N90-22082

SPOT 4 SPACE MAGNETIC RECORDER MECHANISMS

A. BORRIEN* and E. VIALATOUX*
J. L. LHERMET** and A. DIDIER**

ABSTRACT

The French National Earth observation program "SPOT" will enter into a new phase with the SPOT 4 satellite.

The design of this satellite will be quite different from the previous ones. One of the main new parts is the magnetic tape recorder that has been developed by Schlumberger Industries for the French Administration.

This paper presents the design of the magnetic tape recorder, which was derived from industrial knowledge and mission requirements; the main technical characteristics of this recorder; and the mechanical subsystems of the recorder and their locations and contributions to the final performance. The philosophy of the development program, required to achieve the desired performance and reliability for each flight model, is described, and information on the schedule and current development is presented. The components of the tape plate system, which are subjected to heavy mechanical operation, fatigue, and wear in the thermal environment of the mission, are discussed. These three specific system components are described:

- transmission belts
- tape rollers of the recorder
- reel hub ball bearings

For each of these components, a description of its function in the recorder is given, as well as the mechanical stress imposed during the various operational phases. These aspects directed the technical approaches taken during the detail design.

The qualification testing program, which was used to verify the design safety margins, is described. Finally, the first test results of a functioning model of the flight system are presented. These results demonstrate the operation of the mechanical systems under simulated mission environmental conditions.

*Centre National d'Etudes Spatiales Toulouse, France
**Schlumberger Industries Velizy, France

INTRODUCTION

Obviously, an earth observation satellite must be able to fly over any part of the world. However, it only can transmit its pictures when in the visibility of a ground station. Because of the number of stations and their geographical locations, the satellite needs to store these data and restore them later. The storage of high quality pictures requires a large memory capacity and, therefore, the use of a numeric recorder.

Schlumberger Industries has worked for many years in the field of magnetic recorders and has built machines with a tape density of 33,000 bits per inch, magnetic heads with 42 tracks in one inch, and a bit error rate better than 10^{-7}. These recorders are very often used in European industrial centers, in satellite ground stations, and in mathematical centers. Schlumberger has designed different prototypes for avionics, marine, and submarine applications in the United States and Europe. This great competence, acquired from laboratory experience and on-board machines, has allowed this company to study and design a space magnetic recorder for French programs. A version of this recorder has been adapted for use in the SPOT 4 program satellite under a CNES contract. This equipment is composed of two boxes. The first box contains the signal treatment electronics, the electrical interfaces, and the detection and error correction code. The second box, which is pressurized and sealed, contains the mechanical system (see fig. 2). As for all satellite mechanisms, the Space Magnetic Recorder (SMR) has to satisfy the reliability requirements of the satellite mission.

THE SMR CONCEPT

The SPOT 4 mission is characterized by its life duration in orbit of four years, associated with an 1800-hour recorder operation life time. The actual earth-imaging is achieved by a sequence of very short frames, which leads to a great number of start-stop sequences for the recorder (in the order of 45,000 cycles). The SMR design reflects the need to survive the severe vibration constraints imposed by the launch phase.

The quantity of information to be stored requires a digital recording in the order of 50 Mbps and a total capacity greater than 100 gigabits. The quality of the images obtained is directly related to the bit error rate (BER). The use of the high-density digital record mode, in the order of 20,000 bits per inch, is associated with an error correction code permitting the achievement of BER performance better than 10^{-6} during the recorder's life cycle.

This advanced performance is obtained for recording and playback by means of linear magnetic heads with very narrow track width (280 microns) on a magnetic tape 3300 meters long (on a reel 380 millimeters in diameter) winding at a constant speed and tension with very high stability. The magnetic tape consists of a polyethlene terephtalate (mylar) base, a polyester urethane and carbon backing, and a front surface of an oxide iron pigment (F_2O_3).

Due to its nature, exposure in a vacuum is forbidden. Moreover, the performance of the recorder is directly related to the friction of the turning mechanisms (ball bearings). The current technique of lubrication with an Andok C type grease is a proven technique. The use of a solid lubricant, such as MoS2, would be incompatible with the performance objectives and with the life cycle of the mission. It is therefore necessary to enclose the magnetic tape and the transport mechanisms in hermetically sealed enclosures, pressurized with nitrogen (about one bar). The magnetic tape and head interface possess an optimal temperature range and humidity level that requires active thermal control within the container.

This enclosure must guarantee a perfect leakproof condition during storage on the ground and during the mission in order to ensure the mechanical interface between the tapedeck and the satellite platform and to provide for thermal exchanges in orbit.

The principal part of the recorder tape deck is a mono-block transport with coaxial, counter-rotating reels supplied with a double capstan loop in which the magnetic heads are situated. This configuration responds to the need to minimize the variations of the kinetic moment in orbit and to guarantee a very weak winding error (flutter), while creating a zone of high tape stability in the vicinity of the magnetic heads.

THE MECHANICAL FUNCTIONS

The mechanisms required to reel and wind the magnetic tape must accomplish three main functions, specifically, the guidance of the tape during its winding, the tape tension servo, an the tape speed servo. The guidance is an essential function of the recorder. In fact, the performance of the recorder depends on the transversal stability support and on the position accuracy between the forward operation used while recording and the reverse used in reading. The selected coaxial reel's geometry necessitates two parallel reeling planes and requires an inclined plane to allow the magnetic tape to pass from the low plane to the upper plane. This plane change generates some threading constraints that are minimized by the geometry of the tape path. On these reference planes are mounted the winding rollers that guide the magnetic tape in a very precise manner. The capstans have an essential role in the winding. Their geometric precision must be excellent and the pairing of their diameter must be better than 2.5 µm. The pollution coming from the magnetic heads in contact with the oxide and from the rolling friction is a source of errors. The elimination of this pollution is achieved by two cleaners placed on both sides of the heads. The oxide from the magnetic tape is continuously rubbed towards the twisted fibers of a cleaning tape driven by a motorized device programmed in advance.

The tension servo, maintained by the reel motors, guarantees a constant tape tension as the tape passes from one reel plane to the other. This servo is established by coaxial reel holders driven by a synchronous belt and direct current servo motors.

The tape tension at the reel input and output is regulated by the means of spring sensors which provide a tension reference. A braking mechanism of metallic strapping, associated with the tension spring/sensor system, is activated at each stopping of the recorder and the emergency condition of an accidental power loss. This device avoids the creation of tape loops that would jeopardize the mission. Finally, a mechanism locks the two reels at launch.

The speed servo is implemented by means of a double capstan loop that helps change the plane of the tape path. Each capstan is driven by a servo motor of the same type as those of the reels. These motors are equipped with a disk encoder and an optical electronic unit, providing the tachometer function. The capstans also serve to ensure magnetic tape guidance and winding at a constant speed (flutter less than 0.5 percent). They also provide a local increase in tape tension, which helps eliminate any external mechanical disturbances from this zone.

MAIN CHARACTERISTICS AND DESCRIPTION

The main characteristics of the machine are listed in Table 1. The mechanical packaging is composed of an airtight box, the tape plate with all mechanisms, the power supply, and the control loops electronics. This packaging weighs 95 kg and is 700 mm in length, 600 mm in width, and 410 mm in height. The power consumption is 180 W-hrs and occurs in the reproducing mode. The SMR can be operated over a small range of temperature (+10 °C, + 40 °C).

There are numerous mechanical components throughout the machine. There are more than 100 ball bearings of different sizes, 8 electrical motors, 2 synchronous belts, 2 optical encoders, 12 tape rollers, 10 angular position sensors, springs, and a wide range of precision-machined parts. For a reliable design and the best mechanical performance, numerous materials are used. Common materials such as aluminum, magnesium, and titanium alloys are used. However, also incorporated are unusual space mechanism materials such as "numetal" (iron-nickel), cast steel, copper, polymers, and elastomers. Some of these materials are covered with a surface treatment of molybdenium disulfide, anodic oxidation, passivation, nickel plating, or chromium plating. New manufacturing and assembly techniques have been studied and space qualified for this program; for example, chromic anodic oxidation on magnesium.

MAIN STEPS OF THE DEVELOPMENT PLAN

The development of SMR proceeded along the following steps:

Concept Development of All Mechanical Functions and Associated Components

This phase consisted of technology validation programs for the manufacture and assembly of parts that require the use of special materials, often unknown to the European space industry. This was the case, for example, for the reading heads and the capstan motors.

Some components, such as belts, are mass produced for ground applications; manufacturers have only incomplete technical data on them. This situation led to numerous evaluation tests with many samples.

This phase ended with a functional analysis and FMECA on the whole mechanical architecture of the machine. These analyses allow the identification of critical components.

Qualification of Critical Components and Functions

This key phase gives the knowledge of safety margins in accordance with mission requirements. Before the beginning of qualification tests, is is important to ensure that the flight components are exactly the same as the test components, and that the same manufacturing and assembly procedures are used.

It is also important that each component be tested in the same environment (mechanical, thermal, electrical, atmospheric) as it will see in flight. Several functions are distributed in different parts of the machine and only a test with a representative model gives significant performance and lifetime results. That is the case for the rollers, the tape-head interface, and the emergency braking mechanism.

These components are tested on a model very close to the flight machine. Software and hardware installations around the test machine must also be very close to flight standards.

Identification Step

The objective of this step is to demonstrate that, in space conditions (vibrations + orbital lifetime + mission cycles), the BER is less than 10^{-6} for the entire mission life. These tests also validate the control loops of tape tension and tape speed, the cleaning of the tape and, the braking and the locking mechanism.

CNES has decided to conduct three global tests on three machines. With these tests we can, experimentally, check theoretical studies and investigate reliability. This is necessary due to the relative inaccuracy of theoretically calculated results in the field of mechanics.

Manufacture and Acceptance Tests

Flight models have to undergo acceptance tests in order to avoid "premature breakdown" and to be declared "fit-for-flight."

Philosophy of Development Steps

To follow the whole development cycle step by step, will require too much time and will be incompatible with the SPOT 4 program schedule. On the other hand, to conduct phases in parallel will inevitably result in premature decisions and tends to expose the program to dramatic consequences. The aim, then, is to find the best overlap between phases and to put in place some technical "go aheads." For example, to begin the parts qualification, it is necessary to have the knowledge of the following documents:

- calculation notes and definition plans
- mission profile
- FMECA (failure mode effects and criticality analysis)

The analysis of these documents involves results which are combined to define critical elements and to stipulate corrective actions. Critical mechanical aspects are gathered in nine categories:

- vibrations during launch
- thermal stresses
- in-orbit lifetime
- ground storage
- aging
- pollution sensitivity or emission
- technology sensitivity
- manufacturing divergencies
- assembly and adjustment procedures

Qualification plans have to demonstrate the good behaviour of components for all identified critical aspects. Manufacturing criticality analysis leads sometimes to procedural improvements and to define key points for sensitive operations. The beginning of the identification step occurs necessarily before the end of qualification because the storage and aging tests are incompressible. Decisions are based on partial results, knowing that the final results could impact the design of flight models. The decision to start manufacturing flight models requires the careful conclusions of all the qualification test experts.

State of Development

Today, seven flight models have been ordered for planned French earth observation missions. Qualification tests on component lots are still going on. Tests on representative models have been done and have validated:

- tape-head interface
- vibrations behaviour
- BER performance over the thermal range
- control loops for speed and tape tension
- mechanisms lifetime

The first test on an identification model began in 1989. Vibration qualification was accomplished in July 1989. The electronic cards acceptance tests are currently in progress. These tests will be followed by life cycle endurance tests. All mechanical components for all the flight units have been almost fully procured.

TRANSMISSION BELTS

The Role of Belts

The first function of the drive belt is to allow the electric motor to drive the reel hub shaft, through a speed reduction, allowing the use of a smaller motor. When the machine is in the reading or recording mode, the belt has to guarantee a smooth takeup of the tape and a constant tape tension. When the machine is in the stop or startup mode, the belt must resist the transient stresses due to the kinetic momentum variation and not disturb the control loop (see fig. 2). In case of an electrical power failure, the emergency braking device introduces a high friction torque to avoid unrolling of the tape, and puts a high traction to the belt. The second function of the belt occurs during launch. To lock the reel hub and avoid tape destacking, a steel strap is taut on the toothed pinion belt, and the friction between strap and belt must prevent any rotation of the reels.

Design Requirements

The mission imposes a high reliability for any component for which a single failure leads to the loss of the recorder. Mission requirements are:

- emergency braking : 24 ground activations + 8 flight activations
- locking activations : 8 ground activations + 1 launch activation
- ON/OFF cycles : 45,000
- lifetime operation : 200 hours on ground + 1,800 hours in orbit

Other requirements are derived from the actual mechanical design:

- belt sliding is forbidden, thus a synchronous belt is used
- motor size and tape speed require a high transmission ratio
- the compact requirements necessitate a nonstandard transmission size
- the belts directly affect the final performance of the tension control loop

Therefore, the dynamic disturbances generated by the transmission have to be low and the belt must have good rigidity and damping behaviour. To satisfy all these requirements, polyurethane synchronous belts (SYNCHRO FLEX), reinforced with a steel wire manufactured by Continental, were chosen. These belts have the following qualities:

- synchronous drive
- no relaxation
- good wear resistance
- small size
- high power transmission
- low pre-tension; thus, low load on bearings
- high transmission ratio

- high resistance to overloads
- small pitch; thus, smooth transmission

Evaluation Program

The belt design development described above led to the identification of sensitive parameters and performance of elementary tests. These tests give us the knowledge of functional limits and a first estimation of safety margin. Moreover they help to determine the critical parameters list for the hardware and to optimize the preparation of the qualification program, especially for the definition of a representative mechanical environment, the choice of sensors and measurements, and identification of acceptance criteria. This approach led to the identification of the following tests:

- static characterization
- traction on the belt
- traction on the steel wire
- shearing of belt teeth
- cycle fatigue testing
- alternate overload cycles up to rupture

Results

Belt tests have pointed out the following critical parameters:

- pollution : scraps of polyurethane and aluminum dust coming from belt and pinion are scattered throughout the mechanism at the completion of the life mission time.

- steel wire hooking in the polyurethane matrix : the external turn of the reinforcing wire may get outside the polyurethane matrix.

- failure mode of belt : tearing of tooth belt due to crack progression on tooth root.

- failure mode of pinion : indentation and wear of the tooth tip due to friction on steel wire after erosion of the polyurethane matrix.

- life time : experimental margin seems to be comfortable for mission requirements.

- static characteristics are not crucial.

The evaluation program has confirmed the belt design obtained by analysis: (see fig. 3)

belt length : 500 mm
belt width : 6 mm
belt pitch : 2.5 mm
pinion teeth : 24

wheel teeth : 151
ratio : 6.29

Manufacturing Improvements

Manufacturing of the belt qualification lot began after the end of the evaluation program and the expert analysis assessment. To avoid the protrusion of the wire from the polyurethane matrix during life, the following actions have been proposed to the manufacturer:

- winding the wire around the mold at reduced speed in order to have a regular wire turn pitch
- final quality control using X-ray inspection

To minimize manufacturing variations, it was decided to always use the same mold for all belts. To this end, a new mold has been constructed for this application. All the wire is taken from the same reel and is tested at regular intervals. To prevent from mixing evolution, all the belts have to be manufactured from the same polyurethane batch material. Samples of the polyurethane are cut off after polymerization to check the chemical characteristics. The final acceptance of the belt lot is given after mechanical tests have been completed on several belts, as mentioned in the evaluation program. The whole lot can be rejected if the results are not consistent.

Qualification Plan

The reliability required for this component and the dramatic consequences of a failure required the test evaluation of a larger sample of belts. As the lot contains only about 80 belts, the number of destructive tests must obviously be limited. The following summarizes the qualification programs:

- 28 belts are randomly selected for qualification. Both visual and binocular inspection and weighing are done to have a reference condition .
- 10 belts are destroyed with:
    - teeth shearing
    - chemical analysis
    - wire and belt traction
    - fatigue
- 2 belts are mounted on a demonstration model of the recorder mechanisms for vibration testing.
- 10 belts (8 + two previous ones) are mounted on simplified models to expose them to a representative mechanical environment : reel and tape inertia, braking loads, speed variation.

- 8 belts are used for storage : 4 of them are stored under tension and the other 4 are stored in a relaxed state. The storage lasts at least 4 years.

TAPE ROLLERS

Tape Roller Function

The tape rollers are used for transition of the tape from one reel to the other and guarantee the transverse stability of the tape during reading and recording sessions. There are 12 rollers on a machine and each of them has a specific role (see fig. 1). Two rollers guide the tape at the reel entrance or exit. Four rollers allow the transition between the two reels planes and are, for that reason, slightly tilted. Two other rollers guide the tape towards the capstans. Just before the reading heads, two identical rollers located on the capstans motor axis provide a constant drag on the tape. Lastly, two rollers are mounted on the tape tension sensors. They are movable and are part of the tape tension control.

Tape Roller Requirements

The rollers present some critical design constraints. They must rotate during more than 2,000 hours of operation at 1,000 rpm and endure 45,000 start/stop cycles, without damaging the tape by wear pollution, lubrication pollution, or adhesion while the recorder is in stand by mode. The mission life cycle for each roller is approximately 1.5×10^8 revolutions (see fig. 4). A primary concern is the problem of sliding between the roller and the tape when the recorder starts and stops. This sliding increases the wear. It is very difficult to avoid sliding on every roller because of the contact angle, which can vary from 18° to 210° depending on the location of the roller on the tape plate. Additionally, some rollers are in contact with the oxide side of the tape while others are in contact with the back side. Thus, two different tribology and wear mechanisms act on the roller coating.

Rollers Design

To define the best roller geometry, material, and coatings, a test program was implemented. Delrin and aluminum alloy were tested. Aluminum was better for machining accuracy. The wear volume was measured by superposition of the roller profile before and after the test, and by calculation of the area between the two curves. Worn surfaces analysis gives the shape of profile accommodation. Three shapes can be achieved : bi-conical shape, cylindrical shape, and barrel shape. Tests show that the cylindrical shape gives the best results. After a literature search, two surface coatings were selected for evaluation; specifically, a chromic oxidation coating with a 5-µm depth and a hard anodic oxidation coating with a 25-µm depth. Two similar endurance tests on two recorders have been conducted. The choice criterion is based on transverse stability performance of the tape, wear volume generated by the rollers, and pollution analysis. An optical monitoring technique was employed to check the stability of the tape and detect local substrate appearance. The test was divided into three stages with intermediate wear measurements obtained without hardware disassembly. An evaluation was made after 70,000 start/stop cycles and 2,200 hours. The two coatings demonstrated good performance for transverse stability, while wear volume was less with the chromic anodic oxidation coating.

Based on these test results and the fact that the thermal characteristics of the anodic coating are more well known to Schlumberger, the chromic anodic oxidation coating was chosen for the roller coating.

Manufacturing Improvements

Consistent manufacturing results for both the qualification and flight rollers must be achieved. Material uniformity is obtained by tooling every roller from the same bar of metal. Chemical and ultrasonic checks are conducted on the raw material. The machining process includes thermal treatment, and several samples are preserved for coating analysis. These samples are cut into sections and, then, the depth and the adhesion of the coatings is inspected under a light microscope. The diameter, the profile accuracy, and the roughness are carefully measured on each roller to detect any geometrical variation or distorsion due to thermal surface treatment. The assembly and adjustment procedures have been developed to allow precise reproducibility of the tape transverse stability on each recorder.

CONCLUSION

Schlumberger Industries has manufactured the first European Space Magnetic Recorder, with the collaboration of Sextant Avionics and to CNES requirements. Due to the complexity of the tape plate mechanisms, many single-point failure modes exist. To provide more assurance of mission success, through redundancy, two recorders shall be placed on the satellite. The success of this enterprise is dependent on good coordination between various professions : mechanics, electronics, magnetic science, and thermal and computer science. The first in-orbit operation is scheduled for 1993.

CHARACTERISTICS OF THE SPOT 4 RECORDER

RECORDING CAPABILITIES Two channels at Total capacity	 25Mbits > 100 Gbit
REPRODUCE PERFORMANCE Reverse direction only Bit error rate	 $< 10^{-6}$
PHYSICAL PARAMETERS Operating temperature Mass Power requirements	 10°C < 40°C 130 kg 160w (record) 220w (reproduce)
LIFE TIME Life time in orbit Tape running hours Head life Start/stop	 > 4 years > 1800 hours > 8500 km > 45 000
RECORDER CHARACTERISTICS Tape width Reel diameter Tape length Record/repro speed	 1 inch 15 inch 3200 m 1,35 m/s

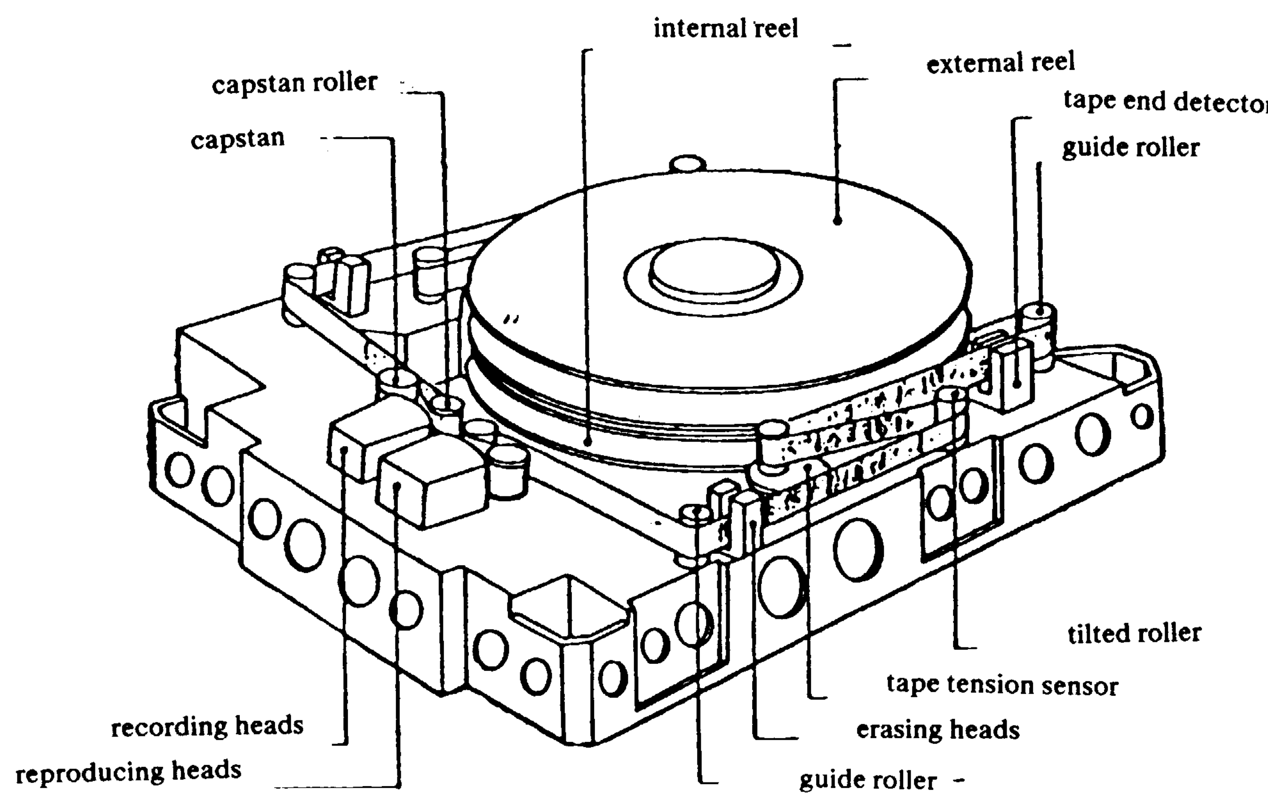
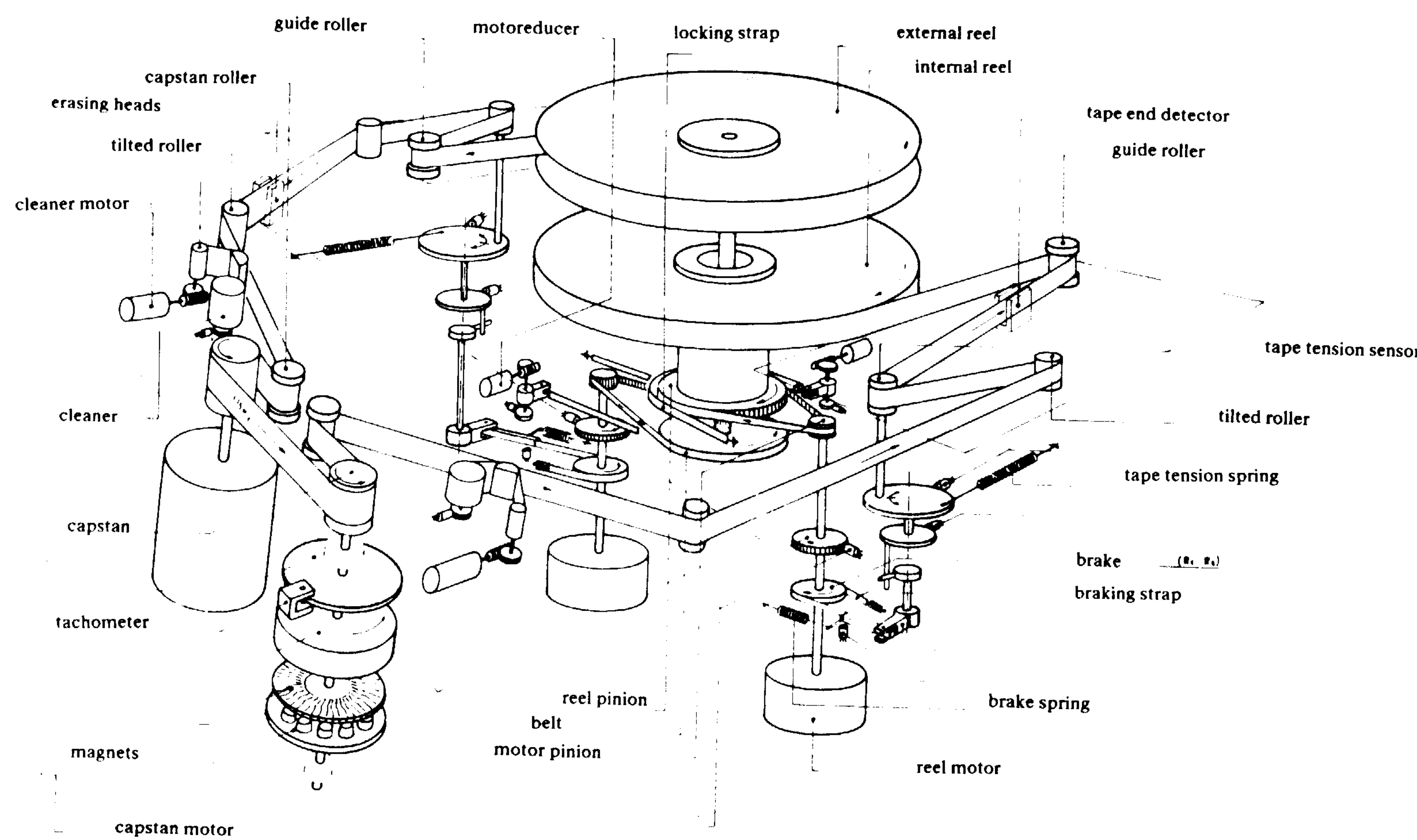


FIGURE 1 : Space Magnetic Recorder (S.M.R.) - Mechanical part

FIGURE 2 : Internal view of the running tape mechanical part



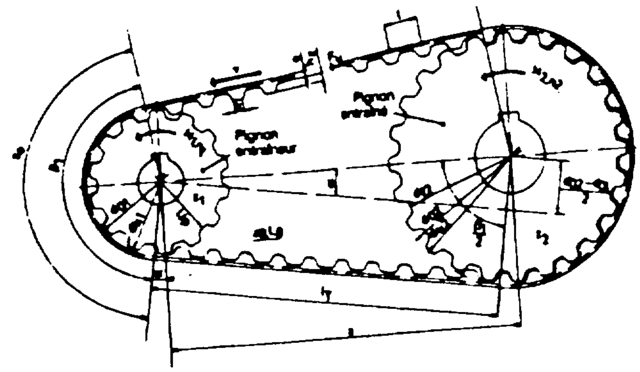


FIGURE 3 : Synchronous belt transmission

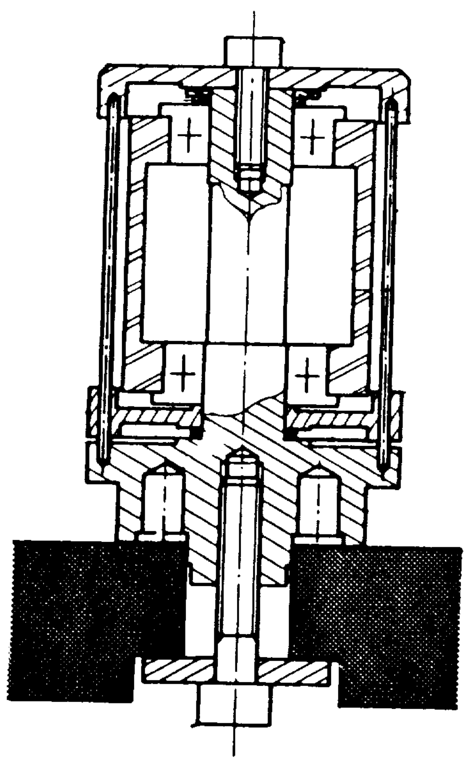


FIGURE 4 : Tape roller sideview