# Optical Chopper Assembly for the Mars Observer

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## ABSTRACT

This paper describes the Honeywell-developed Optical Chopper Assembly (OCA), a component of Mars Observer spacecraft's Pressure Modulator Infrared Radiometer (PMIRR) science experiment, which will map the Martian atmosphere during 1993 to 1995. The OCA is unique because of its constant accurate rotational speed, low electrical power consumption, and long-life requirements. These strict and demanding requirements were achieved by use of a number of novel approaches.

## INTRODUCTION

The Mars Observer is a cost-effective mission that will continue the exploration of the inner solar system, initiated in 1971 by the Mariner mission and carried on by the Viking mission. Mars Observer will further unravel the history of Mars, laying the foundation for further expeditions to the Red Planet.

One of the seven scientific experiments, called PMIRR, will perform continuous radiometric mapping of the planet's atmosphere and surface throughout its one-Martian-year (687 Earth days) mission. Daily maps of surface properties, temperature structure, dust loading, and water vapor distribution will be derived from these measurements.

## MARS OBSERVER MISSION

Mars Observer and its Transfer Orbit Stage (TOS) were launched aboard a Titan III rocket on September 25, 1992. During ascent, the Titan's booster rockets were jettisoned and the spacecraft/TOS separated from the Titan III. After repositioning for the orbit transfer, a TOS burn accelerated the spacecraft to the Earth escape velocity and a rendezvous with Mars in August 1993. The average transfer speed will be 25 km/s (56,000 mph) relative to the Sun. As the Mars Observer approaches Mars, a rocket thrust will maneuver the spacecraft into a highly elliptical orbit around the planet. Numerous adjustments during the next four months will move the spacecraft into a near-circular polar orbit for mapping at an orbital speed of 3.35 km/s (7,500 mph) relative to Mars. The mapping orbit will be Sun-synchronous so that the spacecraft passes over Mars' equator at the same local time during each orbit, which is about 2 pm on the day side and 2 am on the night side. In its mapping orbit, the Mars Observer spacecraft will be rotated once

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per orbit by onboard reaction gyroscopes directed by horizon and star sensors to keep the instruments continuously and uniformly pointed at the planet during the entire Martian year. For about 40 min during each 118-min orbit, the spacecraft will be in the Mars shadow and will rely on battery power. The spacecraft's solar panel (which generates more than a kilowatt of power) and storage battery provide sufficient resources to supply the spacecraft and instruments. Figure 1 shows the launch and transfer orbit sequence.

## SCIENCE PLATFORM EXPERIMENTS

The Mars Observer spacecraft, shown in Figure 2, has two basic parts: the main body (the bus) and the science instruments (the payload). The bus houses the computers and other equipment necessary for operations. Four of the seven science instruments are mounted on the outside of the bus, and three instruments are mounted on booms attached to the bus. The functions of the Mars Observer's seven principal science instruments are:

- Gamma Ray Spectrometer - characterizes surface chemical elements
- Mars Observer Camera - photographs the Martian surface
- Thermal Emissions Spectrometer - measures infrared thermal radiation to determine the surface composition of Mars
- Mars Observer Laser Altimeter - measures topography
- Magnetometer and the Electron Reflectometer - search for planetary magnetic fields
- Pressure Modulator Infrared Radiometer - maps the Martian atmosphere

## PRESSURE MODULATOR INFRARED RADIOMETER

PMIRR has nine spectral channels covering the wavelength range 0.3 to 50 microns and employs pressure modulation and filter radiometry in both limb and nadir sounding modes to perform continuous radiometric mapping of the atmosphere and surface of Mars. Daily maps of the surface properties and high vertical resolution three-dimensional daily maps of temperature structure, dust loading, and water-vapor distribution will be derived from these measurements. As a PMIRR component, the OCA will use its optic disc to direct light from a telescope aimed at the Martian surface, and light from deep space, into the PMIRR optical system. A schematic diagram of the PMIRR optical system is shown in Figure 3. The optical chopper, a 12-toothed, double-sided mirror disc is dimensioned and optically finished to provide 100% signal modulation at 800 Hz over the life of the mission. The OCA has a chopper-blade synchronization circuit to generate a signal for use in timing and signal chain phase synchronization demodulation. The circuit consists of a light-emitting-diode source to switch a light-sensitive transistor at the leading edge of an aperture, which is machined into a skirt on the drive motor shaft. This occurs once per revolution. The sync-circuit configuration is shown in the OCA cross section in Figure 4.

## OPTICAL CHOPPER DESIGN REQUIREMENTS

The chopper's outline requirements were specified by NASA's Jet Propulsion Laboratory (JPL), and photographs of OCA are shown in Figure 5. Although a weight limit of 1.5 pounds was allowed, the OCA was designed to weigh only 1.0 pound. Nominal shaft speed is 67 Hz and steady-state power consumption (for the OCA only) is not to exceed 1 W while operating in the 10-to-45 °C temperature range. OCA runup power limit is 3.0 W maximum, and tooth jitter is not to exceed 1.0 μs rms or 4.0 μs peak to peak.

Time and cost budgets did not allow for an engineering model OCA. The only OCA built is now aboard the Mars Observer.

## MOTOR DESIGN

The OCA disc is directly coupled to an AC hysteresis-synchronous, 2-phase, 6-pole motor excited by a 28-V, 200-Hz supply. The motor performance data is presented in Figure 6.

Although not as weight- and power-efficient as equivalent synchronous or DC motors, the hysteresis motor was selected because of its smooth torque, drive circuit simplicity, and because no commutation is required. Hysteresis motors do not exhibit anomaly torques, such as cogging and torque ripple, and offer excellent speed stability when run open loop from an accurate frequency supply. This makes them ideal for systems requiring low jitter with minimal drive-circuit complexity.

The OCA motor was built by Honeywell's Durham, NC, facility and was based on an existing design to minimize cost and schedule. The motor shares the same materials and fabrication methods developed by Honeywell for high reliability and long life and has been proven in numerous space applications over the past 25 years. The motor was subjected to component performance and acceptance testing prior to integration to ensure specification compliance and provide a data base on unit performance.

Honeywell included a split-winding feature in the motor design, which provides operational flexibility by allowing the motor to be operated with its windings either series or parallel connected. The motor is designed to be operated series-connected while mapping Mars but, during system checkout on Earth in a one-atmosphere ambient, the higher torque output provided by parallel winding operation is needed for the motor to reach synchronous speed.

A characteristic of hysteresis motors that affects jitter is a lightly damped rotational mode with frequency dependent on rotor inertia and the effective stiffness of the motor's magnetic field. The OCA motor has a rotational mode measured at 9 Hz when operated series-connected, which, when excited by system disturbances, caused rate variations about the average speed. Jitter on the synchronous circuit output signal was measured and found to be 7.0 μs peak to peak per revolution.

Because there are 12 teeth, this is well below the 4.0 μs per tooth jitter tolerance. A Hewlett-Packard model 5371 Modulation Analyzer was used for jitter measurements.

## OPTIC DISC

The optical disc was machined from Brushwellman I-2208, Type 2 structural grade beryllium alloy. After lapping and polishing, discs were coated with vacuum-deposited silver over nickel. A vacuum-deposited magnesium fluoride protective coating provided final disc covering. The disc's dimensional and optical requirements are given below:

| REQUIREMENT | SPECIFICATION |
|---|---|
| Outside Diameter | 84.07 mm (3.310 + 0.004 in.) |
| Thickness | 1.52 mm (0.O60 + 0.002 in.) |
| Number of Teeth | 12 |
| Tooth Edge Registration | 50 Arcseconds |
| Flatness, Over Teeth | 0.0006 mm(24 μin.) |
| Flatness, Over Disc | 0.008 mm (300 μin.) |
| Parallelism, Side to Side | 0.005 mm(200 μin.) |
| Scratch And Dig Code | 60-40 (MIL-O-13830) |
| Surface Roughness | 40 Angstroms rms |
| Tooth Corner Radii | 0.005 mm (200 μin.) |
| Surface Coating | Silver (MIL-M-3508) |
| Reflectance | 0.45 to 54 microns, 95% to 98% |

## BEARINGS

Custom bearings are preferred for space-flight applications such as OCA, where designs favorable to the intended application and nonstandard tolerances can be used. Race curvature for example, the race radius to ball diameter ratio, can be chosen to favor load capacity rather than drag torque or manufacturing cost. Custom bearings, however, usually require one year for procurement. Because of the OCA's schedule, dictated by the Mars Observer's launch window, procurement of a custom bearing was not possible. To meet schedule, off-the-shelf size R-3H bearings were selected to suspend the OCA drive motor rotor, and all size R-3H bearings, available from Barden and MPB bearing companies, were purchased. These bearings were disassembled and screened for possible use on OCA. Barden Bearing Company of Danbury, CT, measured the radius of each race, and Honeywell bearing engineers reviewed these data to select races to match the diameters of separately procured Titanium-Carbide (TIC)-plated balls that would provide the required load capacity.

The R-3H bearing is the angular contact type and utilizes a dam machined onto its outer race. During assembly, the ball complement is snapped over the dam to make the bearing inseparable. A drawing of the bearings cross section is shown in Figure 7. The ball cage was designed by Honeywell to have conical shaped ball pockets and is machined from sintered nylon, or Nylasint. The cages were impregnated with Coray 55 lubricating oil. The Nylasint material, which can hold up to 25% of its weight in oil, acts as a lubricant reservoir.

The TIC plating, applied to 440C balls by Centre Suisse D'Electronique et de Microtechnique, S. A. of Switzerland, provides exceptional bearing life and is just now beginning to see usage in space-flight applications. Ball-and-race combinations with curvatures as low as 54% were found. Analyses show that these bearings would support the required pyrotechnic shock and launch vibration loads. Bearing drag torque was minimized to meet the 1.0-W steady-state running power requirement by selecting acceptable preload and lubricant quantities. Prototype R-3H bearings and cages were tested on a torque dynamometer. These tests showed that bearings with seven-ball complements developed less than 2 gm-cm drag torque, and require less drive power than bearings with eight-ball complements. Also, cages with conical pockets were more spin stable than cages with cylindrical pockets. To disassemble and reassemble the bearings for testing, a fixture was made that allowed the ball complement to clear the dam without damaging the balls or races. The fixture tied the outer race thermally to a heat source and the inner race to a liquid-nitrogen reservoir. The fixture also prevented the ball complement and cage from contacting either race during the temperature transfer, which further increased clearances. When thermal equilibrium was reached, the bearing could easily be assembled (or disassembled) by applying a light force (50 gm) to the races.

## LUBRICATION

Analyses and experience show that OCA bearing life depends almost entirely on lubricant life. Sacrificial lubricant reservoirs were therefore designed for OCA to ensure meeting the OCA's three-year life requirement.

Honeywell's experience with size R-3H bearings, used on hundreds of instrument gyroscopes, shows that 30,000-to-40,000-hr Mean Time Between Failures (MTBF) are achievable. Optical Disc Assemblies with R-4H bearings, sintered-nylon cages, Coray 100 lubrication, and operated at 40 Hz in an evacuated housing have up to 50,000 hr MTBFs. Nearly all bearing failures are lubricant related.

As the mission progresses, the OCA bearing's lubricant will be lost through the molecular flow of vapors from the bearing to deep space or within the spacecraft where lubricant vaporized by the vacuum environment will be deposited as it contacts colder bearing surfaces.

The OCA design calls for 2.0 mg of Coray 55 lubricating oil to be applied to the race surfaces of each bearing. This oil is in addition to approximately 20.0 mg of oil absorbed by each Nylasint cage. The lubricant vapor loss rate from the bearing is reduced by a traditional labyrinth seal, which is an annular 0.1 mm (0.004 in.) radial clearance between the fixed-bearing lock ring and the disc mount. The labyrinth seal is shown in Figure 4, cross-sectional view of the OCA.

Another sacrificial lubricant reservoir is mounted within the OCA housing cover. This reservoir stores 1.05 gm of Coray 55 oil and maintains a constant lubricant vapor partial pressure within the housing. This constant pressure extends lubricant life by replacing molecules that escaped through the labyrinth seal.

## BEARING LIFE CRITERIA

Measurements showed that no change in bearing drag torque occurs with free oil within the bearing reduced by 30%. Additional lubricant loss may be possible without increasing torque or reducing bearing life. A 35% loss of lubricant, therefore, provides the basis for acceptable OCA bearing performance, although a 30% loss is used for most Honeywell lubricant-loss analyses.

## BEARING PRELOAD SYSTEM

A preload system is provided to maintain a near-constant 0.9 kg (2.0 lb) axial load on the bearings for all expected temperatures. The preload system prevents damage should temperature gradients cause thermal expansions that load the bearing. A schematic diagram of the preload system is shown in Figure 8. Axial length changes caused by temperature variations are prevented from loading the bearing because the bearing mounting cartridge is free to slide relative to the housing.

The preload system also prevents unloading during launch vibrations. Without the 2-lb preload, random-vibration accelerations greater than 13 g's would cause the 67.7-gm (0.149 lb) shaft assembly to unload the bearing, thereby causing hammering between the balls and races, which could damage the bearings.

## DYNAMIC BALANCING

Dynamic balancing of the OCA rotor assembly is required. Forces induced by imbalance and bearing race irregularities are to be less than 7.7 gm (0.017 lb) between 40 and 50 Hz and less than 10.9 gms (0.024 lb) between 120 and 150 Hz. The Schenk Dynamic 30 balance machine was used for the balancing operations. Balance adjustments are made by positioning size 2-56 UNC setscrews, which are located in threaded holes machined into the rotor and disc mount.

## MECHANICAL STRUCTURE

The OCA housing assembly, shaft, and bearing cartridge were machined from Type 6Al4V titanium alloy. The housing's exterior surfaces were coated with Tiodize V-E17 to improve emissivity for radiation heat-transfer purposes. Other titanium surfaces were coated with AMS 2488 Type 2 Anodic Treatment, used as an antigalling coating for screw thread and bearing cartridge protection.

The disc mount and disc clamp were machined from the same Brush-Wellman structural grade beryllium alloy used for the optic disc. Surfaces that mate with the optic disc are machined to have flatnesses and surface finishes comparable to those of the disc. Helicoil inserts were installed into beryllium parts to receive threaded fasteners.

Versamid 140/Epon 828 epoxy adhesive is used to fasten the optic disc to the disc mount. Disc alignment was performed as the adhesive cured, which was approximately 45 min.

## PMIRR CHECKOUT AT JPL

After assembly and acceptance testing was completed at Honeywell, the OCA was shipped to JPL for integration with PMIRR and system testing on the optic bench. During these tests, JPL found that operating the motor parallel-connected significantly improved PMIRR's optical performance but increased the OCA motor's steady-state power from 0.8 to 1.8 W. The advantages of the improved performance are considerable and JPL requested analyses to find the effect on bearing life of the higher motor power.

Estimates show the higher power increased bearing temperature from 47 to 57 °C. This reduces bearing life from 150,000 to 26,000 hr, with zero margin for the three-year (26,208 hr) mission. A performance comparison is presented in Table 1.

The OCA drive motor was sized for a load torque of 6.0 gm-cm, but power measurements show actual drag torque to be 12.0 gm-cm. Because drive-motor efficiency was higher than expected, the 1.0 W steady-state power specification was met — in spite of the high bearing drag torque — and the high torque source was not identified. Dynamometer tests on the flight OCA motor show 0.5 W are required to turn a 6.0-gm-cm load, and 0.8 W for a 12.0-gm-cm load. With the motor parallel connected, it is estimated that 1.8 W are required to drive a 12.0-gm-cm load; bearing temperature will reach 57 °C; and bearing life will be 26,000 hr. Power measurements by JPL, with the OCA assembled into PMIRR, agree with the 1.8-W value.

The 12-gm-cm power measurement could be caused by excessive lubricant, bearing misalignment, or higher preload. If excessive lubricant causes high torque, then bearing life may be increased by the extra lubricant.

Although assembly records show no discrepancies on the machined parts, the high sensitivity of bearing torque to misalignment makes misalignment a possible cause for the high torque. For misalignment to cause the high torque, high points on the races, cartridge, and other components would have to be aligned at assembly to maximize misalignment. Determining the probable torque magnitude will require tolerance and statistical studies.

Dynamometer test results (Figure 9) show that bearing drag torque increases significantly with lubricant quantity and, to a lesser degree, with preload. Preload was probably adjusted to within 0.25 kg (0.5 lb) and is an unlikely cause of the high bearing torque.

An observation during checkout suggests that the bearings have excessive lubricant: after a several-month period of nonoperation, a chirping noise coming from the OCA was heard immediately following motor startup. The noise was intermittent and went away completely after several hours of operation. The chirping noise was believed caused by gravity-related puddles of lubricant formed in the bearing-race area. The puddles caused the ball cage to become unstable, which caused the noise. After several hours operation, the lubricant became redistributed throughout the bearing and the noise ceased.

Bearing-life studies and PMIRR temperatures measured in flight are being evaluated at the time of this paper's preparation. JPL will review this data and, if needed, will have the opportunity of reducing the time OCA is operated with windings parallel connected. For example, during the long periods of Martian dust storms, PMIRR observations will be impaired, and the OCA might be operated series connected to prolong bearing life.

## SUMMARY AND CONCLUSIONS

1. The OCA was designed, built, tested, and shipped on schedule. Cost and performance objectives were met.

2. Subsequent PMIRR system tests on the JPL optical bench showed that optical performance could be improved by operating the motor with its windings parallel connected, rather than series connected, as originally intended. Parallel operation increased motor power and raised the bearing temperature. A study to show the effect on bearing life was requested by JPL.

3. In the study, a data review showed that OCA bearing drag torque exceeded the design limit, however, better-than-expected motor efficiency brought motor input power within tolerance. The high torque is assumably caused either by excessive lubricant or bearing misalignment/high preload. If extra lubricant is present, bearing life will exceed the prediction. If misalignment/preload causes the extra torque, the three-year life requirement can be met with parallel operation, but with zero safety margin.

4. Honeywell studies will be continued to determine the effect of bearing misalignment, lubricant quantity, and related factors on drag torque and bearing life. This data can be used by JPL as needed to modify the OCA operational regimen during mapping.

5. The positive effect of TIC-coated balls was not considered in the bearing life estimates and will be further evaluated by Honeywell.

## ACKNOWLEDGEMENT

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C-3.

Table 1. Motor Operating Mode Comparison

| Motor Operation Configuration | Units | Start Parallel Run Series | Start Parallel Run Parallel |
|---|---|---|---|
| Pull out torque | gm cm | 24 | 34 |
| Power; 6.0 gm cm load | W | 0.5 | 1.5 |
| Temperature | °C | 38.0 | 47.0 |
| Bearing life | hr | >200,000 | 150,000 |
| Power; 12 gm cm load | W | 0.8 | 1.8 |
| Temperature | °C | 47.0 | 57.0 |
| Bearing life | hr | 150,000 | 26,000 |

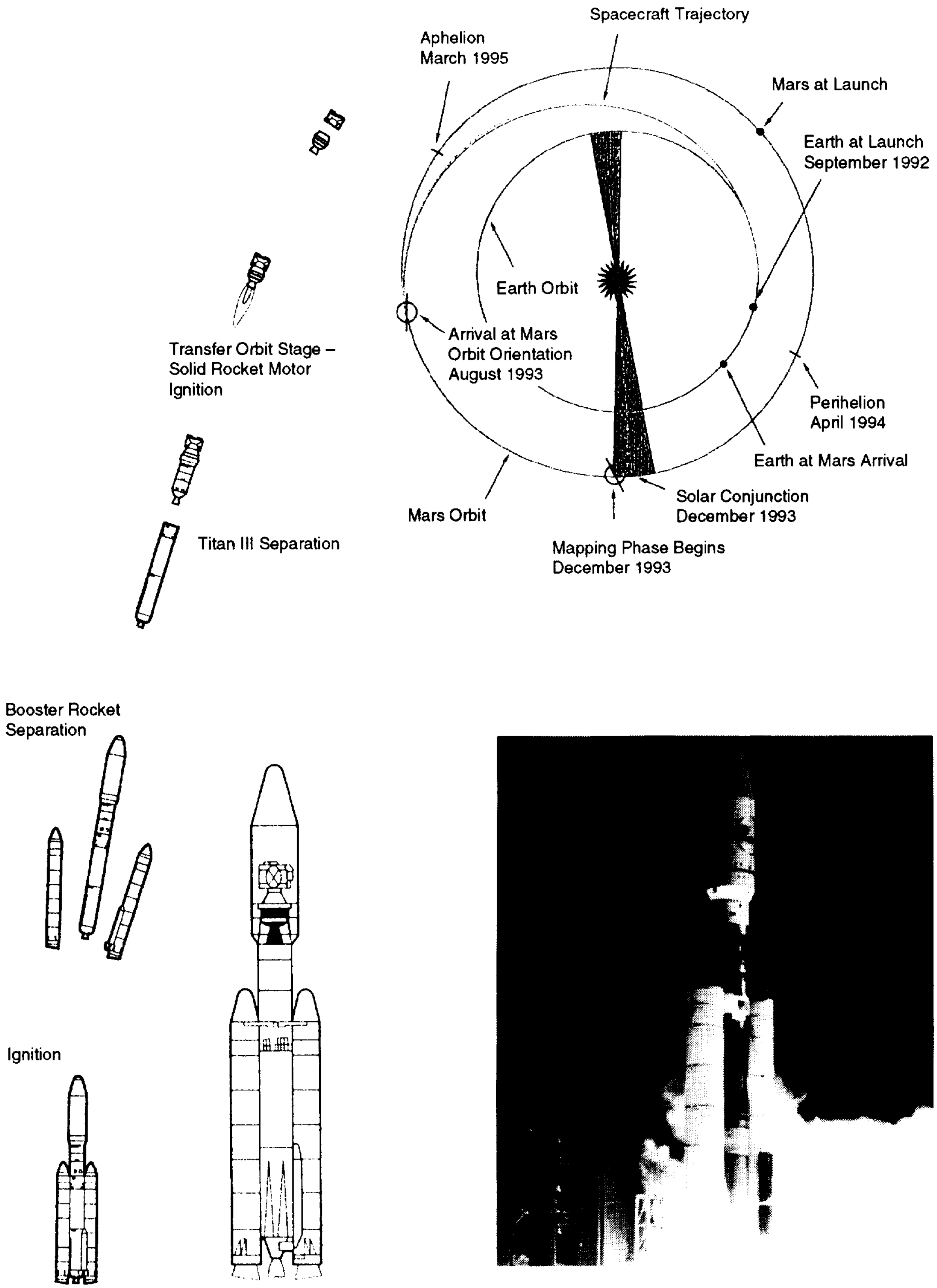


Figure 1. Launch and Transfer Orbit

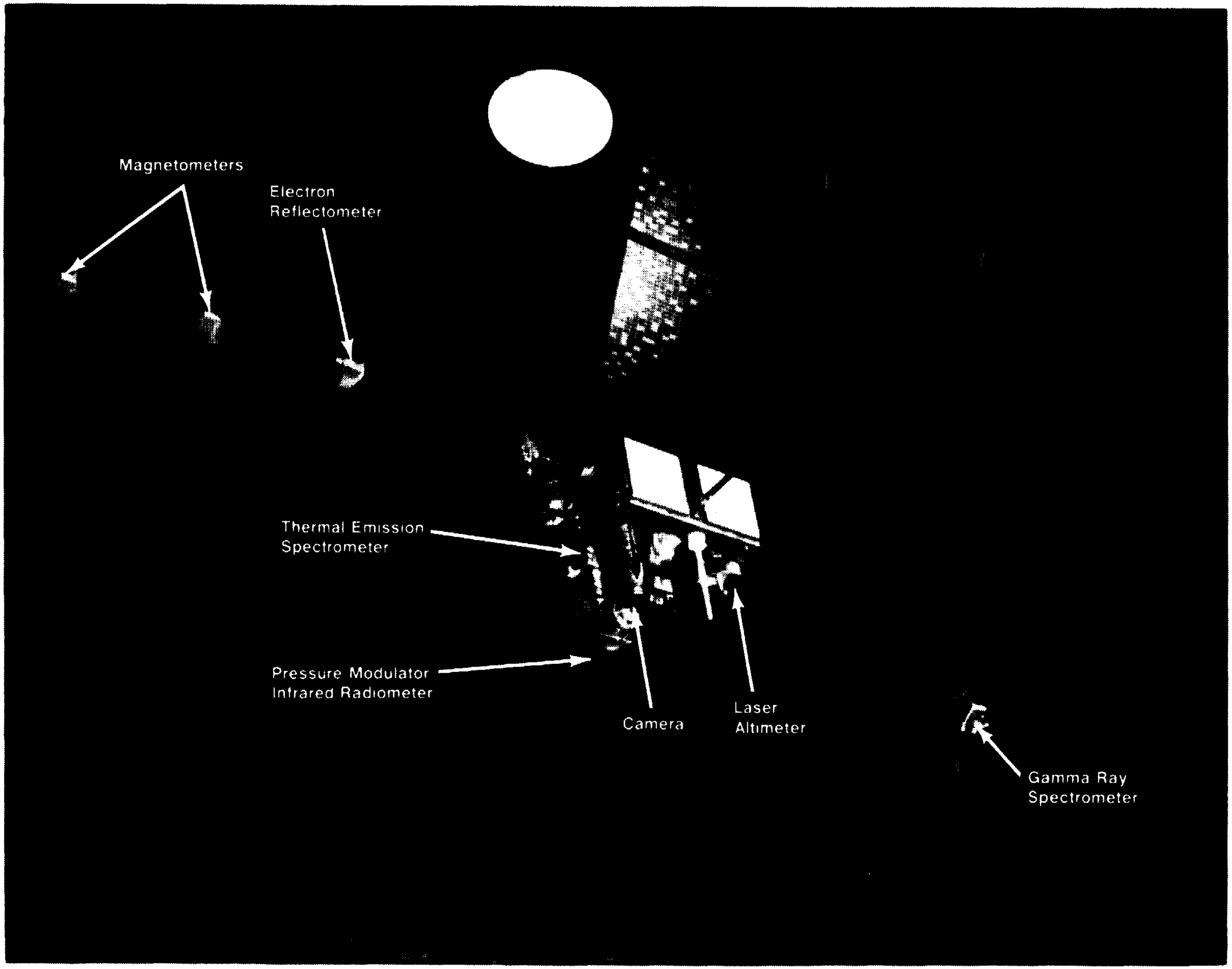


Figure 2. Mars Observer Spacecraft

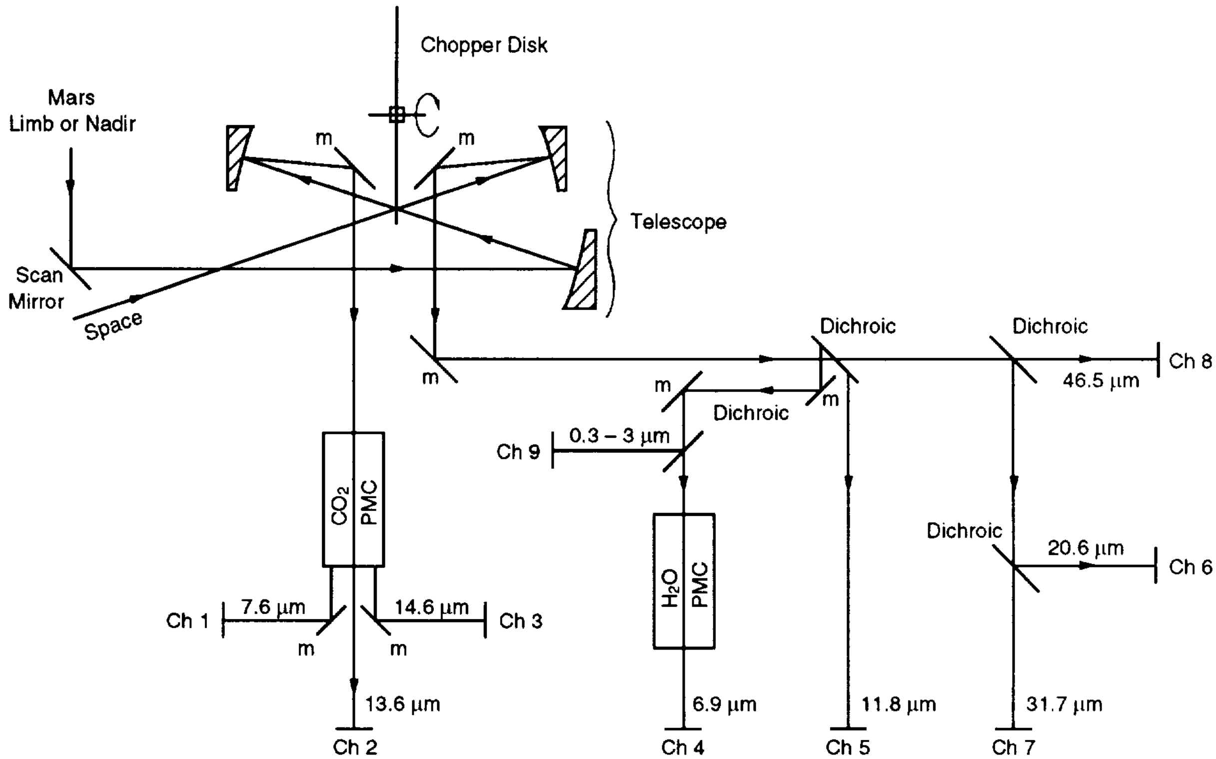


Figure 3. PMIRR Optical Schematic

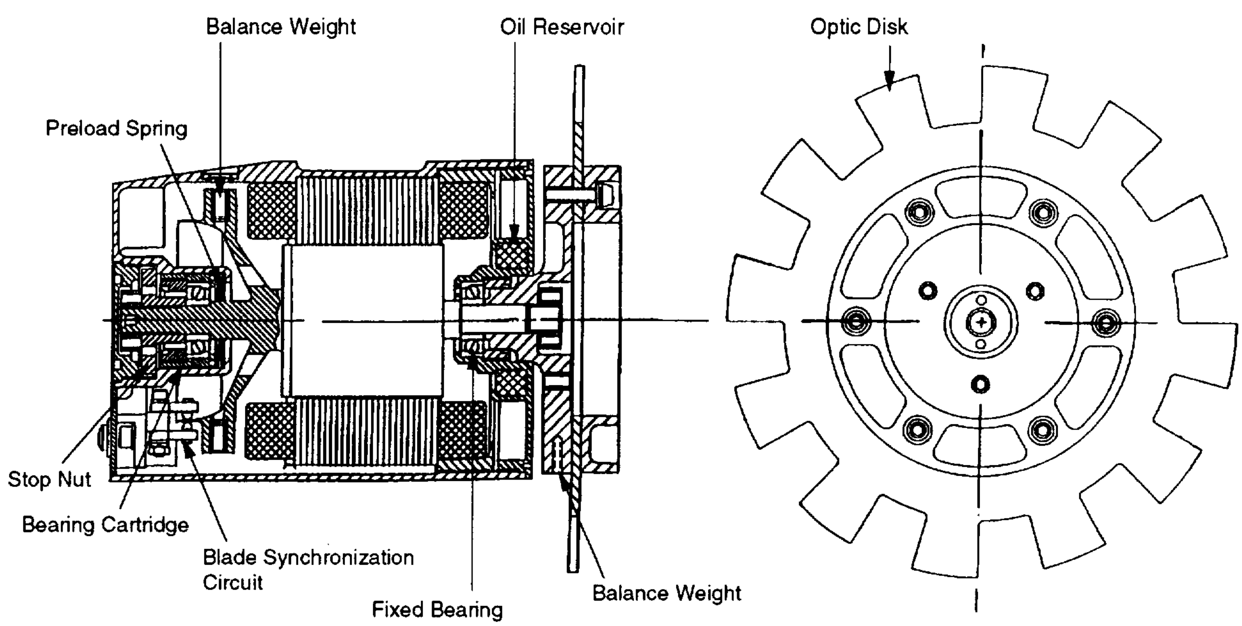


Figure 4. Optical Chopper Assembly (OCA) Cross Section

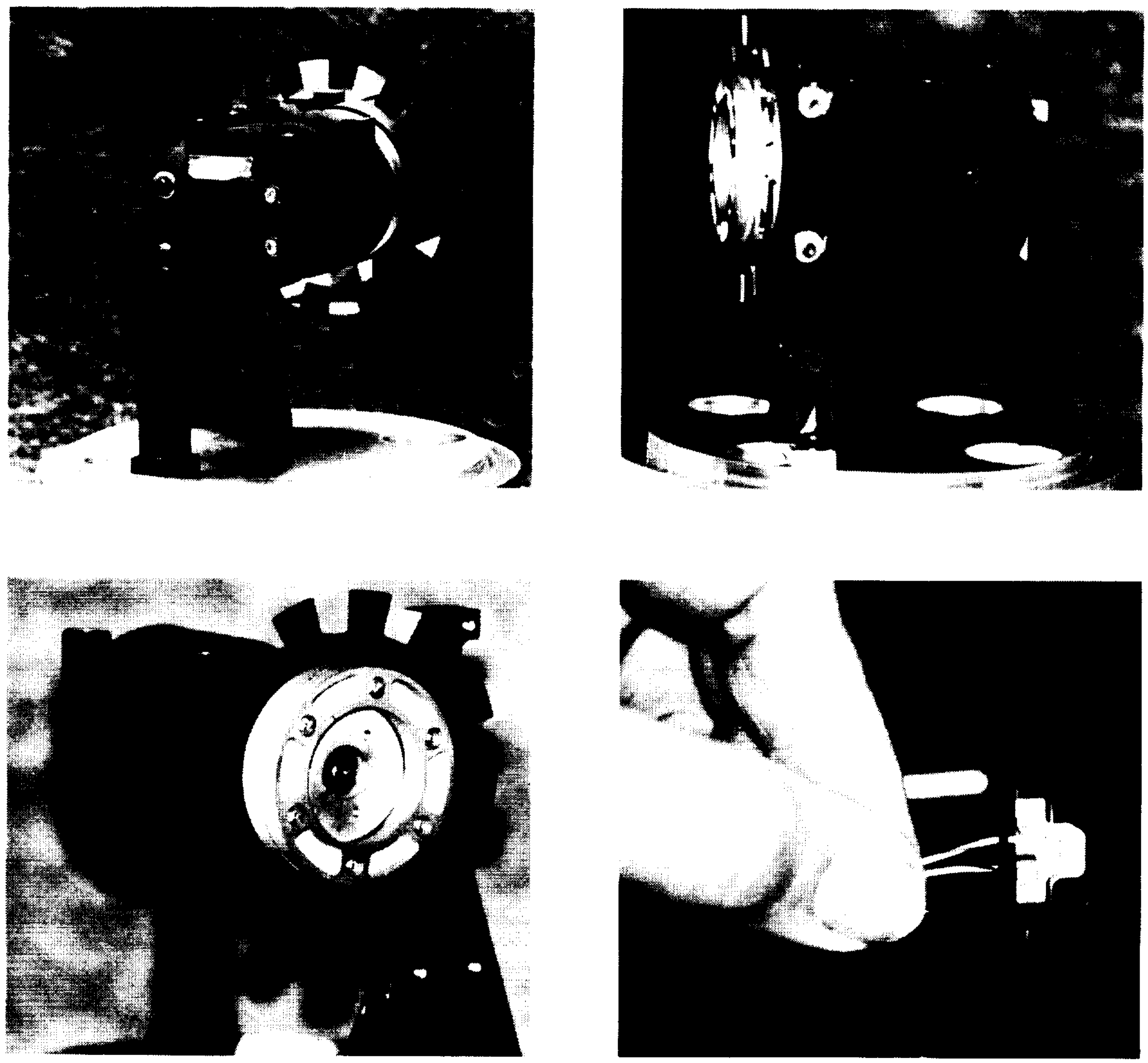

Figure 5. Optical Chopper and Sync Circuits

| | |
|---|---|
| Motor: | AC, Synchronous, Hysteresis |
| Phases: | 2 |
| Poles: | 6 |
| Weight: | 10 oz |
| Rated Speed: | 4000 rpm (67 Hz) |
| Torque:<br>Running<br>Runup | <br>4 gm-cm, minimum<br>6 gm-cm, minimum |
| Power:<br>Running<br>Runup | <br><1 W at 4000 rpm & 4 gm-cm<br><3 W |

Excitation: 200 Hz, 27.5 ± 8% V rms

Split winding provides drive flexibility

Design satifies SOW paragraphs 5.2.2 and 6.2e

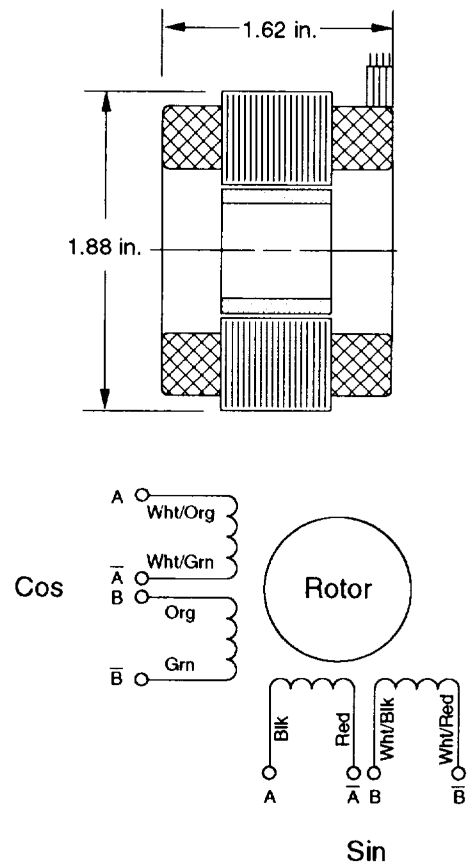


Figure 6. Motor Performance Data

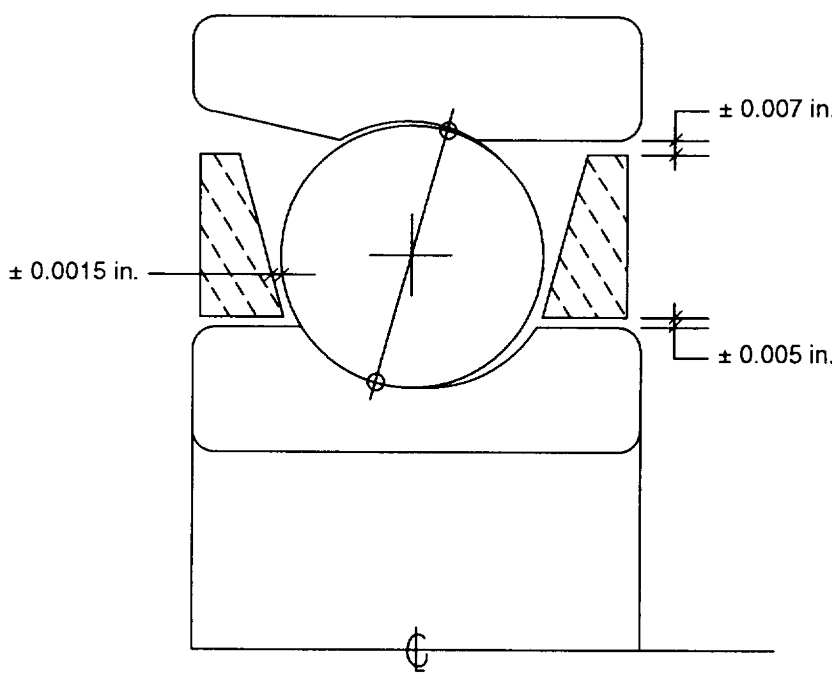


Figure 7. Bearing Cross Section

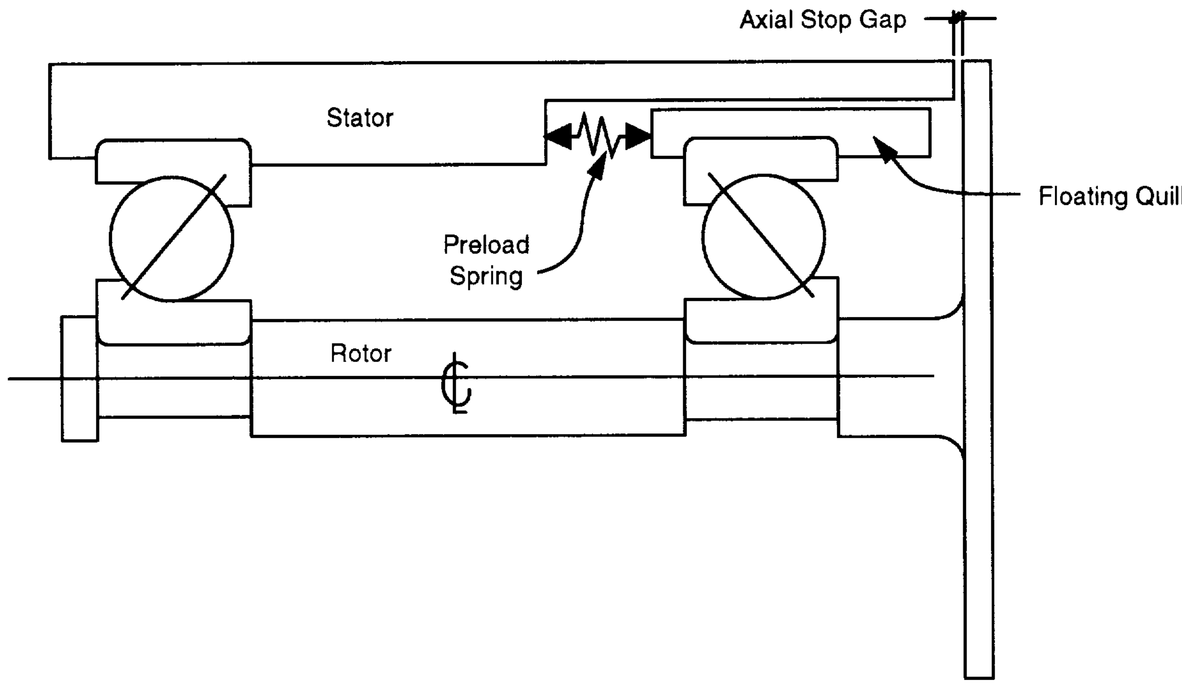


Figure 8. Bearing Preload System Schematic

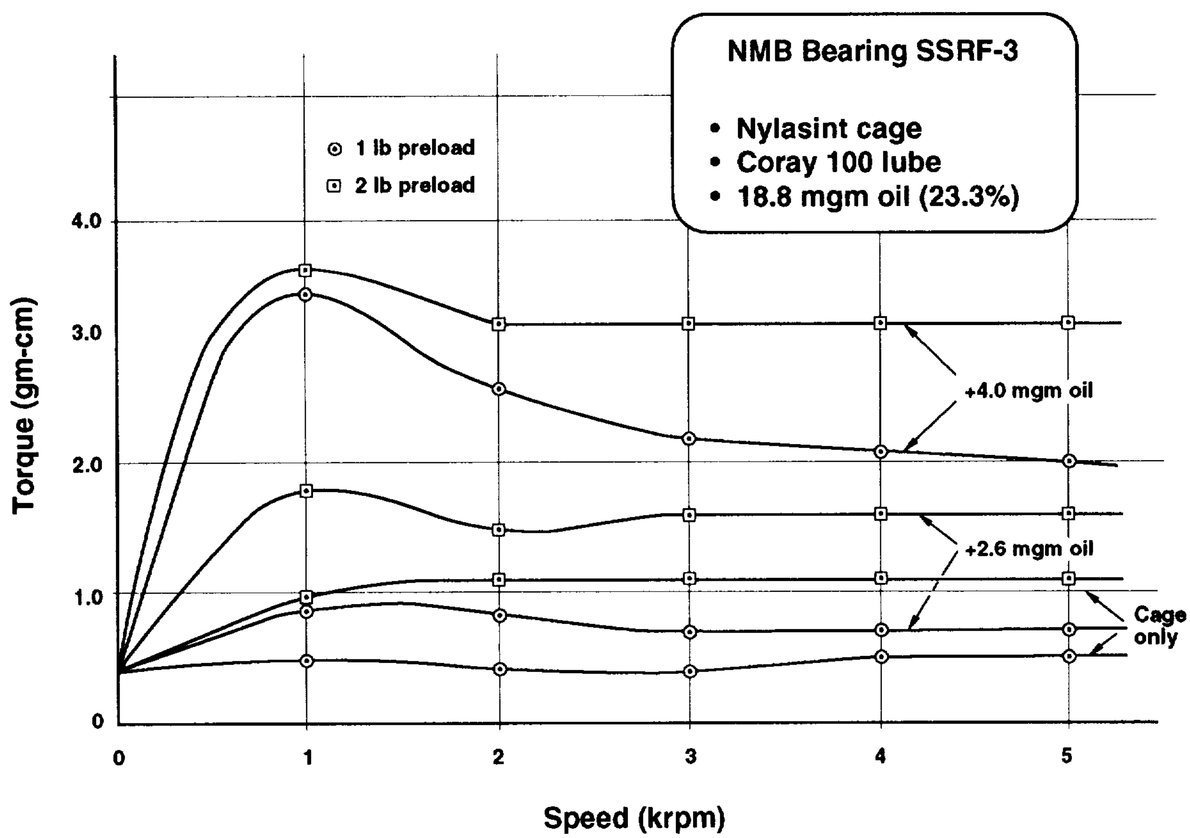


Figure 9. Drag Torque Versus Lubricant Quantity