Parachute Swivel Mechanism for Planetary Entry

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ABSTRACT

A parachute swivel mechanism (PSM) for planetary entry missions such as a Mars probe (MARSNET) or return of cometary material samples (ROSETTA mission) has been developed. The purpose of the PSM is to decouple the spin of the probe from the parachute, with low friction torque, during both the deployment and descent phases.

Critical requirements are high shock loads, low friction, low temperatures, and several years of storage in the deep space environment (during the cruise phase of the probe, prior to operation).

The design uses a main thrust ball bearing to cope with the load requirement and a smaller thrust ball bearing for guiding of the shaft. Except for use on the Viking and Galileo swivels, it appears that this type of bearing has very rarely been employed in space mechanisms, so that little is known of its friction behavior with dry lubrication. A slip ring assembly allows the transfer of electrical power for post-reefing of the parachute.

A test program has been conducted covering the environmental conditions of Mars entry and earth re-entry.

This paper describes requirement constraints, model missions of planetary entries, a bearing trade-off, analyses performed, design details, the lubrication system, and test results (friction torque versus load / spin rate). In addition the design of the test rig is addressed.

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1. INTRODUCTION

The PSM for decoupling the parachute rotation from spinning probes during descent is a critical device which must operate after long storage time under severe environmental conditions. Very low friction torque is required and knowledge of its characteristics is essential for managing the spin of the probe by means of vanes for stabilization and scanning onboard instruments. The operational conditions and requirements have been identified and analyzed. A PSM has been designed, manufactured and tested. The basic PSM design will be used on swivels of the HUYGENS probe parachutes for Titan entry.

1.1 Model Missions

According to Reference [1], probes for parachute-borne descent in the atmospheres of Earth and Mars, with mass in the range between 45 kg and 300 kg, are considered typical applications for the PSM. The corresponding descent profiles are defined in Table 1.

The baseline data, i.e., total probe mass, altitude at start of parachute deployment, etc. were taken from available references, see e.g. [2], [3]. The number of parachutes (drogue, pilot, main) were defined using a trajectory calculation for vertical descent so as to meet the requirements as far as velocities and altitudes were concerned.

2. DESIGN APPROACH AND ANALYSES

2.1 Trade-offs

A review of existing technology revealed that swivels with the required load capacity predominately utilize a pair of axial ball bearings.

The baseline concept was selected as a result of trade-off studies. First, a bearing trade-off study was focused on the selection of promising bearing types (see Fig. 1). These types were then entered into a trade-off to find suitable bearing arrangements optimized for high and low loads. A third trade-off study was made to select the baseline for the test model and considered load bypass, preload and lubrication techniques

Baseline Design Selection Criteria The design was directed toward the following functional tasks of the PSM, to be accomplished with a minimum-mass requirement:

- decoupling of the probe and parachute with lowest possible friction torque
- reliable functioning after long-term storage on the ground and in deep-space vacuum
- assurance of mechanical and electrical connection (bonding)
- provision for load transfer
- withstanding deployment shock
- provision for power transfer

The crucial elements of the swivel are its bearings; for this reason a detailed bearing trade-off study was performed. The main tasks for the bearings are:

- high shock load capability
- resistance to extreme environmental conditions
- lowest friction torque
- no contamination risk due to the lubrication

The evaluation of all bearing candidates revealed that the most advantageous design in terms of mass, size, lowest friction level and load capability utilizes a thrust ball bearing.

A design with load by-pass was also taken into account. The load by-pass design is shown in Fig. 2a. The needle bearing of high load capacity is normally offloaded (by an axial clearance of ≈ 0.15 mm). Under parachute-inflation shock loading, the Belleville spring allows an axial motion of the shaft to load the needle bearing and to off-load the main axial ball bearing. This approach is of special interest for a parachute system having a very high opening shock (i.e. greater than 25 kN), in relation to the post-opening drag force level.

Preload Technique To ensure smooth running of the bearings, which means no sliding between balls and race, and to ensure a correct geometrical point of contact, a specified axial preload must be applied.

This force may be applied in two ways:

- **Rigid preloading**: created by an exact dimensioning of the housing and shaft and a predetermined elastic deformation
- **Compliant preloading:** induced by spring force (Belleville springs) on the bearings

The rigid preload is very sensitive to thermal changes (gradients) whereas the compliant (spring force) preload can be designed to cover a large temperature range, so that only small changes in preload and friction torque occur. Another advantage of the compliant preload is that the bearings can better tolerate debris in the race ways without high risk of blocking or seizing, via the inherent high degree of flexibility. Therefore compliant preloading was selected.

Lubrication System Since the swivel is required to tolerate cryogenic temperatures and to fulfil stringent cleanliness requirements, only dry lubrication was feasible. Candidate lubrication systems considered in a trade off study were:

• Races:	Sputtered or ion plated lead films CVD [4] or sputtered MoS_2 [5] Coating Tungsten Stabilized Carbon Coating [6]
• Balls:	Sputtered lead films CVD or sputtered MoS_2 Coatings TiC coating only or TiC + MoS_2 coating
• Retainers:	PTFE/MoS2/Glass fibre composite [7](Duroid, Rulon A, Klueberplast LD) Steel with CVD or sputtered MOS_2 coatings or tungsten Stabilized carbon coating or leaded bronze

The trade-off resulted in an initial selection of lubrication systems for thrust ball bearings as follows:

• Races:	MoS_2 thin film coating (PVD)
• Balls:	TiC Coating (CVD), and MOS_2 thin film coating (PVD)
• Retainers:	MoS_2- thin-film-coated steel

The rationale for selection was:

- MoS_2: Provides lowest friction coefficients
- TiC: Assures very low wear, provides best cold welding protection

After the first tests of this system, in an attempt to minimize the friction torque the following changes were successfully introduced:

- On the main bearing, TiC balls were used without MoS_2 thin film coating
- The standard retainers made from steel were replaced by special retainers (washer type, raceway guided) made from Rulon A
- Bearing radial runout was measured and taken into account at assembly for compensation.

2.2 Analyses

Load Analyses A two degree-of-freedom analytical model of the Probe-PSM-Parachute System (PPPS) was developed for calculation of the loads on the PSM due to parachute inflation. The Mass-Time Method, as described in [4], was applied. A typical force-time history of these calculations is shown in Fig. 3. As a result, the maximum loading on the PSM can be limited to 7000 N by proper design of the drogue, pilot and main parachutes.

A more sophisticated model of the PPPS, characterized by four degrees of freedom, was developed for determining the loads acting on the PSM when the probe with fully inflated parachute is subjected to vertical or horizontal gusts or wind shear. The dynamic model utilized for this analysis is depicted in Fig. 4. Wind shear can readily be converted into an equivalent horizontal gust. Even a sudden gust, which represents a conservative assumption, leads to negligible radial loads on the PSM and causes axial loads of the same order of magnitude as parachute inflation (see Fig. 5).

Thermal Analysis The thermal analysis considered heat transfer by conduction, radiation, and on the outside surface, forced convection. The assumed inital temperature was -20°C for the function-critical, cold case. The results were low temperature extremes of -44 °C for Earth reentry and -37°C for Mars entry missions. A maximum gradient analysis revealed 12°C between housing and shaft for Earth reentry. The maximum temperature difference for the Mars mission was predicted to be 5°C.

Structural Analysis Analytical and numerical methods were used for stress and strength analysis. The chosen design load capacity of the PSM of 16000 N was found to be suitable to withstand the loads, as derived from the mission requirements, with sufficient margin.

Thermal Effects The PSM design is insensitive to expansion. Its compliant preloading by two Belleville springs compensates the expansion. The temperature-induced preload change is in the range of 20 N, which has minor impact on the friction level. The nominal preload was initially set to 160 N but was reduced to 100 N after the first tests in an attempt to minimize the friction torque.

3. DESIGN DESCRIPTION

The baseline design (see Fig. 2b) employs axial ball bearings for the main and guiding bearing (FAG types 51203/51100). This combination was found to be optimum with respect to the restricting demands of very low torque and mass, under the applicable load conditions. The maximum static load capacity of the PSM main bearing is 27 kN.

The housing is made of aluminum 7075. The housing and shaft include lugs for the interface to the parachute and to the probe. Low friction between the parachute clevis and PSM is attained by use of a bonded MoS_2 film in order to minimize radial loads on the swivel bearings. The same treatment was applied on the lug of the shaft. The shaft is made from titanium which matches the thermal expansion coefficient of the bearing races.

Power transfer through the swivel for the post-reefing system of the parachute (pyro cutter or release device) is accomplished with a MECANEX slip ring assembly. The slip ring has 5 lines of 2 amps capacity. One of the slip rings serves as electrical bonding between shaft and housing. The 4 remaining lines allow power transfer to a redundant post-reefing actuator, if required. The slip rings are of an alloy composed of gold, silver and copper, while the brushes are made from an alloy composed of gold, silver and palladium. Each brush contact is redundant. The brushes are embedded in a block of epoxy resin.

The PSM size and mass is:
Outer diameter: 46 mm
Length: 120 mm
Mass: 38 grams

The applied tribological system is as follows: The balls, made from AISI 440C stainless steel, are coated with titanium carbide (TiC). The nominal thickness of the coating is 3-4 µm, with a fine grained microstructure (0.1 µm typically) and high hardness (3500 HV). High accuracy balls (Grade 3) and a very smooth surface finish (0.006 µm Ra) are obtained. The race washers of 1.3505 steel are coated with 3-5 µm of thin dense chromium for corrosion protection and are lubricated with 0.4 µm MOS_2 (PVD process). The bearing cage is machined from Rulon A. The cage has been designed to achieve low friction by low surface roughness and to ensure a positive clearance for the balls under temperature extremes.

The total friction torque comprises the contributions of friction in the main bearing, the guiding bearing and slip rings. The main bearing is loaded with the descent load and the preload, whereas the guiding bearing is loaded with the low preload of 100 N only.

Torque predictions were performed by ESTL using a sliding friction coefficient for MoS_2 and steel in vacuum of 0.07 (worst case). A comparison of prediction and test results is shown in Fig. 7.

4. TESTING

4.1 Test Program

The test sequence comprised electrical tests of slip rings, followed by a torque characterization test at room temperature with loads from 100 N to 8800 N at rates between 1.5 and 60 rpm. A shock load test at no rotation consisted of 10 load cycles up to 8800 N (7000 N parachute-inflation load times an uncertainty factor of 1.25). A life test in a simulated Mars environment (CO_2) required 4 hrs operation at 500 N load at - 55^{o}C and at a pressure of 1 mbar.

An Earth environment life test in humid air of 70% RH required 10 minutes of operation at 3000 N at 15 rpm. A static load test of 20 kN completed the test program.

4.2 Test Results

The test results of the torque characterization test are shown in Table 2. A typical torque test record in the simulated Mars environment is shown in Fig. 6. Plots of the test results are depicted in Figures 7 and 8. The mean torque is determined by the difference of torque at rate reversals. The PSM survived the test program without detrimental degradation in performance.

The influence of rate on the torque which was experienced had not been predicted. The measured torque was lower than the predicted torque at high loads and vice versa at low loads. For low load cases one has to consider that the predictions by ESTL did not cover the friction of the cages. The slip ring friction (not directly measured) is considerably below the predicted value of 0.4 Ncm.

Operating Life Test

Earth Environment: The mean friction torque at room temperature, 70% RH, was 12 Ncm under a 3kN Load at 15 rpm. The torque was found to be higher by a factor of 3 than the values at vacuum or dry GN2. The predicted factor was a minimum of 3. The post life test at 100 N load showed an increase about 0.2 Ncm in torque (slight degradation) compared to the test value at 100 N load at the beginning.

Mars Environment: The mean friction torque at -55 °C , 1 mbar CO_2, was about the same as measured at room temperature at 1 bar GN_2. The mean and ripple torque both showed considerable variation. No residual degradation occurred. These variations may be caused by traces of humidity in the test atmosphere. It is possible that the vapor entered the test chamber via the O-ring seal of the mechanical drive feedthrough of the test rig.

4.3 Test Rig A special Test Rig (see Fig.9) was designed and manufactured to allow simulation of PSM operation under the loads and environmental conditions to be expected during parachute-borne descent through a planetary atmosphere.

The PSM to be tested is suspended by means of brackets inside of the sealed test chamber. Arbitrarily composed atmospheres from very low pressure to ambient pressure can be established in this test chamber. A "cold wall" envelopes the PSM to perform radiative heat transfer. This wall consists of a sheet metal surface with an attached tube coil for circulation of a cooling or heating fluid, such as liquid or gaseous nitrogen A test at a temperature of -55°C was successful. Temperatures to -180°C are considered to be feasible.

The brackets are attached to fiber glass rods used to minimize conductive heat transport to the PSM from the exterior of the chamber. Axial load and torque are transferred to the PSM through these brackets and the fiber glass rods. The axial load can be applied either statically or as a transient starting from a specific value and increasing to a preset force.

The Test Rig can be used for performing tests in atmospheres of arbitrary composition and for pressures between 100 Pa and 100 kPa as follows:

(i) Measurement of PSM friction torque in the range from 1 Nmm to 3 Nm for specified static axial loads up to 16 kN at rotational speeds from 1 to 20 rpm and different temperatures,

(ii) Application additionally of transient load to the (rotating) PSM and measurement of the same friction torques as in (i).

5. CONCLUSION AND SUMMARY

A low-torque parachute swivel mechanism for planetary entry missions has been developed. Analysis of the loads acting on the probe-parachute system during parachute inflation and parachute-borne descent showed that radial loads are negligible. A test model was built and subjected to torque measurement. Descents in the low-temperature Mars atmosphere and the Earth atmosphere were simulated. The tests were successful. The mean friction torque at -55°C , 1 mbar CO_2, was about the same as measured at room temperature at 1 bar GN_2. The friction torque of thrust ball bearings exhibited an unexpected increase in friction at rates above 1.5 rpm on both unlubricated and lubricated bearings. The thin, dense chromium plating survived all tests.

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celestial body	m [kg]	para-chutes	v_0 [m/s]	ρ_θ [kg/m^3]	h_0 [m]	v_e [m/s]
Earth	300	drogue	457.0	0.0184	30000	61.4
		pilot	61.4	0.4663	9000	30.6
		main	30.6	0.9091	3000	6.0
	250 1)	no	457.0	0.0184	30000	105.0
		pilot	105.0	0.4663	9000	27.9
		main	27.9	0.9091	3000	6.0
	45		457.0	0.0184	30000	26.3
		main	26.2	0.9091	3000	6.0
Mars	300	pilot	336.0	0.004	18000	86.7
		main	86.7	0.0106	6400	25.0
	84 2)	main	270.0	0.0074	11000	25.0
	66 3)	main	270.0	0.0074	11000	80.0

1) ROSETTA (Land)

2) MARSNET Semi Hard Lander

3) MARSNET Hard Lander

m	total mass, i.e., mass of probe, PSM and parachute
v_0	velocity of probe at start of parachute inflation
_0	atmospheric density at start of parachute inflation
h_0	altitude of probe at start of parachute inflation
v_e	velocity of probe at touch-down or at start of inflation of next parachute

Table 1 Probe Masses and Descent Profiles Representing Typical Applications for the PSM.

LOAD [N]	RATE [RPM]	MEAN TORQUE [NCM]	RIPPLE TORQUE [NCM] 0-peak
100	1.5	0.4	0.2
300	1.5	0.6	0.3
300	60	1.2	0.2
500	1.5	0.4	0.4
500	15	1.5	0.3
500	60	1.5	0.25
1000	1.5	0.6	0.35
1000	15	2.2	0.45
1000	60	2.1	0.6
3000	1.5	2.8	1
3000	15	4.3	0.5
3000	60	4.2	0.9
8800	1.5	11.5	2
100	1.5	0.2	0.2

Table 2 Summary of Torque Characterization Test Results

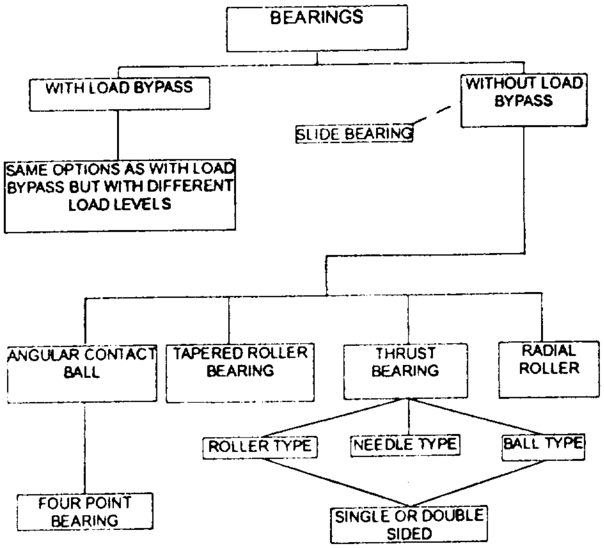
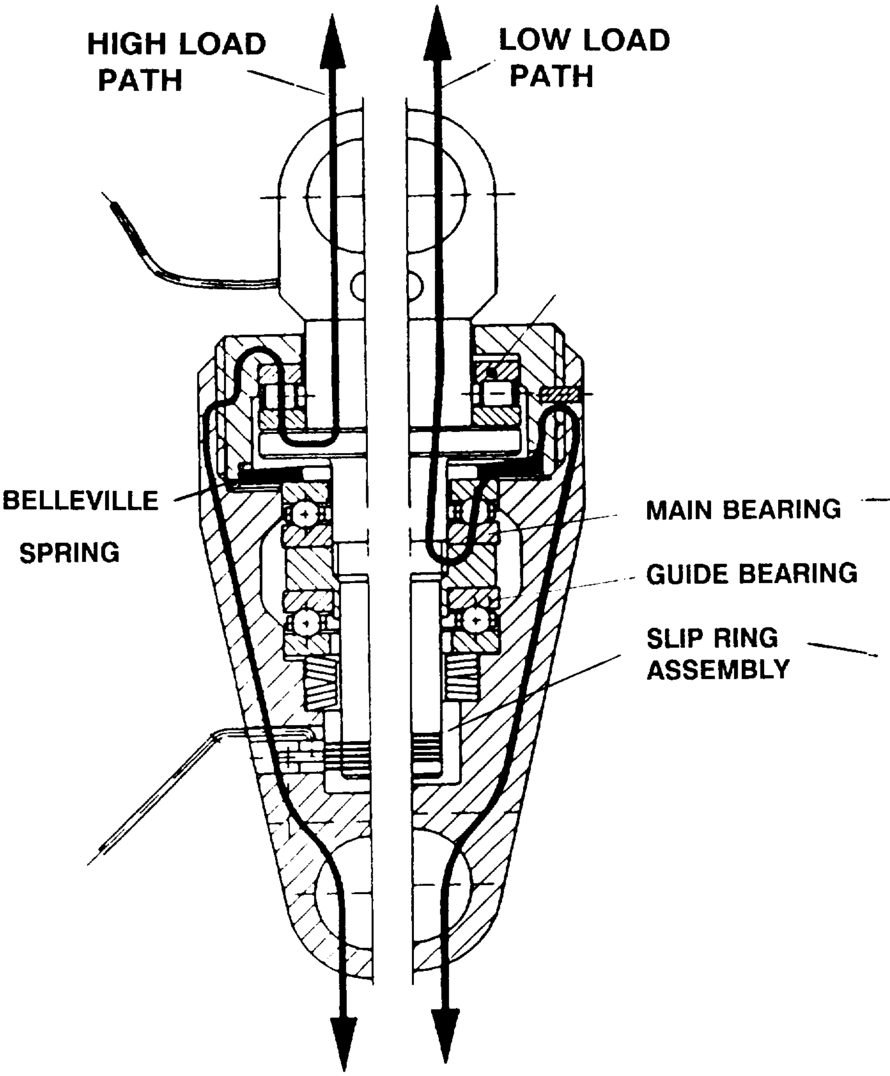


Figure 1 Bearing Trade Off Tree



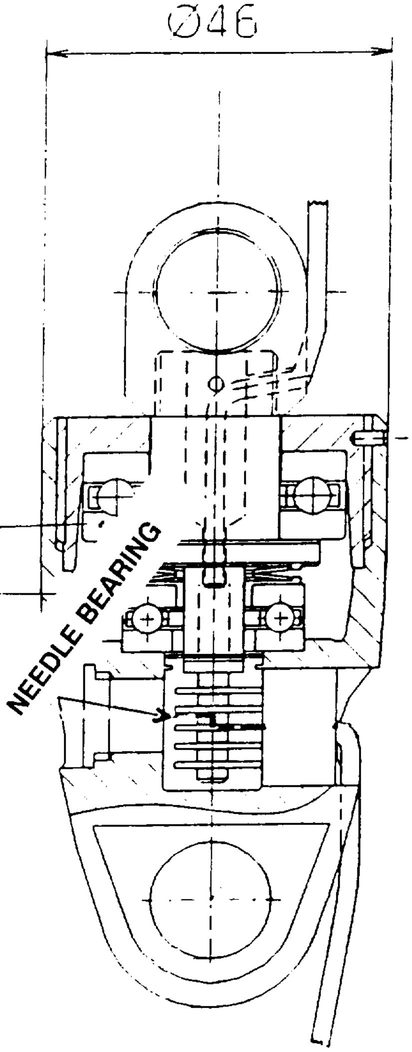


Figure 2b   PSM Baseline Design

Figure 2a   High Load PSM Design with Load By-Pass

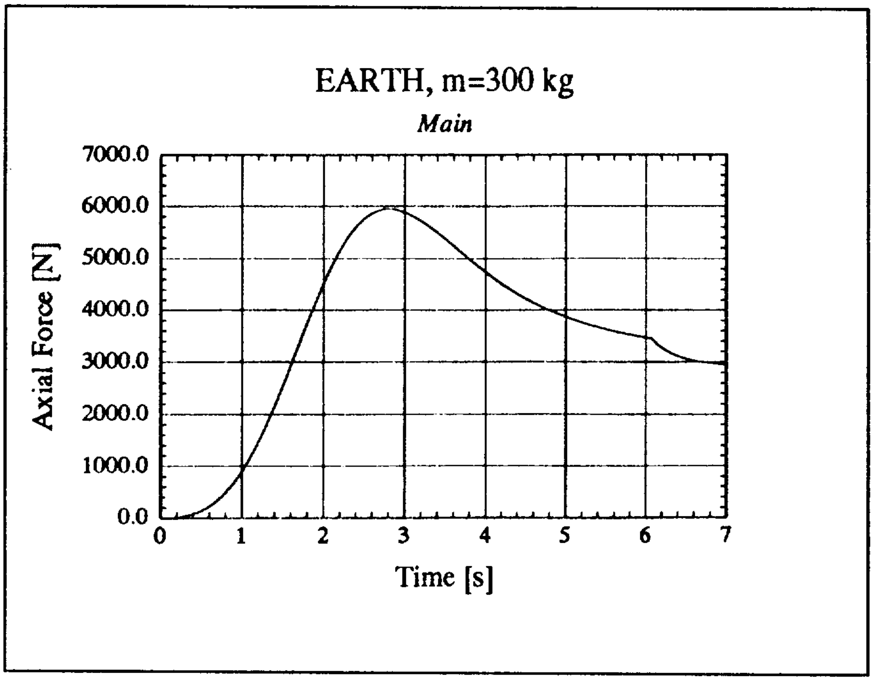


Figure 3 Force vs. time during inflation of the main parachute for earth descent, probe mass m = 300 kg, see Table 1 for reference.

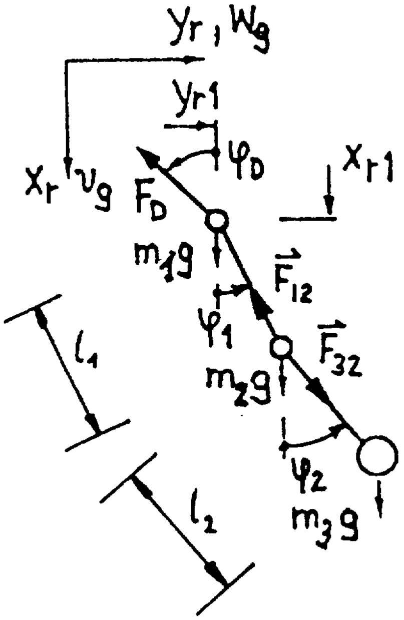
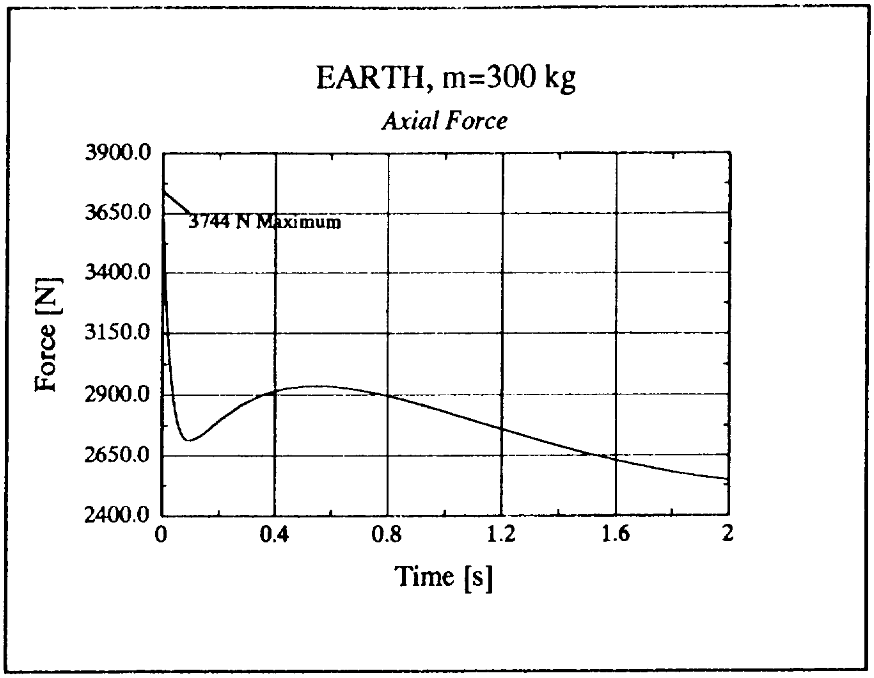


Figure 4 Dynamical model of the Probe-PSM-Parachute System represented by three point masses (four degree of freedom model).



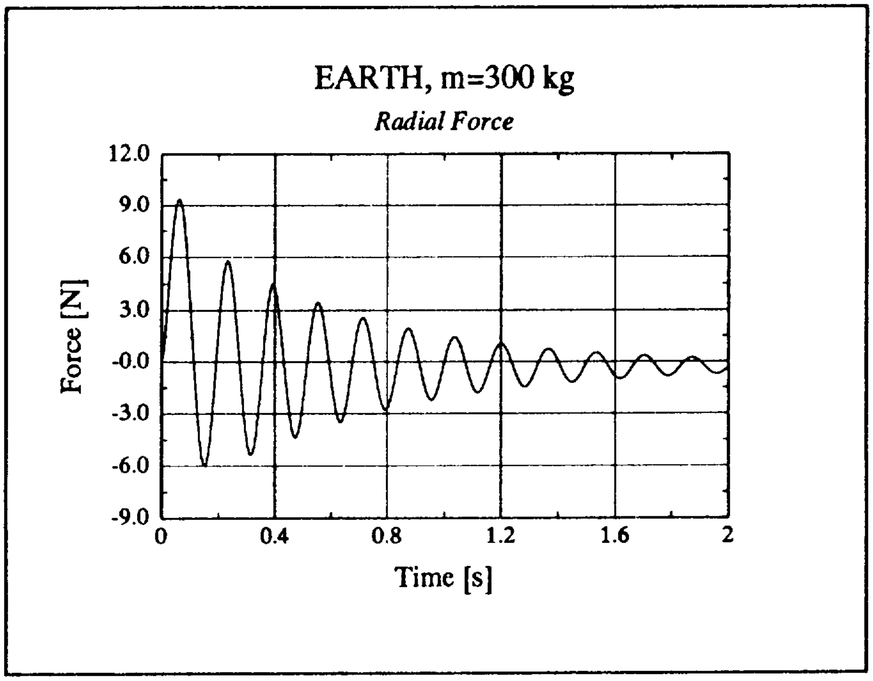


Figure 5a Response of the Probe-PSM-Parachute System (PPPS) represented by three point masses (four degree of freedom model) to a sudden horizontal gust. The PPPS is initially in steady state vertical descent with 6m/s (parachute fully inflated). See Figure 5b for further data of Probe-PSM-Parachute System.

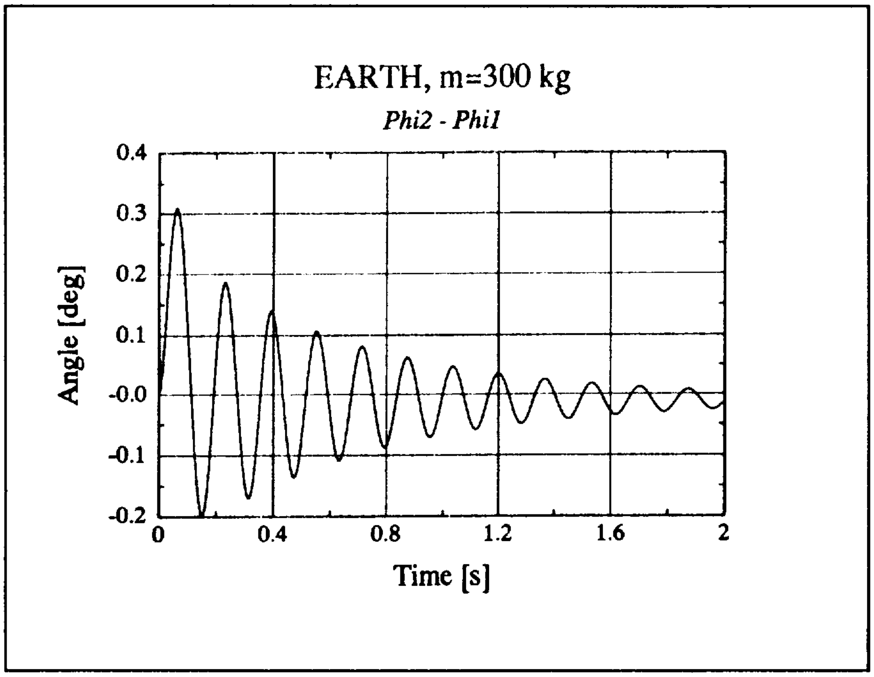


Figure 5b Difference between the angles φ_1 and φ_2 as a function of time.
Masses: m_1 = 30 kg, m_2 = 0.6 kg, m_3 = 269.4 kg;
parachute: area = 190.6 m^2, drag coefficient c_D = 0.7;
atmospheric density = 1.225 kg/m^3;
gust: 6 m/s, suddenly in horizontal direction.

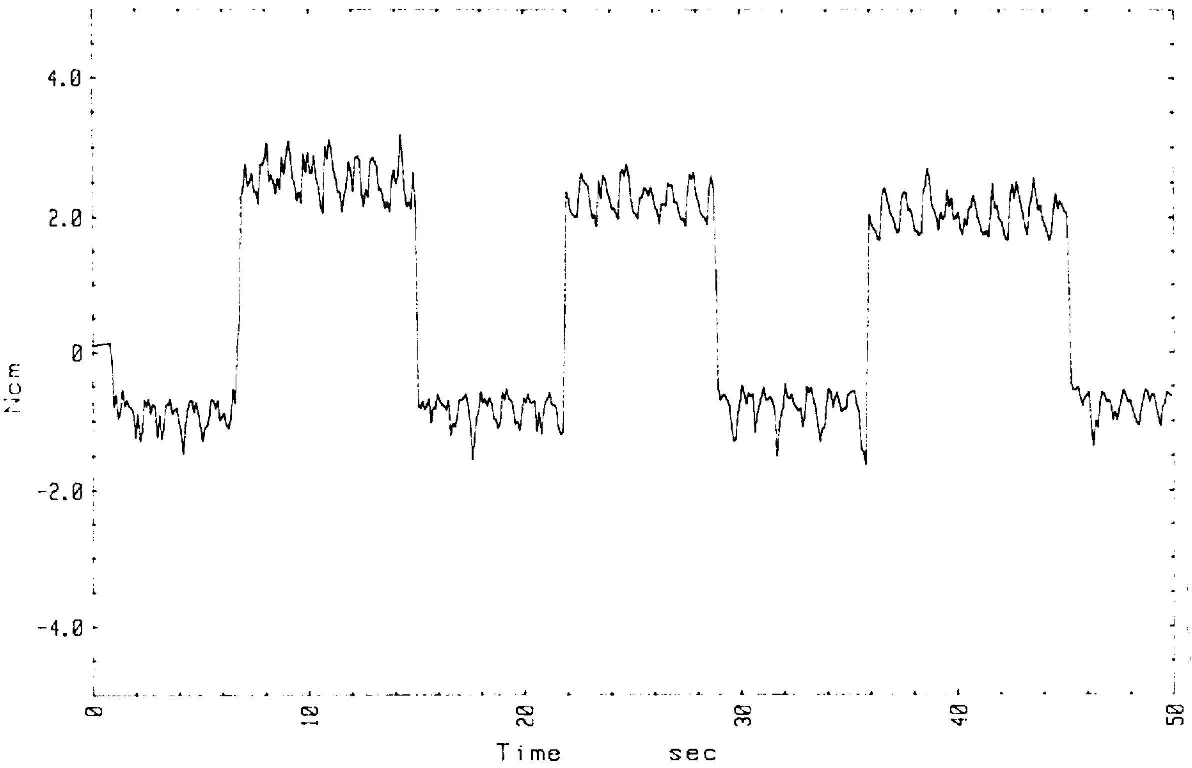


Figure 6 Torque versus Time at 500 N Load, 60 rpm, -55°C, 1mbar CO_2

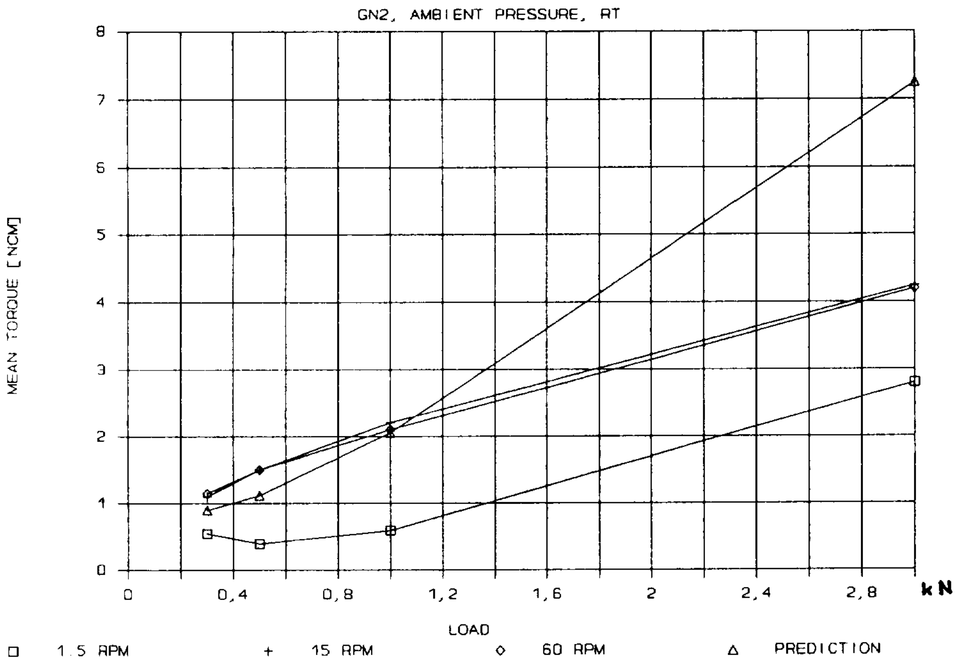


Figure 7 Torque versus Load up to 3 kN

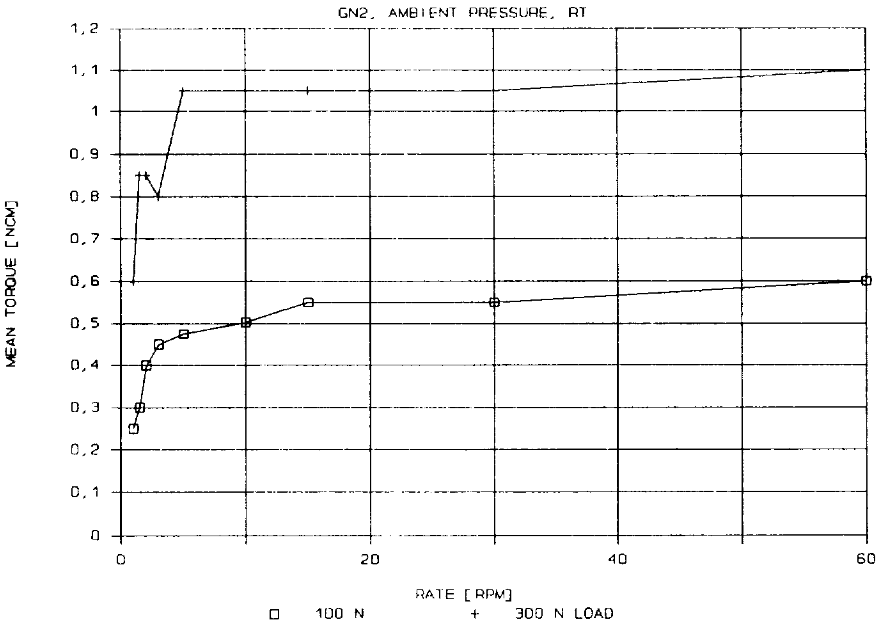


Figure 8 Torque versus Rate at 300 N Load, 1.5 rpm

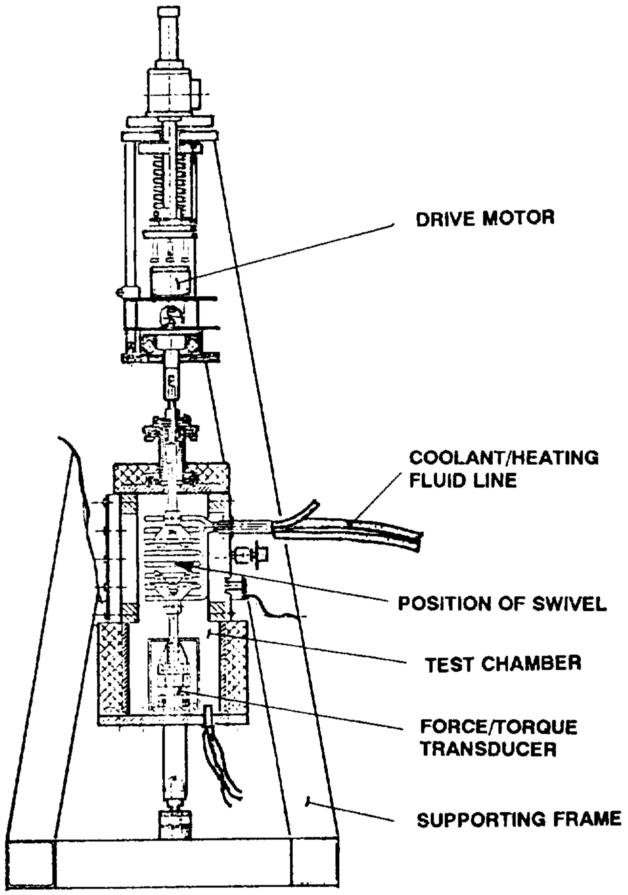


Figure 9 Test Rig for Simulation of PSM Operation under Loads and Environmental Conditions to be expected during Parachute-borne Descent through a Planetary Atmosphere.