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THE MECHANISMS OF THE SAMS EXPERIMENT FLOWN ON NIMBUS 7
WITH PARTICULAR REFERENCE TO THE 2 AXIS SCANNING MIRROR

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SUMMARY

The Stratospheric and Mesospheric Sounder (SAMS) experiment on Nimbus 7 which was launched in October 1978 includes a 2 axis scanning mirror and 7 pressure modulator cells. The SAMS experiment is a limb sounding instrument to measure the temperature profile and minor constituents of the atmosphere. The limb scan requires small mirror steps over a 3° range, while the scan in azimuth is in larger steps over a 15° range. The mirror is plane, 20 cm in diameter, and of zero expansion glass-ceramic. It is supported on two tilt tables, fitted one on the other, with the axes at right angles. The angle of tilt is adjusted by means of recirculating ball screws which are ion plated with lead for lubrication and driven by stepper motors.

The seven gas filled cells are each pressure modulated by a 3 cm diameter, 0.3 cm stroke piston which is supported by diaphragm springs and driven electromagnetically at the system's mechanical resonant frequency. The mean pressure of the filling gas, which is the atmospheric constituent being measured, is changed by varying the temperature of a suitable molecular sieve.

INTRODUCTION

This paper describes the mechanisms of an infrared radiometer called the Stratospheric and Mesospheric Sounder (SAMS), which is flying in Nimbus 7 and which was devised by the Department of Atmospheric Physics - Oxford University under Professor J. T. Houghton. It is a development from the Nimbus 6 Pressure Modulated Radiometer which is described in a companion paper (Ref. 1). The Rutherford Laboratory of the Science Research Council provided the engineering design, the mechanisms and the management for this project. The sensor housing and electronics unit was made by British Aerospace (Dynamics Group).

The pressure modulator technique, more correctly called gas correlation spectroscopy, uses cells filled with CO_2 for the temperature measurement, based upon the known distribution of CO_2 in the atmosphere. With the temperature accurately known, other cells filled with gases which are constituents of the atmosphere and stable under pressure modulation will provide a signal which is related to their presence in the atmosphere. This leads the way to a further family of instruments to measure the ozone chemistry of the atmosphere, water vapour, methane and various pollutants such as carbon monoxide.

To obtain the highest resolution, the sounding instrument should look through the limb of the atmosphere to deep space, (i.e., parallel to the horizon) so that the path length is very long and the slice thickness being observed is as thin as possible. The SAMS instrument does this and has 7 pressure modulator cells filled with 6 different constituents. (See Fig. 1 and Ref. 2).

THE SAMS SCANNING REQUIREMENT

To scan the limb of the atmosphere from a satellite at a height of 1000 km, a path length of 3700 km to the tangent is required. A 10 km slice of the atmosphere requires a field of view of 0.16°, which is extended by a factor of 10 in azimuth. The limb scan step is half this, requiring a movement of the mirror of 0.04°. In total, a movement of 1.5° is required for complete cover of the atmosphere, including a view to space for calibration purposes. This movement is doubled to allow for uncertainties in the orbit and attitude achieved.

The limb scan must be normal to the direction of flight and therefore is greatly affected by the roll error and the roll rate of the spacecraft. The error is likely to be more than 3 times the step size specified. However, provided the roll rate is slow enough, the experiment itself, using its CO_2 reference channel, is able to measure the tangent height of its field of view to an accuracy of 0.1 km over the range 43 - 47 km, and is sufficiently accurate down to 30 km. If the scan is wholly outside this range then the roll rate determines how often the mirror is moved within this range and its position measured in order to make a check.

The scan in the azimuth direction is a doppler scan and image motion compensation of ± 15°, requiring a mirror motion of ± 7.5° over a period of 250 seconds. This motion must be very smooth and continuous or in steps at 2 second intervals between signal integrations, which makes the mechanism similar to that of the limb scan system. The step rate required is thus 125 steps, totalling 15° (i.e., 0.12°/step with a flyback rate the fastest possible). When no doppler scan is commanded, only complete scans are required with the mirror facing the half way or zero position.

The SAMS Scanning Mirror

The scanning mirror is a "Zerodur" (similar to CER-VIT) glass-ceramic plane mirror 20 cm in diameter, 1.5 cm thick at its support ring and hollowed out at its rear face to weigh only 450 gm. The flatness tolerance requirement of 2 fringes (Na) per cm is not difficult to achieve. The support arrangement is 3 sectors of invar. Each is bolted with 3 screws and silicone rubber bushes to the inside of the mirror support ring and then moulded in place with silicone rubber, filling the 0.05 cm gap left for this purpose. The invar sectors carry 3 radial titanium pins (120° spacing), each burnished with MoS_2 and clamped to a thick aluminium tube fitted with a small clearance inside the invar sectors, thus forming a kinematic mount. The curing of the silicone rubber distorts the flatness by one or two fringes per cm but the final assembly can be repolished before gold coating without any difficulty. The complete mirror weighs 600 gm.

Scanning Mirror Mechanism

The two axis mirror mechanism consists of two tilting tables, one mounted on top of the other, with the main pivots at right angles to each other as shown in figures 2 and 3. The mirror carrier is an inverted triangular frame, top hung from two pivots at the corners and a jack screw at the lower apex. The stationary nut of the jack screw is flexibly coupled to the carrier and the screw is driven by a stepper motor, moving the nut along the screw and adjusting the tilt angle. The driving motor is connected to the screw via a single dog and is thus readily removable. The motor is supported by pivots to an intermediate frame which also supports the other half of the top hung pivots mentioned above. The limb scan moving assembly weighs 1.7 kg.

The intermediate frame, which is the top of the second tilt table, is supported by trunnions on one side, with the trunnion base fixed to the radiometer housing. The other side of the frame supports the nut of the second jack screw, while the driving motor is supported from the structure in a similar manner to that of the limb scan, thus providing the azimuth or doppler scan. The weight of this moving assembly is 3.4 kg.

All the pivots used are Bendix Flexural Pivots Cantilever Series (crossed-leaf spring flexi-pivots), with the top hung and trunnion pivots being 1.59 cm (5/8 in.) dia., 100-kg zero deflection load units. For the limb scan loads and deflections, these units have a life of over 10^7 cycles and for the azimuth scan loads, 2.5 x 10^5 cycles, which is many years at the duty cycle envisaged. The spring rate for the pair is 3 Nm/radian. The motor support pivots are 1.27 cm (1/2 in.) dia., 64-kg zero deflection load with 1.5 Nm/radian/pair. The nut pivots are 1.27 cm dia. 6.4-kg zero deflection load with 0.2 Nm/radian/pair. The latter were originally specified to be the same type as the motor pivots, but at the maximum azimuth angle the twisting load on the nut was sufficient to back drive the jack screw against the detent torque of the motor. The small load capacity of the nut pivots is not a problem since loads greater than 10 kg or so will cause the motor to back drive. All the 1.27 cm pivots were mounted in bushes arranged so that radial motion was limited to 0.01 cm. The main 1.59 cm dia. pivots were clamped at one end with a key at the other end and burnished with MoS_2, which allowed axial motion with a PTFE thrust washer between the two housings. The key-ways were spark eroded into the thicker walls of the flexi-pivot. This design relieves the pivots of all axial loadings which would cause the spring leaves to buckle. In addition, pegs adjacent to the jack screws enter slots with clearances of 0.03 cm at the position chosen for the launch configuration. The pivots are assembled so that their zero deflection position occurs at this launch position, which is about 40% of maximum travel. Vibration testing for all prototype mechanisms was 20 g sine wave and 13.4 g rms random ($0.09g^2/Hz$), with the sine wave level reduced to 6.7 g for the complete flight sensor unit but with the same random excitation level.

Mirror Mechanism - Jack Screw and Nut

The limb scan step of 0.04° using the longest lever arm possible resulted in a step size of about 0.15 mm so that 8 steps from a 45° stepper motor would give a pitch of 1.25 mm (or 0.05 in). Ball screws are available for these pitch dimensions, and also standard screw threads provide this pitch if nuts of self lubricating materials are used.

Tests were carried out on a ball screw with the screw shaft and nut burnished with MoS_2, but this was not satisfactory. An ESRO report then available confirmed that it could not meet the lifetime required (reference 3). A number of self lubricating plastic materials were tested and the best results and the lowest torque were obtained using PBO3 loaded with 47.5% PTFE by weight and 2.5% MoS_2 by weight. This material available from Yorkshire Chemicals is a loaded aromatic polybenzoxazole. This would work as a second choice using two half nuts, spring loaded, with due allowance for wear and thermal expansion compared to stainless steel.

The solution adopted was to use 1.25 mm pitch ball screws (type ED513/V501 from RMB Switzerland), which use two half nuts in a housing, each with 1½ tracks of 1 mm stainless steel balls (440 C). The half nuts are machined from beryllium copper (hardness Rockwell C39-44) since they cannot have their tracks ground. Each half can be rotated and locked against the other to reduce backlash to a specified value. The shaft is stainless steel (440) and is lead coated to provide long life lubrication. The disadvantage of lead coating is that all testing must be done either in vacuum or with a dry nitrogen purge, since in air oxidation occurs. For each axis of the scanning mirror a cumulative maximum total of 1 hour use in air for setting up and adjustment checks was allowed.

Lead lubrication of ball races for space use is well established using electroplating or vacuum deposition of lead onto the raceways (ref. 4) so ESTL (European Space Tribology Laboratory) was asked if they could apply their ion plating technique to the ball screw to give a coating of lead 0.3 to 0.6 µm thick to the screw thread. We were considering coating the nut as well as the screw, but the nut material (Berylco 33-25) is a good bearing material. Also reference to some other development work then being completed in the UK (ref. 5) showed that the torque is increased by about a factor of two with the nut and screw plated compared with the screw only.

The ion plating process at ESTL Risley uses oil free vacuum pumps and gives a final clean to the screw by ion bombardment for a period of 30 mins followed by lead evaporation for 1 minute. The throwing power of the method is high because the plating is done at a pressure of ≃1Pa(≃7.6µm Hg) of argon. With the screw in a horizontal position under the electrode, it was found that due to gas scattering the thickness limits specified could be achieved without the necessity of rotating the screw into a second 180° position. Dummy shafts were coated to establish the optimum ion current, times and accelerating potential, while electron probe analysis provided the thickness measurements. If the design had been able to allow a 1.5 cm length of screw which was not travelled by the nut when in service, it would have been possible to coat an assembled ball screw unit with the nut moved to the unused portion and masked off. In our case the shaft and nut had to be returned to RMB in Switzerland for reassembly.

After reassembly the ball screws felt lumpy, rough and 'gritty' with peak torque figures of 2.8 mNm (28 gcm) and minimum figures of 0.2 mNm (2 gcm).

After running in air slowly for 10 complete travels of the nut up and down the screw in an unloaded condition, the torques were reduced to an average of less than 0.4 Nm (4 gcm) with peaks reduced by at least 2 but with little difference in the actual 'feel' of the assemblies. Some black powder (no doubt lead and lead oxide) could then be seen on the screw. All work was done under Class 100 clean conditions, and it is a fault in the design that space did not allow the ball screws to operate inside of bellows or telescopic tubes since it is a prime design requirement to protect the ball screw from external contamination and from wear debris from the bearing assemblies. Unfortunately one unit was damaged after initial use by being jammed by a sliver of 'Solithane' compound used to lock access panel screws, and the unit allocated to a life test program was installed in its place.

These ball screws can be supplied with backlash as little as 2 μm. For the above use the backlash specified was 10 μm since the spring loading of the main flexi-pivots over the limb scan range, where it mattered, was all in one direction to take up any clearance. This provided repeatability of each step position. The 3° limb scan movement required from this ball screw was extended by a further 2° so that a quasi-vertical earth view position (actually 70° to the local earth vertical) could be selected. This is a single commanded position and no scanning is required over this additional movement.

Stepper Motor

The requirement for the stepper motor is: 45° per step; running torque at 40 steps per second 0.085 Nm (1.2 oz in) min; stall torque 0.127 Nm (1.8 oz in) min; zero input detent torque from permanent magnet rotor at least 0.02Nm (0.3 oz in) to resist flexi-pivot loads plus normal gravity loads during all test orientations. The rotor inertia plus the ball screw inertia is the major component of the accelerating torque, and motors are available with rotor inertias of less than 1.2 gm cm^2. The above ratings are based upon a 24 volt 4 phase system. The mirror must be able to step at least 4 limb steps (i.e., half a rev of the screw) in 175 ms including settling time.

Two motors met these requirements and were tested, but the more efficient motor of the two (65 ohms/phase compared to 30 ohms/phase) had a difference of about 3° between the energised and the non-energised detent positions, and this movement occurred at the end of the 175 ms period. The other motor was therefore used (IMC 011-869) and supplied with 'BarTemp' bearings and spring washers to provide some preload and differential expansion take up. No axial load is carried by the motor because of the driving dogs coupling the shaft to the screw. Thrust of the screw is carried by a preloaded duplex 'BarTemp' bearing at the motor end of the screw.

Mirror Position Control

The position of the mirror is monitored in each axis by means of a linear variable differential transformer (LVDT) coupled alongside each ball screw. The maximum and minimum limits of travel are controlled by optotransducers with mechanical stops outside these limits. The limb LVDT is connected to a 14 bit triple-slope integration type analogue-to-digital converter and, when corrected against the LVDT's temperature coefficient, gives a system resolution of 7 x 10^{-6} radians (1.5 arc secs) in mirror position (i.e., 1/100th of a step). The azimuth LVDT is a simpler system to give a resolution of 2.5 x 10^{-4} radians (1 arc min) independent of temperature over the range 10 to 20°C.

The scan is controlled in each axis by stored programs which can be loaded into a memory by ground control, and a back-up mode allows the mechanism to respond to single step relay commands. The program instructions are converted to "step and settle" pulses to the stepper motors under control of clock signals, and the limb motion can be set to any position within the 3° range or down to the earth view opto-controlled stop. Periodically (usually ten times per orbit), the mirror is driven to the other end of the scan for a space calibration and the drive is limited by the opto stop. Should any steps be lost, the control will reset correctly to this position. Full travel excursions are also introduced to even out the lead coating. Scans always commence at the end of the 1.8 second signal integration period, and if the number of steps is such that they exceed 0.2 seconds, then the data from the next period(s) is ignored. The block diagram for these controls is shown in figure 4 which is a schematic of the complete radiometer.

PRESSURE MODULATED CELLS

The SAMS radiometer incorporated 7 pressure modulator cells filled with 6 different gases operating with mean pressures up to 50 mbar. The design is a development of the Nimbus 6 PMR units. However, the higher pressures demand a more efficient drive system, so a moving coil with an internal ring permanent magnet not unlike a loud speaker drive unit is used. With the higher pressures, a smaller head path can be used so that compression ratios of up to 3 are obtainable. The pistons are 3 cm dia and a peak stroke of 0.3 cm is required. The drive shaft is supported by two beryllium copper diaphragm springs but the constant stress springs used before do not provide sufficient radial stiffness so that the reduction in radial width is limited to a ratio of 2:1 (max. to min.) and this, with a radial gap at the piston of 0.005 cm, allows the cells to operate normally for bench testing with the cylinder axis horizontal.

The pressure modulator assembly is shown in section in figure 5. An extension to the shaft that carries the piston and the coil is seen, which carries a soft iron slug. This extension passes into the end plate where it is surrounded with a coil system which constitutes a differential transformer position sensor. Oscillation is maintained at constant amplitude and at the resonant frequency, which varies from 25 Hz (evacuated) to 50 Hz (40 mbar pressure), by a control loop coupled to the position sensor. The loop can also be switched into a negative feedback mode to inhibit piston motion since up to three PMCs are in the same optical path to a single detector and only one is measured at a time. The mean gas pressure is again controlled by molecular sieve material with the thermostat settings controlled by the program control unit. Piston frequency is used to monitor cylinder pressure and is measured and telemetered to 1 part in 6000. The various gases used demanded extensive development to determine the choice of adhesives and materials that will not outgas, will not absorb, and will not corrode with the individual filling gas. Molecular sieve materials had to be found that with a volume of a few cm^3 (2 to 6 gms) would give the pressures required for the various gases within a temperature range of 30^oC to 100^oC. Finally, each assembled PMC has an extensive schedule of bakeout, vacuum pumping, leak testing and filling.

OTHER COMPONENTS

The other mechanisms included in this radiometer are a vibrating reed chopper driven by redundant pairs of piezo-electric ceramic plates and covering 10% of the view. A small black body target is switched into the focus of the primary optics by means of a 90^o stepper motor (IMC 008-845) with a spring and powered return. The cooler door release latches are operated by rotary solenoids. The Sensor and electronics module weighs 26 kg and consumes 25 watts.

CONCLUSION

Nimbus 7 was launched on 24 October 1978 and now after 14 months the SAMS mechanisms are still operating faultlessly. The mirror was operated only in the limb scanning mode for the first six months and then the azimuth scan was operated for the first time apart from the centering operation after launch. The repeatability and precision of the mirror movement has exceeded our expectations and meets its specification more than adequately.

The limb scan has now executed over 30 million steps mostly over a 25% length of the ball screw. The use of ion-plated lead as a solid lubricant for use in space, particularly for recirculating ball screws or for ball races for rotation over small angles, has been proved satisfactory provided that occassional excursions to the maximum limits are made to even out the lead coating.

The use of crossed spring flexi-pivots has been demonstrated, but the design must incorporate mechanical stops to limit motion under launch and test conditions. Vibration loads at launch must be accurately predicted or the chosen pivots must be very conservatively rated, well within the manufacturers recommendations. The fatigue lifetime must be many times the experiment life required. It may be necessary to clamp the pivots during launch or otherwise off load any axial loads from the flexi-pivots.

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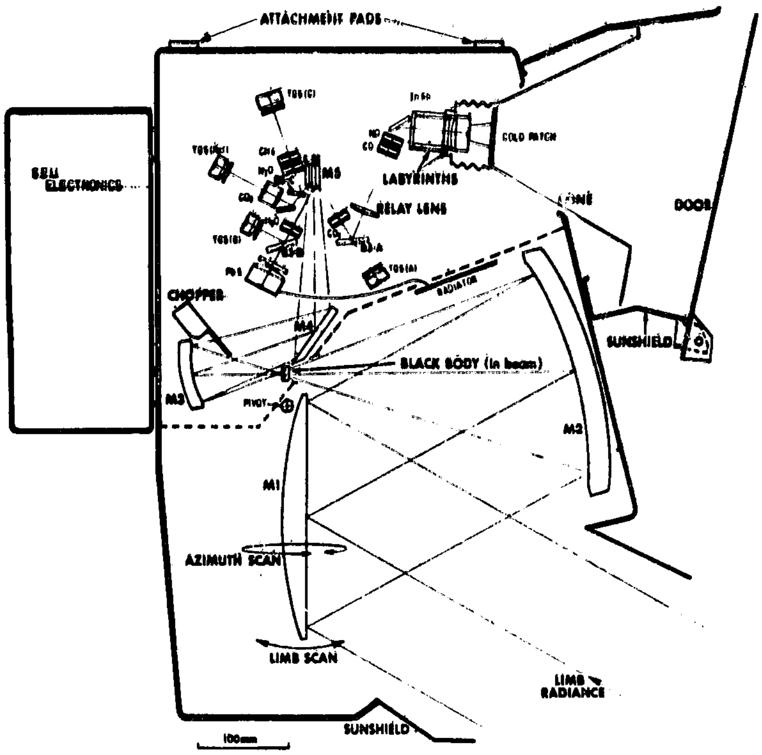

Figure 1.- Stratospheric and mesospheric sounder on Nimbus 7.

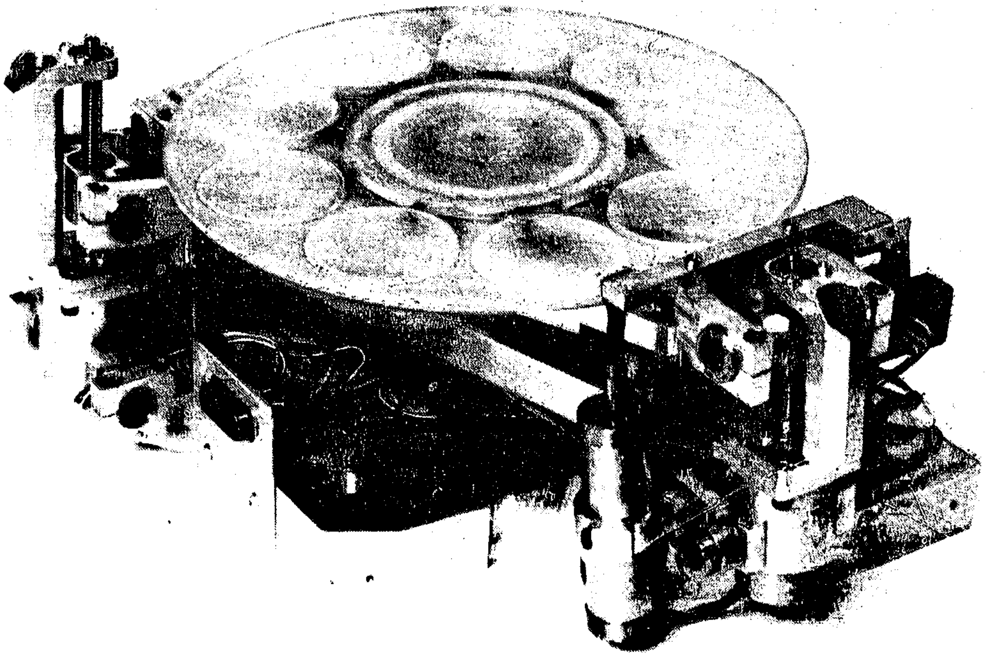

Figure 2.- Scanning mirror mechanism for SAMS (uncoated and on vibration jig).

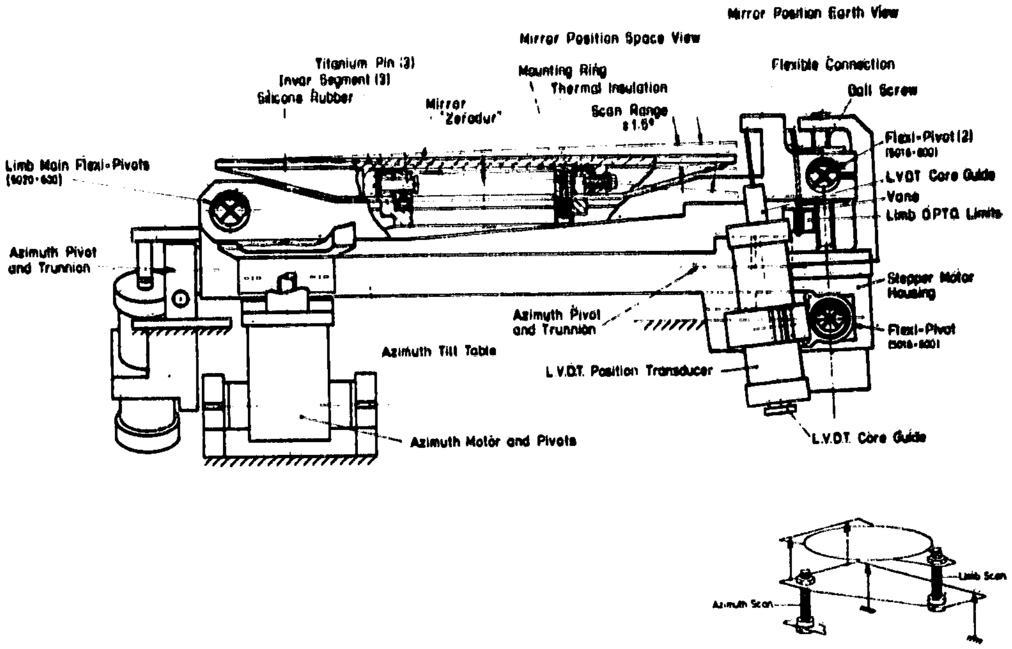

Figure 3(a).- Details of limb scan movement.

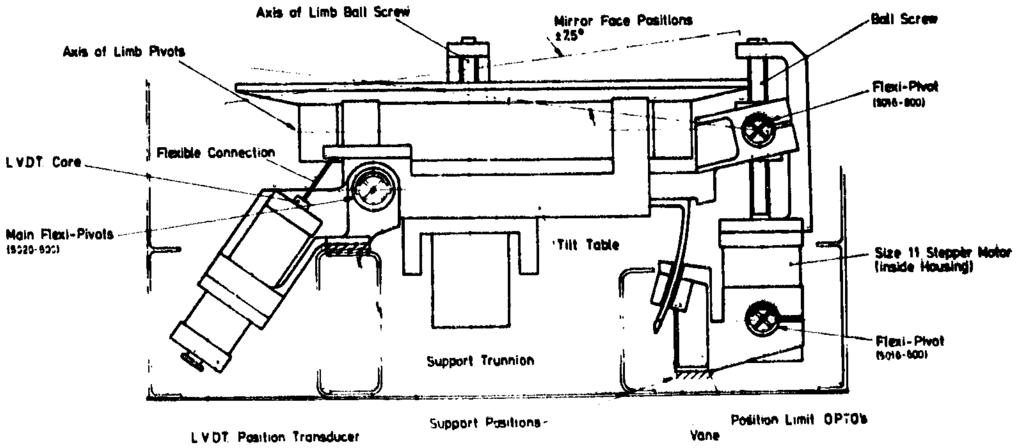

Figure 3(b).- Details of azimuth scan movement.

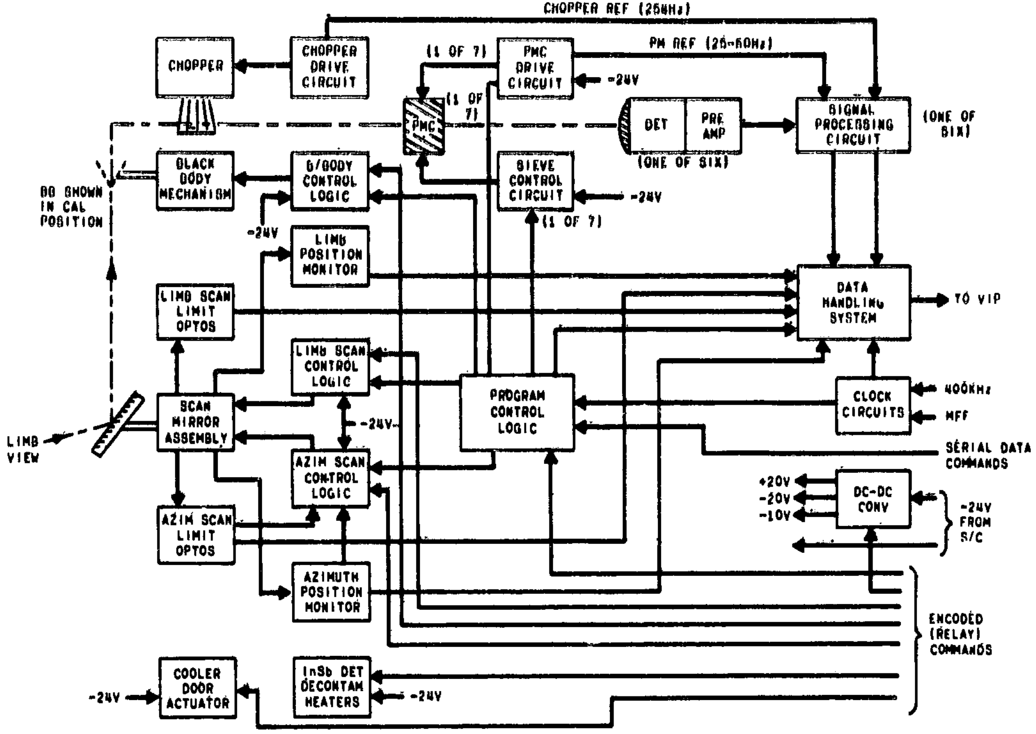

Figure 4.- Block schematic of SAMS radiometer.

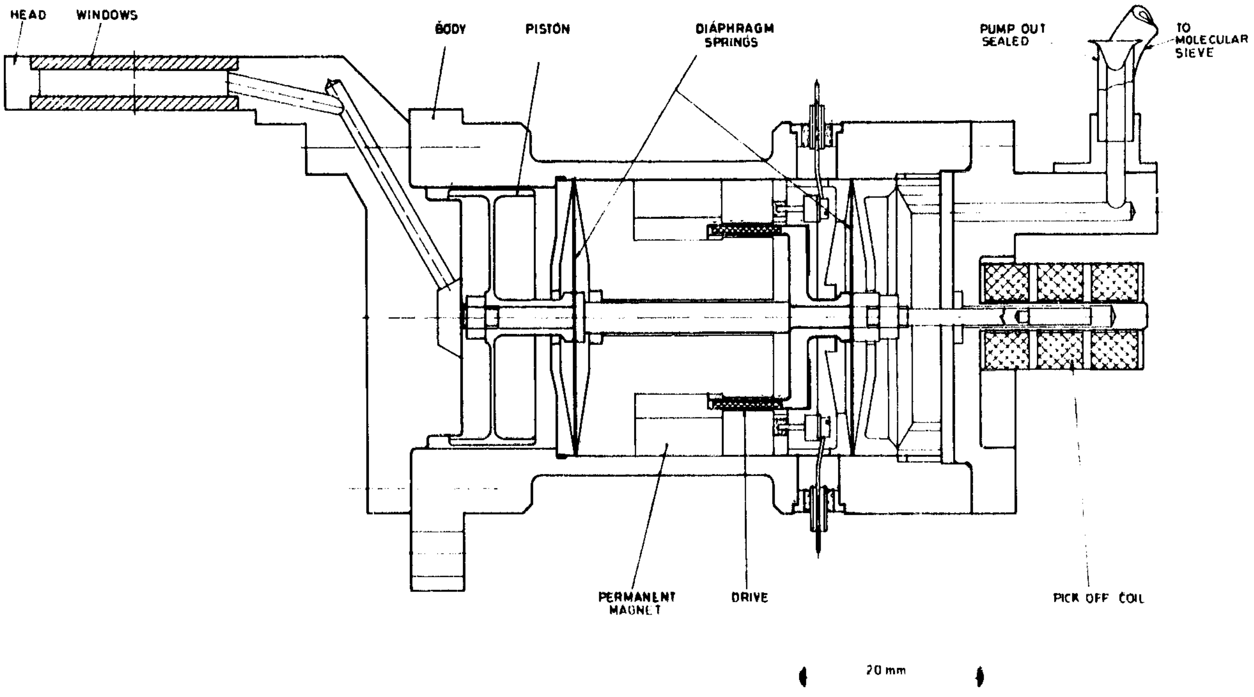

Figure 5.- Pressure modulating cylinder for SAMS.