GOME SCAN MECHANISM

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ABSTRACT

The scan mechanism is a self sufficient unit mounted on the Global Ozone Monitoring Experiment, GOME, to reflect the incoming radiation by means of a scanning mirror to the spectrometer, covering a spectral range from 240 nm to 800 nm.
The scan equipment is mounted on a pair of slim, angular contact, lead lubricated bearings, in back-to-back mounting configuration, under elastic preloading.
To overcome problems arising from scan equipment low inertia and from lead lubrication high torque noise a relatively wide servo loop band was achieved.
To reduce unsuitable high friction torque values, ESTL modified the selected commercial bearings, even by designing a completely new lead bronze cage, and performed vacuum life tests to ensure the design requirements would have been met.
Following the successful life test, the experiment evaluation continued and successfully overpassed 60 million oscillations.

1. INTRODUCTION

The GOME is a grating spectrometer in the wavelength region from 240 to 800 nm, at present successfully flying in sun-syncronous 98 deg inclination polar orbit, with a mean altitude of 780 km, on ERS-2 satellite.
The nadir viewing spectrometer is monitoring the content of ozone and trace gases in the Earth's atmosphere and their dynamic behaviour through both differential absorption and backscattering in the UV.

2. MECHANISM DESCRIPTION

In the frame of the entire GOME instrument, the scan mechanism, also called Scan Unit, can be considered a modular and independent unit to be mounted and aligned through its interface flange on the optical bench structure.
A dedicated electronics, self contained in an adjacent and separate box mounted on the same optical bench, drives and controls the scan unit.
The scan electronics is connected to the GOME Digital Data Handling Unit, DDHU.
DDHU constanly receives information on the angular position of the scan mirror axis and sends commands
- to change scan amplitude and angular central position, in scanning mode;
- to change angular position, in pointing mode.

The scan unit mirror reflects the incoming radiation to a telescope system and, hence, to 4 spectrometric channels; it performs several types of motion in scanning mode and in pointing mode within an angular range from - 57.5 deg to + 186.1 deg, limited by software control (and by end stops).

The scanning mode provides:
- 5 possible mechanical swath amplitudes from ± 2.2 deg to ± 15.5 deg (respectively, 2.2, 4.4, 6.5, 8.5, 15.5 deg) around any pointing direction with full scan limited either by - 48 deg, or by + 85 deg (any complete scan requires a fixed 5.7 sec period, made of 4.2 sec for forward scan, 1.35 sec for flyback and 0.15 sec stop time to avoid disturbances due to the forward scan inversion);
- default center position around nadir, at switching on;
- "deblocking" ± 60 deg mechanical scan amplitude around nadir to reduce possible blocking effect on bearings.

The pointing mode provides pointing:
- to the Moon, within + 70 deg and + 85 deg;
- to the Earth's poles at + 47.6 and at - 47.1;
- to the calibration sun diffuser at + 180 deg;
- to the calibration lamp at + 167 deg;
- to a safety position at + 98.6 deg for launch and decontamination;
- deep space within + 70 deg and + 85 deg;
- for heating at 0 deg;
- for calibration anywhere in the scan range.

The Scan Unit architecture is given by fig. 2.1
The scan electronics is contained in an aluminium alloy box of 2090 cm3 and 2 kg mass, mounted to optical bench through 3 M5 bolts, and is thermally self sufficient with reference to its power consumption (9.3 W max peak power) from GOME spectrometer by means of reduced thermal contact areas (about 13 sq cm) and proper thermally passive coatings on box external walls.

For the scan mechanism (see fig 2.2), because of the required decontamination in orbit, an aluminium alloy

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mirror had to be selected to be heated up to 80 C by a 5W heater at 28 V.

The accuracy of the selected resolver is ± 20 arcsec for x8 speed over the entire qualification temperature operating range (- 40 C and + 50 C).

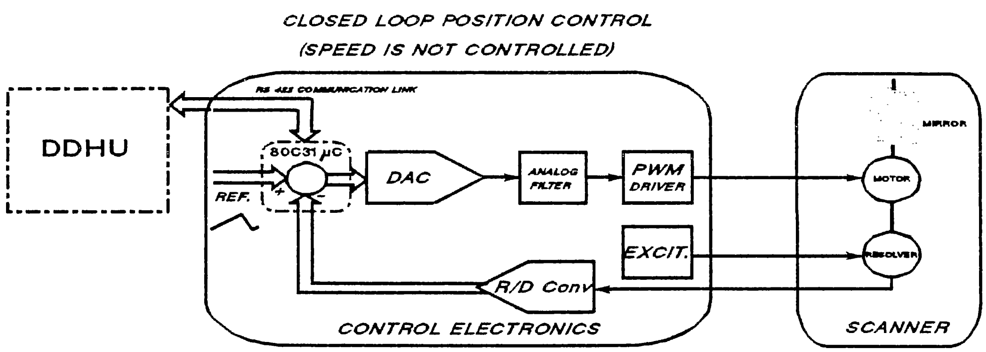

Fig. 2.1 Scan Unit Architecture

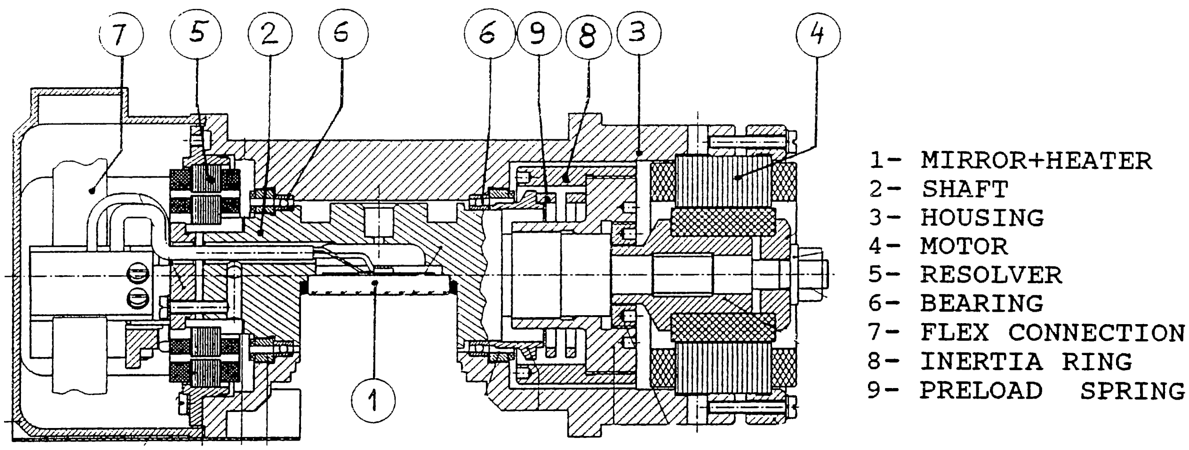

Fig. 2.2 Scan Unit lay out

To avoid distortion due to different thermal expansion, the mirror was decoupled from the supporting titanium alloy scan shaft by compliant adhesive bonding.
A brushless, multipole, three phase, DC torque motor drives the scan equipment in a closed loop controlled in angular position by a double speed, brushless, multipole resolver.

The resolution of the resolver depends only on the adopted Resolver-to-Digital Converter.
For a 14 bit Resolver-to-Digital converter and for a x8 speed resolver resolution (i.e. LSB, less significant bit) is given by
360 deg / (2^{14} bit x 8) = 0.003 deg/bit = 10 arcsec/bit
(and it is equal to the resolution for x1 speed and a 17 bit R/D converter).

The main characteristics of motor and resolver are given on table 2.1.

Table 2.1. ELECTRO MECHANICAL COMPONENTS

MOTOR:	Type: brushless DC Peak Torque: 0.76 Nm Motor Constant: 0.047 Nm/W Torque Sensitivity: 0.07 Nm/A Number of Poles: 8 Number of phases: 3
RESOLVER:	Type: brushless, wired rotor Double Speed: x1, x8. Frequency: 2400Hz Accuracy: ± 20 arcsec

Motor and resolver are mounted on the opposite ends of the scan shaft to minimize electro magnetic interferences between them.

The brushless motor rotor requires no moving wire to be powered, since it is a permanent magnet.
On the contrary, since the selected resolver acts as a rotary transformer, requiring power and one AC high frequency input signal and two AC output signals, moving wires are necessary for the resolver rotor.
Indeed, brushless resolvers with no wire on the rotor are available but have insufficient accuracy for GOME requirements.
Moreover, further moving wires are required for the power to the mirror heater and for the temperature sensor.
Instead of a bundle of twisted wires, a flexible connection, made of kapton rigid flex, was selected

- because of greater capability of keeping position during rotation,
- because of more uniform, lower spring rate (measured to be 0.6 mNm/rad) and no friction effect.

Stresses during scanning are very low and the rigid flex manufacturer guaranteed a 24 10^6 scan cycle life.
By the way, a test campaign for the flexible connection, mounted in operating configuration with a 120 deg alternating rotation (max mechanical deflection, see fig. 2.3) and a 1.5 sec period, was foreseen and 10^4 cycles, corresponding to a calibration per day per 3 years including a safety factor of 10, were successfully passed.

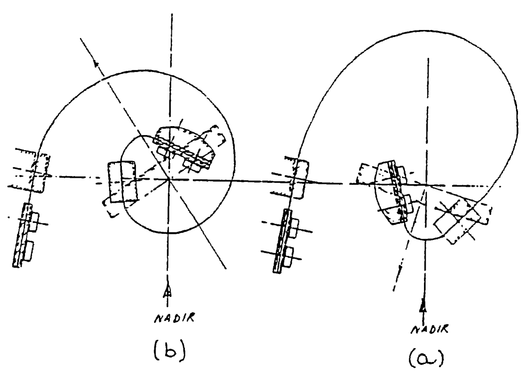

Fig. 2.3 Flexible connection

The scan equipment is rotating on a pair of thin section, angular contact bearings, mounted in back-to-back configuration, under a compliant preloading.
Angular contact and preloading reduce backlash in flight and under 1 g environment; back-to-back mounting provides moment stiffness of the scan axis; therefore, all the three design choices provide high pointing mechanical accuracy in the whole scanning range.

The small diameter (1/16 in) of thin section bearing balls provides full revolution and, hence, uniform wear of the lubricant and enhanced life, even under relatively small oscillations.
Even though the shaft and the housing of the scan unit are made of titanium alloy to minimize dissimilar thermal expansions between the seats and the bearing rings (made of 440 C martensitic steel), a 45 N elastic preload was selected to reduce friction torque increase due to possible thermal gradients in orbit.
On the other hand, since no locking device has been provided for the scan equipment, elastic preload has to be sufficiently stiff, with respect to the 0.56 kg mass of the scan equipment, in order to reduce the number and the intensity of hammering impacts on lubricant at launch and during qualification random vibrations.

The use of liquid lubricants was rejected to avoid any molecular contamination to UV optics.
Solid lubrication was selected, although it generates wear debris and, as consequence, particulate contamination and torque noise variation.
The only viable solution to overcome the stringent service life up to 3 year (i.e. 24 million cycles including a safety factor of 1.5) was deemed to be the combination of lead ion plating of races and lead bronze cages, even though that solution, from literature data at the moment, was told capable to overpass some tenth of million cycles under oscillation.
Therefore, just from the beginning of the mechanism design, a life test was planned on a development breadboard, very representative of GOME mounting configuration.
Moreover ESTL modified commercial bearings and designed and manufactured lead bronze cages to reduce possible blocking effects.
A further reason for lead lubrication selection was the need of extensive calibration and tests in air with no nitrogen purging nor vacuum environment.
The assumed capability to operate in air up to more than 1500 cycles without degradation is to be extended to more than half a million cycles following the operation results of GOME breadboard model.

Due to the high foreseen torque noise (about 5 mNm at BOL) for thin section 30 mm ID bearings and to the low inertia of the scan equipment, a relatively high bandwidth had to be achieved and the inertia had to be increased by introducing an inertia tungsten ring: with the 45 % of the total 0.56 kg scan equipment mass, it represents more than 75 % of the total 130 kg cm^2 scan equipment inertia.

3. MECHANISM SERVO LOOP

A big challenge for GOME scanner servo design was the presence of the very high friction torque due to lead lubrication.

Moreover, the bearing friction torque shows a considerable time modulation (about 100% of mean value) and a spectral distribution that covers all the servo loop band.
Friction torque is relatively low when compared to the inertial torque and therefore the servo loop is strongly non linear.
To overcome these constraints and to comply the requirements specification a wide servo band is needed.
The selected 100 Hz band is a good trade off between performances and stability of the servo system.
Actually, due to the current loop, to the R/D converter and to the sampling rate, the stability of the servo loop would not be merely guaranteed by a wider servo loop bandwidth.

The angular position of the scan mirror, directly mounted on the motor shaft, is transduced by a multipole resolver.
The brushless motor is driven in current; i.e. the current flowing in the motor is sensed and then is controlled by a current loop with a bandwidth of about 1 kHz.

The position information is available to the processor with a rate of about 1 kHz.
Every 1 msec the Digital Signal Processor, DSP, computes the difference between the position reference signal, digitally generated, and the actual position measurement from R/D converter.
The obtained numerical position error is converted to a proportional voltage by a D/A and then analogically filtered and amplified by the PID servo loop filter.
The filtered position error drives the power stage of the servo actuator.
The simulation results of the frequency domain stability analysis are given in Table 3.1.

Table 3.1 FREQUENCY DOMAIN STABILITY

- Open Loop cut off frequency	= 50 Hz;
- Closed Loop bandwidth (-3 db)	= 100 Hz;
- R/D converter bandwidth (-3 db)	= 300 Hz;
- Phase margin (LINEAR MODEL)	~ 49 deg.
- Gain margin (LINEAR MODEL)	~ 10 dB.

Since a sampling rate of 1 kHz is actually present, at the cut off frequency an additional phase loss of $360 \times 50 \times 0.5 \times 10^{-3} = 9$ deg results.
Therefore the real phase margin is about 40 deg.

Simulation results from Time Domain Analysis give the following step response (under NO friction NO current saturation assumptions):

- Rise time	= 10 msec
- Settling time	= 40 msec
- Overshoot	= 20 %

The real NON LINEAR situation is given by the following figures:

- Current range	= ± 1 A;
- Friction mean value	= 3.75 mNm;
- Friction RMS value (1σ)	= 1.10 mNm.

The time response to a 10 mrad input step presents the following features:

- no current saturation;
- stable and very little amplitude limit cycle stimulation by the signals quantization.

In order to meet the requirements about the mirror angular error at the inversion instants it has been necessary to design a servo loop having a bandwidth of about 100 Hz.

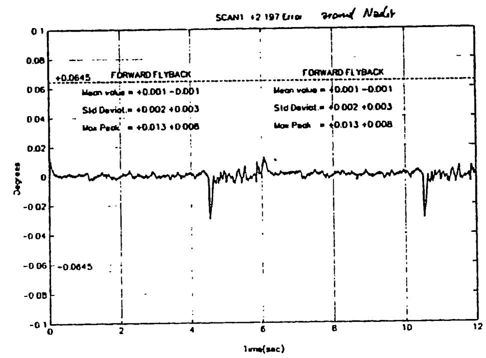

Fig. 3.1.a

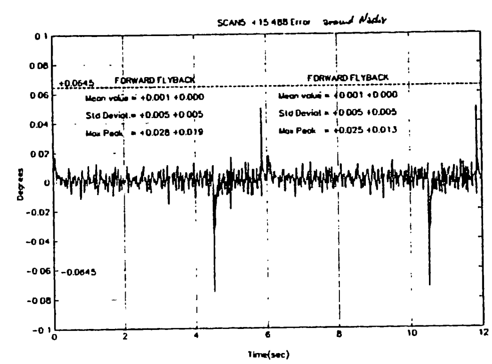

Fig. 3.1. b

The following results refer to the minimum and maximum input ramp amplitude, i.e. 4.4 deg and 31 deg:

min swath in air (± 2 deg, in air)
- max position error = 0.012 deg,
- max speed error = 0.16 deg/sec

max swath in air (± 15 deg, in air)
- max position error = 0.028 deg,

- max speed error = 0.29 deg/sec

Figures 3.1.a and 3.1.b show the tested angular position errors in air respectively for min and max swath amplitudes.

Fig. 3.2 shows that the max tested pointing error is 0.014 deg in moon pointing.

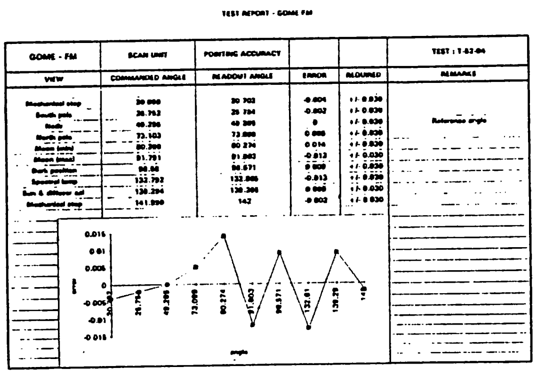

Fig. 3.2.

4. BEARING DESIGN AND LIFE TESTING

Initial operation of the bearing indicated that the standard lead bronze cage produced unsuitable torque values which tended to increase with oscillations.

A series of tests, carried out using several variations of the standard cage, determined that the most suitable design of cage was that with enlarged ball pockets alternated with ball slots (produced by opening up the cage between two consecutive ball pockets) with the completed cage having 10 ball pockets alternated with ball slots compared with the commercially standard 38 ball pockets and the number of ball reduced from 38 to 20.

The life test was carried out using a pair of flight standard bearings with modified cages, which had previously subjected to launch equivalent random vibration.

During the life test the bearings were mounted in a bearing test housing and elastic preload to 45 N using slotted disc springs.

The bearing housing was rigidly connected to the shaft of a rotary ferrofluidic feedthrough.

The latter was connected via zero backlash torsional bellows to a programmable microstepping motor.

The initial thermal vacuum life test consisted of 24 million cycles in sequences of 7 oscillations between ± 2.2 and ± 15.5 deg (3.5 million sequences).

Subsequenly a further 36 million oscillations of the bearings were performed, 16 million at the request of Officine Galileo and then 20 million (bringing the total at 60 million) at the request of ESTEC.

In addition a total of 1120 "nominal" scan profiles for twice a week controls were completed.

The results from the three phases of the life test, given in fig 4.1, show the "worst" case mean and peak to peak torque values of each set of 1000 sequences measured at the nominal scan speed.

Fig 4.1.a shows the results from the first test phase.

The mean torque reduced gradually throughout the duration of the first test, reaching a minimum of 36 gmcm after 3397500 sequences.

The torque levels then slightly increased toward the end of the test.

At the completion of the first test the mean torque was 45 gmcm.

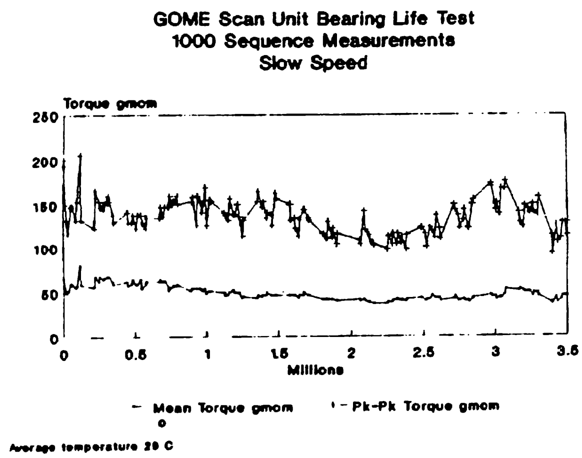

Fig. 4.1.a

The peak to peak torque (2 times the "torque noise" value) showed a greater variation than the mean one, but the general trend remained the same.

The initial peak torque was 193 gmcm, reducing gradually to reach a minimum of 93 gmcm after 397500 sequences. The torque then increased slightly rising to 129 gmcm by the end of the first phase.

Fig. 4.1.b shows the results from the test phase from 24 to 40 million cycles (i.e. from 3.5 to 5.7 million sequences).

Prior to the start the bearings were operated at ± 60 deg for 500 cycles.

The torque remained relatively stable for the duration of the test, reducing slight towards the end.

The trace was similar to that from the first test phase but with nominally higher torque values.

The peak torque reduced gradually, reaching a minimum after 4.401 million sequences then increasing, to reach 130 gmcm by the end of the second phase of the test.

Fig 4.1.c shows the results of the final test phase from 5.715 to 8.573 million sequences (60 million cycles). The mean torque throughout the final phase remained stable at nominally lower values than the first and second phase of the test.

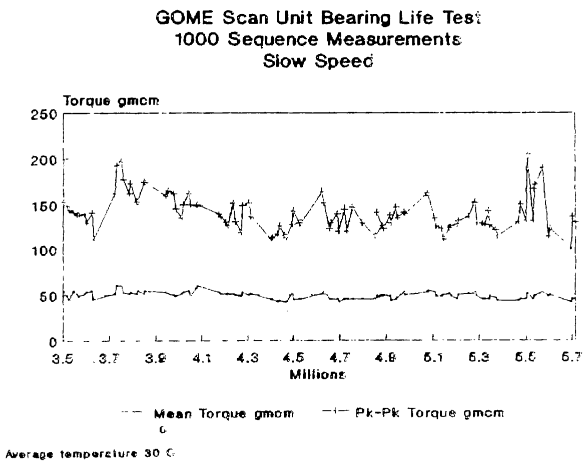

Fig. 4.1.b

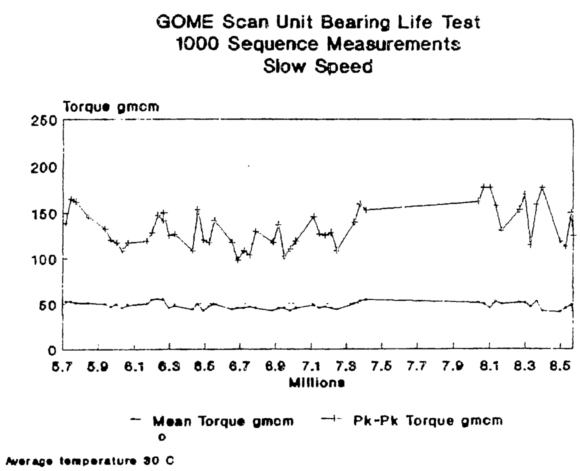

Fig. 4.1.c

The peak to peak torque values were more stable than in either of the first two phases and also show nominally lower values.
The final mean and peak to peak torque values were 42gmcm (i.e. mean friction torque = 4.2 mNm) and 195 gmcm (i.e torque noise ~ 9.8 mNm) compared with 125 gmcn and 194 gmcm at the start of the the life test.

The torque traces from all three phases essentially show that the mean torque and torque noise have gradually reduced over the duration of the test.
This reduction and stabilisation has been observed with other long life application of this lubricant cage combination when operated in continuous rotation. The torque levels for this bearing test are nominally higher than those which would be expected from the same bearing when subjected to continuous rotation.
Evidence from previous tests carried out on oscillatory bearings suggest that this torque increase is a function of oscillatory motion and should therefore not be considered a sign of abnormal behaviour of the bearings.
The strip down examination showed the bearings to be still in very good condition with no evidence af abnormal behaviour.
As well as unexpectedly long life duration, the test demostrated the satisfactory torque beaviour of lead lubricated bearings, with modified cages, for the GOME application and, by the way, for extended operation under oscillatory motion.

5. CONCLUSIONS

All the performance tests executed on GOME Scan Unit Flight Model widely met the requirements of pointing accuracy, angular position error, angular speed error.

The final bearing design in the GOME scan equipment mounting configuration even extended the space life expectation of lead lubrication under low and medium oscillations.
Indeed, due to the very good condition of the bearings and of the lubricant at the end of the life tests, even a much higher life than the experienced 60 million cycles of oscillation can be expected.

Finally, the good performance resuts measured in air on FM Scan Unit are being confirmed by first performance data from space.