THE INSTRUMENTATION OF SPACE VEHICLE IN CONNECTION WITH THE SUCCESSFUL SATURN FLIGHT TESTS

By

Otto A. Hoberg

U. S. National Aeronautics and Space Administration
George C. Marshall Space Flight Center
Huntsville, Alabama

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SUMMARY

Instrumentation of the Saturn space vehicle represents a considerable effort during the development phase. For proper design evaluation of this new configuration, its propulsion system, and its structure and control characteristics, an unprecedented number of measurements are required to be carried onboard and to be recovered. These measurements are expected to work properly and to furnish the design engineer with information that is not available by ground testing.

This paper reviews the Saturn instrumentation philosophy and describes the instrumentation system used on the first two flight tests.

Based on flight tests of SA-1 and SA-2, the actual performance of the instrumentation system and the quality of recovered data with respect to accuracy and reliability are examined.

SATURN INSTRUMENTATION

In watching a phase of a space vehicle's spectacular launching, especially the first Saturn shortly after takeoff, most observers are fascinated by the noise and flame of the propulsion system, by the giant size of the space vehicle, and by its steady, properly-controlled flight into the blue sky (figure 1).

The thousands of small items representing the instrumentation system generally perform unnoticed; yet the recovery of flight test data greatly depends on these items.

Instrumentation and communication engineering, in its true sense, has no purpose of its own; in reality, it is a service to the development engineer in his effort to build space vehicles and to make space flight, in general, more efficient, economical, and reliable.

In planning a flight test program for a project such as the Saturn, the gathering of requirements for flight measurements appears to be the first step. In practice, however, the instrumentation engineer does not have to gather; he is overwhelmed with requests and must consequently disappoint propulsion, structure, aero-dynamics, guidance and control engineers by denying them a large percentage of — in their opinion — essential flight test data. For example, about 2,000 flight measurements were requested for SA-1; not quite 600 could finally be accommodated.

The question may well be asked: What is the reason for such limitations? The answer is that some requirements just can not be translated into vehicle-borne equipment because of the following reasons.

1. There is no method known to sense parameters as requested.
2. Even if laboratory equipment exists, it may not be suitable for the environment of a flight test.
3. Limitation by the transmission system may render unsatisfactory data.
4. The time frame for design release, vehicle assembly, and test may not agree with procurement, research and development, and testing requirements.
5. Priority of mission assignments to special flight tests.
6. Particular consideration of volume; here all phases must be considered, beginning with preliminary development work in the laboratory over packaging, testing, checkout, calibration, static test, preflight test, recovery, and recording and ending with analysis and evaluation.

In describing instrumentation on SA-1 and SA-2, I will assume that general vehicle characteristics have been presented elsewhere and only briefly discuss the vehicle and its trajectory.

Figure 2 shows the major features of this particular vehicle configuration in some detail. The S-I stage carries eight engines similar to the type flown in the Jupiter and Thor programs. Its tank configuration is clustered with eight outside tanks of 70 inches diameter, surrounding one inner tank of 105 inches diameter. The adapter section between the first and second stages carries four instrument canisters where all instrumentation control and other electrical equipment are housed. The second and third stages are dummies S-IV and S-V, respectively; the nose resembles the Jupiter nose cone with angle-of-attack meters and protective cover material as used with the Jupiter project. The liftoff capability is approximately 920,000 lbs and the takeoff thrust is about 1,300,000 lbs. Instrumentation, which must be located in the vicinity of the engine compartment, is mounted below the tanks.

Figure 3 shows the trajectory that had a propelled time of 111 seconds where the four inboard engines were cut off. At 117 seconds the outboard engines were cut off, and from then on the vehicle followed a ballistic trajectory. When fired under an azimuth of 100 degrees east of north, the vehicle reached an altitude of 143 kilometers and impacted 365 kilometers from the launching site.

The task of an instrumentation engineer is to assure that data recovered from such a flight test — representing a sizable effort in engineering and dollars — are suitable to analyze parameters which are important for the mission assigned to this particular test flight. In the case of SA-1 and SA-2, the priority had been set as follows: performance of the eight-engine propulsion system, characteristics of structure and tanks, behavior and use of propellants, and finally the flight dynamics and control.

The first measuring program for SA-1 shows an issue date of May 28, 1959, with a launch date of October 27, 1961, amounting to almost eighteen months lead-time. Changes — the daily bread of an instrumentation engineer — had to be incorporated as time progressed. The final measuring program contained the following categories as shown in figure 4 in condensed form for SA-1 and in figure 5 for SA-2.

As a matter of policy, Marshall Space Flight Center prefers to purchase items, whenever possible, from industrial sources and to modify them if required or to initiate development. Items that cannot be procured are developed in our existing laboratories. All components and systems are intensely tested before they are approved for flight tests. Details on every sensor or associated electronic circuitry cannot be discussed here; however, I would like to direct your interest to a system used to adapt various types of end organs with respect to their electrical output to the telemetry set. A system that performs this function and also allows tests, adjustments, and remote calibration is shown in figure 6. These units have been developed as easily exchangeable plug-ins called modules, 20 of which are housed in one rack. The heart is an amplifier that can be made to operate in various modes by an exchangeable sub-module board; 287 of these modules, shown in figure 7, have been flown for adapting sensors of dc-ac pulse and other type outputs into the telemetry system which required, in general, 0-5 volt positive dc looking into 100 K ohms.

The telemetry system suitable to transmit the foregoing data was selected mainly by two considerations.

1. What equipment could be made available within schedule requirements without compromising on quality?

2. What typical Saturn characteristic could be satisfied within the restriction of consideration #1?

An FM/FM telemetry set in its basic form, previously developed at the Marshall Space Flight Center, was selected for the first consideration. In turn, this selection made possible, at least partially, a solution for the second consideration by complementing the basic equipment with a variety of specially developed switching and time multiplexing devices. Typical Saturn characteristics such as the eight engine concept, clustered tanks, and critical environment areas could be monitored.

Figure 8 shows the telemetry system as flown with SA-1; it consists of eight basically identical sets with the necessary special features added.

The transmission frequency and the channel capacity are also shown. Unfortunately, the results of an analysis of bandwidth requirements could not be satisfied for SA-1. A compromise was reached by sampling in time intervals wideband data such as vibration information, etc. In SA-2 (figure 9), however, we were able to substantially improve this condition.

Here we introduced two sets of wideband data transmission telemetry of the single sideband type. Each set has a capacity of 15 continuous channels with a frequency response from 50 to 3,000 cycles. All other sets are similar or identical to the ones allotted to SA-1. One glance at the block diagram of the single sideband telemetry system (figure 10) will make you aware of the similarity with carrier communication techniques used in telephone nets. Besides common problems in the development and engineering of such a new telemetering system, one particular difficulty had to be solved — the bandpass filters. Results of environmental testing, which was still going on during the time the vehicle was being prepared and checked out for flight test, necessitated a change in mounting of the filter can with respect to the flight direction. After this was accomplished, the system performed as expected.

Measuring and telemetering systems give proper flight information and data created by and in the vehicle. Radio frequency systems are concerned with transmission of signals, control command links, and tracking systems as part of ground instrumentation. Figure 11 shows in block form the radio frequency systems used with SA-1 and SA-2. The command system of the type DRW-13 is arranged in parallel as required by Range Safety Regulations. The Azusa system, C-band radar, S-band radar, and the UDOP system were employed to provide tracking data; in the case of Azusa and C-band, both systems were used for range safety purposes as well. The UDOP (ultra high frequency Dovap) is the modification of the old Doppler system formerly used for tracking and guidance with the V-2. Higher frequencies are utilized now to gain higher accuracies of tracking data.

The antennae shown in figure 12 have been developed within the Marshall Space Flight Center's laboratories as integral parts of the structure. They are either cavity-backed slots or of the leaky waveguide type. Pattern characteristics and antenna location on the vehicle were dictated by the attitude of the vehicle during flight and by the trajectory relative to the location of respective ground stations.

Telemetry commands and UDOP signals should reach their ground stations regardless of the behavior of the vehicle to be able to analyze possible deficiencies or a failure; ideally, omnidirectional patterns are required. The other tracking aids operate on higher frequencies and somewhat directional antenna patterns, assuming normal behavior of the vehicle as previously calculated.

After this short description of the overall instrumentation system, let us discuss the results of the two test flights: SA-1 on October 27, 1961, and SA-2 on April 25, 1962. Both tests have been extremely successful.

The results of an evaluation of the measuring and telemetering performance are tabulated in figure 13; ground station receiving and recording equipment as well as playback and data reduction are included. The columns (measurement type and total) are identical as presented within the condensed measuring program before. For SA-1, we find 2.1 percent of data were partially usable and 1.6 percent were unusable. For SA-2, .76 percent of data was partially usable and .76 percent was unusable (figure 14). These results apply to the complete length of flight; the flight of SA-2 was deliberately terminated by command in connection with Project Highwater.

In addition to an exceptionally good performance of the measuring and telemetering system, the radio frequency system also worked perfectly. All transponders performed correctly and good trajectory data were consequently recovered. On SA-2, the command system had been actuated and showed the desired reaction to initiate Project Highwater: the release of ballast water in 65-mile altitude. The problem of flame attenuation had been anticipated; however, the effect was minor because of proper design and location of the antennae. A comparison of predicted and actually recovered field strength is plotted in figure 15 for the telemetry signal strength in dbm over flight time in seconds. Results on SA-1 and SA-2 are comparable and encouraging for future flight tests.

What is expected from the instrumentation of space vehicles in the future? I like to select again the Saturn project. Now in its advanced development status, the C-5 version consists of three stages: S-IC, S-II, S-IV, and its instrument unit. Figure 16 shows instrumentation items anticipated for developmental flight tests; payload requirements were not considered.

Twenty-three telemetry links appear to be required of various types employing frequency modulation, single sideband techniques, and pulse code modulation. The system includes digital telemetering and data acquisition systems for automatic checkout of stages as well as the complete vehicle system. The channel capacity based on such a layout will be 3,275 which is suitable for more than 4,000 data points. Seventeen radio frequency links of different nature than used for telemetry will assure command capability and correct tracking during all phases of the flight.

Without the experience gained from Saturn flights SA-1 and SA-2, an advanced project of the magnitude of Saturn C-5 does not seem to be possible. With the instrumentation planned for the Saturn's first two flight tests and the quality of data successfully recovered, the design engineer can analyze the performance of the complete vehicle system. This will enable him to gain an extensive amount of information and then apply his knowledge to future developments; for example, the Saturn C-5. Helping to achieve such progress is a rewarding result for the instrumentation engineer.