# A Two-axis fine Tracking Mechanism for Satellite Antennae

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## Abstract

This mechanism, also referred as Dual Gimbal Antenna (DGA) mechanism, is essentially a two axis rotary drive actuator mechanism which rotates an antenna about two orthogonal axes. The mechanism drives the antenna on-board a satellite to track the desired ground station in real time as the satellite is maneuvered. The need to slew the DGA during imagery collection which requires satellite jitter to be $< 3 \times 10^{-4}$ deg./sec. has led to challenging requirements for the mechanism design. The mechanism mainly consists of mechanical housing, bearing assembly, brushless DC torque motor, multi-speed Resolver, cable twist capsule assembly and non-contact type RF Rotary joint for RF transmission. A Shape Memory Alloy (SMA) based Pin-puller is also developed for locking the drive actuators during launch and release of the same in orbit. The mechanism has been designed, qualified, flown and successfully operating onboard Cartosat-2 satellite. This paper gives the overall description, design and test results of the mechanism.

**Keywords:** Gimbal, Resolver, Pin-puller, Flexi-print cable, Shape Memory Alloy

## 1 Introduction

The DGA mechanism consists of two drive modules mounted in orthogonal configuration to rotate the antenna about two perpendicular axes. The azimuth drive module (along yaw axis of Satellite) mates to the DGA support structure, while the elevation drive module provides a mounting interface for the linear patch array antenna. Both modules are connected to each other by a intermediate bracket. The elevation drive module (Module-2) drives the antenna by ± 117° while the azimuth drive module (Module-1) drives the Module-2 together with antenna by ± 150°. Both drive modules are prevented from rotation during launch by a launch restraint assembly (SMA Pin-puller) that will be released in the orbit [1].

The following technologies are developed to realize the complete system which can work flawlessly in extreme environments of space and vacuum.

- Development of rotary drive modules based on Brushless DC motor without use of any gear unit.
- Development of Shape memory alloy based Pin-puller assembly.
- Accommodation of Non-contact type Rotary joint.
- Development of Flexi-print cable based Twist capsule assembly.

Fig. (1) shows the overall configuration of DGA mechanism.

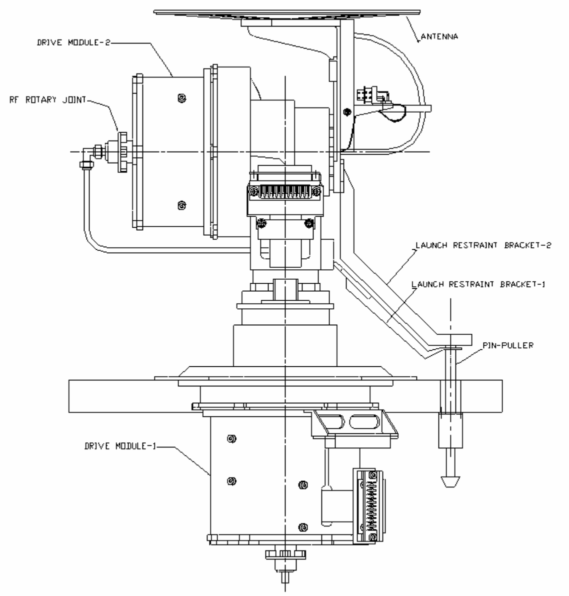


Figure 1: Overall configuration of DGA mechanism. It shows two orthogonal axes drive labeled as Drive module-1 and drive module-2 with Planar Antenna.

The location of DGA mechanism on satellite is as shown in Fig. (2).

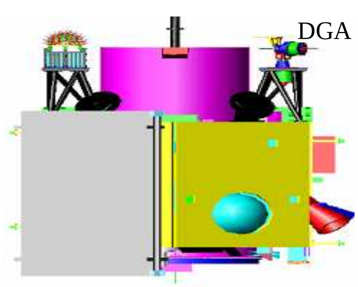


Figure 2: Location of DGA mechanism on satellite platform. DGA is mounted on top deck over a support structure.

Overall specifications of DGA mechanism are as shown in Table 1.

Table 1: Specifications of DGA mechanism

| *S.No.* | *Description* | *Design value* |
|---|---|---|
| 1. | Tracking rate | 0.1 – 20 deg/sec |
| 2. | Pointing accuracy | < ± 0.3 deg |
| 3. | Motor torque (Brushless DC torque motor) | 0.63 Nm (with main or redundant winding) |
| 4. | Resolver accuracy (Multi-speed resolver) | Coarse: ±7 Arc Min.<br>Fine: ±40 Arc Sec. |
| 5. | RF Rotary joint<br>Insertion loss:<br>Return loss: | Non-contact without bearing<br>: < 1.5 db<br>: > 15 db |
| 6. | Launch restraining device | SMA Pin-puller |
| 7. | Electrical power & signal transfer assembly | Twist capsule |
| 8. | Weight | 6.5 Kg |
| 9. | No. of operations for 5 years life | 3,20,000 |
| 10 | No. of operations qualified | 5,00,000 |

# 2 Mechanism Description

Each drive module consists of:

- Bearing assembly with oil lubrication
- One redundantly wound Brushless DC motor
- Two Resolvers (Main and redundant)
- Twist capsule assembly for electrical transfer
- Non-contact RF rotary joint

Fig. (3) shows the sectional view of Azimuth drive module..

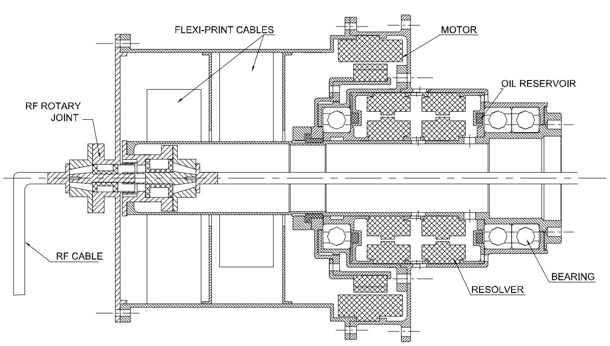


Figure 3: Sectional view of Azimuth drive module depicting its main elements supported by bearings over shaft and housing.

Electrical power and signals must be continuously transmitted through the two drive modules while they are rotating. To accomplish this, each gimbal drive module incorporates a wire twist capsule consisting of flat conductors embedded in Kapton tapes (referred as Flexi-print cables) mounted in a clock spring configuration. Nested within each twist capsule is a choke-coupled, Rotary RF joint for transmission of the wideband RF signals across the rotary interface. Other critical components for the drive module include Brushless DC torque motor with redundant windings, Multispeed resolvers (2 nos. – main and redundant) and a preloaded matched pair of Angular contact ball bearings with another floating angular contact ball bearing.

Drive module materials are chosen for thermal compatibility with the standard components like motor, resolver and bearing and consist primarily of titanium and aluminium.

## 2.1 Bearing and lubrication

Bearing assembly is one of the most critical components of the DGA mechanism. The bearing assembly is designed to meet the following functional requirements.

- to withstand the launch vibration and shock loads.
- to operate with minimum bearing torque noise during the required mission period.

The selected bearing is non-separable angular contact ball bearing. .A bearing configuration of one duplex bearing pair in Face-to-Face arrangement and another single bearing separated by a distance are used per drive module. The duplex pair is rigidly preloaded by a nut while the single bearing is preloaded through a flexible spacer. The flexible spacer will allow the bearing to float in case of temperature differential between shaft and housing. The size and the number of bearings are decided taking into account the adequate margin over launch vibration loads. A summary of bearing load capacities, external loads on bearing and factor of safety is as shown in Table 2.

Table 2: Factor of safety for bearing loads

| *Description* | *Axial load* | *Radial load* |
|---|---|---|
| External Load | 250 Kgs | 195 Kgs |
| Bearing capacity | 1340 Kgs | 1070 Kgs |
| Factor of safety | 5.4 | 5.5 |

### 2.1.1 Lubrication

Oil lubrication system is preferred over dry lubrication as it has got inherent advantages of minimum or nil debris formation and smooth torque characteristics (low bearing noise). A long life lubrication system is designed using several techniques to control lubricant loss and replenishment. A proven, stable under boundary layer condition, long life lubricant with very low vapour pressure is selected. Oil retention and replenishment to the bearing is done mainly by the phenolic resin cages. Oil lost to space is minimized by providing labyrinth seal (small annular and axial gap between shaft and housing) and in addition oil loss from the bearing is minimized by sacrificial oil reservoirs, made of Nylasint material, built inside the mechanism to maintain oil vapour pressure.

The selected lubricant is Nye synthetic oil 2001A with 1% of TCP. The balls of the bearing are coated with TiC and thin film of Maplub grease [2].

### 2.1.2 Estimation of lube loss and sealing

There are two mechanisms by which oil can be lost in space environment-

- Through evaporation
- Through migration.

Using barrier film coating on the bearing outer surfaces prevents oil loss due to migration. Providing labyrinth seal minimizes oil loss due to evaporation. The controlled leakage through the labyrinth seal is related to the molecular flow of the gases. At low pressure (vacuum pressure), the mean free path of the oil vapour molecules is large compared to the characteristics dimension (cross-sectional area) and flow of vapour is limited, not by collisions between molecules, but by collision of the molecules with the wall. The analysis of the flow is primarily a geometrical problem of determining the restrictive effect of the walls on the free flight of a molecule. Few equations are developed by modifying the classic kinetic gas theory to model the lube loss through a labyrinth seal by calculating the escape rate of oil from a bearing assembly [3]. Estimation of oil loss is calculated as shown in Table 3.

Table 3: Oil loss estimation for different labyrinth gaps

| *S. No.* | *Axial Labyrinth gap (mm)* | *Nye synthetic oil 2001A with 1% of TCP* |
|---|---|---|
| 1 | 0.2 | 12.88 mg/year |
| 2 | 0.1 | 3.6 mg/year |

An axial labyrinth gap of 0.1 to 0.15 mm is selected. A factor of safety of 4 exists on oil retained in bearing cages alone in case of 0.2 mm labyrinth gap. In addition, 600 mg of oil is vacuum impregnated in oil reservoir [4].

## 2.2 Twist capsule assembly

Each drive module of the mechanism has rotating wires, which have to be terminated to the stationary connector. For example, drive module-1 has to carry its Resolver rotor wires and all wires from drive module-2 (as the stationary wires of drive module-2 will also become the rotating wires for drive module-1). However, these wires do not need multi turn continuous rotation, only limited angle rotation is required about both the axes. Hence, cable flexing (winding/unwinding) through the required angle will be sufficient to transfer electrical signals and power from rotating point to stationary point. Twist capsule assembly does the same function as mentioned above. A schematic of the Twist capsule assembly for Azimuth drive module is as shown in Fig (4).

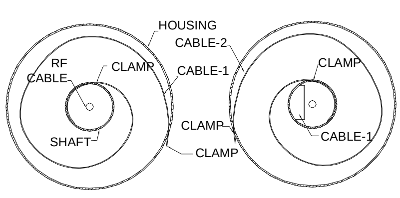


Figure 4: Schematic of Twist capsule.

This assembly consists of a cable drum inside which two flexi-print cables are wound in clock spring configuration one by the side of the other. They are wound in opposite directions- one in clockwise and other in anti-clockwise direction. This configuration helps to keep the resisting / aiding torque from cables to a minimum. The arrangement of two flexi-print cables on a simulated shaft is as shown in Fig (5).

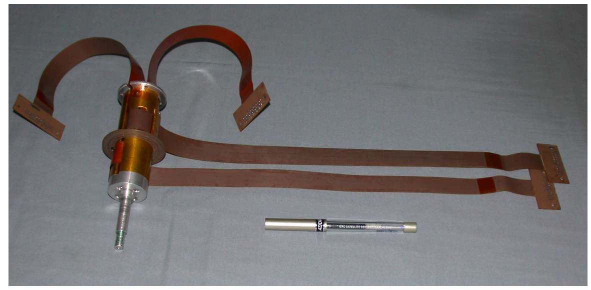

Figure 5: Flexi-print cables wound on a simulated shaft. Other end of the cable is attached to housing. Cable ends are having rigid PCB interface for connectors.

The cable terminates to a PCB connector. This cable is made from copper lines sandwiched between kapton sheets. The layout has been optimized for track width, spacing between tracks, ground lines between tracks and relative locations of tracks that carry different types of signals/ currents..

The resistive torque due to twisting of these cables is very low and almost linear. Torque variation is negligible with respect to temperature variation which becomes an important factor as the mechanism sees temperature extremes in space environment. Variation of twisting torque with respect to angle is as shown in Fig (6).

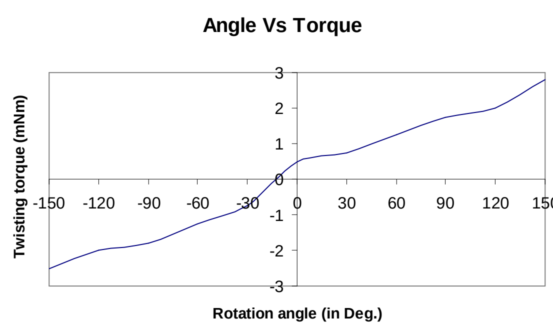


Figure 6: Twist capsule torque with respect to rotation angle. Maximum torque is about 3 mNm at ± 150º.

## 2.3 Non contact coaxial RF Rotary joint

RF rotary joint is a electro-mechanical component which allows the rotational motion while transferring the RF energy from a rotating part to a stationary part or vice versa without degrading the RF electrical performance. The axis of coaxial rotary joint coincides with the shaft axis. It allows RF transmission from spacecraft electronics to planar antenna without twisting of any RF cable through two rotary joints. It does not use any bearing unlike commercially available coax rotary joints. As there is no contact between the rotating and stationary RF components, there is no wear and tear and hence this gives long life and zero friction torque. The RF rotary joint parts are supported by the mechanism bearing assembly.

The stator and rotor of rotary joint are connected to the shaft and housing of main mechanism respectively. Stator and rotor of rotary joint mainly consists of inner and outer conductors. The inside ends of both inner conductors and outer conductors are designed such that they provide the desired precise radial and axial gaps between respective outer conductors and inner conductors of stator and rotor in the assembled mode. Both the inner and outer conductor surfaces will be coated (on choke length) with a thin layer of Teflon material in order to safeguard these delicate parts in case they come into contact due to misalignment or during launch.

# 3 Launch Restraint

During spacecraft launch, the drive modules are not held but are restrained from rotating using a launch restraint assembly. The launch loads are taken by mechanism bearings only but drive modules cannot be allowed to rotate freely during launch. As DGA mechanism is not a fully balanced system and sufficient detent torque is not available, it can rotate under the influence of vibration causing possible damage to cables and hitting stoppers with high force. A single launch restraint assembly is used to restrain both the drive modules from rotation during launch and release them in the orbit as shown in Fig (1).

## 3.1 SMA Pin-puller

To restrain the rotation of drive modules during launch, a Pin-puller has been designed. It holds the modules with its pin inside tapered holes of two brackets attached one each to drive modules in locked condition. Pin is pulled out of the hole after actuation to release them. The design is based on the Shape memory alloy (SMA) wire actuation by direct electrical heating unlocking a ball latch mechanism to allow a preloaded compression spring to pull the pin. A few important parameters of Pin-puller is listed as shown in Table 4.

Table 4: Pin-puller important parameters

| *S. No.* | *Parameters* | *Value* |
|---|---|---|
| 1 | Pull out force | 12 kgs |
| 2 | Pull stroke | 8 mm |
| 3 | Actuation current | 2 amps |
| 4 | Voltage | 2-3 V |
| 5 | Actuation time | 2 -3 sec. |
| 6 | Redundancy | Redundant SMA wires |

The schematic sectional view of Pin-puller is as shown in Fig (7).

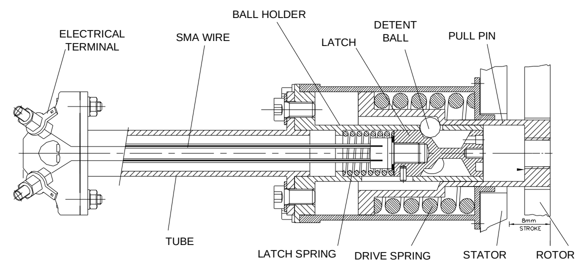


Figure 7: Pin-puller assembly shown in locked condition

In locked position of pin, drive spring is compressed and is restrained from release by balls and latch.. The latch that can slide inside the ball holder rests against a latch spring to prevent it from sliding due to vibration or any inadvertent external load. The latch is connected to two SMA wire loops (one is redundant loop). To release the ball latch, SMA wires are heated electrically by passing direct current through it. SMA wires contract upon heating. This provides sufficient force to overcome latch spring resistance and detent balls frictional resistance. As SMA wires contract and pull the latch inside the ball holder, the vertical component of drive spring force on balls pushes them inward into the exposed latch groove. The fall of balls inside the groove triggers the release of drive spring to pull the pin from its locked position. The resetting of pin is done manually. The balls are removed from the latch groove, latch is pulled back, the drive spring is compressed and then the balls are repositioned to keep the pin remained in its locked position. Fig (8) shows the locked and released positions of Pin-puller.

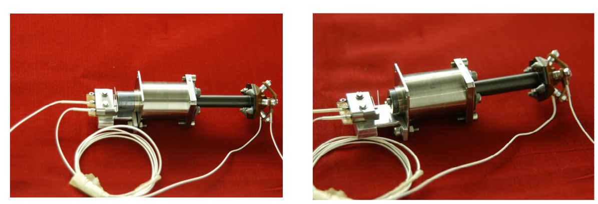

Figure 8: Performance testing of Pin-puller. Figures show the assembly in locked and in released condition.

Pin-puller is fully resetable and reusable and is having in built redundancy.

# 4 Analytical Verification

A detailed finite element modeling of the DGA mechanism has been carried out for the launch configurations. This model is used for the following purposes.

- Parametric studies and design modifications, if any, to achieve requisite stiffness of > 30 Hz.
- Estimation of natural frequency.
- Thermal distortion analysis of launch restraint brackets of DGA mechanism.
- Stress Analysis.

Finite model of mechanism along with Pin-puller is made as shown in Fig (9).

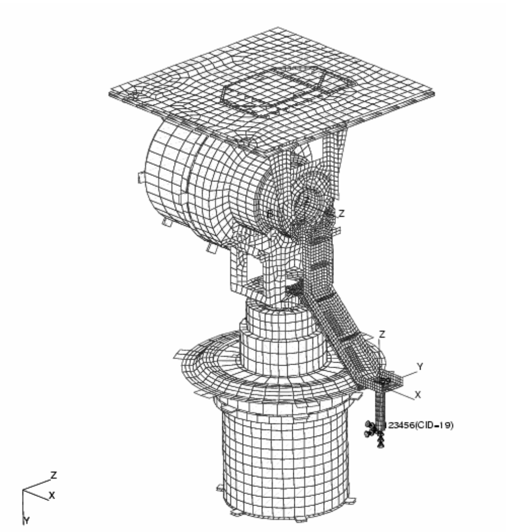

Figure 9: F E model of DGA mechanism.

The natural frequencies of the DGA system in its launch configuration have been estimated. A comparison between the measured and estimated values are as shown in Table 5.

Table 5: Comparison between estimated and measured natural frequencies of DGA mechanism

| *Mode No.* | *Mode description* | *Estimated frequency* | *Measured frequency* |
|---|---|---|---|
| 1 | Lateral mode along Y-axis | 34.8 | 38 |
| 2 | Lateral mode along X-axis | 44.5 | 48 |
| 3 | Longitudinal mode along Z-axis | 160 | 184 |

In addition, the stress analysis of launch restraint bracket has been carried out for 50g acceleration. Buckling analysis of motor casing for 50g indicated a large buckling factor and the peak stress was well below the yield stress of material indicating a sufficient design margin.

# 5 Qualification and Testing

Despite designing the mechanism with good margin and analytical verification, it is highly desirable for any space system to undergo testing in simulated space environments and launch loads. Hence one qualification model similar to flight model has undergone all the qualification tests as mentioned below.

- Performance test in ambient condition.
- Vibration test.
- Thermo-vacuum test under extreme temperatures.
- Performance test post vibration, during thermo-vacuum test and post thermo-vacuum test.
- Life test.

Mechanism underwent all the tests successfully. Fig (10) shows the mechanism undergoing vibration test.

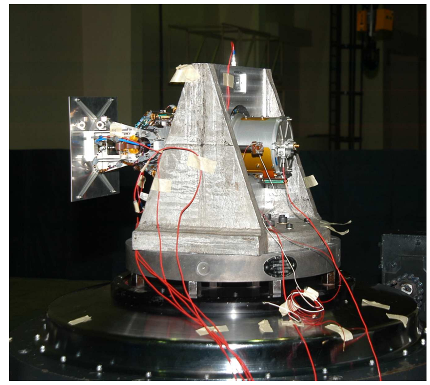

Figure 10: Mechanism mounted on vibration shaker. During vibration test, drive modules are held by Pin-puller.

## 5.1 Life test

Mechanism contains many elements whose endurance have to be verified under space equivalent conditions for the life span of satellite. Mechanism was subjected to 5,00,000 operations similar to mission profiles (1.5 times the actual no. of operations in 5 years life-time) in Thermo-vacuum conditions. Separate test plans were made and executed for Twist capsule assembly and Pin-puller assembly to qualify them as a stand alone units. RF rotary joint also was qualified along with the mechanism as its very performance depends on the mounting and alignment with the main mechanism. Life testing of mechanism inside thermo-vacuum chamber is shown in Fig (11).

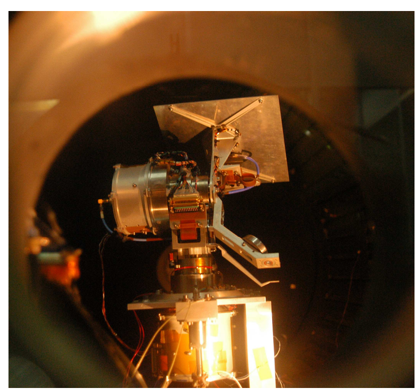

Figure 11: Mechanism undergoing life test inside thermo-vacuum chamber

# 6 On-orbit operation

DGA mechanism was flown on board Cartosat-2 satellite on 10th January, 2006, launched by PSLV rocket. Pin-puller was actuated on 3rd orbit of the satellite to release the mechanism. Since then mechanism is performing well within its specifications.. RF data sent through DGA is as expected. There is negligible disturbance on satellite platform due to rotation of drive modules. Real time imaging and play-back alone of data is being done using DGA. Fig (12) shows the Pitch rate of Satellite with DGA is operating in continuous mode.

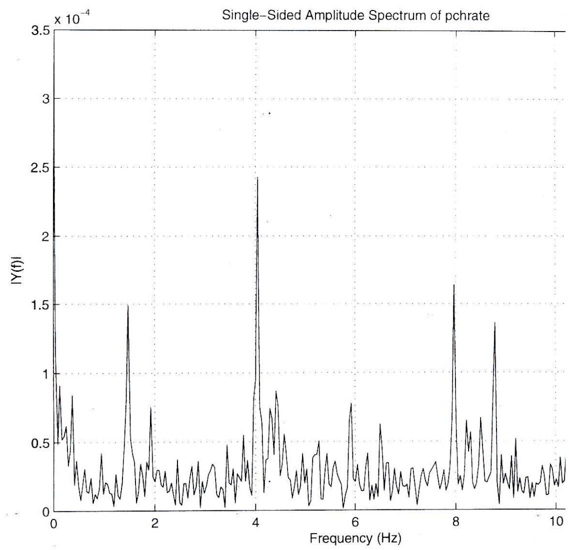


Figure 12: Pitch-rate of Satellite platform during payload operation with DGA operating in continuous mode.

## 7 Conclusions

The DGA mechanism along with SMA Pin-puller was designed, fabricated and qualified on ground to all the qualification levels of vibration and Thermo-vacuum. It was flown in Cartosat-2 satellite and is performing well within its specifications in orbit. Following points summarize the conclusion.

- A simple but reliable mechanism to track and point an Antenna towards a ground station with a large tracking range of ±150º in azimuth axis: ±117º in elevation axis and pointing accuracy better than ±0.3º is designed.
- Flexi-print cable based twist capsule assembly for electrical lines transfer is realized. It gives very low twisting torque at fairly large temperature range. No bearing and brushes are involved in this scheme, hence increasing the life and reliability of the system.
- Accommodation of RF rotary joint without any integrated bearing for RF transmission is achieved. This saves the mechanism from any additional friction torque and associated lubrication.
- Shape Memory Alloy (SMA) based Pin-puller with in built redundancy for restraining drive modules during launch or similar vibrating conditions is realized. It is resetable and reusable type.
- The usage of mechanism elements with minimum friction and torque in fact make it feasible for the system to go for a low disturbance direct drive non-geared motor and still gets high margin in terms of drive torque.

## Acknowledgment

We specially thank Control systems group, ISAC for developing the drive electronics for the mechanism and Communications group, ISAC for making the electrical design of RF rotary joint. The authors thank Dr. V. Krishnan, VSSC, Sri M. Krishna Reddy, VSSC and Sri M. Krishnaswamy, PD, Cartosat-2 for their guidance and support. The authors thank Sri M. Nageswara Rao former GD, SMG, Dr. P.S. Nair, Deputy Director, MSA and Dr. K.N. Shankara, Director, ISAC for their constant encouragement.

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