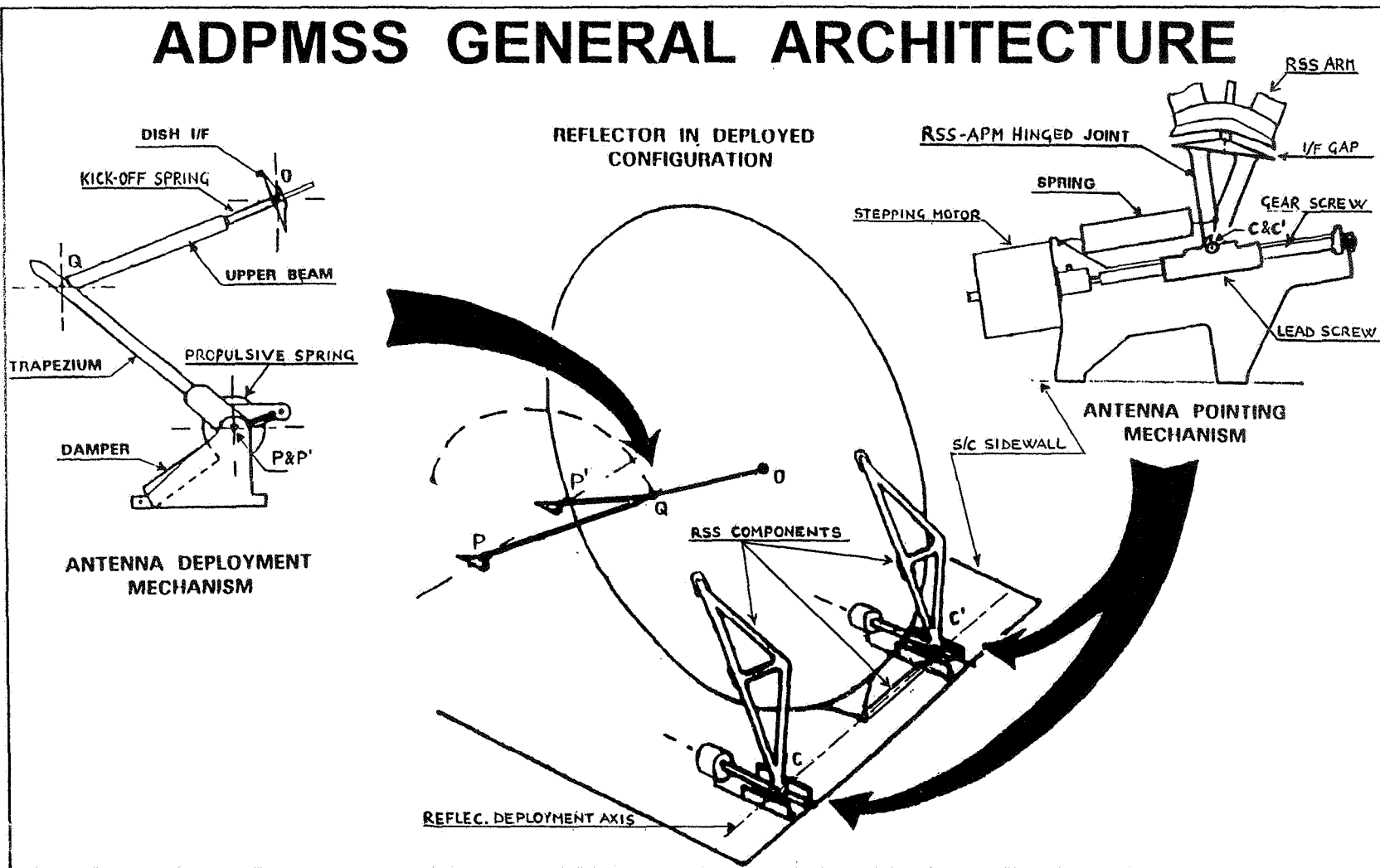
The launch of the ITALSAT 2 satellite is currently scheduled for Summer, 1996. ASI and Alenia Spazio are now waiting for the in-orbit ADPM behavior confirmation and are looking forward to possible new future applications of the presented mechanism concept for other spacecraft.

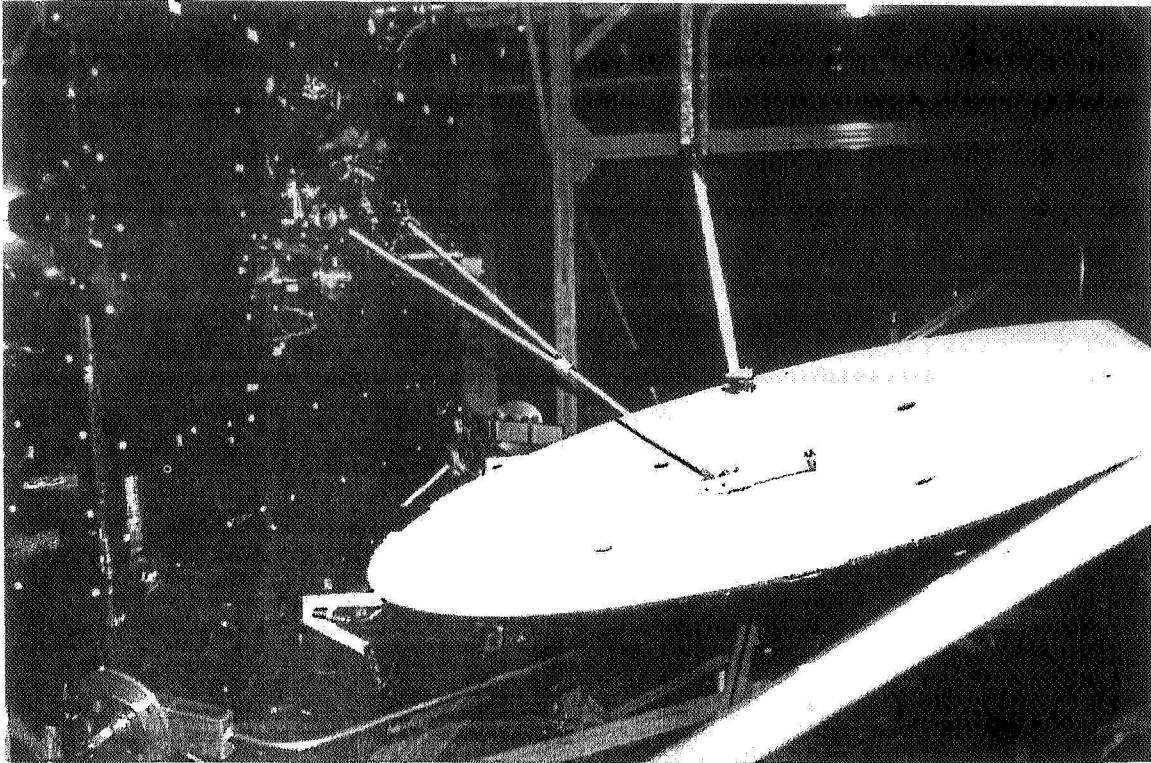
TABLE 1 ADPMSS MAIN TECHNICAL FEATURES AND PERFORMANCE

DESCRIPTION	VALUE
MASS	5.2 KG
REFLECTOR DEPL. ANGLE ADJUSTMENT CAPAB. (on ground)	$\Delta\alpha = \pm 0.3^\circ$
REFLECTOR DEPLOYMENT ANGLE ACCURACY	$\Delta\alpha = \pm 0.001^\circ$
DEPLOYMENT TORQUE MARGIN	M = 8 (minimum)
REFLECTOR POINTING ANGULAR RANGES	Az.: $\pm 2.1^\circ$, El. : $\pm 3.1^\circ$
POINTING ANGULAR RESOLUTION	Az.: $\Delta\alpha = 0.0006^\circ$ El. : $\Delta\varepsilon = 0.001^\circ$
STEADY STATE POINTING MODE ACCURACY (thermal and mechanical errors contribution)	$\Delta\alpha = 0.05^\circ$
REFLECTOR SLEW RATE	$\omega = 0.11$ deg/sec
ON ORBIT STIFFNESS	1st mode at 11.1 Hz
OPERATIONAL LIFE	10 Years
RELIABILITY	P = 0.9966

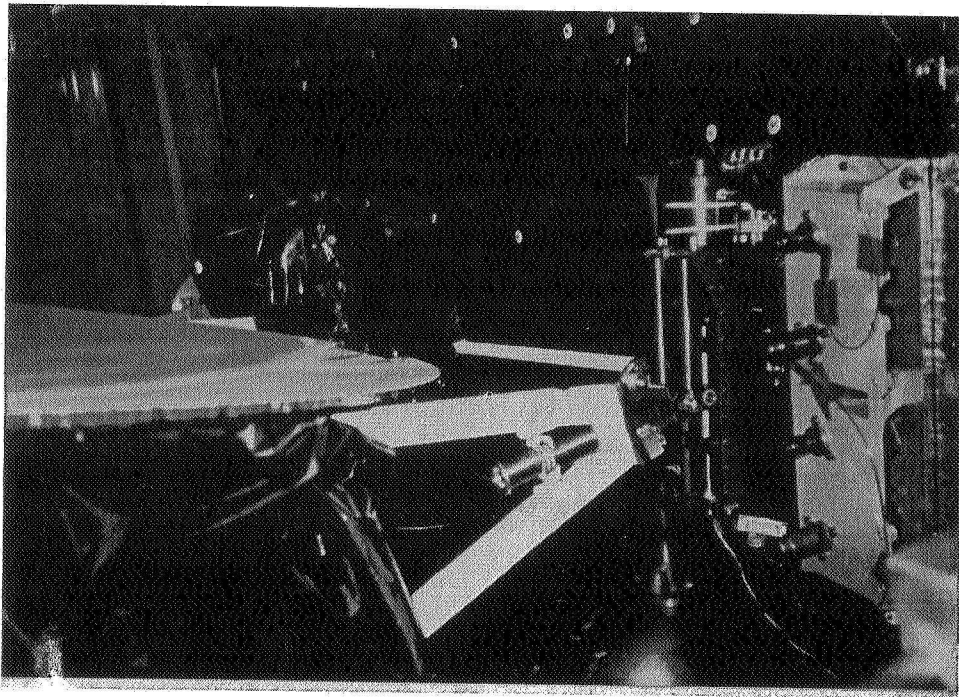
ADPMSS GENERAL ARCHITECTURE

FIGURE 1 ADPMSS GENERAL ARCHITECTURE

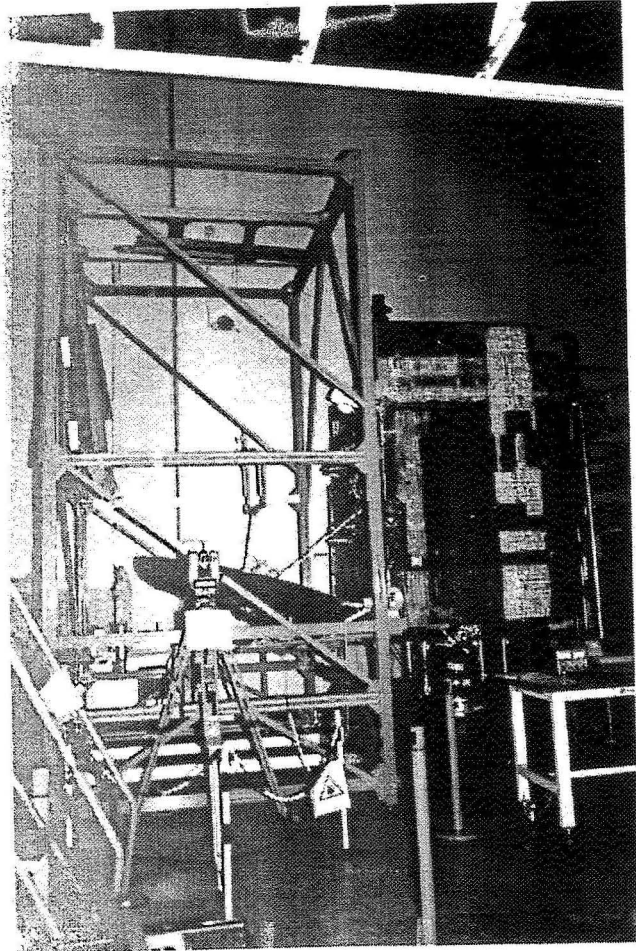




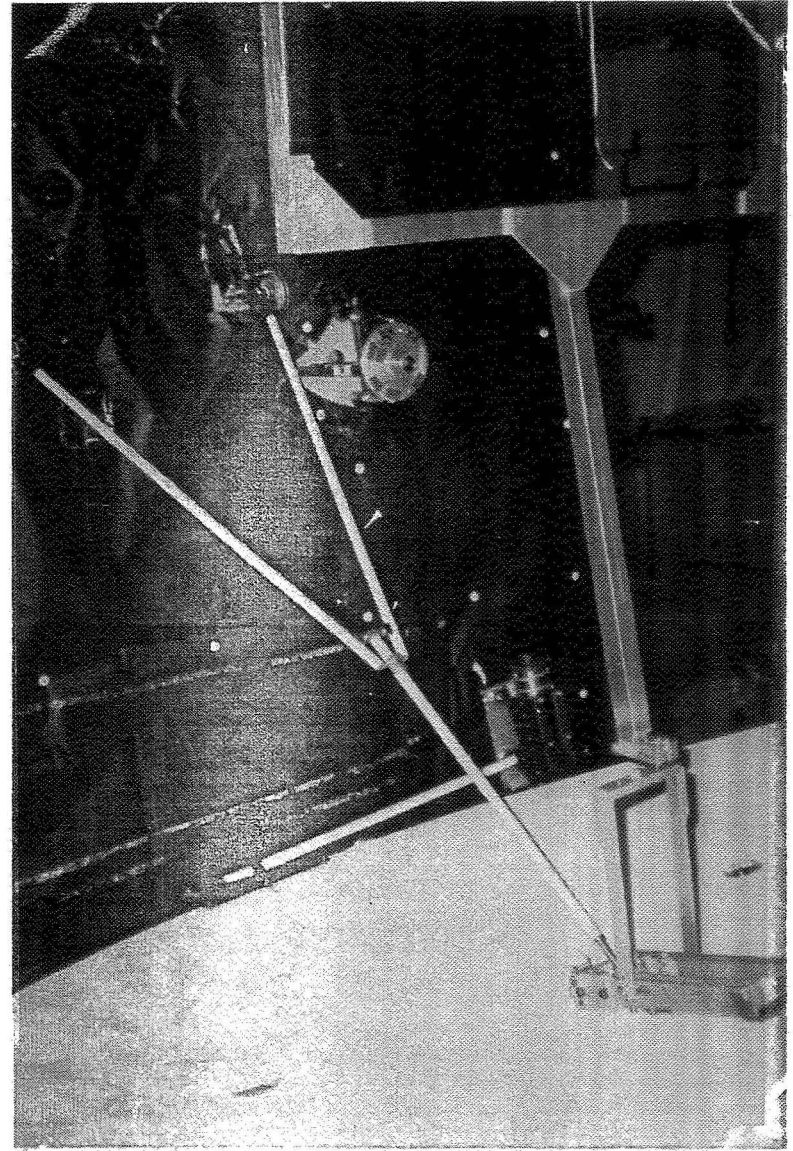
REFLECTOR AND ADPMSS ON THE ITALSAT SATELLITE



APM ACTUATOR DETAILS



SYSTEM LEVEL TESTING



ADM DETAILS