Metering Wheel-Wire Track Wire Boom Deployment Mechanism

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Abstract

The NASA MMS Spin Plane Double Probe (SDP) Deployer utilizes a helical path, rotating Metering Wheel and a spring loaded Wire “Holding” Track to pay out a “fixed end” 57 meter x 1.5 mm diameter Wire Boom stored between concentric storage cylinders. Unlike rotating spool type storage devices, the storage cylinders remain stationary, and the boom wire is uncoiled along the length of the cylinder via the rotation of the Metering Wheel. This uncoiling action avoids the need for slip-ring contacts since the ends of the wire can remain stationary. Conventional fixed electrical connectors (Micro-D type) are used to terminate to operational electronics.

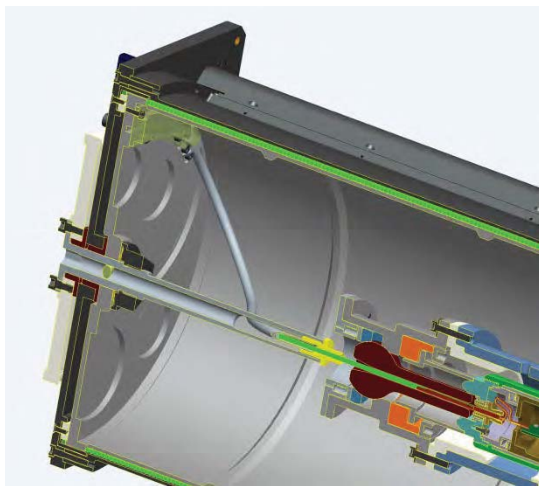

Figure 1. SDP x-section, Wire Boom (green) between stationary cylinders & exiting on axis

Introduction

The original concept for this mechanism was first put forth by the Royal Institute of Technology (KTH) Stockholm, Sweden[1]. Engineering and manufacturing limitations at KTH necessitated the support of a strong design and flight fabrication capable institute to make SDP a reality. Collaboration with the University of New Hampshire Space Science Center was initiated and a competitive proposal was won, landing this challenging project and bringing this instrument from concept level to flight deliverable hardware in less than 36 months. A total of 16 flight-qualified SDP Deployers have been integrated, tested and delivered to NASA for the upcoming MMS mission. The unique approach toward wire coil storage and deployment provided by this instrument is the impetus for writing this paper.

Metering Wheel & Wire Track Background

The Metering Wheel is keyed to the Metering Wheel Shaft which is supported in the instrument “Back Plate” via an integral Hub Bearing (journal type) made from SP-3 Vespel for low friction and good load carrying capacity. A Bellville washer and pre-load nut combine to provide a consistent pre-load of the

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Metering Wheel Shaft into the hub bearing. A polycarbonate cover, a polished stainless steel conduit tube and PEEK Exit Ferrule complete the subassembly.

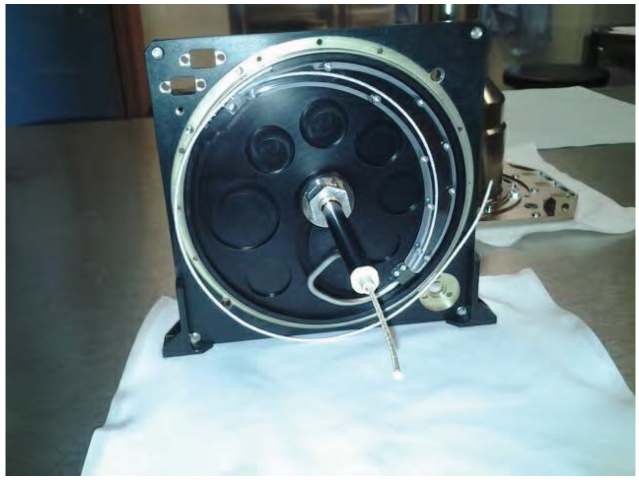

Figure 2. MMS SDP Metering Wheel Back Plate Sub-Assembly

The Metering Wheel has opposing conduit ramps which simultaneously load the wire into the wire holding track, and uncoil the wire from the track. A hard-coat anodized “Outer Race” provides the reaction surface for the wire while under spring load in the track. As the wire moves relative to the metering wheel, the coils transition from the track and are linearly displaced within a helical tube conduit along the instrument principle axis. This mechanism operates clockwise and counterclockwise dependent upon commanded “deployment” or “stowage.”

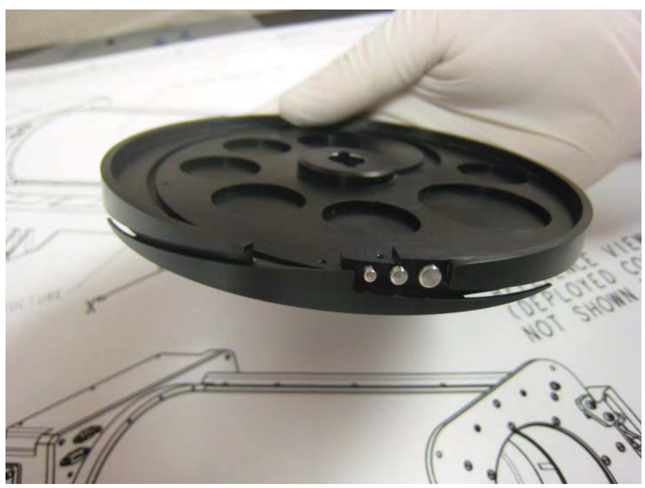

Figure 3. SDP Metering Wheel, Conduit Ramps

A key aspect of this instrument application is the ability of the Metering Wheel and Track to adequately hold the sphere and wire boom when exposed to the maximum centrifugal acceleration of the rotating MMS satellite. As calculated by the instrument P.I. P-A Lindquist[2], KTH, this applied load is 5.22 N (1.17 lb) and occurs during spin up. Although a modest value, quantifying the load carrying capability of the SDP Metering Wheel & Track became paramount to design approval going forward. Early simplified models with high friction silicone races showed promise in generating holding power; however deflections of the non-linear elastomeric silicone, and unknown friction values were not quantifiable, leading to an ambiguous assessment of Metering Wheel & Wire Track load capability.

To quantify the load in the track, a series of simple, integral radial leaf springs, were machined into the PEEK Holding Track at an un-deflected radius. When the wire is loaded into the PEEK Track, the leaf springs deflect and a resultant spring load is generated for each spring, holding the wire in compression against the hard-coated Outer Race. The springs are implemented in opposing pairs so that the track will work equivalently for both deployment and stowage rotations. Shown in Figure 4 is a developmental one-piece track/race depicting the spring deflection and subsequent compression reaction against the outer race.

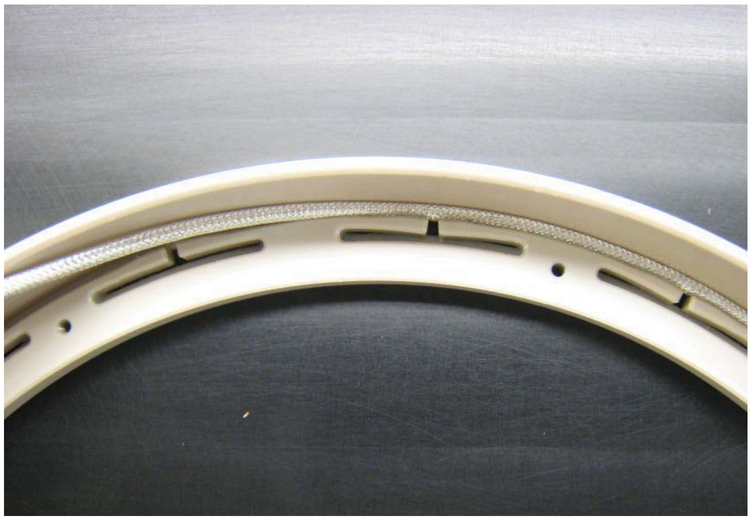

Figure 4. PEEK Holding Track - spring deflection w/Wire (non-flight hardware)

The following expression from Spott's[3] Fig. 1-13-5 is used to calculate the load generated by each spring deflection:

$\mathbf{S_{pring\ load} = (Y_{max} \times 3 \times E \times I)/L^3}$ (multiply result by number of active springs)
Where:

- $\mathbf{Y_{max}}$ = deflection of spring 0.3 mm (0.012 in)
- **E** = Young's Modulus for PEEK
- **I** = MOI for Spring Section ($bh^3/12$)
- **L** = length of spring arm

Due to the overlapping ramps of the Metering Wheel, about 259° (of 360°) of the of the Track, and hence springs, are active at any given moment. This results in 22 active springs for a total Normal load "**N**" of about 25 N (5.6 lb). Implementing the expression $F=\mu \times N$ with μ of PEEK[4] being about 0.3, the load in the track (**$F=T_T$**) is calculated as about 7.5 N (1.7 lb). If the track was a linear or straight device, that would be your holding power. However, with the circular geometry of the Metering Wheel and Track, a "band brake" analogy is drawn and allows us to calculate the additional load holding capability of the Metering Wheel and Track via the following expression:

$\mathbf{T_S = T_T \times e^{\mu\alpha}}$ (Spott's Eqn. 18, 5th Edition, Chap. 6)
Where:

- $\mathbf{T_S}$ = load holding capacity at SDP Sphere end of wire boom, N (lb)
- $\mathbf{T_T}$ = load in Track via spring normal force, friction coeff. & qty of active springs, N (lb)
- **μ** = Friction Coefficient of PEEK, 0.3
- **α** = 259° Boom wrap angle in track, = (259/360) × 2π = 4.52
- **μα** = 0.3×4.52 = 1.357

Solving yields: T_S = 28.5 N (6.4 lb)

This resultant load capacity of the SDP Metering Wheel and PEEK Wire Holding Track provides significant margin over the applied centrifugal load generated by the MMS spin rate. Load testing carried out with the SDP gear train engaged, i.e., with the Metering Wheel main gear locked through the engaged gear train all the way to the stepper motor pinion, yielded a pull test value of over 90 N (20 lb). This testing demonstrated analytical conservatism, and that there exists additional friction sources in our mechanism contributing to this robust margin for the flight assembly.

Figure 5. MMS SDP Metering Wheel Pull Test slips at 21.6 lb (96 N)

Stress

The individual springs can be treated as classic cantilever beams with bending stress calculated via:

S_b = MC/I

Where:

M = bending moment of load P at deflection x moment arm length L
C = distance to neutral axis of spring
I = MOI for Spring Section ($bh^3/12$)

Solving yields 25.5 MPA (3700 psi) stress

With PEEK 450G having a tensile stress limit[4] of 97 MPA (14065 psi) and considering the NASA standard calculation for margin of safety, MSY >0:

MSY = [mat'l limit/(1.6 x applied stress)] -1 = [97/(1.6 x 25.5)]-1 = 1.37>0

With this resultant >0, the stress margin is acceptable.

Fatigue

Figure 6 depicts the Victrex PEEK 450G fatigue curve[5]. Extrapolating for 25.5 MPA, cycles to failure for the SDP Wire Track springs should exceed $10e^7$ cycles. With each 57 meter SDP deployment, each spring sees approximately 170 actuations. With the Engineering Qualification Model demonstrating 14 complete deployments, along with 14 stowage cycles, the life test unit springs experienced more than 4700 actuations. With this significant margin of cycles to failure, and with the demonstrated life testing margin at 3.5 X flight model total actuations, fatigue of the PEEK Wire track springs is not considered significant.

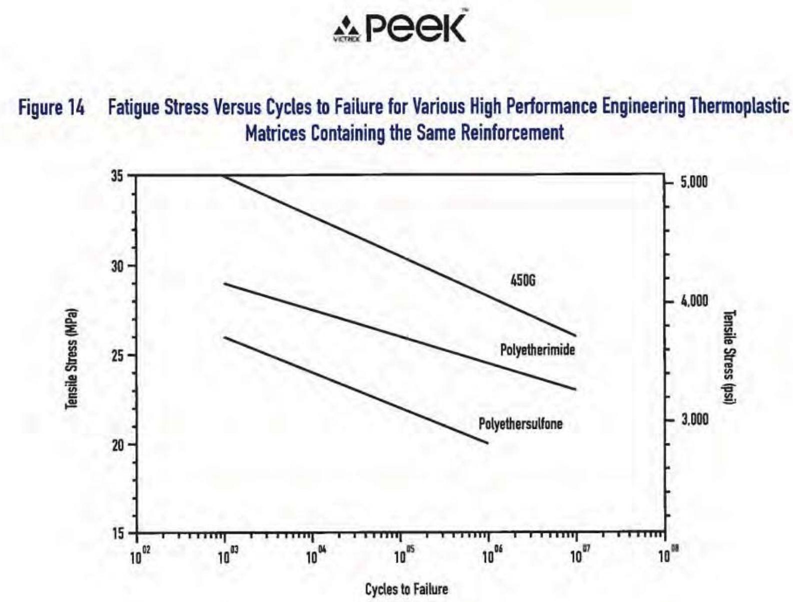

Figure 6. Victrex PEEK Fatigue Curve, 450G

<u>Thermal Considerations</u>

During developmental thermal testing at UNH[6] it was determined that there was too large a mismatch in Coefficient of Thermal Expansion (CTE) between the Habia Boom Wire ($27.9e^{-6}/^{\circ}C$) and the original PEEK ($42.4e^{-6}/°C$) outer race feature leading to deployment of "small coils" during cold plateaus. The resultant was a binding of the coils along the inner storage cylinder. Subsequent testing determined that the CTE of the Habia wire was very close to that of Aluminum ($23.4e^{-6}/°C$) and the outer race feature was implemented into a separate part, a hard coat anodized Aluminum Outer Race. With CTE's for the Habia wire, Outer Race and Inner Cylinder now all matched, successful thermal deployments were achieved.

Integration of the PEEK Track and Aluminum Outer Race into the SDP Back Plate is shown in Figure 7. The 16 pairs of opposing springs are relieved toward the Back Plate to allow unimpeded (non-rubbing) deflection. The track is held in place via 16 miniature M1.6 metric screws that thread directly into tapped holes in the track. Note the Vespel Hub Bearing shown installed at the Back Plate center.

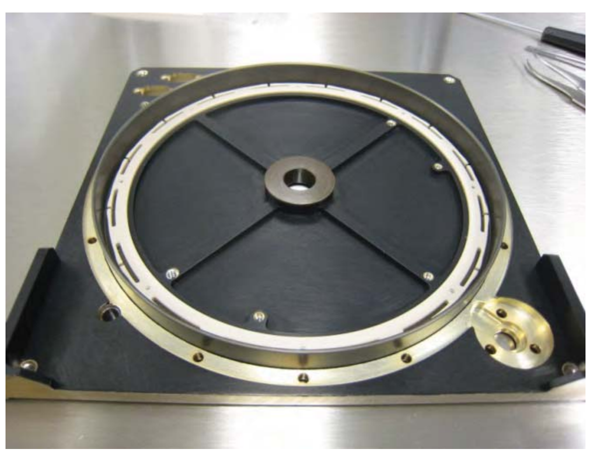

Figure 7. PEEK Wire Holding Track & Outer Race installed in SDP Back Plate (flight hardware)

Boom Wire

The Wire used for the SDP Boom is manufactured by Habia Cable in Soderfors, Sweden[7]. Habia provided a custom 7 conductor, Kevlar/Kapton overwrap layup with a silver-plated copper GND shield. UNH worked closely with Habia to tailor the mechanical characteristics of the layup to ensure optimal consistency in cross sectional diameter as well as overwrap stiffness. The nominal diameter of the composite wire was specified to be held within 1.50 mm ± 0.05 mm, critical for consistent spring deflection in the PEEK Track/Outer Race geometry. Inspection data from Habia via laser measurement of each spool of wire for SDP demonstrated even tighter control of this important aspect of the wire. A sample plot of this diametral inspection is shown in Figure 8[8]. This modest actual variation in diameter, +0.02 mm / -0.01 mm was typical for SDP flight spools.

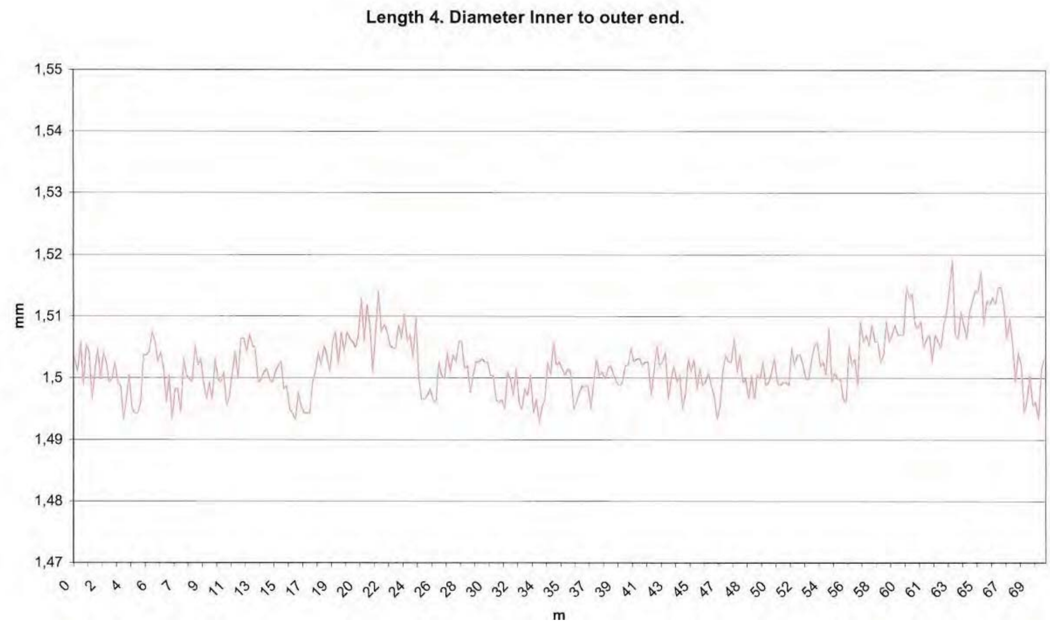

Figure 8. Habia Boom Wire inspection data, diameter variation over 70 meter spool

Material Specifications

The materials used in manufacturing the SDP Metering Wheel and Wire Track sub-assembly were optimized during the comprehensive, and flight fidelity engineering model development at UNH. Surface treatments were optimized for friction and wear; all materials meet the stringent NASA Reference Publication 1124 for outgassing of materials intended for spacecraft use[9]. The materials list follows:

- Metering Wheel - 7075-T7351 Aluminum w/General Magnaplate Tufram low friction plating
- Wire Track- PEEK Victrex 450G
- Hub & Thrust Bearings - Dupont Vespel SP-3
- Outer Race - 6061-T6 Aluminum w/clear hard-coat anodize
- Conduit Tube - 300 SS tube, custom formed and internally polished
- Belleville Spring - BeCu heat treated
- Cover - Lexan Polycarbonate
- Ferrule - PEEK Victrex 450G
- Nut & Key Pin - 6AL-4V Titanium
- Back Plate - 7075-T7351 Aluminum w/black hard-coat anodize
- Shaft - 7075-T7351 Aluminum w/black hard-coat anodize

Testing
Comprehensive full deployment testing and powered stowage of each 57-meter SDP Boom is conducted at several junctures during flight integration and testing resulting in a minimum of 4 complete deployments and stowage operations. Developmental testing for life assessment was conducted on the flight-like Engineering Qualification Model which demonstrated 14 complete deployments and powered stowages, ensuring adequate margin over flight for the Metering Wheel-Wire Track deployment mechanism.

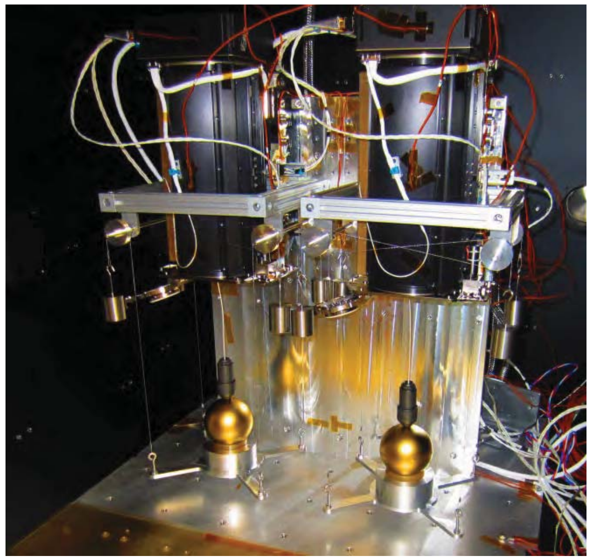

Figure 9. MMS Flight Model SDP deployment testing, UNH vacuum chamber

Conclusions

The successful integration, test and delivery of the 16 MMS SDP instruments validated this unique approach to Wire Boom Deployer design. The integral Wire Track springs allowed quantification of the load in the track, and the Metering Wheel un-coiling rotation allowed the use of stationary storage cylinders and fixed electrical terminations.

Figure 10. Flight Model MMS SDP instruments, fixed Wire Boom Termination at left

References

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