# GIOTTO'S ANTENNA DE-SPIN MECHANISM: ITS LUBRICATION AND THERMAL VACUUM PERFORMANCE

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## Abstract

Except in the near-Earth phase of GIOTTO's mission to Comet Halley, the HGA (high gain antenna) on board GIOTTO was the only designed means of up/down communications. The spacecraft spin stabilisation required that the HGA be "de-spun" at the same rotational rate of nominally 15rpm in order to keep the HGA pointing accurately to Earth. A dual servomotor de-spin mechanism was designed and built by SEP of France for this purpose.

The expected thermal environment suggested that dry lubrication was preferable to wet for the ball bearings but there existed no relevant data on the torque noise spectrum of candidate solid lubricants. Therefore ad hoc torque noise tests were run with two solid lubricants: ion-plated lead film plus lead bronze cage (retainer) and a PTFE- composite cage only. The lead lubrication showed the better spectrum up to the mission lifetime point so it was selected for continued test over some 20 times the Halley mission life, with periodic torque spectrum monitoring. The spectrum remained well within the pointing error budget over the 100 million revolutions covered.

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Following the bearing test, an engineering model of the de-spin mechanism, driven via a feedthrough outside the vacuum chamber, yielded transmitted torque spectra in which harmonics of the rotational frequency dominated over the nearly-white noise from the bearings.

The effect of these harmonics was quantified during a later thermal vacuum (TV) test of the complete energised mechanism, with dummy antenna, which was carried out a few months before launch in July 1985. Besides allowing functional checks of the servo-system, this test yielded the reacted torque spectra at all thermal states in the correct vacuum and inertial conditions. At particular motor speeds there was high and sustained reacted torque, implying out-of-tolerance undamped resonance of the antenna.

## 1. Introduction

GIOTTO, the ESA scientific probe to comet Halley, made its planned close encounter with the comet in March 1986.

GIOTTO was built by a consortium of European industries, the prime contractor being British Aerospace. The spacecraft was spin-stabilised and its high gain antenna (HGA) had to point off-axis towards Earth, Fig. 1.

A de-spin mechanism (DSM) drove the antenna to cancel out the spin. This mechanism was a new development and its correct function was crucial to the whole mission.

The DSM was designed and manufactured by the Societe Europeenne de Propulsion (SEP) of Vernon, France. It consisted of a stepper motor drive (operated in the synchronous mode by sin/cos waveforms) and a redundant motor on the rotating shaft supported upon flexibly preloaded angular contact bearings. During launch and perigee motor firing the bearings were offloaded.

The Earth-pointing accuracy required of the HGA (maximum constant error +/- 0.1 degrees, maximum jitter +/- 0.05 deg.) between design speeds of 14 to 16 rpm, together with the anticipated range of working temperature of the DSM – from -20C

to +40C - imposed limits upon the tolerable torque noise, part of which would be generated by the bearings. There was very little information on the torque spectrum of ball bearings or on how significant other sources of torque noise might be.

This paper therefore discusses the supporting experimental work on: long-term torque noise behaviour of solid-lubricated ball bearings in vacuo; the transmitted torque spectrum of an externally driven DSM and; the subsequent thermal vacuum testing of the energised DSM and HGA (dummy) with associated spectra of reacted torque, ie. that experienced by the spacecraft itself.


## 2. Description Of DSM And Control Of Speed

A description of the DSM has already been given by SEP (ref. 1) and by ESA (ref. 2) and a paper in this Symposium discuses design and dynamics of control for the GIOTTO DSM (ref. 3).

The cross-section in Fig. 2 shows the arrangement of bearings, motors and offload device, the HGA itself (not shown) being attached to the interface flange (1).

After launch and the release of the offload device (items 3,6,8 and 9), the two angular contact bearings (5) of 55mm ID carried a preload of 300N supplied by the membrane, 7. Of the two synchronous stepper motors (4) to drive the shaft, only one of the motors was normally energised.

Antenna spin-up after injection into heliocentric orbit was accomplished by a ramping sequence. When the desired speed was attained it was controlled by a servosystem relying upon the counting of internal clock pulses. These pulses measured the time difference between the actual and the desired position of the antenna. Because the time difference (as a number of clock pulses) was used only once per revolution to correct the motor speed over the next revolution, controller performance was necessarily sensitive to the fluctuation in angular velocity caused by torque variation within the DSM. That is, too much resistive torque variation during "coasting" in each revolution would produce a false error signal which might lead to control instability or to excessive HGA jitter.

From discussion with SEP in the early stage of the development, an overall limit on the torque noise from the bearings, regarded <u>at that time</u> as the chief cause of noise, was prescribed as 0.12Nm rms over the frequency range 0.01 to 12Hz. In addition, no prominent torque spectral peaks were to be contributed by the bearings over the frequency range of 1 to 3Hz which was regarded as the "sensitive" region by virtue of the expected antenna torsional resonance.

## 3. Choice of Lubricant

The criteria for the DSM bearing lubrication were:

- long-term stability in space vacuum

- low torque noise over the mission life

- insensitivity of mean torque to temperature change

- validity of accelerated testing

- simplicity in design, ie, preferably no lubricant reservoirs or molecular seals

The last criterion implied that greases or oils were not welcome since their supply and containment would inevitably lead to complexity of design. Additionally the known sensitivity of wet lubricants to temperature was an important factor in this application and so was the validity of accelerated testing.

A solid lubricant was thus favoured and the long experience in Europe with ion-plated lead film (ref. 4) made it a strong contender for this duty. Another solid lubricant - transferred PTFE film from a composite cage (retainer)- was also interesting.

Although early work in the UK on lead-plated bearings (refs. 5,6) had yielded time domain data on the torque noise over very long lives, eg. 300 million revs. of ref. 6, there was apparently no information on frequency domain noise (spectrum) with such solid lubricants in this type of duty. Existing

applications, eg. mainly to solar array drives and to other
limited cycle ball bearings did not approach the continuous duty
of several million revolutions required of the DSM bearings.

## 4. Accelerated Torque Spectrum Test of Solid Lubricated Bearings

### 4.1 Experimental Conditions

Bearing pairs of the same type as in the DSM were lubricated
either by:

> ion-plated lead with cast lead-bronze cage

or

> PTFE-composite cage (PTFE/glass fibre/MoS$_2$)

The bearings were mounted as shown in Fig. 3 in a small
vacuum chamber and their housing was driven round via a vacuum
feedthrough.  An inductive torque transducer restrained the shaft
from rotating and measured the transmitted torque of the bearings
only (the torque transducer having no bearings).

After a short 10000 revs. test in air to reproduce likely
ground testing, the chamber was evacuated to a pressure of < 1
microtorr and the main test was begun.  A target of $10^7$
revolutions was initially set but this was later extended, in the
case of the lead-plated bearings, to $10^8$ revs. to give some 20
times the duty in the Halley mission (4 -6. $10^6$ revs.).

To fit this test into a reasonable timescale, we chose a
speed of 100 rpm, with regular reduction to a nominal de-spin
speed of 16 rpm for the recording of torque spectrum.  Since,
with these solid film lubricants, temperature was known to have
little effect on bearing torque, all the tests described here
were done at a nominal ambient temperature of 20C.

### 4.2 Results and Discussion of Torque Spectra From Bearings Alone

A comparison of the power spectral density (PSD), in units of
$(Nm)^2$/Hz, at a similar number of revolutions, between the ion-

plated lead film/bronze caged bearings and the PTFE-composite caged bearings is shown in Figs. 4 and 5. There are many more peaks in the latter spectrum, probably because of the thick, uneven transfer of the PTFE film to the ball and raceways. On the grounds of the prominent peaks in the "sensitive" bandwidth of 1-3Hz the test on the PTFE-caged bearings was discontinued.

The typical spectrum in Fig.4 from the lead-plated bearings at a stage equivalent to the Halley mission lifetime ($6.10^6$ revs.) shows peaks from the cage rotational frequency (<0.1 Hz) and from debris impact frequencies ca. 2Hz. Such peaks were features of all recorded spectra but their amplitude varied over the test. At end of test, $10^8$ revs., we show the spectrum in Fig. 6. The background level has increased to approx. $3.10^{-7}$ $Nm^2/Hz$ but there is rather less variation in PSD than in Fig. 4, ie. the noise appears to become "whiter" with time.

We may now set these bearing torque spectra in context by comparing them with the acceptable level of torque noise for the DSM. The above-specified maximum rms value of 0.12Nm over the frequency range 0.01 to 12 Hz implies, if it were pure white noise, a constant power spectral density of $1.2.10^{-3}$ $(Nm)^2/Hz$. This level is many times greater than observed from the lead-plated bearings.

In fact the highest individual peak observed at any point in the test was $<10^{-4}$ $(Nm)^2/Hz$. In the time domain, the highest rms torque monitored during the test was 0.009Nm at $80.10^6$ revs. - to be compared with the limit of 0.12Nm quoted above.

The lead-lubricated bearings themselves thus generated far less torque noise than the limit set for this application.

## 5. Torque Behavior of Driven DSM (Engineering Model)

### 5.1 Test Conditions

The first accelerated "thermal vacuum" life test on a model (EM) of the DSM was carried out at ESTL in the arrangement shown in Fig. 7.

In Fig. 7 an electric motor drives a feedthrough shaft which

passes through the vacuum chamber lid, through a central hole in
a piezo-electric torque transducer and is then connected to the
interface flange of the DSM shown in the lower part of Fig. 7.
The torque transmitted from the drive to the housing of the DSM
is sensed by the torque transducer to which the DSM body
(housing) is attached.  The slip rings shown at the top are used
for thermistors on the rotating shaft.

The mechanism was externally driven, with no energisation of
the stepper motors, mostly at 200 rpm except for periods of
torque measurement and analysis which were at 15rpm.

Thermal conditions were as follows: shaft 20C, housing 20C;
shaft 20C, housing 40C and shaft -25C, housing -5C.

Torque spectra were taken in all these temperature states
every $5.10^5$ revs. until a total of $6.10^6$ revs had been
accumulated.


## 5.2   Results And Discussion Of Driven DSM Test

We show a typical power spectrum of the driven DSM torque in
Fig. 8 at a comparable number of revolutions to those in Fig. 4
by the lead-plated bearings alone.   The most obvious difference
between these spectra is the prominent set of harmonics of the
rotational frequency (0.25Hz = 15rpm) in Fig. 8.   Since Fig. 4
shows a much quieter spectrum and no such harmonics, it was
concluded that they must arise from the stepper motors
themselves.   However the reason for this effect was not
investigated further by the present authors. A discussion of
motor-induced oscillations is given in ref. 1.

No significant effect of temperature state or of gradient
was seen in the observed torque spectra.

## 6.   Reacted Torque Behaviour Of Energised DSM (FM1)

### 6.1   Introduction

Following the "driven DSM" tests described above and after
some further development work, it was decided to measure directly

in vacuum the _reacted_ (or reaction) torque, ie. that torque which would be experienced by the spacecraft in driving the antenna. We shall describe one of these thermal vacuum tests on the DSM (FM1) carried out at ESTL a few months before launch in July 1985.

## 6.2 Test Arrangement

To accommodate the dummy antenna of the same polar moment of inertia (1.85 $kgm^2$) as the actual HGA, the DSM was mounted in a vacuum chamber of 1m diameter with the DSM supported by a piezo-electric torque transducer as in Fig. 9a. This configuration allowed the reacted torque to be measured as the DSM drove the HGA dummy. The DSM is shown in Fig. 9b (without the HGA dummy) mounted on the lower half of the vacuum chamber, prior to this test.

The thermal control surfaces in Fig. 9a were used to impose different temperature states in which the motor power, pointing accuracy, run-up and run-down times were measured by staff from SEP. These data will not be discussed here; we will confine ourselves to the reacted torque data.

## 6.3 Reacted Torque Spectrum From Speed Sweep

### 6.3.1 In Vacuum (Average Level: $3.10^{-8}$ Torr)

We show in Fig. 10 a typical "quiet" spectrum of reacted torque over the DSM speed range of 14 to 16 rpm. Fig. 10 was recorded at 15 rpm and the fundamental of 0.25Hz is visible as a small peak. The natural resonance frequency of the antenna, which can be regarded as a torsional pendulum with the (non-linear) restoring torque being the magnetic stiffness of the energised stepper motor, occurs at 1.8375 +/- 0.0125 Hz in the conditions of Fig. 10. There is seen to be some excitation of the resonance by a nearby harmonic (the 7th) of the rotational frequency. These harmonics are clearly visible in Fig. 8 from the test on the driven DSM.

Corresponding to Fig. 10, the time-domain trace of torque is seen in Fig. 11. The beat frequency between the two major peaks

of Fig. 10 is evident in the envelope of the torque/time record. However the maximum rms torque is only ca. 0.01Nm which implies a pointing jitter of the HGA amounting to not more than 0.004 degree, ie. well below the tolerance level of 0.05 degree. For this reason we referred to the spectrum as "quiet".

As the rotational speed was varied, the exciting motor harmonics moved proportionately to speed and when the resonance and exciting frequencies coincided (this occurred at 15.527 rpm at 20C isothermal) a very strong oscillation was seen - Fig. 12.

It is to be noted that the resonance frequency had itself shifted from the value shown in Fig. 10 to 1.8125 +/- 0.0125 Hz. Thus the resonance frequency was a function of oscillation amplitude, because of the non-linear stiffness of the motor (as noted in ref. 1). In Fig. 12 the energy content of the peak is some $10^3$ times that of the quiet spectrum of Fig. 10. Note the change of ordinate scale between Fig. 10 and Fig. 12.

The time-domain record of this strong, undamped oscillation is seen in Fig. 13 which may be contrasted with Fig. 11. The rms torque has risen to 0.25Nm which can be roughly translated into a pointing jitter of 0.1 degree. This is twice the tolerance limit for jitter (0.05 degree).

Because of the closeness to launch and consequent time pressure, detailed sweeps through the resonance at all thermal states were not possible. However, from the torque spectra showing strong excitation in other temperature conditions, it was possible to find the speeds at which the 6th, 7th and 8th harmonics of rotational frequency would coincide with the natural frequency and thereby cause excessive antenna jitter. Table 1 shows the observed resonances at hot and cold conditions and the corresponding excitation speeds from the harmonics given.

In the mission itself a spin rate of 15.007 rpm was set (ref. 7), and the behaviour of the antenna (pointing accuracy) suggested that there was never any significant resonance excitation at this speed.

### 6.3.2 In Atmospheric Nitrogen

The torque behaviour in one atmosphere of dry nitrogen contrasted greatly with that in vacuum. Fig. 14 shows the spectrum under otherwise identical conditions to those in Fig. 12 where the strong oscillation occurred in vacuum. It is seen that the strength of the resonance peak is much attenuated from Fig. 12. This result illustrates the great importance of gas damping forces.

## 7. Concluding Remarks

The lubrication and thermal vacuum evaluation of GIOTTO's de-spin mechanism have provided some new information on this type of drive in space.

Though the use of lead ion-plated bearings and in particular their torque noise characteristics were originally perceived as problematic, we have shown experimentally that this lubricant was easily capable of meeting the mission life and that its noise spectrum was always rather insignificant compared with the tolerable noise.

With the externally driven DSM, the transmitted torque spectrum of the stepper motors was found to be dominant over the bearing spectrum and contained strong harmonics of the rotational frequency.

The subsequent thermal vacuum test of the complete energised DSM with its dummy inertia (all in high vacuum) quantified the effect of the stepper motor harmonics in exciting a strong, undamped torsional resonance of the antenna at certain motor speeds. Much weaker resonance was seen in atmospheric nitrogen because of gas damping. The frequency of the resonance depended not only upon temperature (because of the thermal change in electromagnetic stiffness of the motor), but also upon the amplitude of the oscillation. It was possible to identify de-spin speeds at different thermal states where the resonance would be excited.

The tests identified a safe operating regime for the GIOTTO de-spin mechanism and contributed to the eventual mission success.

This work underlines the importance of a full simulation of the flight environment. It also illustrates the usefulness of the reacted torque technique.

## Acknowledgements

## References

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        Vol 321 15 May 1986

Table 1

**Resonance Frequencies Of HGA And Corresponding Excitation
Speeds**

| Thermal state | | Natural frequency | de-spinspeed (rpm) for excitation by harmonics: | | |
|---|---|---|---|---|---|
| | | Hz | 6th | 7th | 8th |
| Shaft ($^o$C) | Housing ($^o$C) | | | | |
| -18 | 7 | 1.75 | 17.5 | 15.0 | 13.13 |
| 20 | 20 | 1.8125 | 18.12 | 15.53 | 13.59 |
| 40 | 40 | 1.85 | 18.5 | 15.86 | 13.88 |

Note: at each of these temperature states a strong resonance was
observed (peak torque power density at least 0.2 $(Nm)^2$/Hz).  At
other temperature states the resonance frequencies were less
reliable since the excitation was much less.
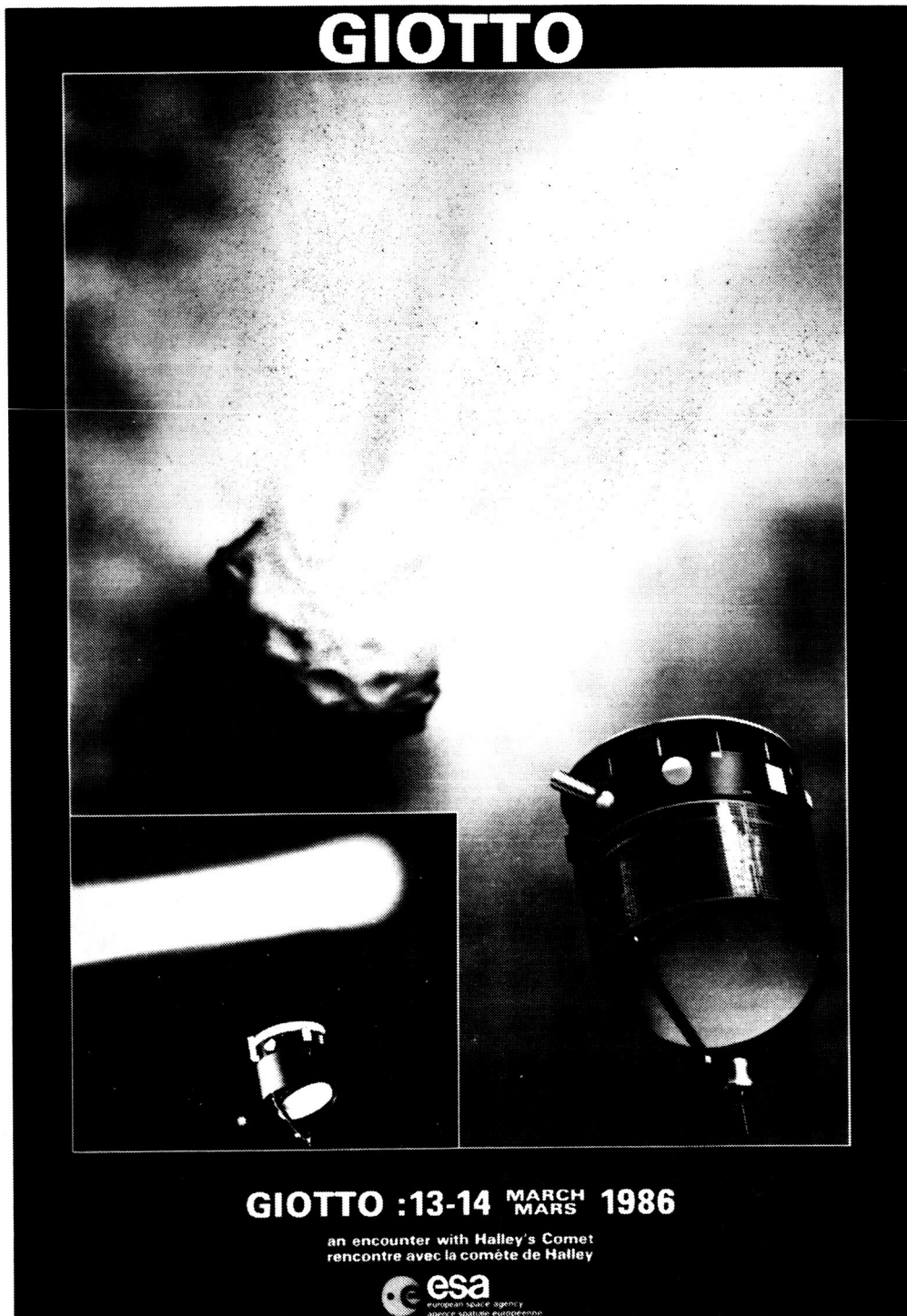
**Fig.** 1  GIOTTO approaching comet Halley (artist's impression)
showing Earth-pointing high gain antenna

1) Interface flange
2) Shaft
3) Bearing off-load device ( BOLD)
4) Stepper motors
5) Bearings
6) Pyrotechnic cutter
7) Membrane for bearing pre-load
8) Main off-load lever
9) Secondary off-load lever
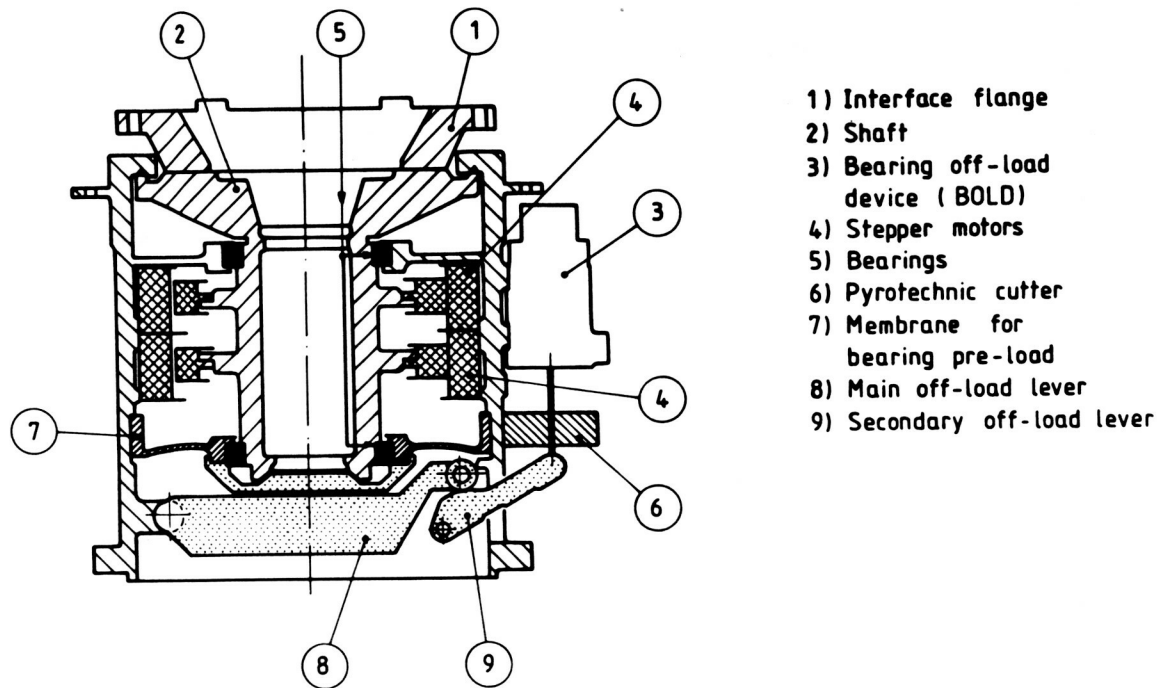
**Fig.** 2  Cross section through GIOTTO's de-spin mechanism (DSM)



PRELOAD APPLIED BY SPRING WASHER

DRIVE SHAFT FROM ROTARY MOTION VACUUM FEED THROUGH

INNER RING SPACER

55 mm BORE BEARING PAIR IN FACE-TO-FACE CONFIGURATION

ALUMINIUM SHAFT ( stationary)

TORQUE TRANSDUCER RESTRAINED IN HOUSING CLAMP
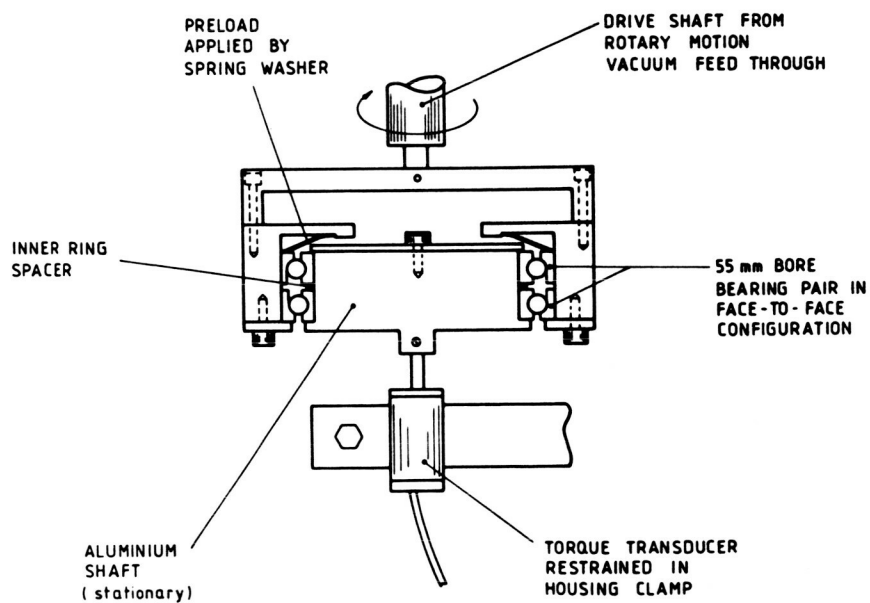
**Fig.** 3  Section through experimental rig for bearings-only torque test
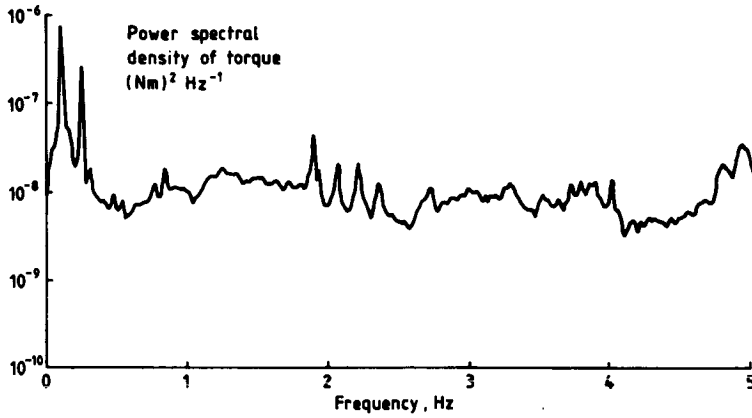
**Fig. 4**
Power spectrum of torque from lead-plated bearings at ca. Halley mission lifetime (6.7 million revs.)
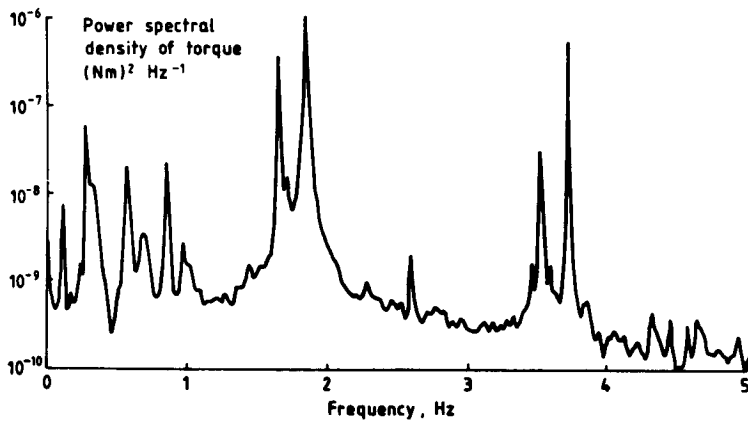


**Fig. 5.**
Torque spectrum from PTFE-composite-caged bearings at ca. Halley mission lifetime (6.9 million revs.)
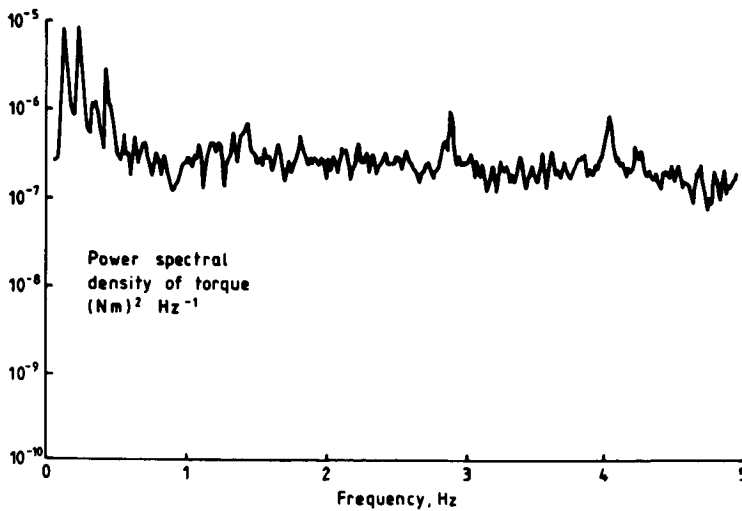


**Fig.6**
Torque spectrum at $10^8$ revs. from lead-plated bearings
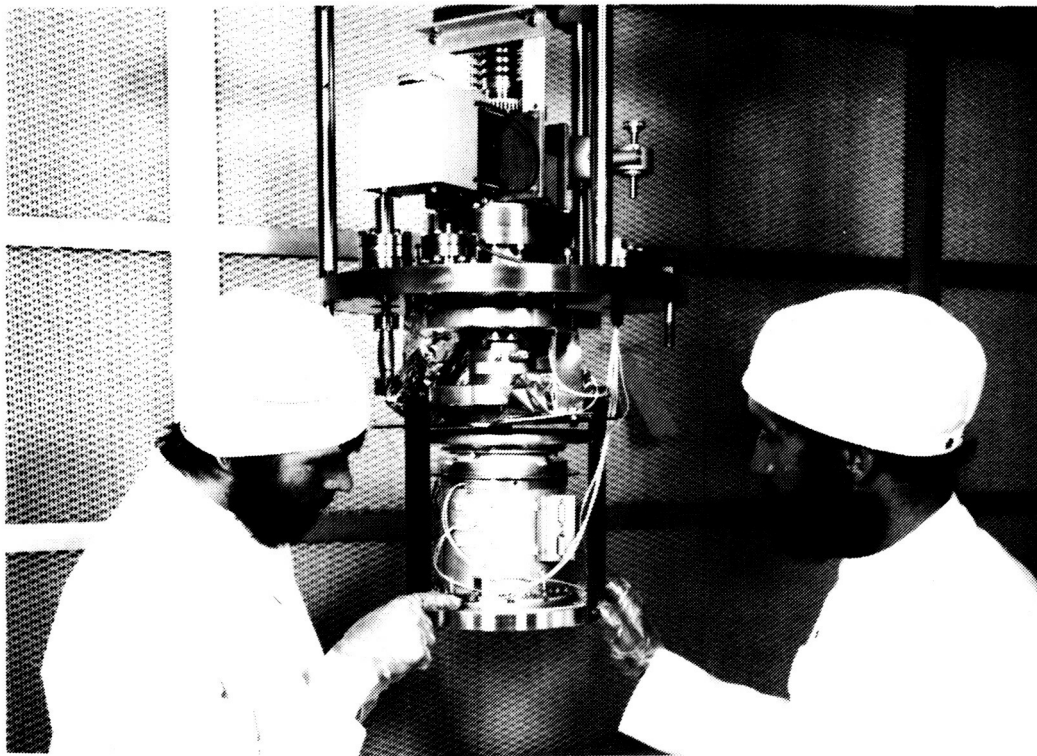
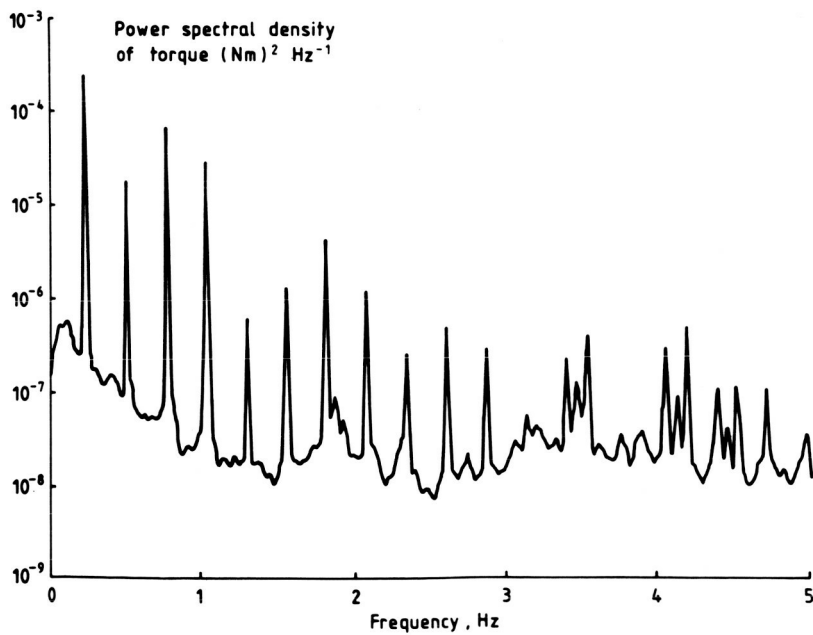**Fig. 7** Photo of DSM (Engineering Model) being prepared for thermal vacuum test



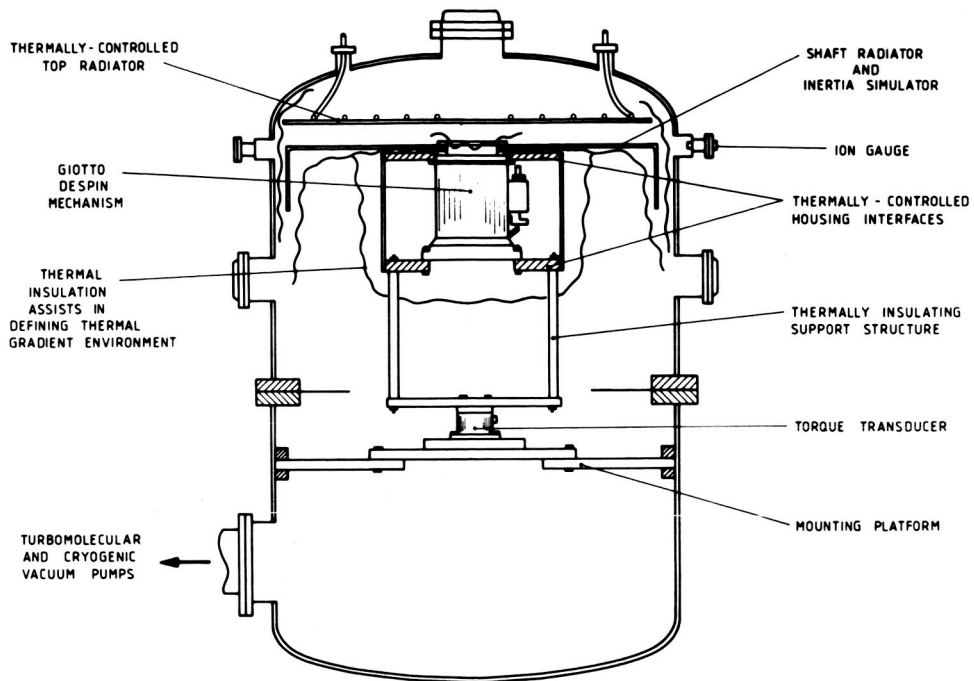**Fig. 8** Typical torque spectrum from driven DSM.

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Fig.9a Arrangement of DSM (Flight Model 1) with dummy antenna in thermal vacuum chamber
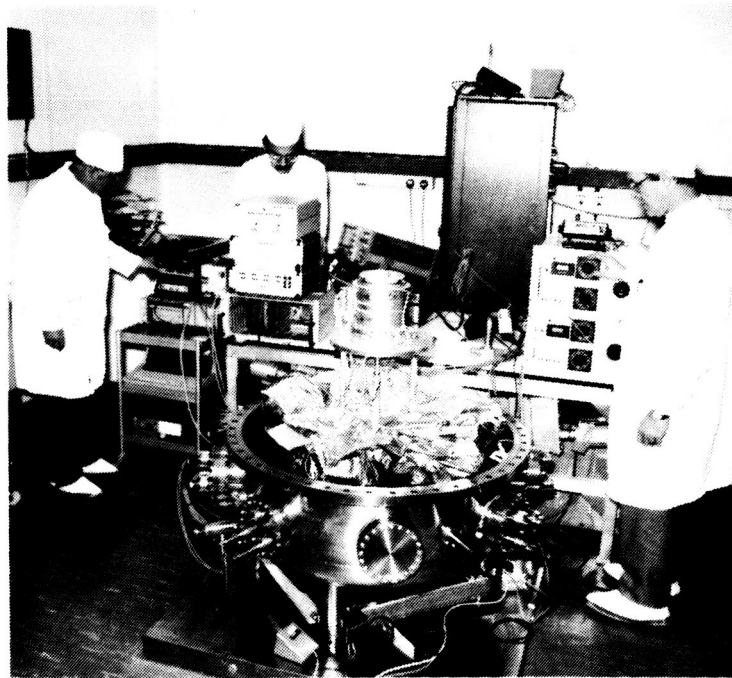


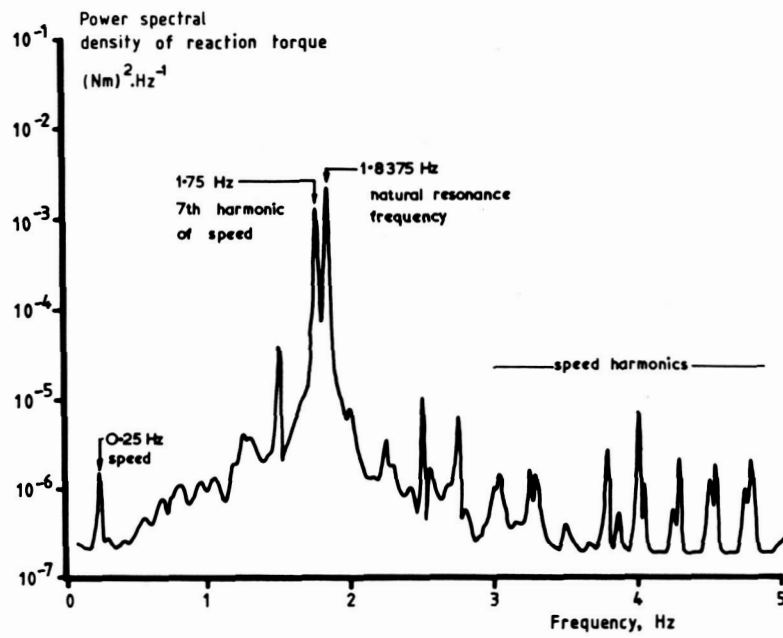**Fig.** 9b GIOTTO FM1 DSM being installed in ESTL test chamber

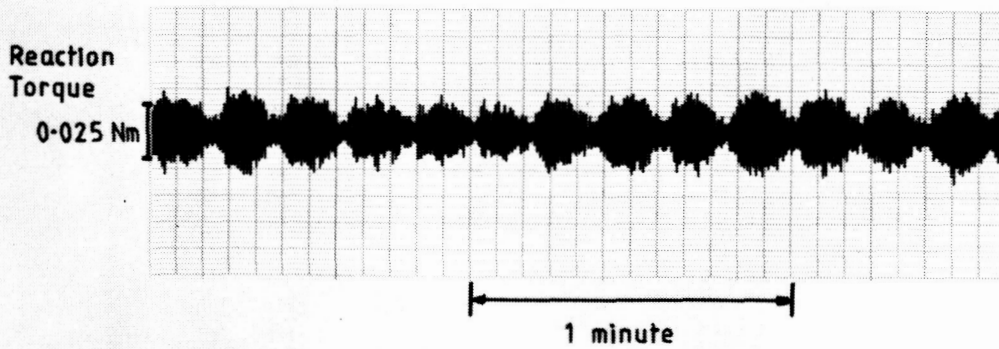**Fig.** 10 Typical "quiet" power spectrum of reacted torque from DSM(FM1) in vacuum



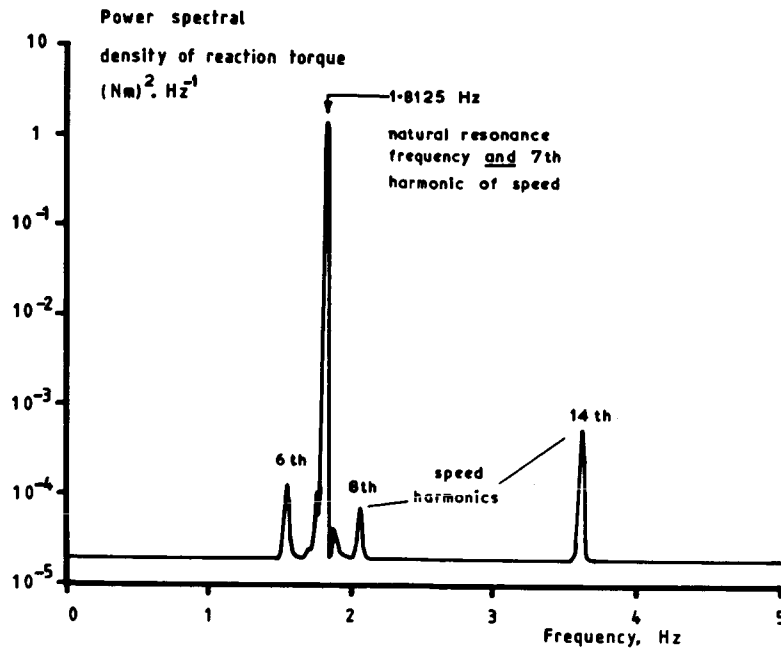**Fig.** 11 Corresponding time-domain trace of reacted torque in Fig. 10

Power spectral density of reaction torque $(Nm)^2 . Hz^{-1}$

10

1

$10^{-1}$

$10^{-2}$

$10^{-3}$

$10^{-4}$

$10^{-5}$

1·8125 Hz

natural resonance frequency **and** 7th harmonic of speed

6th

8th

speed harmonics

14th

0   1   2   3   4   5

Frequency, Hz

**Fig. 12** Power spectrum at resonance condition from DSM (FM1) in vacuo

Reaction Torque
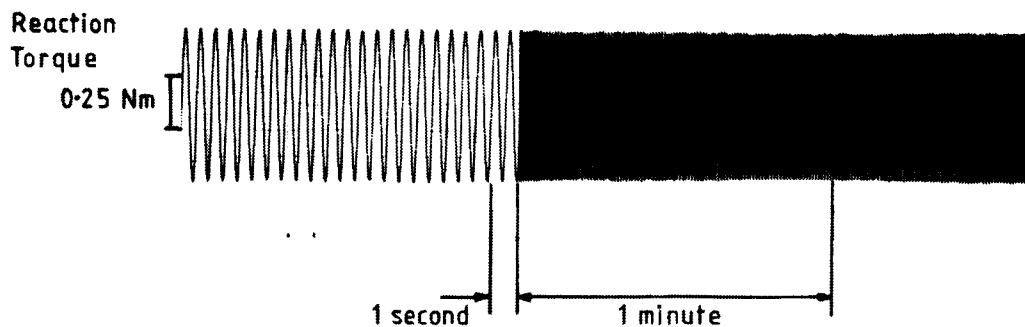
0·25 Nm

1 second

1 minute

**Fig. 13** Time-domain trace corresponding to torque spectrum of Fig. 12

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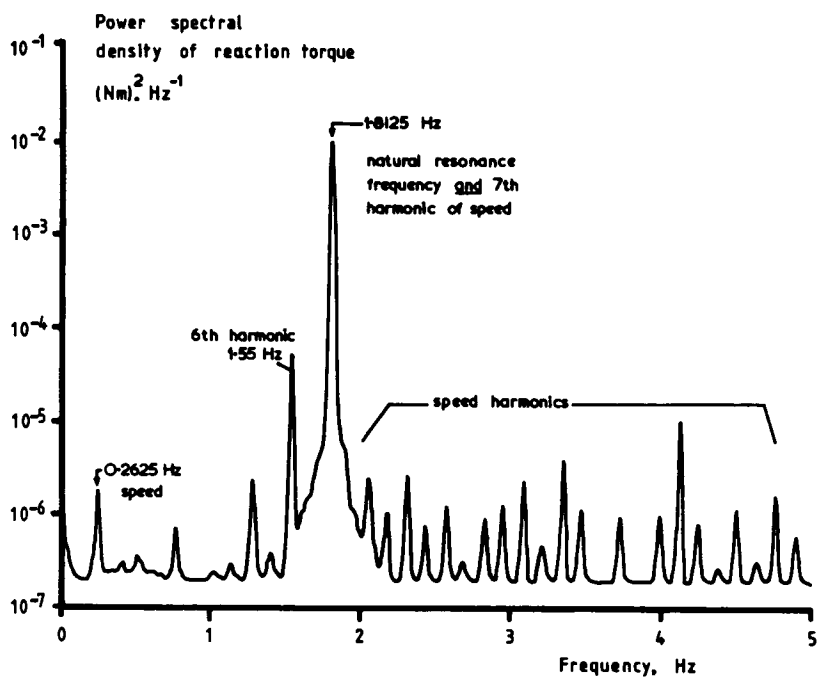**Fig.** 14   Power spectrum at resonance condition from DSM (FM1) in atmospheric nitrogen