ever, because of their relatively high subsonic L/D, cruise for these configurations is feasible without additional wing area. For this class of vehicle, the ferry package might consist of cruise engines and fuel tanks only. Although this discussion has focused primarily on the orbiter, carrier weight also may be substantially reduced by downrange landing and application of the ferry package concept for fly-back.

The TIROS Operational Satellite (TOS) System as a Case Study

CLIFFORD A. SPOHN*
National Environmental Satellite Center, U. S. Dept. of Commerce, Washington, D. C.

THE TIROS Operational Satellite (TOS) System of the Environmental Science Services Administration (ESSA) became operational in February 1966, with the launch of ESSA I. Since that date it has operated continuously, with no breaks in service. This excellent record is due in no small part to the high degree of cooperation, coordination, and intelligence interchange which has been developed among the three agencies concerned, namely; NASA, ESSA and RCA (the prime contractor). Most of the day-to-day interchange is accomplished by the working teams at the NASA/GSFC (Goddard Spaceflight Center) TOS Project Office, the ESSA National Environmental Satellite Center (NESC), which operates the system, and the RCA TOS Project Office, which has designed and built most of the system and hardware.

This Note presents some of the lessons learned with respect to the following areas: whole system design, coordination, redundancy, simplicity vs sophistication, and centralized data processing (economy or bottleneck?).

Whole System Design

There is a great tendency to concentrate on the satellite and sensors, to give less consideration to the ground station needs and to assume that the data processing and data output systems will fall in place. A typical unconsidered item might be the formatting of the data to provide for the simplest and most reliable recognition and reduction in the data processing phase. It is very possible that the spacecraft sensors will equally easily permit several data formats, one of which is particularly amenable to the planned data processing. If the decision on format is made in ignorance of the data processing needs, however, the preferred format will probably not be the one selected.

The need for whole system design shows itself most clearly if a large number of ground readout stations will be accepting data from the satellite. It may make very good economic sense to make the satellite more complex or expensive, if by so doing, a large number of ground stations are made simpler, more reliable or even sufficiently less expensive. So long as the increased complexity of the satellite does not result in a disproportionate increase in failure probability, one would certainly want to select such an option—but the option must be available to select. In the ESSA system, one of the problems in the operation of our Automatic Picture Transmission (APT) System, which provides data to many independent ground stations, is that the slow degradation of the cameras results in less and less adequate pictures. Less adequate pictures also occur during the winter season, because of reduced surface lighting. Since there are a wide variety of ground receivers and recorders around the world, the capability of these various stations to overcome the picture deficiencies is varied. If NESC had elected to include in our APT cameras some form of remote controllable sensitivity, we might have readily compensated for these deficiencies to a large extent on the spacecraft, and provided better data at less expense to our various users. The added cost and risk of this feature on the spacecraft would have to be balanced against the improved utility of the received data.

Coordination

Perhaps the greatest difficulty in the early days of the operational meteorological satellite program resulted from a failure to provide sufficient continuing coordination between the agencies concerned. The tacit assumption was made that requirements could be adequately defined in writing. However, it was found that the written word is a very poor device for coordination. It can be extremely valuable as a record of what has been agreed orally, when both parties know what the other means by the written word; it can be worse than useless without the oral coordination to guarantee understanding. Over the years NASA, ESSA, and RCA have developed relatively elaborate, but very effective coordination procedure for the meteorological satellite program. At the top is the Meteorological Satellite Program Review Board (MSPRB). Chaired jointly by the Associate Administrator for Space Science & Applications of NASA and the Administrator of ESSA, it provides the vehicle for major policy and funding decisions. The MSPRB meets several times a year. At these meetings each agency reviews its present program status and funding, then jointly they examine the proposed program for the next 12–18 months. Policy decisions on major program tradeoffs or problem areas are often made, or differences aired for further review. Since the board includes members or observers from several organizational levels below the principals, it provides an especially effective vehicle for coordinated guidance throughout both organizations.

At the working level is the TOS Working Group. This unit is comprised primarily of NASA/GSFC, ESSA/NESC and RCA personnel at the principal technical supervisory level and meets monthly. It reviews recent progress in the project, problems which have arisen, and possible solutions. It assigns responsibility for further investigation of unresolved problems. It provides a means for coordinated implementation of the MSPRB decisions and passes on to ESSA and NASA management and to the MSPRB problems requiring policy decision. Below both of these formal bodies, there is a continuing coordination on a day-to-day basis at the working level. Both GSFC and NESC have designated individuals who have primary technical responsibility for their agency in specified areas (i.e., spacecraft operations, sensor status, communications, etc.). These personnel work directly with each other on any problems which arise in their specified areas. This method has been found to be much superior to the use of a single person for all coordination for each agency, since such single points of contact almost invariably become either bottlenecks or simply relay points. It is, of course, essential that the individuals who are the specified coordinators keep their superiors informed of the results of their coordination (and any others who may be affected). In fact, the TOS Working Group meetings serve to insure such intelligence distribution, since all of these special coordinators are members of the Group.

Finally, but by no means last in importance, NESC maintains an office right in the GSFC TOS Project area, staffed full time with personnel who are always available to provide a channel for questions not appropriate to the special coordina-

Received March 1, 1970; presented as Paper 70-283 at the AIAA Earth Resources Observations and Information Systems Meeting, Annapolis, Md., March 2–4, 1970; revision received May 6, 1970.

* Director, Office of Operations, Environmental Science Services Administration.

tors, to sit as observors in all the TOS Project planning and review meetings, and to inject the NESC expertise and context in those areas where NASA does not have the necessary familiarity and background. This office participates in such items as proposal evaluation, award fee determination and other contract matters involving work for ESSA.

All of the elements of this coordinating structure are useful and viable. It would be a mistake to structure such an organization too rigidly—much of their activity is of necessity ad hoc. Formal memoranda are useful as items of record and for informing others concerned with actions and decisions taken or to be taken. A basic lesson of this activity has been that each organization must be responsive to the problems and capabilities of the others—and it can only do so if it understands them thoroughly through frequent, meaningful contact.

Redundancy

The essence of an operating system is that it is supplying a product required by its customers on a regular basis, otherwise it would not be operating. The degree of redundancy required in the system is closely related to the perishability of the data (i.e., either the rate of change of the data elements, or the time interval acceptable between observation and use). If data are not very perishable, then redundancy is keyed to the cost of replacement when a loss occurs. For instance, a spacecraft sensor might be made redundant because the cost of a replacement spacecraft launch was uneconomic when weighed against the cost of including a redundant sensor on the spacecraft (including the cost of thereby giving up some other capability). On the other hand, a ground processing system, for nonperishable data, would probably not be made redundant since in case of a failure the data could be held and processed after repair, if the through-put capacity were large enough to permit catching up after repair.

Since weather data are highly perishable, the TOS System is highly redundant at vital points. All primary spacecraft control and sensor systems are built with redundant major components, so arrayed that it requires the loss of two identical major components to lose either spacecraft or primary data. Sufficient redundancy is provided at ground stations and processing centers to insure the capability of producing a minimum product for users. Our one major lack of redundancy is in ground communications between our control stations and our processing center. This redundancy lack is keyed to both the high cost of such redundancy and to the infrequent breakdown and the very quick recovery capability of the communications system. As an added safeguard, we provide the control station with the capability to store the data in unprocessed form so that it is not lost during short outages.

It should be noted that redundancy can readily take the form of less complex or sophisticated equipment that can substitute for the primary gear during repair and recovery phases. (In our case, that includes substituting people for computers in emergency conditions for both limited data reduction and spacecraft operation).

In the final analysis, redundancy must be keyed to the effect on meeting user requirements, and the penalty of not meeting them. It is generally an economic question. It would be mighty embarrassing, though, to have a ten million dollar† satellite gathering data that are not recoverable beause of the lack of a $10,000 piece of ground equipment.

Simplicity vs Sophistication

There is a constant trade-off required between the frequently conflicting desires for simplicity versus sophistication. One of the pitfalls in this area arises from the understandable desire, in the early stages of the system operation, to preserve all possible options. The net result is usually to produce system complexity that creates its own pitfalls in operation at the expense of dependability, and at greatly increased cost. One particular display device developed by the NESC early in our program to provide a variety of possibly needed options was expensive to have built and has been difficult to maintain. If we had designed for only the two primary functions which finally evolved, we would have reduced both cost and complexity with no real effect on our operational posture.

This same problem arises with respect to the spacecraft itself. Should a spacecraft be devised as a "space bus," carrying many sensors, or should it be relatively simple, with only a few sensors? A good case can be made for the economics of the "space bus," especially in the reduction of launch costs—a major cost item. The crunch in the "space bus" situation arises when sensor "A" fails. Must a replacement spacecraft be launched to provide for the data lost from that one sensor failure? If not, was the sensor necessary in the first place? If yes, does the replacement spacecraft carry the whole family of sensors that were on the first spacecraft? On the other hand, launching separate spacecraft with only individual sensors or pairs of sensors may pose a problem in both the launch costs and the space management of a relatively large number of spacecraft. Up to this time ESSA has operated under the single primary sensor per spacecraft arrangement. The TIROS-M spacecraft recently launched will, when it becomes operational, be our first space bus. Even here we will be flying only two primary sensors—a set of visual channel sensors and an infrared channel sensor. With a very high degree of redundancy incorporated in the spacecraft, we hope to minimize the replacement problem. Future ESSA satellites, however, will see the variety of primary sensors increased, and we will then face the replacement problem full on.

The opposite side of the coin is the desire to design the human animal out of the operating system. Every point at which a human operator must intervene and make a decision becomes a potential problem. Murphy's Law clearly applies here! The trick is to define those points from which the man cannot be excluded in such a matter that his mistakes cannot be catastropic. Thus, although it may make the system simpler to interject the operator at decision points, it will certainly increase fallibility.

Centralized Data Processing

There is a very real and very appealing economy to be obtained from centralized data processing. It is just because of its real benefits that such a processing arrangement must be approached and planned with a clear view of the real purpose of such a facility, namely, the provision of data in a useful form to the user as expeditiously as possible.

To attain that objective, it is essential that the data processing facility remain fully responsive to the user community. It is very easy to fall into the trap if one views the facility from the standpoint of its own efficiency. At that point data processing begins to be done so as to maximize the utility of the processing facility, and not to maximize the delivery of useful data to the customers. The response of the customers to this development will frequently be to try to find ways to bypass the facility in obtaining their needed data, and thus the very real gains which were possible are negated.

Summary

A full-time operational data gathering system must operate under different conditions than an experimental system. It must be a fully planned system—the personnel responsible for design, construction, operation, and data use must all be fully aware of each others' plans, capabilities and needs. It must provide for continuing operation, with the degree of

† Approximate cost of satellite, including launch vehicle.

sophistication needed to provide for flexibility and safety, and as much simplicity as possible to insure dependability. Above all else, it must serve a useful purpose by providing to the user community data in a form and at a time so as to insure maximum utility in supporting its design functions.

Thrust Termination Analysis Utilizing an Aluminized Solid-Propellant Rocket Fuel

DAVID L. BADAL* AND BERTRAM N. VINCENT†
Lockheed Missile & Space Company, Sunnyvale, Calif.

Nomenclature

a,b	= burning rate constants
A	= area
C_W,C_d,C_F	= mass flow, discharge, and thrust coefficients
F	= thrust
g	= gravitational constant
N	= number of ports
P	= pressure
R	= gas constant
T	= temperature
TRR	= thrust reversal ratio
t	= time
V	= volume
$W,\dot{W}$	= flow and flow rate
α,β	= motor inner and outer stack angles to longitudinal axis of motor
γ	= ratio of specific heats
ρ	= density
ϵ	= expansion ratio
τ	= burning rate

Subscripts

A	= reverse thrust parallel to port centerline
AR	= reverse thrust parallel to motor centerline
a,c,e	= ambient, chamber, and exit conditions, respectively
b,g	= burning surface and gas, respectively
i	= condition along stack wall
M,P	= motor and propellant, respectively
R	= reversal port
S	= scarfed portion of port
SR	= scarfed portion of thrust parallel to main motor centerline
t	= main nozzle throat
vac	= vacuum condition

Introduction

ANALYSIS of the forces acting at the time of thrust termination requires the evaluation of all the vehicle forces. However, the parameter of greatest concern is the discharge coefficient. During the past several years, data have been collected by many investigators testing orifices of various inlet designs with air and/or nitrogen as a working fluid. This Note correlates those data with thrust termination data derived from a highly aluminized, double-base solid propellant exhausting through a straight-edge orifice. These hot-gas data were obtained from both static tests at ambient conditions and flight tests at near vacuum conditions. In addition, a simple one-dimensional analysis has been derived and utilized to predict the thrust reversal ratio under vacuum conditions.

Received March 20, 1970; revision received May 18, 1970. This work was accomplished under U.S. Navy Contract N00030-66C-0186.

* Senior Flight Test Analysis Engineer. Member AIAA.

† Senior Research Design Engineer.

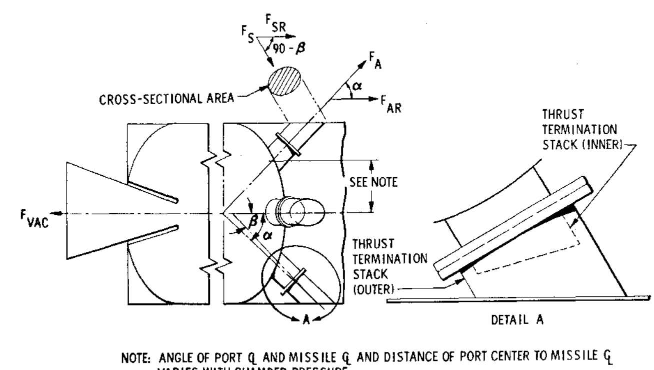

Fig. 1 Thrust termination schematic.

Figure 1 shows a schematic of the thrust termination system utilized on the C3 Poseidon. This system is initiated by a detonator that ignites a flexible linear-shaped charge and results in cleanly cut straight-edged venting orifices. For each port, there is a canted outer stack as shown in Fig. 1.

Mathematical Model

The general equations used to obtain the motor thrust prior to thrust termination can be derived from Zucrow[1] by assuming one-dimensional flow and are as follows:

$$F_{\text{vac}} = P_C A_t C_{F\text{vac}} \tag{1}$$

where

$$C_{F\text{vac}} = C_d\{2\gamma^2/(\gamma - 1)[2/(\gamma + 1)]^{(\gamma+1)/(\gamma-1)} \times [1 - (P_e/P_c)^{(\gamma-1)/\gamma}]\}^{1/2} + (P_e/P_c)\epsilon \tag{2}$$

Using the terms in Fig. 1, the thrust contribution from the inner stack parallel to motor centerline can be expressed as

$$F_{AR} = P_c A_R C_{F\text{vac}} \cos\alpha \tag{3}$$

and the force generated by the scarfed portion of the outer stack parallel to motor centerline can be given by

$$F_{SR} = P_S A_S \sin(90 - \beta) \tag{4}$$

Thus, the total thrust reversal is

$$F_R = N(F_{AR} - F_{SR}) \tag{5}$$

and the thrust reversal ratio is

$$TRR = F_R/F_{\text{vac}} \tag{6}$$

The discharge coefficient (C_d) for the main nozzle is assumed to be near unity because of a well-designed entrance section; however, for the thrust termination port (a straight-edge orifice), this is not true. A theoretical C_d derivation from the mass-flow equation is

$$\dot{W}_{\text{out}} = (C_{wt}C_dP_cA_R)_{\text{ports}} + (C_{wt}P_cA_t)_{\text{main nozzle}} \tag{7}$$

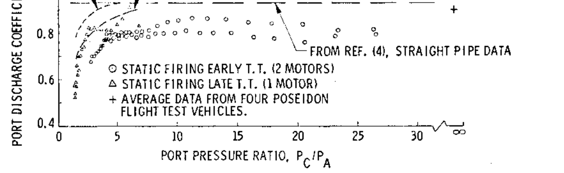

Fig. 2 Discharge coefficient vs pressure ratio.