# TECHNOLOGIES FOR ANTENNA SHAPE AND VIBRATION CONTROL

Edward Mettler,* Robert Scheid,* Daniel Eldred*

This paper describes the application of advanced control methods and techniques to the second- and third-generation mobile satellite (MSAT) configurations having wrap-rib offset feed construction. The technologies are generically applicable to other designs such as hoop-column and other elastically deformable non-rigid structures. The focus of the discussion is on reflector shape determination and control, dynamics identification, and pointing jitter suppression.

## INTRODUCTION

The static shape determination and control of the MSAT reflector as an on-orbit capability is required to provide knowledge of the shape to an accuracy of 0.3 mm, and to then control the deformations to an accuracy of 1.0 mm using rib-root actuators. The shape determination methodology involves the combination of structure deformation modeling with electro-optic sensing to estimate overall distortion. Shape control to achieve the desired radio frequency (RF) pattern quality incorporates the shape determination inputs and synthesizes the predicted control function to correct for elastic deformations that are quasi-static in nature.

The antenna dynamic control objectives include active correction of both feed and reflector boom structural dynamic motions so as to provide reflector hub-to-feed line-of-sight stability of $\leq 0.07°$ (BW/10) for a 20-meter dish at 1.61 GHz. To support this control precision, a dynamics characterization of the overall structure system, based on in-situ measurements and system identification processing methods, is integrated into the control system design.

Representative control hardware is identified in Figure 1, which refers to the JPL Antenna Technology Shuttle Experiment definition effort in 1986. That study provided examples of control methods that have a general utility for MSAT-X spacecraft concepts of the 20- to 64-meter diameter reflector class. The following sections provide an overview of selected techniques for static and dynamic antenna control.

---

*Member of Technical Staff, Jet Propulsion Laboratory, California Institute of Technology, Pasadena, California 91109.
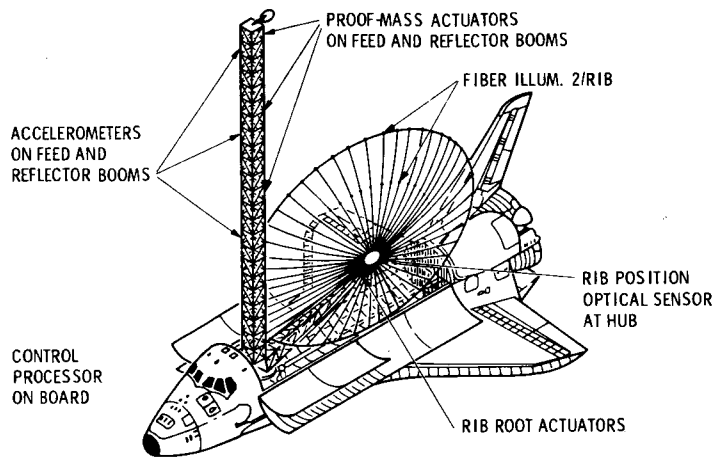
Fig. 1. Antenna Control Hardware

STATIC SHAPE DETERMINATION AND CONTROL

Many important applications in the shape control of large flexible
space structures can be analyzed as static distributed systems. In this
context one can include applications where the time-varying effects of
the model are changing slowly with respect to the scale on which control
operations must be carried out. These quasi-static disturbances may
include gravity gradient, aerodynamic, and thermal effects, and the
control system may be designed to carry out a local temporal averaging of
the resulting quasi-static effects.

The introduction of statistical model errors allows the treatment of
effects that have been ignored in the modeling or that occur on too fine
a scale to be adequately modeled. As a result, the observational data
can be statistically referenced to a plant, and the shape estimates can
be addressed in the framework that includes modeling errors and
observational errors. This makes it possible to use a variety of models
and sensing/actuation systems. These may range from coarse geometric
models that characterize overall features to fine-scale structural
models that can resolve local features. The fine-scale models we
consider are represented by stiffness matrices or elliptic partial
differential equations.

Our particular interest concerns the proposed large space antennas
where requirements in communications and radiometry call for antenna
diameters in the tens of meters and a global root mean square (RMS)
surface error of $\lambda/60$, and require on-line shape determination/control
after deployment and periodically during operations.

Algorithm Descriptions

In this section, the static shape determination and control
algorithms are summarized. This approach, depicted in Figure 2, is an
integrated methodology that combines the techniques of modeling, optical
sensing, and estimation for static control of distributed systems that
are characterized by infinite-dimensional state and parameters spaces. A
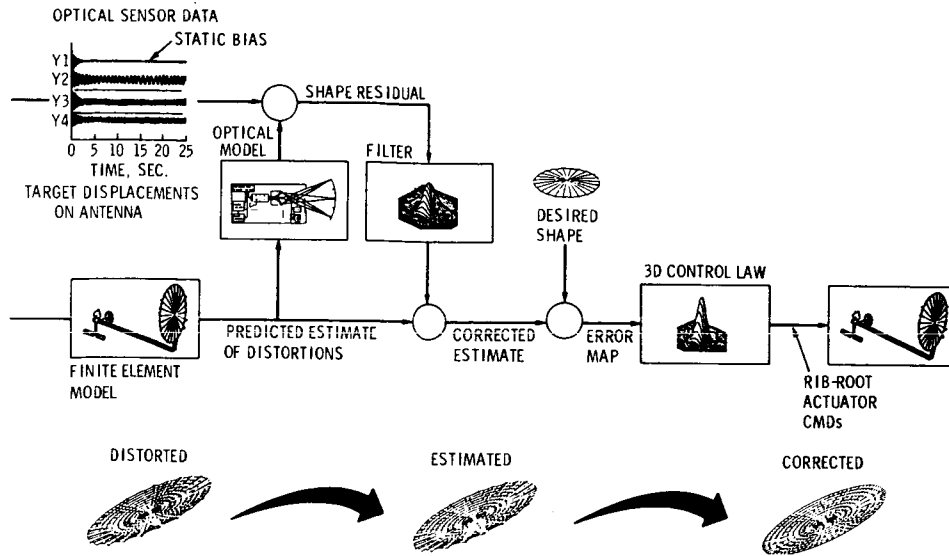more complete discussion is given in [1].

478

Fig. 2. Integrated On-Orbit Shape Determination and Control

Modeling. Let the state variable be given by u. The models considered have the general form

$$A(\theta)u(\theta) = B(\theta)\omega + C(\theta)f \tag{1}$$

$$Y(\theta) = H(\theta)u(\theta) + F(\theta)\eta. \tag{2}$$

Here A is an operator that represents the system model. Detailed resolutions are obtained by taking A to be a stiffness matrix. This can be idealized by assuming A to be a self-adjoint elliptic differential operator defined over some spatial domain and to be invertible with inverse $\Phi$. H is an operator that characterizes the state-to-observation map, and C is an operator that models the relevant deterministic forces including controls. It is assumed that the observation space has dimension $N_s$, which corresponds to a finite-dimensional sensing scheme, and that the control space has dimension $N_a$, which corresponds to a finite-dimensional actuation system. The appropriately dimensioned operators $B(\theta)$ and $F(\theta)$ model the statistical influence of the process error $\omega$ and the measurement error $\eta_s$, which are treated as normalized spatial white noise. The limiting cases B -> 0 and F -> 0 represent the assumptions of perfect modeling and perfect measurements, respectively. The integrated form of the observation equation is given by

$$Y(\theta) = H(\theta)\Phi(\theta)C(\theta)f + H(\theta)\Phi(\theta)B(\theta)\omega + F(\theta)\eta. \tag{3}$$

Estimation. The preceding assumptions lead to a framework for the analysis of minimum variance estimators of the state. Here the expected observation m is characterized by

$$m = H\Phi Cf \qquad E[y] = m \qquad E[(y-m)(y-m)^*] = R_\omega + R_\eta \tag{4}$$

and uv* denotes the outer product, and u*v denotes the inner product. The process, measurement, and estimator covariances $R_\omega$, $R_\eta$ and P are given by

$$R_\omega = \Phi BB^* \Phi^* \qquad R_\eta = FF^* \qquad P = R_\omega - R_\omega H^* (R_\eta + HR_\omega H^*)^{-1} HR_\omega. \quad (5)$$

The resulting formulas are analogous to what is typically derived for finite-dimensional systems. The estimate $u_{est}$ has the form

$$u_{est} = Cf + G(y-m) \qquad g = RH^* (R_\eta + HR_\omega H^*)^{-1}. \quad (6)$$

Control. After the estimation problem has been solved, it is then possible to consider the associated control problem

$$\min_{f_c} \| u_o - \Phi Cf_c \|^2 + \| f_c \|^2 \qquad u_o = u_d - u_{est}. \quad (7)$$

Here $u_o$ is the correction from the accepted shape estimate $u_{est}$ to the desired shape $u_d$. And $f_c$ is the control force that is constrained to be in a set which corresponds to the limits of the actuation system. The solution of this problem is given by

$$f_c = (I + C^* \Phi^* \Phi C)^{-1} C^* \Phi^* u_o. \quad (8)$$

## DYNAMICS IDENTIFICATION AND CONTROL

### Identification

In order to support the dynamic control methodology, an accurate structural model is required. Accordingly, a multifaceted approach to identification and control is developed as shown in Figure 3. The structural survey response to thruster firing is analyzed first using Fourier methods to establish the integrity of the system and the existence of the major bending groups, and to establish bounds on their frequencies and damping ratios. These results are used to develop an input sequence for high-precision parametric identification, which maximizes the model information returned by the sensors. For excitation, proof-mass actuators (PMAs) are used. Sensing consists of accelerometers distributed about the antenna and support structures in sufficient numbers to provide adequate observability of the major dynamic modes (Figure 1). Processing methods, including recursive least squares, maximum likelihood estimation, prediction error, and other methods in the time domain are used to derive final parameter values.

### Jitter Control

The objective of hub-to-feed line-of-sight jitter control is to correct for static and dynamic motions that adversely affect RF pattern precision. Static errors (those that occur very slowly) are caused by mechanical bias errors and thermal loading. Dynamic motion is primarily caused by spacecraft thruster firing and/or control moment gyro (CMG) induced vibration. For vibration suppression, three methodologies are considered (Figure 4). The simplest strategy is to use proportional rate plus position feedback in the PMAs (Figure 4a). This results in moderate performance but the robust behavior of the control system. For increased performance and higher bandwidth vibration suppression, the linear quadratic Gaussian (LQG) methodology is used to suppress jitter in
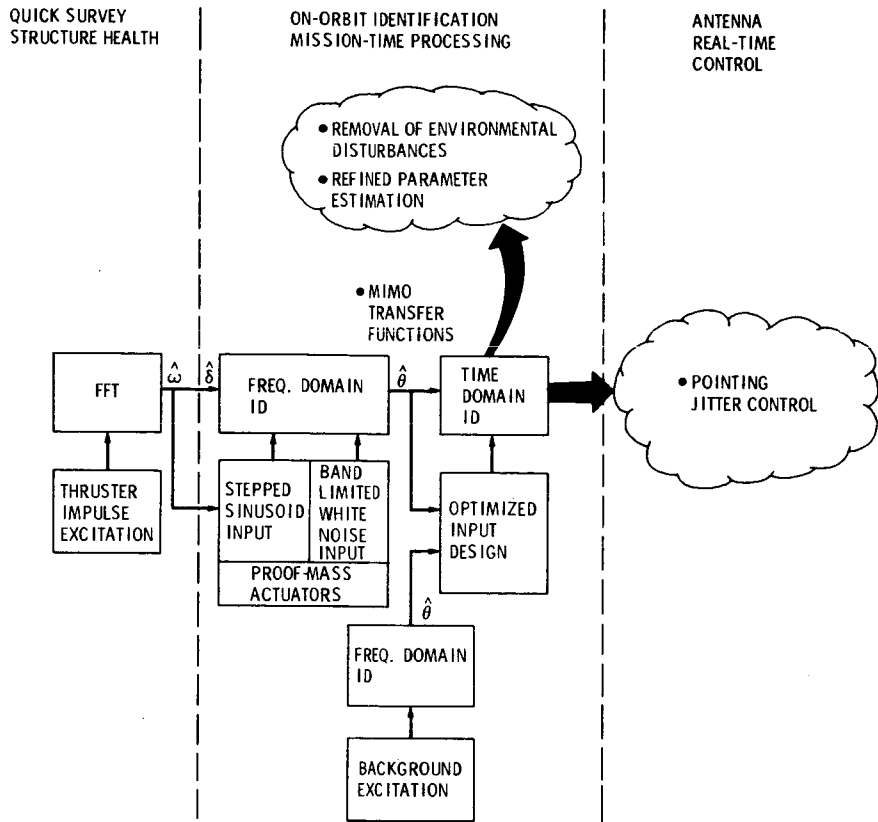
QUICK SURVEY
STRUCTURE HEALTH

ON-ORBIT IDENTIFICATION
MISSION-TIME PROCESSING

ANTENNA
REAL-TIME
CONTROL

- REMOVAL OF ENVIRONMENTAL DISTURBANCES
- REFINED PARAMETER ESTIMATION

- MIMO TRANSFER FUNCTIONS

- POINTING JITTER CONTROL

FFT

$\hat{\omega}$ $\hat{\delta}$

FREQ. DOMAIN ID

$\hat{\theta}$

TIME DOMAIN ID

THRUSTER IMPULSE EXCITATION

STEPPED SINUSOID INPUT

BAND LIMITED WHITE NOISE INPUT

OPTIMIZED INPUT DESIGN

PROOF-MASS ACTUATORS

$\hat{\theta}$

FREQ. DOMAIN ID

BACKGROUND EXCITATION

Fig. 3. Dynamics Identification Strategy

a. ROBUST CONTROL

MEASUREMENT SYSTEM

COMPUTATION VELOCITY & POSITION FEEDBACK

PROOF-MASS ACTUATORS

X, Y

$U = CX - KY$

U

FEED-BOOM

REFLECTOR BOOM

b. HIGH-AUTHORITY CONTROL

MEASUREMENT SYSTEM

COMPUTATION KALMAN FILTER/ OPTIMAL CONTROL

PROOF-MASS ACTUATION

X, Y

$\hat{X} = A\hat{X} + KZ$
$U = C\hat{X}$

U

FEED-BOOM

REFLECTOR BOOM

A, K, C,

RESPONSE HISTORY

PARAMETER IDENTIFICATION

c. TWO-BODY TRACKING

MEASUREMENT SYSTEM

COMPUTATION KALMAN FILTER/ OPTIMAL CONTROL

PROOF-MASS ACTUATION

X, Y

$\hat{X} = A\hat{X} + KZ$
$U = C\hat{X}$

U

FEED-BOOM

REFLECTOR BOOM
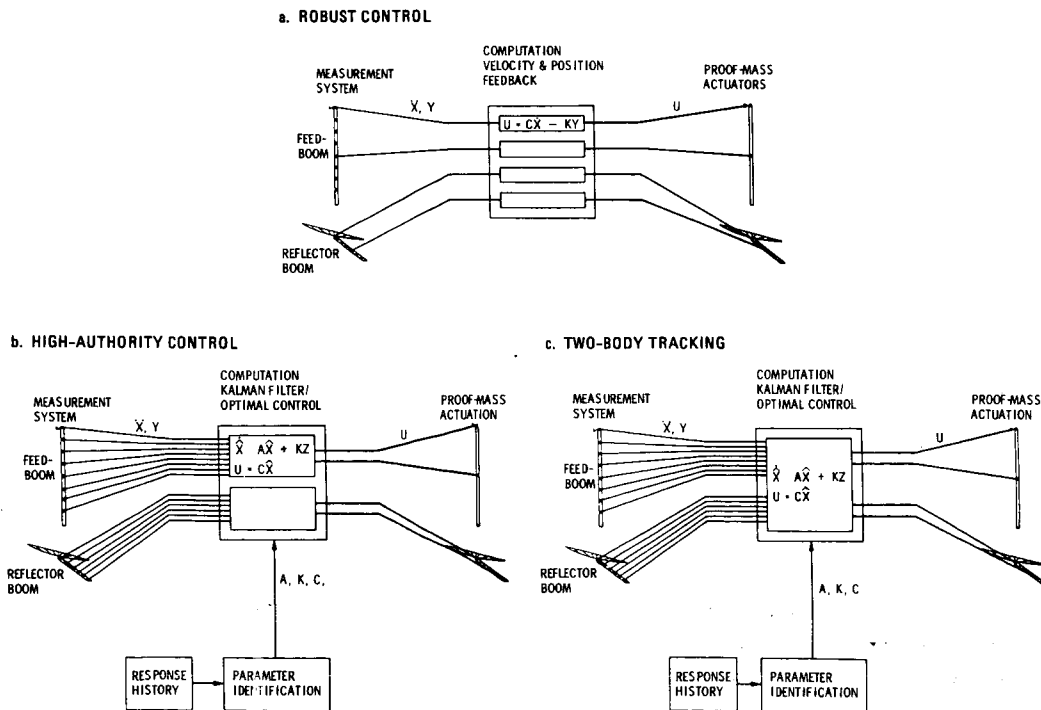
A, K, C

RESPONSE HISTORY

PARAMETER IDENTIFICATION

Fig. 4. Antenna Vibration and Pointing Jitter Control

each of the major structural components independently (Figure 4b), while for highest precision the RF performance measure is maximized directly as the control objective, again using LQG methodology (Figure 4c). Simulation studies demonstrate that pointing jitter can be dramatically suppressed by employing these control strategies.

CONCLUSIONS

This paper has highlighted the significant role to be performed by using integrated sensing, control, and actuation technologies for the MSAT space segment. Advanced methodologies in on-orbit system identification, shape estimation, and distributed control are ready to be applied to the next generation of systems.[2-6] These key control technologies are seen to be basic to the attainment and on-orbit maintenance of the high-precision mobile satellite communications that is the goal of the MSAT-X initiative.

ACKNOWLEDGEMENT

REFERENCES

1.  R. Scheid, G. Rodriguez, "An Integrated Approach to Modeling, Identification, Estimation and Control for Static Distributed Systems," Fourth IFAC Symposium on Control of Distributed Parameter Systems, Los Angeles, California, June 1987.

2.  D.S. Bayard, F.Y. Hadaegh, and D.R. Meldrum, "Optimal Experiment Design for On-Orbit Identification of Flexible Body Parameters in Large Space Structures," Fourth IFAC Symposium on Control of Distributed Parameter Systems, Los Angeles, California, June 1986.

3.  E. Mettler and M.H. Milman, "System Identification and Modeling for Control of Flexible Structures," First NASA/DOD CSI Technology Conference, Norfolk, Virginia, November 1986.

4.  D.S. Bayard, F.Y. Hadaegh, D.R. Meldrum, and E. Mettler, "On-Orbit Flexible Body Parameter Identification for Space Station," Vibration Damping 1986 Workshop II, Las Vegas, Nevada, March 5, 1986.

5.  R.L. Kosut, "On-Line Identification and Control Tuning of Large Space Structures," Proc. Fifth Yale Conference on Adaptive Systems Theory, Yale University, May 1987.

6.  D. Eldred and H. Vivian, "A Facility for Control Structure Interaction Technology Validation," Second NASA/DOD CSI Technology Conference, Colorado Springs, Colorado, November 17-19, 1987.