was conducted as part of an evaluation of the 8μlb thruster system with respect to geosynchronous satellite requirements. As a result, colloid propulsion has been shown to be compatible with typical flight specifications.

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FEBRUARY 1971 J. SPACECRAFT VOL. 8, NO. 2

Microthruster Development in France under Direction of the Centre National d'Etudes Spatiales (CNES)

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In the CNES program on micropropulsion for orbit control of satellites, priority has been given to geostationary satellites. Low-I_{sp} (60-sec) thrusters (cold gas and subliming solid) will be available in France for satellites to be launched after 1970. Medium I_{sp} (200-sec) thrusters (hydrazine and ammonia) could be used after 1972. Ion engines (cesium contact + thrust vectoring through beam deflection) will be used after 1975. Other French studies, not supported by the CNES, have dealt with chemical or electric thrusters. For the 1970–1975 period, the CNES plans to concentrate its activities on hydrazine monopropellant thrusters, which are particularly simple and reliable, and ion engines, which permit important weight saving.

Nomenclature

DFVLR	= Deutsche Forschungs und Versuchsanstalt für Luft und Raumfahrt (German government aerospace research laboratories)
DRME	= Direction des Recherches et Moyens d'Essais (French Army research organization)
ELDO	= European Launcher Development Organization
ESRO	= European Space Research Organization
LEP	= Laboratoires d'Electronique et de Physique Appliquée (French electronics research company)
MATRA,SNIAS	= French aerospace companies
ONERA	= Office National d'Etudes et de Recherches Aérospatiales (French Air Force research laboratories)
RAE	= Royal Aircraft Establishment (U.K.)
SEP	= Société Européenne de Propulsion (French space propulsion company), formerly SEPR: Société d'Etude de la Propulsion par Réaction
SNECMA	= Société Nationale d'Etude et de Construction de Moteurs d'Avions (French aircraft propulsion company)
SAGEM, CdC THOMSON-CSF	= French avionics companies

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Introduction

THE Centre National d'Etudes Spatiales (CNES) decides on the programs for, and implementation of, French space activities. Its annual budget of approximately $100,000,000 covers both national projects and French participation in international organizations such as ESRO and ELDO. At the outset, CNES was founded to support scientific research. In 1966, however, the development of applications satellites appeared to be a more important task, and it was then decided that CNES should be in a position to launch geostationary satellites during the 1970's. Although some attitude control studies had already been done, no microthruster with good performance and long lifetime had been developed in France. CNES created a new department to begin research and testing of hardware constructed by industry under CNES sponsorship and technical supervision. The main target has been to create a know-how rather than the development of one microthruster in particular.

This work was accomplished in collaboration with other organizations, both French (DRME and ONERA) and in-

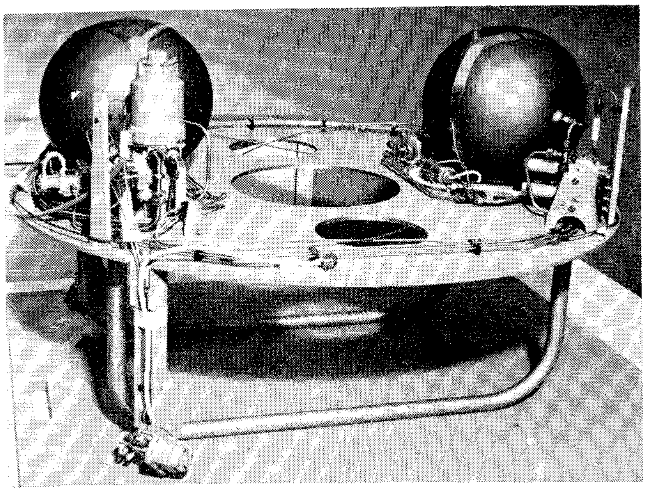

Fig. 1 D-2 cold-gas system.

ternational (ESRO and ELDO). Some contacts were also established with the space agencies of other nations (NASA, RAE, DFVLR), but these were limited for political reasons.

The French microthruster development program can be divided into three stages corresponding to low, medium, and high specific impulse (I_{sp}).

Low-I_{sp} Technology

Cold Gases Systems

Work on cold gases began early in France. Systems have been developed for the attitude control of military payloads designed for the study of re-entry problems. As early as 1962, CNES asked MATRA to build a 3-axis stabilization system for the Diamant A Satellite-launcher. This device, which used Freon 14 as a propellant, was successful, and the Diamant B launcher has been fitted with a similar system. A cold-gas device for the stabilization of sounding rocket payloads, called Cassiopee, has also been developed. Designed for scientific research, it is manufactured by SAGEM and CdC and uses either nitrogen or neon, depending on the nature of the experiment and on tolerable light absorption. Each of these systems was only intended to work for a few minutes.

The first system designed for a longer lifetime was the one for D-2, a scientific satellite which carries experiments related to solar activity and will be launched at the end of 1970 or early in 1971. It must be directed towards the sun with an accuracy of 30 ft. Total lifetime should be six months. It was decided that the satellite should spin at 1 rpm and that a cold-gas correction system should be used.[1] Work started in 1964. The cold-gas system built by Nord-Aviation (now SNIAS) under CNES direction is shown in Fig. 1, and its characteristics are given in Table 1. The SNIAS will probably use its know-how to build the cold-gas system of the Franco-German telecommunications satellite Symphonie,

Table 1 Characteristics of D-2 and Symphonie cold-gas nitrogen systems

Parameter	D-2	Symphonie
Number of thrusters	6	8
Unit thrust, N (lb)	0.028(0.0063)	1.0(0.135)
Number of tanks	2	4
Initial tank pressure, atm	230	250
Low pressure, atm	3.5	10
Nitrogen weight, kg (lb)	2(4.4)	2.2(4.85)
Total weight, kg (lb)	8(17.7)	8.15(17.8)
Lifetime, yr	0.5	5

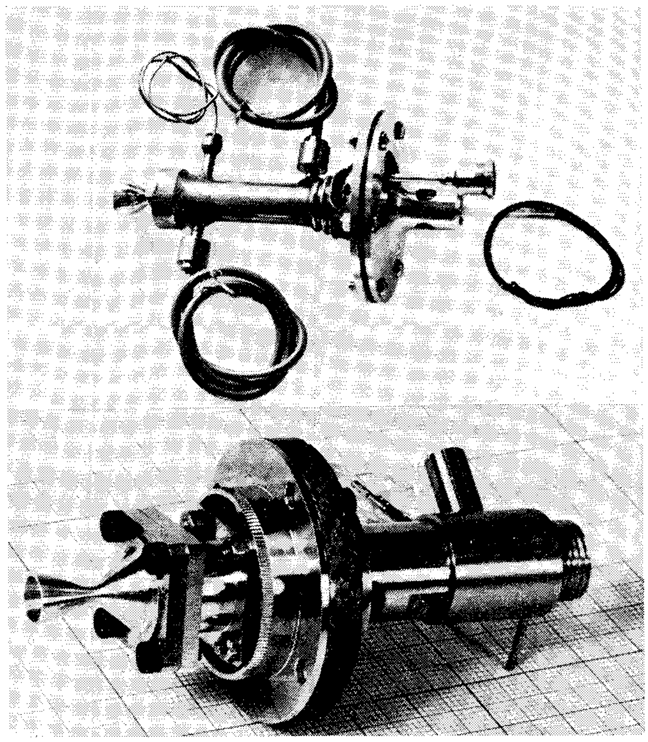

Fig. 2 Hydrazine "long-bed" (top) and "short-bed" thrusters.

which is to be launched about 1973. Characteristics of the Symphonie system are also given in Table 1.

Since cold-gas technology was well known, no basic research was undertaken. As a safety measure, some foreign parts have been or are being bought, but it has not yet been necessary to change any French parts.

Subliming Solid

Very low thrust levels are particularly convenient for attitude control or east-west orbit correction of geostationary satellites. They give a high level of accuracy and lower the disturbance caused by thrust misalignment. In 1967 the only low thrust systems that could be developed in France seemed to be those using subliming solids. CNES then asked the Space Department of SNECMA (now a part of the SEP, Société Européenne de Propulsion) to build and test a thruster which was called Sublijet. Its characteristics are given in Table 2.[2] Models of the Sublijet have been checked in vacuum chambers after vibration and acceleration tests. A ground-qualified model is shown in Fig. 2.

Medium-I_{sp} Technology

Hydrazine Decomposition Systems

The foregoing low-I_{sp} systems cannot reasonably be used either for orbit acquisition or north-south station-keeping of geostationary satellites, because the weight of propellant needed for an assured 5-yr lifetime would account for half of the total weight of the satellite. Thus, another technology had to be developed. The catalytic decomposition of mono-

Table 2 Characteristics of single-thruster Sublijet system

Thrust	2mN (0.45 mlb)
Propellant	ammonium bicarbonate
Impulse duration	5–100 sec
Outside temperature limits	0–50°C (32–122°F)
Power consumption	15 w
Propellant weight	2.20 kg (4.85 lb)
Total weight	4.3 kg (9.5 lb)

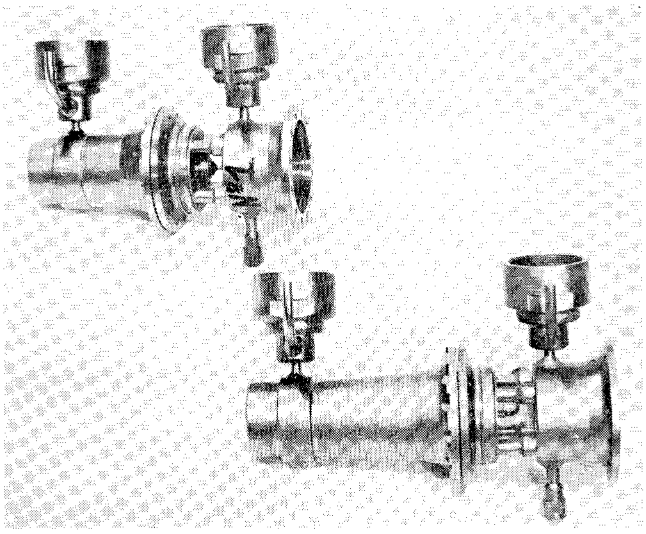

Fig. 3 Postcombustion thrusters.

propellants was chosen because of its simplicity and reliability. Work was inaugurated at SEPR (which is now part of SEP). Two monopropellants were experimentally tested, H_2O_2 and N_2H_4, the latter eventually selected. The work was then divided into two parts: 1) catalyst problems, including research on the fundamentals of hydrazine catalytic decomposition as well as the development of a French catalyst (the contractor was Prof. Pannetier of the Faculte des Sciences de Paris, Paris University, who was assisted by the Compagnie des Metaux Precieux and Pechiney); and 2) engine design and testing, assigned to SEP.

Professor Pannetier has published many articles relative to his studies,[3] and the catalysts he derived compare favorably with Shell 405. One of them, now being prequalified, will soon be available. Catalyst tests in decomposition chambers are conducted by SEP in Villaroche near Paris, in a new test center built to comply with CNES requirements. The European Space Research Organization (ESRO) showed an interest in this work and provided part of the backing through CNES.

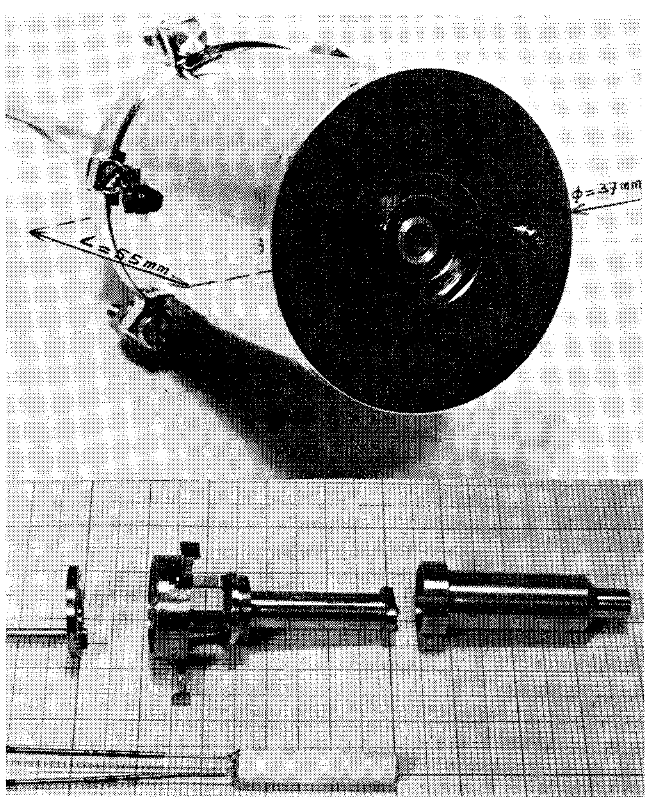

Fig. 4 Ammonia resistojet: outside view of complete thruster and details of heating part.

Table 3 Postcombustion thruster performance

Parameter	N_2H_4 only	With post-combustion
Decomposition chamber pressure, atm	4	7.4
Postcombustion P_c, atm	3	7.0
N_2H_4 flow rate, g/sec (lb/sec)	5.25	5.25
N_2O_4 flow rate, g/sec (lb/sec)	0	4.35
Thrust, N (lb)	12(2.7)	29(6.5)

Simultaneously with catalyst testing, the SEP is developing and qualifying a complete propulsion system using Shell 405 catalyst.[4] This system, or a similar one, could be used on the meteorological satellite, which is part of a joint Franco-American program. Two models of thrusters built and tested by SEP are shown in Fig. 2; one has a long catalyst bed, the other a very short one. Each has a thrust level of 4 N (0.9 lb). One of the many problems that the SEP had to solve was the development of a positive expulsion device for hydrazine tanks. One successful system employs metallic bellows. In all, a considerable amount of work has been carried out on N_2H_4 monopropellant technology with very successful results. A technology satellite designed to test hydrazine thrusters in space is now under study. It probably will be launched by a Diamant B rocket in 1972.

Postcombustion Systems

A drawback of hydrazine as compared with bipropellants is its relatively low I_{sp} (200 sec vs 300 sec). One way of increasing performance without much sacrifice in reliability is postcombustion; i.e., an oxidizer is injected into decomposed hydrazine, yielding an I_{sp} comparable to that obtained from the usual bipropellant thrusters. Should a breakdown occur in the oxidizer circuit, the thruster still works on hydrazine alone. SEP has studied two oxidizers, H_2O_2 and N_2O_4, both theoretically and experimentally. The H_2O_2/N_2H_4 combination was dropped because of its lack of hypergolicity, but successful work was carried out on the N_2O_4/N_2H_4 combination (see Table 3.) Tests have been made on long and short postcombustion chambers (see Fig. 3) and hypergolicity has been bench-tested.

Ammonia Resistojet Systems

Another drawback to hydrazine engines is the relatively high thrust level. Ammonia resistojets give low thrust, while maintaining an acceptable I_{sp}, and their technology is simple.[5] Research has been conducted on forced ammonia convection by CEA in Grenoble,[6] and SEP has developed and qualified a thermal storage resistojet model (Fig. 4 and Table 4). Its relatively low I_{sp} is due to low nozzle efficiency, which could easily be corrected by 15%.

Some preliminary work on paper has been done by SEP on thrusters where ammonia is heated by radioisotopes instead

Table 4 Ammonia resistojet characteristics

Thrust	5 mN (1.13 mlb)
Propellant flow rate	3 mg/sec (6.6 mlb/sec)
Average propellant temperature	1100°K (1500°F)
Number of thermal screens	6
Outside length	55 mm (2.15 in.)
Outside diameter	37 mm (1.45 in.)
Power consumption	20 w
Thruster weight	60 g (0.13 lb)
Thermal efficiency	60%
Nozzle efficiency	60% (in I_{sp})
Specific impulse	170 sec

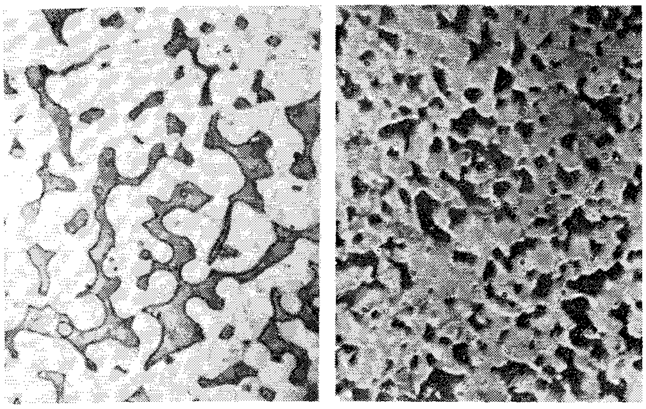

Fig. 5 Microscopic view (1850 ×) of porous tungsten ionizers for cesium contact ion thrusters. Right: standard Ugine powder; left: spherical Ugine powder.

of an electric resistance. The best radioisotope was found to be Actinium 227, which is produced in Belgium. No real advantage was revealed with respect to conventional heating systems.

High-I_{sp} Technology

Ion Propulsion

Ion propulsion has been selected as a possible solution for control of satellites to be launched after 1975. Cesium contact engines with electrostatic beam deflection appeared to be the best suited to French and European needs. Development began in February 1969 after preliminary work performed by CNES and ONERA.[7] The first stage of development includes basic technological research conducted by the LEP (Laboratoires d'Electronique et Physique Appliquée) in Limeil-Brevannes near Paris.[8] The LEP was chosen because of previous experience with its use in the design of electronic tubes. The main points studied were ionizers (made of tungsten powder or by any other means), optics, and neutralizers. The influence of the sphericity of the tungsten powder used to make the ionizers has been pointed out (see Fig. 5). After microscopic control, the ionizers were tested on a special device (Fig. 6). Neutralizer wires were tested under ion bombardment conditions in another apparatus. Although no decision has as yet been made as to what the thrust level of the engine should be, research is oriented toward a thruster having the characteristics indicated in Table 5. The second stage of development is due to begin in 1971 after the choice of prime contractor for the complete propulsion system (including the cesium tanks and power signal conditioning).

Research Conducted without CNES Support

Some work has been carried out on bipropellant thrusters by SEP. The important research work on hydrazine monopropellant engines done at Vernon by LRBA should also be mentioned. Many electro-thrusters have been built in

Table 5 Estimated cesium contact ion engine characteristics

Thrust	0.53 mN (0.12 m/lb)
Ionizer material	porous tungsten
Ionizer area	1.35 cm² (0.21 in.²)
Propellant flow rate	0.04 g/hr (88 10^{-6} lb/hr)
Beam current intensity	8 ma
Beam current density	6 ma/cm²
I_{sp}	5000 sec
Global efficiency	35%
Lifetime	18,300 hr during 5 yr

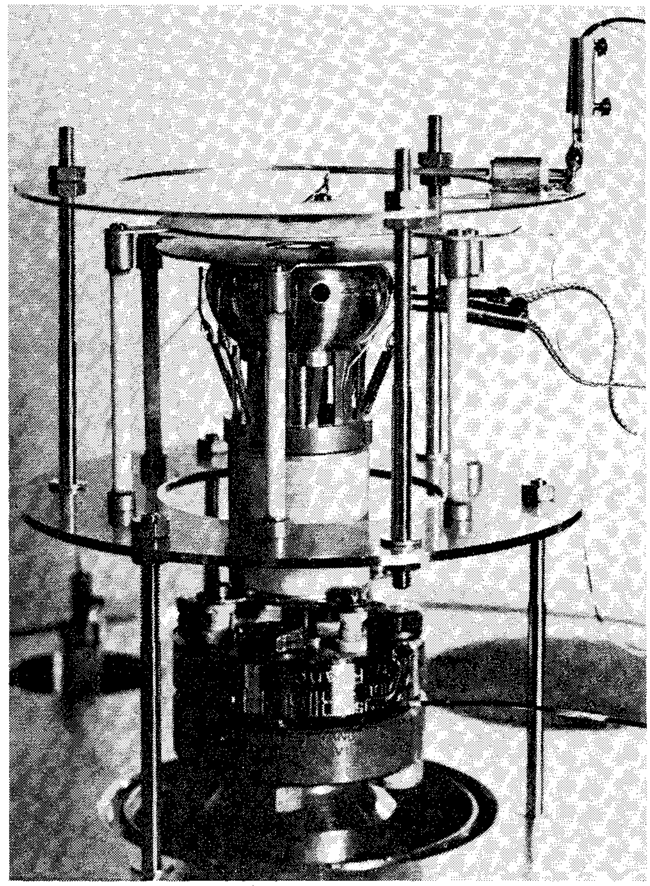

Fig. 6 Ionizer test bench.

France, the more outstanding examples being mercury ion engines (CEA), mercury ion and plasma engines (ONERA), plasma rail gun (SNIAS),[9] electrothermal engine (SEP),[10] and subliming solid and plasma thrusters (Thomson-CSF); however, most of these engines did not go through the development stage for financial reasons, and further investigation has not been undertaken.

Technology Projection and Plans

We have estimated the evolution of the weight fraction of a geostationary satellite stabilization system (Fig. 7) using various levels of technology. Much weight could be saved

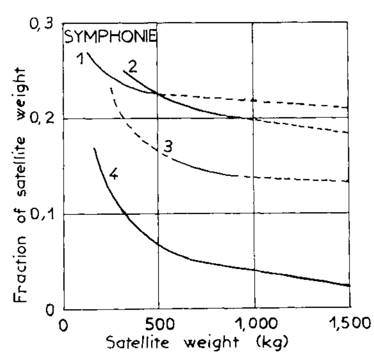

Fig. 7 Projections of stabilization (orbit and attitude) system weight fraction vs satellite weight for a geostationary satellite (lifetime—5 yr): 1) 1972 technology: bipropellant or cold gas, flywheel; 2) 1975 technology: NH_3 resistojet (I_{sp}, 300 sec); 3) hybrid technology (1975 ?): bipropellant for orbit acquisition, ion propulsion for attitude control and station-keeping; and 4) 1979-80 technology: acquisition by apogee engine, ion propulsion afterwards.

by using ion propulsion after 1975. Considering the fact that the European launching capacity is likely to remain limited for financial reasons, CNES plans to concentrate its effort on 1) hydrazine catalyst decomposition thrusters for satellites to be launched after 1972, and 2) ion engines for satellites to be launched after 1975.[11]

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FEBRUARY 1971 J. SPACECRAFT VOL. 8, NO. 2

Stochastic Crew Motion Modeling

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For the design of attitude control systems for large spacecraft, it is desirable to have a statistical description of the disturbing forces and moments resulting from crew motion. Through extensive simulation programs, data have been obtained which are representative of forces and moments that would result from typical crew activities. An analysis has shown the data to be stationary, meaning that equivalent data with the same frequency and rms amplitude characteristics can be generated by passing white noise through linear filters. Filter parameters were obtained by a special technique of least-squares curve fitting of various filter structure equations to the power spectral density curves of the data. The result is a convenient method for continuously generating crew motion disturbance data for input to computer simulations.

Nomenclature

A_i, B_i	= parameters defined by Eq. (15); $i = 1,2,\ldots,n$;
D^*	= constant denominator defined by Eq. (18)
D	= defined by Eq. (16)
E	= error function defined by Eq. (17)
F_x, F_y, F_z	= forces in the specified directions, lb
$H(j\omega)$	= synthesizing filter transfer function
$\bar{M}_{cm}$	= moment due to the center of mass moving from its initial position, $\bar{M}_{cm}$ $(M_{cmx}, M_{cmy}, M_{cmz})$, ft-lb
M_x, M_y, M_z	= moments due to subject's motion ft-lb
m	= mass of the subject
$P(\omega)$	= power spectral density (PSD) defined by Eq. (4)
$\bar{r}_{cm}$	= position vector locating the c.m. position relative to the load cell centroid, $\bar{r}_{cm}(x_{cm}, y_{cm}, z_{cm})$
$R_T(r)$	= truncated autocorrelation function, Eq. (5)
$\bar{W}$	= subject's weight defined as a vector
Δ	= the denominator of Eq. (14)
σ	= standard deviation of a random variable
μ	= mean of a random variable
$\tau_i, \zeta_i, \omega_i$	= free parameters of the synthesizing filter, $i = 1,2$

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Introduction

As early as 1962, it was recognized by Roberson[1] that with the advent of manned spacecraft the effects of the motion of the crew might produce significant spacecraft disturbances. Later investigations (Murrish and Smith,[2] Poli,[3] and others) have verified Roberson's conclusions. One current example is seen in Skylab, for which analysis has shown that the Apollo telescope mount (ATM) must be mechanically isolated from the basic vehicle in order to obtain the desired pointing accuracies for the ATM solar experiments.

Previous studies of crew motion effects have not resulted in a convenient technique of incorporating the disturbances in ground simulation programs. Normally, the crew motion forces and moments would have to be recorded on digital or analog tape and continuously fed into the simulation programs, thereby requiring a large tape library with the resulting tape handling problems. In the search for a more