

DEVELOPMENT OF DYNAMICS MODELS  
& CONTROL SYSTEM DESIGN FOR  
THIRD GENERATION SPACECRAFT

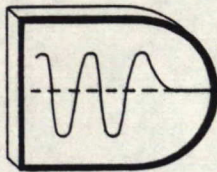
(Executive Summary)

[DOC-CR-SP-82-056]



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**YNACON** *Enterprises Ltd.*

DYNAMICS AND CONTROL ANALYSIS

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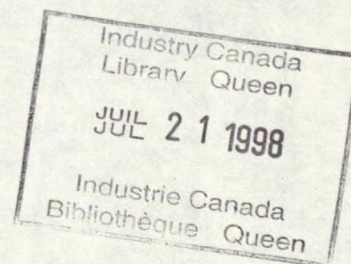
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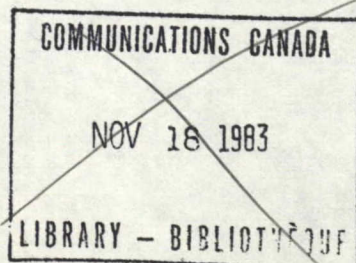
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P. C. Hughes



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Dynacon Report MSAT-9





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**TITLE:** Development of Dynamics Models & Control System Design for Third Generation Spacecraft (Executive Summary)

**AUTHOR(S):** P. C. Hughes

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## PREFACE

This is an Executive Summary of the work performed by Dynacon Enterprises Ltd. under DSS Contract No. 15ST.36001-1-0953. The Customer's Scientific Authority for this contract was A. H. Reynaud of the Communications Research Centre.

This report is the Final Report identified as Milestone 6 under this Contract.

### Note

This report uses S.I. units and North American spelling.

## 1. INTRODUCTION

The Space Mechanics Directorate and the other cognizant technical groups within the Department of Communications (DOC) have correctly identified *flexible spacecraft control* as a key technology area for the foreseeable future. The economics of placing structures in Earth orbit require lightweight structures; the technology specifications of future communications satellites demand more accurate pointing, configurational integrity, and even control of the detailed 'shape' or 'figure'. Together, these two trends make evident that the dynamical modeling and control system design for communications satellites will continue to be the subject of advanced technology effort in the decades ahead.

### 1.1 Satellite Generations

The notion of communications satellite 'generations' is a useful one. It is used in this context in the sense suggested by S. P. Altman, the DOC Director of Space Mechanics. The idea of 'generation' is not, however, connected with 'satellite lifetime'--although the two ideas may seem superficially related. The demise of an individual satellite is signaled by the failure of some essential life-support system: the control fuel becomes exhausted; the on-board computer malfunctions; or any of an increasingly large number of critical spacecraft components fails. (The most drastic meaning of 'satellite lifetime' is the one used by specialists in orbit decay: a satellite's lifetime is said to be 'over' when it experiences cremation in the incandescent heat of atmospheric entry.)

The notion of 'generation', as used here, has to do instead with the evolution of satellite technology, and, more specifically, with *attitude control technology*. A first-generation spacecraft, in its purest form, is one that may be



considered rigid for all attitude control purposes. A footnote to this definition is that it also includes satellites that are 'slightly' flexible--satellites assumed rigid during attitude control system (ACS) design, but for which the tentative ACS design is subsequently examined in the light of simulated flexibility. Often this examination leads to additional laboratory tests and to surprisingly extensive modifications to the ACS design. Hermes (CTS) is an excellent example of this almost-second-generation genre of first-generation spacecraft.

The chief axiom in ACS design for a first-generation spacecraft is that the devices that supply information to the control system (the *sensors*) and the devices that impose the will of the control system (the *actuators*) can all be located on the rigid portion of the spacecraft. For a first-generation spacecraft in its simplest form, the entire vehicle is rigid and it is therefore a matter of indifference where the sensors and actuators are located. However, for 'slightly' flexible spacecraft--the most important example for most readers of this report being Hermes (CTS) satellite--the configuration consists of a virtually rigid central body (often called a 'main bus' by configuration planners) to which one or more slightly flexible structures are appended. For these 'slightly' flexible spacecraft, the sensors and actuators are invariably located on the 'main bus', in spite of the fact that the sensors would sense more, and the actuators would be more efficient, if they were located at the extremities of the appendages. The additional information that could be made available to the control system by placing the sensors on the appendage peripheries, and the significantly longer (thruster) moment arms that could be achieved by situating the actuators (assuming them to be thrusters) on the appendage edges, are both gladly sacrificed in exchange for the design simplifications that accompany the assumption of quasi-rigidity, i.e., the assumption that the spacecraft is 'first generation' as far as its ACS is concerned.

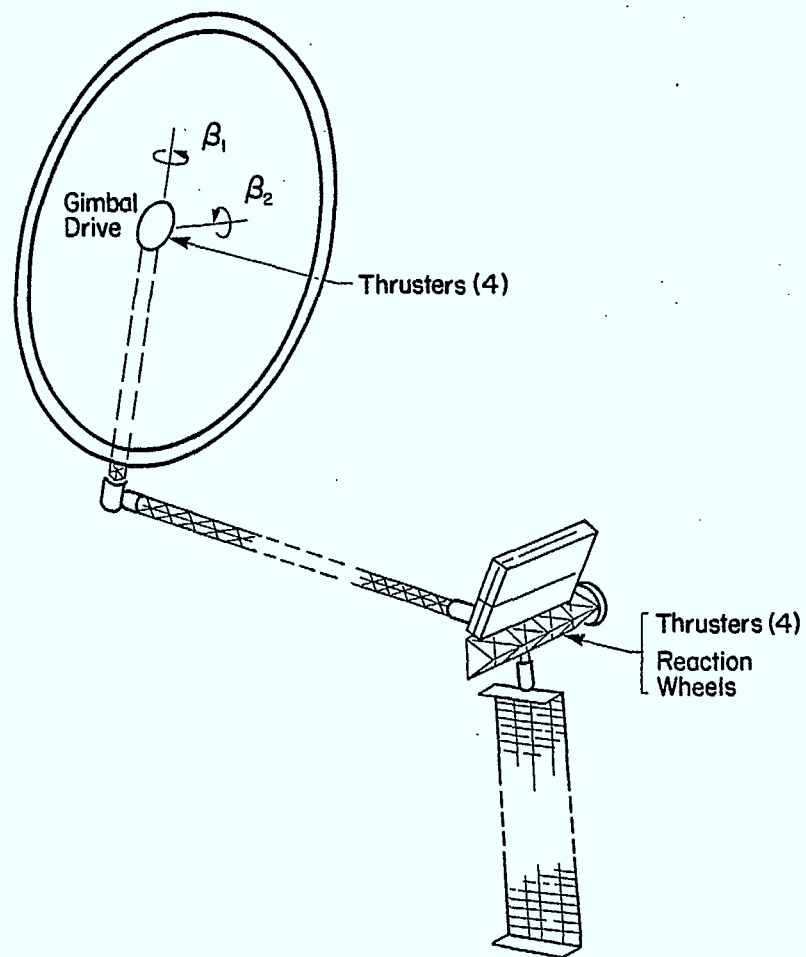


A *second*-generation spacecraft (in the present ACS context) can no longer be assumed rigid, or even quasi-rigid. No matter how ingenious the feedback control law, no matter how accurate the sensors, no matter how muscular the actuators--the ACS requirements simply cannot be met if the sensors and actuators are confined to the rigid main bus. The sensors must be deployed throughout the flexible portions of the spacecraft structure, although the actuators may still be restrained to lie on the main bus. The sensors are now called upon to reveal troublesome structural deformations to the control system in order that it may take them into account in executing the control policy.

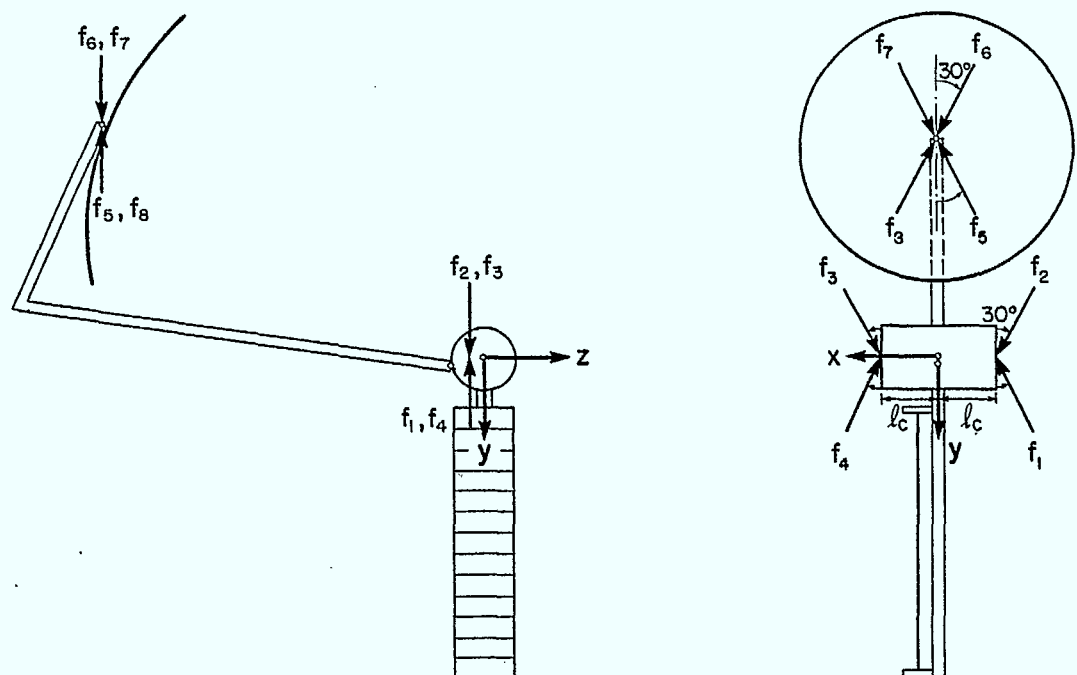
For a *third*-generation spacecraft, actuators that lie only on the main bus are no longer adequate to meet control objectives. Indeed, for the very large configurations of the farther future, constructed in orbit from materials carried up on many Shuttle flights, the concept of a 'main bus' may become an obsolete one, a vestige of a primitive launching system.

#### 1.2           "MSAT" -- A Third-Generation Spacecraft

It is useful to conceptualize in generalities, but concrete experience can be developed only in terms of a specific spacecraft configuration. To that end, the configuration shown in Fig. 1 was stipulated in the contract to be the reference configuration for this study. This satellite is largely a multi-beam communications antenna whose reflector is offset from the axis of the confocal paraboloid of revolution of which it is the only visible segment. This configuration will be referred to simply as "MSAT", because it is motivated by the possible need in the 1990's for a North American "operational" multi-beam satellite for mobile ground communications. Thus 'M' in 'MSAT' stands for either 'mobile communications' or 'multi-beam transmission'.



(a) Actuator Locations (specified by Spar R.1113)



(b) Thrust Directions (specified by Spar R.1113)

FIG. 1: CONFIGURATION STUDIED (LAZY-Z OPERATIONAL MSAT)

This configuration is also of great interest in the U.S., where it's attitude control has been the subject of recent investigation. It is hoped that the handy moniker 'MSAT' will not create confusion with the 'other MSAT'--the 'Demonstration MSAT' configuration now under design as a DOC project. Incidentally, whether the Demonstration MSAT (D-MSAT) is or is not easier to control than Hermes was, the control of the 'operational' configuration in Fig. 1 (O-MSAT) is a more demanding enterprise than is the control of D-MSAT. Demonstration of attitude control for D-MSAT is a necessary condition, but not sufficient one, for attitude control of O-MSAT. To state this point yet another way: D-MSAT may be a 'demonstration' of technology for O-MSAT for some subsystems (perhaps communications) but D-MSAT is not (in the writer's opinion, of course) a complete demonstration of attitude control technology for O-MSAT. The reason is that O-MSAT (Fig. 1) may well be a third-generation satellite (in the sense defined above) while D-MSAT is at most a second-generation satellite. It is the intent of this study, and of studies performed by others in parallel, to treat O-MSAT as a third-generation satellite.

## 2. SUBSTRUCTURAL MODELS

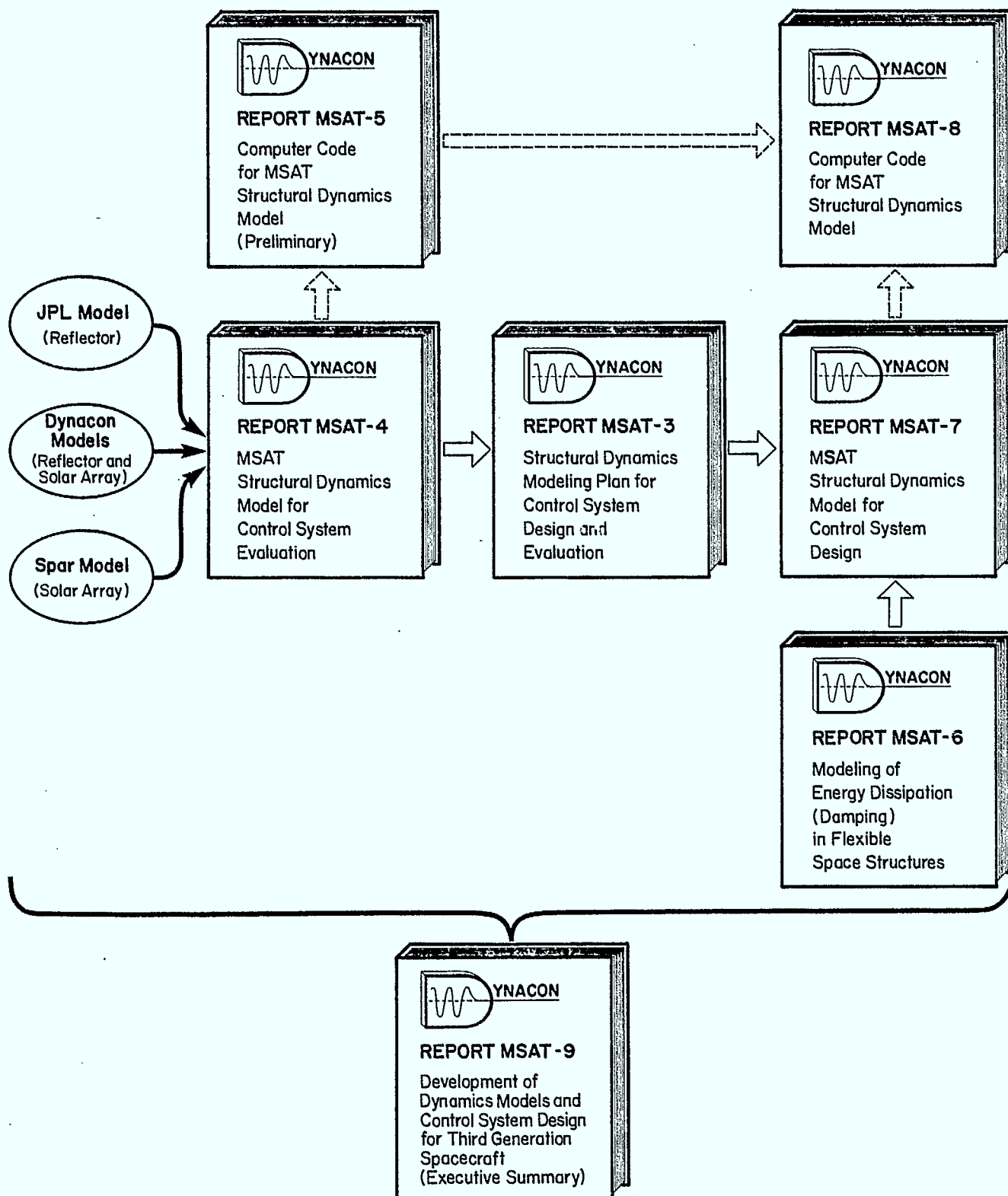
This Executive Summary provides an overview of a program of dynamical modeling that has been the subject of several Dynacon reports. A pictorial representation of this overview is the subject of Fig. 2. (A table showing the correspondence between these reports and their DOC-CR numbers is also appended.) Even though the satellite of Fig. 1 is a 'paper study' at the moment, it has been modeled with a care and an attention to detail that are appropriate to an 'actual' spacecraft.

It is clear from Fig. 1 that the structural flex-



# FIG. 2

## DYNAMICS MODELS FOR THIRD GENERATION SPACECRAFT



ibility resides chiefly in three places:

- (a) the reflector tower,
- (b) the reflector itself, and
- (c) the solar-cell array.

Each of these substructures has been modeled, and these models then combined to form an overall dynamical model for MSAT that is both accurate and economical to simulate.

## 2.1 Antenna Reflector

Details of the reflector model are given in Dynacon Report MSAT-4. The model assumes a Lockheed wrap-rib design. The best model of this reflector has been developed by structural analysts at the Jet Propulsion Laboratory. Their model was based on the finite element method and comprised over 29,000 degrees of freedom. If a modal analysis were carried out, the reflector would, according to this model, have over 29,000 modes! Obviously, only some of the lower modes are of engineering significance (not to mention that, as with any structural model, only the lower modes are of any accuracy). For this reason, only 42 of the lowest modes were explicitly calculated by JPL.

This model and a more classical reflector model are described in Dynacon Report MSAT-4, as are various accuracy checks that were applied to the JPL model in the present study. Further discussion can also be found in Section 3 of Dynacon Report MSAT-7. In the end, 18 of the 42 modes were retained in the reflector model, based on a criterion that recognized not only the natural frequency of a mode, but also its level of damping, its degree of (inadvertent) excitation by the control system, and its cruciality to the control objectives.

## 2.2 Antenna Tower

A description of the antenna tower model is pre-

sented in Dynacon Report MSAT-4. A model in which each of the two constituent Astromasts is taken to be a single conventional beam finite element is highly accurate, and if each Astromast is modeled as *two* finite elements the accuracy is even higher. These two models, being simple and accurate, are the only ones used in this study.

### 2.3 Solar-Cell Array

Models for the solar-cell array are also described in more detail in Dynacon Report MSAT-4. The model finally used was arrived at in collaboration with Spar Aerospace, RMSD. The first 38 modes of a finite element model were taken as the initial description. After substructure model reduction, based on the same criterion as used for the reflector, 27 of these modes were selected for inclusion in the gross spacecraft model.

## 3. SPACECRAFT MODEL

At this point in the development, structural models are available for each of the constituent flexible substructures. These models have included as few modes as possible, given that high accuracy is required at this stage of modeling. One must now combine these models to form an overall model for the spacecraft. The two fundamental principles needed are easy enough to state: at each point of contact between two substructures, the forces and torques must be equal and opposite, and the displacements must be compatible. Working out the mathematical details for a particular configuration takes longer.

### 3.1 Overall Model Assembly

The *method* for combining substructural models to form an overall spacecraft model is given in mathematical detail in Dynacon Report MSAT-3. For reasons that are technically extraneous, this particular work was done by Dynacon for Spar Aerospace Ltd. and was not part of the present contract.



This report is shown in Fig. 2 anyway, to clarify the flow of the technical work.

Even after the method has been spelled out, however, two nontrivial tasks still remain:

- (a) computer coding of the assembled model from the sub-models, and
- (b) reduction of the 'size' of the model (synonymous with reduction in model 'order', in number of coordinates, and in number of 'degrees of freedom').

The assembly process comes to fruition in Dynacon Report MSAT-7.

Several criteria for model size reduction are introduced and discussed, both qualitatively and quantitatively, in Report MSAT-7. After initial assembly, the model has the following coordinates:

- (a) 3 'rigid' spacecraft translational coordinates;
- (b) 3 'rigid' spacecraft rotational coordinates;
- (c) 2 gimbal rotations at the reflector hub;
- (d) 3 translations of the tower tip, with respect to the main bus;
- (e) 3 rotations of the tower tip, with respect to the main bus;
- (f) 14 coordinates associated with structural deformations of the tower, in addition to those in (d) and (e) above;
- (g) 18 coordinates associated with structural deformations within the reflector;
- (h) 27 coordinates associated with structural deformations within the solar array.

Thus, altogether, there are 73 coordinates in the dynamical model of the spacecraft, even after substantial reduction in coordinates (but not in accuracy) at the substructural level.

### 3.2 Model Size Reduction

Seventy-three coordinates are still far too many.

Despite the elimination of many coordinates along the way, there are still too many of them. Their quantity has been left intentionally numerous so that the final reduction in model size can be made in terms of the coordinates that are most significant for the spacecraft as a whole--the coordinates associated with the vibrations of the whole spacecraft.

There are two closely related objectives in the present work:

- (a) to prepare a model suitable for control system design, and
- (b) to prepare a model suitable for control system evaluation (by computer simulation).

With respect to Objective (a), the model should be sufficiently accurate to permit a control system design; it is especially desirable for design purposes to have a mathematical model of the system that is simple. With respect to Objective (b), confidence is to be won in the control system design through detailed computer simulations. It is therefore mandatory to use a model that is more accurate than the 'design' model, but that is still economical in its consumption of computational resources. These observations imply that

- (a) the control design model will have fewer coordinates than the evaluation model, and
- (b) both models deserve to have their final coordinates chosen with care.

These objectives are achieved by the methodology used in the present investigation.

The two models eventually arrived at in Dynacon Report MSAT-7 are as follows:

- (a) a 'control design model' with 12 coordinates, including 4 spacecraft modes, and
- (b) a 'control evaluation model' with 19 coordinates, including 11 spacecraft modes.

The design model permits a modeling error (in the sense of modal convergence) of 12%; the evaluation model converges to within 1% of its final value.

#### 4. OTHER SYSTEM CHARACTERISTICS

The preceeding discussion has centered primarily on the modes of the spacecraft, calculated from mass and stiffness properties. There are, however, several other characteristics of the system that must be known in order to carry out a control system design. All these characteristics were also calculated under this contract.

##### 4.1 Control Input Matrix

Given a set of actuators (see Fig. 1), it is necessary to relate the influence of each actuator on all the coordinates of the spacecraft. This is done via the 'control output matrix' which is provided as part of the present model.

##### 4.2 Sensor Output Matrix

Given a set of sensors (as done by Spar Report R.1113), it is necessary to relate how much each coordinate is sensed by each sensor. This is done via the 'sensor output matrix' which is provided as part of the present model.

##### 4.3 Performance Weighting Matrix

It is desired to have the attitude errors of the main bus as small as possible, and also that the internal structural distortions of the reflector tower be as small as possible. These requirements are all packaged into a single measure of controller performance by a weighted sum of squares. The weights, calculated on the principle that the beam should be as pure as possible, form a 'weighting matrix' which is also provided as part of the present model.



#### 4.4 Damping Characteristics

Damping is virtually as important as stiffness. A review of damping and its significance was carried out under this contract as reported in Dynacon Report MSAT-6. The formulations reviewed there were then used in Dynacon Report MSAT-7 to construct a 'damping matrix' for the structure. It is shown that all modes do not have the same damping factor (as is frequently assumed). Moreover, these damping factors are useful in the selection of modes for the final models.

#### 4.5 Gyroscopic Characteristics

Some control strategies include one or more large spinning wheels on the main bus. To take into account the consequent gyroscopic effects on the dynamics, three 'gyroscopic matrices' were calculated, one for a wheel in each of the principal directions of pitch, roll and yaw. Any wheel, whether aligned with the principal directions or not, can be replaced by a dynamically equivalent set of wheels that are so aligned. Therefore the three gyroscopic matrices provided are applicable to any wheel system on the main bus.

#### 5. COMPUTER CODE

The modeling results obtained under this contract have been used to develop a computer code to represent satellites of the type shown in Fig. 1. This code has been extensively commented and has been intended for use by others. In addition, a User's Manual has also been prepared-- Dynacon Report MSAT-8.

# TABLE OF REPORTS IN THIS SERIES

<u>Dynacon Number</u>	<u>DOC Number</u>	<u>Author(s)</u>	<u>Title</u>
MSAT-1	CR-SP-81-005	Hughes, P.C.	MSAT Structural Flexibility and Control Assessment
MSAT-2	CR-SP-81-006	Hughes, P.C.	A Dynamics Modeling Plan for MSAT
MSAT-3	(see Note 1)	Hughes, P.C.	Structural Dynamics Modeling Plan for Control System Design and Evaluation
MSAT-4 <sup>†</sup>	CR-SP-82-022	Hughes, P.C. Sincarsin, G.B.	MSAT Structural Dynamics Model for Control System Evaluation
MSAT-5 <sup>†</sup>	CR-SP-82-023	Sincarsin, G.B. Stoddard, I.A. Hughes, P.C.	Computer Code for MSAT Structural Dynamics Model (Preliminary)
MSAT-6 <sup>†</sup>	CR-SP-82-024	Hughes, P.C.	Modeling of Energy Dissipation (Damping) in Flexible Space Structures
MSAT-7 <sup>†</sup>	CR-SP-82-054	Sincarsin, G.B. Hughes, P.C.	MSAT Structural Dynamics Model for Control System Design
MSAT-8 <sup>†</sup>	CR-SP-82-055	Sincarsin, G.B. Stoddard, I.A. Hughes, P.C.	Computer Code for MSAT Structural Dynamics Model
MSAT-9 <sup>†</sup>	CR-SP-82-056	Hughes, P.C.	Development of Dynamics Models and Control System Design for Third Generation Spacecraft (Executive Summary)

REFERENCES

<sup>†</sup>Prepared under the current contract

Note 1: Report MSAT-3 was prepared for Spar Aerospace Ltd. RMS Division

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- Development of dynamics models & control system design for third generation spacecraft; executive ...

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