SPIN BALANCE PROCESSING OF THE CLEMENTINE SPACE VEHICLE

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ABSTRACT

The Clementine program was started in the spring of 1992 and launched on January 25, 1994. This fast-paced program served as a test-bed for several advanced lightweight sensor and component technologies developed by the Ballistic Missile Defense Organization. Using these technologies, the mission has provided digital imaging of the entire lunar surface for the planetary science community.

Spin balance processing was one of the spacecraft processing activities affected by the fast-paced schedule of the Clementine program. Because of tight scheduling, complicated by safety constraints involved in the integration of a solid rocket motor (SRM), spin balance processing activities had to be tailored around the delivery of the SRM. Since the Payload Processing Facility of the Naval Research Laboratory is not approved for hazardous operations, spin balance processing required the flight SRM be replaced by a suitable substitute. Typically this would be accomplished with an inert version of the flight SRM. However, due to time and budget constraints, a "simple" mass simulator was chosen. The spacecraft-SRM mass simulator assembly and flight SRM were balanced separately. Following environmental testing and integration at the Naval Research Laboratory, the spacecraft was shipped to Vandenberg AFB for launch processing where a hazardous processing facility was available. The spacecraft was then integrated with the flight SRM and unbalance properties of the loaded assembly was successfully measured.

By spin balancing major spacecraft components separately and substituting a mass simulator for the flight SRM, the Clementine processing schedule could be maintained while satisfying all SRM safety constraints. More importantly, final measured unbalanced properties of the spacecraft-flight SRM assembly were accurately determined and proven to be well within the requirements for the spacecraft attitude control system.

INTRODUCTION

Due to tight scheduling complicated by safety constraints involved in the integration of a solid rocket motor (SRM), spin balance processing activities for the Clementine program had to be tailored around the delivery of the SRM.

Clementine consisted of two components: 1) the spacecraft and 2) the interstage-SRM assembly. Both components made up the Clementine space vehicle as shown in Figure 1. The spacecraft was 3-axis stabilized. The space vehicle was spin-stabilized during the SRM translunar trajectory burn. The interstage assembly provided the SRM interface to the spacecraft and was then jettisoned following the SRM burn.

As with most spacecraft projects, a major hurdle during design and construction was components requiring a long lead-time for manufacture and delivery. Most long lead-time

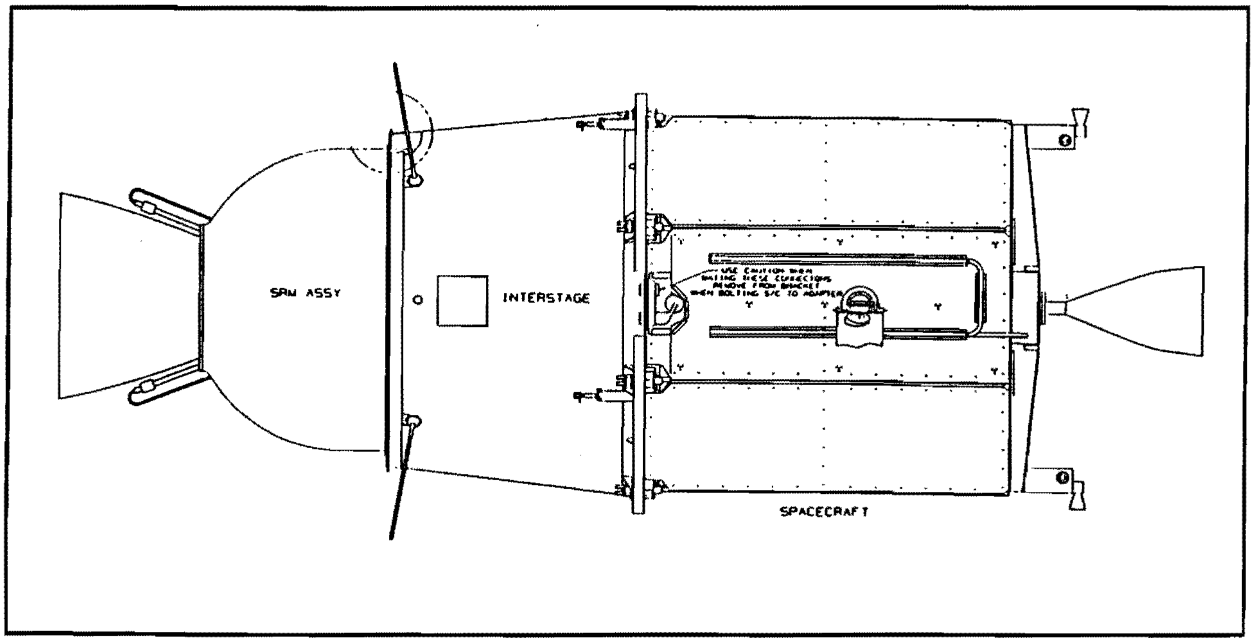

Figure 1: Clementine Space Vehicle and Components

components utilized for the Clementine program were delivered within one year of the order date. The fast-pace schedule of the Clementine mission resulted in many of these items, such as the SRM, being delivered only months prior to the launch date. Therefore, rapid integration and processing were key to meeting such a tight launch schedule. Rapid integration and processing requires the maximizing of parallel tasks and the minimizing of serial tasks for the spacecraft. This is especially true for launch site processing activities which tend to be serial in nature. However, whenever applicable, parallel tasks were also employed in the field.

In order to minimize the launch site spin balance activities, a processing flow was developed that required the spacecraft to be delivered to Vandenberg Air Force Base (AFB) in a balanced configuration. The spacecraft was configured to offset any unbalance induced by the SRM and the assembly of the space vehicle. Due to safety constraints, the flight SRM could not be delivered to the Naval Research Laboratory (NRL) for integration. Instead, it was delivered to Vandenberg AFB for integration during launch site processing

Because of these conditions, a suitable substitute for the flight SRM was required to complete the necessary integration and testing at NRL. Standard procedures for spin balance typically dictate the use of an inert duplicate SRM as a substitute for a live SRM. An inert duplicate

SRM would not be deliverable until the flight SRM was also ready. In addition to schedule constraints, budgetary concerns stipulated that a "simple" mass simulator be chosen over an inert SRM. The mass simulator was balanced to represent the unbalance properties of the actual flight SRM.

Mission operations requirements dictated that the spacecraft be 3-axis stabilized, statically balanced, and the space vehicle be spin-stabilized, dynamically balanced. This resulted in the need to balance the spacecraft and the interstage-SRM mass simulator separately, and measure the unbalance condition of the final launch configured space vehicle assembly (including the flight SRM).

Prior to the final manufacturing of the flight space vehicle components and the flight SRM, the spin balance test flow was successfully proven using the space vehicle engineering model components and SRM mass simulator. Balancing of the flight interstage-SRM mass simulator assembly separate from the spacecraft permitted the integration of the interstage to the flight SRM at Vandenberg AFB in parallel to the final spacecraft integration. Upon completion of spacecraft launch site processing activities, the spacecraft and the interstage-flight SRM were mated and the final unbalance condition of the flight space vehicle assembly was measured.

MISSION BACKGROUND

Preliminary design of the Clementine mission was started in the spring of 1992. The spacecraft was launched on a Titan IIG expendable launch vehicle from Vandenberg AFB on January 25, 1994. The Clementine program was jointly sponsored by the Ballistic Missile Defense Organization (BMDO) and the National Aeronautics and Space Administration (NASA). Spacecraft integration was the responsibility of NRL. The primary objective of this mission was to space qualify advanced lightweight sensor and component technology developed for the Department of Defense. Targets such as the moon and the spacecraft interstage assembly were used to demonstrate the performance of these technologies. The secondary objective was to digitally map the lunar surface. All advanced lightweight technology utilized on the spacecraft has been space qualified. Furthermore, digital imaging of the entire lunar surface has been accomplished and is available to the planetary science community.

INTRODUCTION TO SPIN STABILZATION AND SPIN BALANCE

Spin Stabilization is one of three types of attitude control techniques (the other two are passive and 3-axis stabilized attitude control). In spin stabilization, the entire spacecraft rotates about its spin axis. This technique utilizes the gyroscopic stiffness of the spinning body so that the angular-momentum vector, the principal inertia spin axis, remains fixed in inertial space. Spin stabilized spacecraft allow for a large delta-V along the spin axis (such as that provided by an SRM burn).

In the Clementine space vehicle design, the SRM thrust vector is aligned along the geometric spin axis of the structure as shown in Figure 2. Pointing accuracy is dependent upon the alignment of the geometric spin axis with respect to the principal inertia spin axis of the space vehicle. The vehicle spins about its principal inertia spin axis. Angular misalignment between these two axes contributes to thrust misalignment The reduction of angular misalignment minimizes nutation and cone angle growth. This results in minimizing thrust alignment which minimizes cross-track thrust, thus maximizing the desired delta-V level delivered from the SRM. Therefore, the static

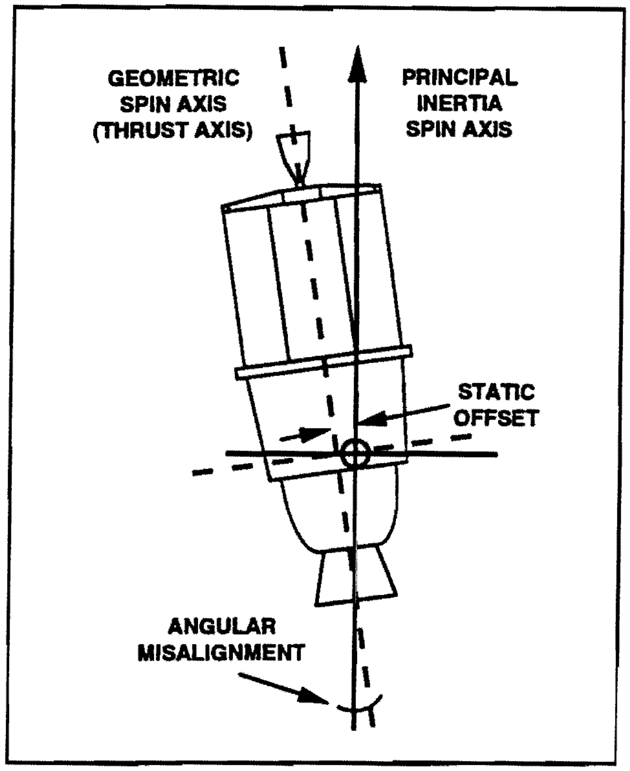

Figure 2: Clementine Space Vehicle Spin Axes Definition

offset and angular misalignment of the principal inertia spin axis with respect to the geometric spin axis must be reduced to acceptable levels defined by the attitude control system (ACS) design.

Dynamic spin balancing of a space vehicle will reduce the static offset and angular misalignment between the axes to a desired level required by the ACS design. Unbalance measurement and dynamic balancing of a test specimen is accomplished using a spin balance machine. These machines have the capability of measuring static and dynamic unbalance as well as dynamic unbalance in two planes. Using a spin balance machine, the static and dynamic unbalance is reduced to the required ACS design levels. The final spin axis misalignment and final static offset with respect to the spin axis is calculated from the final measured unbalance data.

Static unbalance is an unbalance condition for which the principal inertia axis is displaced only parallel to the geometric spin axis. Static offset, the distance between both parallel axes, can be derived from the final static unbalance using the following equation:

$$e = U_S / W$$

where: U_S = Static Unbalance
W = Weight of Test Specimen

Dynamic unbalance is an unbalance condition for which the principal inertia axis is not coincident with the geometric spin axis. Angular misalignment of the principal inertia axis with respect to the geometric spin axis can be derived from the final dynamic unbalance using the following equation:

$$\varnothing = 2U_D / (I_{AXIAL} - I_{TRANS})$$

where: U_D = Dynamic Unbalance

I_{AXIAL} = Moment of Inertia about the Axial or Spin Axis

I_{TRANS} = Moment of Inertia about the Transverse Axes

Dynamic balancing and unbalance measurement of the Clementine spacecraft, interstage assembly, and space vehicle were made using the Schenck-Trebel Model E6 Spin Balance Machine. Correction plane location (top and bottom planes) and separation, location, spin rate, and machine constant data were loaded into the spin balance machine. The dynamic unbalance in two planes of each test specimen was measured and recorded. Based on the measured dynamic unbalance, the machine determined the angular position and magnitude of each balance correction weight for each correction plane. These weights were bolted to the test specimen structure at locations determined by the machine. This process was repeated iteratively to minimize static and couple unbalance of the test specimen. The final spin axis misalignment and final static offset with respect to the geometric spin axis was then calculated from the final measured unbalance data.

ATTITUDE CONTROL SYSTEM BALANCE REQUIREMENTS

The attitude control system balance requirements for the final Clementine dry spacecraft and processed space vehicle are listed in Figure 3.

SPIN BALANCE PROCESSING

The spin balance processing operations took place at both the NRL, Building A-59, Payload Processing Facility and Vandenberg AFB, Building 1610, NASA Hazardous Processing Facility during the months of August 1993 through January 1994.

The goal of the spin balancing test flow was developed to minimize the launch site activities, thus compressing the overall integration schedule. The key element was the ability to accurately mate the separate space vehicle

Assembly	Static Unbalance (oz-in)	Static Offset (in)	Dynamic Unbalance ($oz\text{-}in^2$)	Angular Misalignment (deg)
Processed Space Vehicle	3100	0.05	100000	0.27
Dry Spacecraft (Stowed)	250	0.03	1100	0.24

Figure 3: Final Clementine Balance Requirements

components without violating the ACS unbalance condition requirement. This process was proven successful during pathfinder activities with the engineering model (EM) by performing a worst case study. This EM pathfinder activity took place during the months of August 1993 through October 1993 in Building A-59 of NRL.

Spin balance processing operations for the flight components, excluding the SRM, also took place in Building A-59 of NRL during the months of November 1993 through December 1993. Since Building A-59 is not approved for hazardous operations, the flight SRM could not be delivered to NRL. As a result, the flight SRM was delivered directly to Building 1610 at Vandenberg AFB where spacecraft propellant loading and flight SRM integration took place in mid-January of 1994.

Engineering Model Spin Balance Pathfinder Activities

Pathfinder activities to prove the ability to accurately mate separate space vehicle components without violating the ACS unbalance condition requirements took place during the months of August 1993 through October 1993. The spacecraft EM and the interstage EM-SRM mass simulator assembly were balanced separately using the NRL spin balance machine. These two components were assembled and the unbalance was measured for the final assembly.

Since the flight SRM manufacture was not complete at this time, the SRM mass simulator was configured into a worst case unbalanced condition based on past history of the SRM and contractual agreements with the manufacturer, Thiokol Corporation. The unbalance condition of the interstage EM was measured. The unbalanced SRM mass simulator was then mated to the interstage EM in a worst case configuration by aligning the phase angles of the unbalance properties for the two components. The static and dynamic unbalance of the interstage EM-SRM assembly was then corrected and measured. By mating in a worst case configuration, the allotted weight budget for counterweights was verified.

The spacecraft EM, a structural and mass simulator of the flight spacecraft (stowed wet launch configuration) was also dynamically balanced. The dynamic mode was used because it satisfied both the static requirement during spacecraft 3-axis stabilization and the dynamic requirement during space vehicle spin-stabilization. Static and dynamic unbalance was measured for the final correction. The spacecraft EM and interstage EM-SRM mass simulator were then mated with the use of optical alignment tooling. The resulting unbalance condition was measured and verified to be within the ACS requirements. Therefore, the following was confirmed: 1) the validity of the spin balance flow, 2) the ability to accurately mate the separate space vehicle components, and 3) the allowed counterweight budget.

Flight Vehicle Spin Balance Processing Operations

During the months of November and December of 1993, the following spin balancing activities took place at Building A-59 of NRL. Using the NRL spin balance machine, both the dry flight spacecraft and the flight interstage-SRM mass simulator assembly were balanced separately. Static and dynamic unbalance was measured and corrected for the dry spacecraft in the stowed launch configuration.

The SRM mass simulator representing the unbalance properties of the actual flight SRM was mated to the flight interstage. The unbalance of the SRM mass simulator was previously matched to simulate the actual unbalance of the loaded flight SRM as specified in the Thiokol STAR 37FM Rocket Motor Logbook. The unbalance properties of the SRM mass simulator are based on data collected during flight SRM spin balance operations conducted at NASA Wallops Flight Facility in October 1993. Thiokol Corporation was responsible for the balancing of the flight SRM. Static and dynamic unbalance was also measured and corrected for the flight interstage-SRM mass simulator assembly.

Following spin balance operations, both the spacecraft and interstage were shipped to Vandenberg AFB for launch processing. After spacecraft propellant loading and interstage-flight SRM integration at Building 1610 of Vandenberg AFB, the two components were mated together in the space vehicle configuration. Final unbalance measurements of the space vehicle were made using the NASA spin balance machine. Based on the EM spin balance pathfinder activities and preliminary calculations, balance correction was not expected following mating of the flight space vehicle assembly. Final unbalance measurements were well within the required specifications and balance correction to the processed space vehicle was not necessary.

SPIN BALANCE RESULTS

Engineering Model Spin Balance Pathfinder Results

Final Unbalance measurements of the EM space vehicle and the ACS requirements for static and dynamic unbalance are listed in Figure 4A

Flight Vehicle Spin Balance Results

Unbalance measurements were corrected to represent the actual flight configuration of the test specimen. Corrected unbalance measurements of the Clementine interstage-SRM mass simulator, dry spacecraft and the space vehicle are listed in Figure 4B.

Based on the corrected nominal static unbalance and dynamic unbalance for the dry spacecraft and processed space vehicle, the static offset and the angular misalignment of the principal inertia axis with respect to the geometric spin axis was calculated and are listed in Figure 4C.

Engineering Model	Static Unbalance (oz-in)	Dynamic Unbalance ($oz\text{-}in^2$)
Measured Space Vehicle EM	226	1771
Required Unbalance	3100	100000

Figure 4A: Unbalance Measurements of the Clementine Space Vehicle Engineering Model

Assembly	Static Unbalance (oz-in)	Phase Angle (deg)	Dynamic Unbalance ($oz\text{-}in^2$)	Phase Angle (deg)
Interstage-SRM Mass Simulator	5.0	135	208.2	310
Dry Spacecraft - No Propellant Load - Stowed Launch Configuration	12.0	160	297.9	250
Processed Space Vehicle - Full Propellant Load - Flight SRM	350.1	288	11843.8	252

Figure 4B: Corrected Unbalance Measurements of the Clementine Space Vehicle and Components

Assembly	Static Offset (in)	Required Static Offset (in)	Angular Misalignment (deg)	Required Angular Misalignment (deg)
Processed Space Vehicle	0.006	0.05	0.023	0.27
Dry Spacecraft (Stowed)	0.001	0.03	0.023	0.24

Figure 4C: Corrected Spin Axis Location of the Clementine Space Vehicle Spacecraft

ANALYSIS

SRM Mass Simulator and Flight SRM Comparison

The measured unbalance of the SRM mass simulator and the flight SRM is listed in Figure 5.

Processed Space Vehicle Unbalance Prediction

Recall that the interstage assembly was spin balanced using the SRM mass simulator. The final unbalance of the processed space vehicle (full propellant load and flight SRM) was predicted using the measured unbalance of the spacecraft, measured interstage-SRM mass simulator assembly unbalance, the measured SRM mass simulator unbalance, the measured flight SRM unbalance, the uncertainty associated with the mechanical mating of the spacecraft and interstage, and the predicted propellant load:

$$(SV)_{FLT} = [(SC)_{FLT} + (P)] + [(ISA)_{SIM} - (SRM)_{SIM} + (SRM)_{FLT}] + (UN)_{MATE}$$

where:

$(SV)_{FLT}$ = Unbalance of the Processed Space Vehicle

$(SC)_{FLT}$ = Measured Unbalance of the Dry Spacecraft

(P) = Predicted Propellant Load Unbalance (worst case fuel loading offset by weight = 0.125%)

$(ISA)_{SIM}$ = Measured Unbalance of the Interstage with the SRM Mass Simulator

$(SRM)_{SIM}$ = Measured Unbalance of the SRM Mass Simulator

$(SRM)_{FLT}$ = Measured Unbalance of the Flight SRM

$(UN)_{MATE}$ = Unbalance due to Uncertainty in Mating of Spacecraft and Interstage Assembly

Measured and Predicted Space Vehicle Unbalance Comparison

The measured unbalance and the predicted range for unbalance of the processed space vehicle is listed in Figure 6. The unbalance for the space vehicle fell within the predicted unbalance range. The minimum predicted unbalance would equal the measured if the offset between the lateral center of gravity (CG) of the spacecraft and the lateral CG of the interstage-SRM assembly had been zero. The maximum predicted unbalance would equal the measured unbalance if the offset between the lateral CG of the spacecraft and the CG of the interstage-SRM assembly had been the worst case uncertainty in mating alignment between the spacecraft and interstage SRM assembly (0.006 in) as demonstrated with the EM spin balance pathfinder activities.

The remaining margin of the measured and predicted data to the required values are listed in Table 7.

Solid Rocket Motor	Static Unbalance (oz-in)	Phase Angle (deg)	Dynamic Unbalance (oz-in^2)	Phase Angle (deg)
SRM - Mass Simulator	73	149	1303	252
SRM - Flight Motor	74	166	1231	248

Figure 5: Comparison Between Measured Unbalance for the Flight SRM and SRM Mass Simulator

Processed Space Vehicle	Static Unbalance (oz-in)	Dynamic Unbalance (oz-in^2)
Measured Unbalance	350.1	11843.8
Predicted Minimum Unbalance	232.7	9695.4
Predicted Maximum Unbalance	584.3	15100.8

Figure 6: Comparison Between Measured and Predicted Space Vehicle Unbalance

Processed Space Vehicle	Required Unbalance Remaining Margin	
	Static Unbalance (oz-in)	Dynamic Unbalance (oz-in^2)
Measured Unbalance	88.71%	88.16%
Predicted Unbalance	92.5%	90.30%
Required Unbalance	3100 oz-in	100000 oz-in^2

Figure 7A: Remaining Margin of the Processed Clementine Space Vehicle to the Required Unbalance

Processed Space Vehicle	Requirements - Remaining Margin	
	Static Offset (in)	Angular Misalignment (deg)
Measured Unbalance	88.00%	91.48%
Predicted Unbalance	92.00%	92.96%
Requirements	0.05	0.27

Figure 7B: Remaining Margin of the Processed Clementine Space Vehicle to the ACS Spin Axis Requirements

CONCLUSION

By substituting a mass simulator for the flight SRM and spin balancing the major spacecraft components separately in parallel to other integration tasks, the Clementine processing schedule could be maintained while satisfying all SRM safety constraints. It was estimated that at a minimum, ten days of launch site processing was eliminated from the integration flow. The final measured unbalance for the processed space vehicle were within the predicted values. The final measured static and dynamic unbalance properties of the processed space vehicle were well within the tolerance required by the ACS design and balance correction to the space vehicle was not necessary. All unbalance values as well as static offset and angular misalignment met the ACS requirements with a minimum 88% margin remaining .

Minor sources of error can be attributed to propellant loading uncertainties and difficulties associated with using two different spin balance machines.

Major sources of error could be attributed to mating alignment uncertainties due to the difficulties associated with accurate and repeatable mating of major assemblies. Alignment uncertainties between the interface of the spacecraft and the interstage-flight SRM assembly were noted prior to the final unbalance measurement. Alignment uncertainties were also noted between the space vehicle-spin balance test fixture interface. These uncertainties were attributed to ill fitting alignment target pins. These machined pins were used to measure alignment by means of optical tooling. Interface bolt holes of the forward interstage interface were inadvertently damaged and degraded during previous processing. Therefore, the alignment target pins did not fit as precisely as intended into the interface bolt holes resulting in alignment uncertainties. Problems associated with balancing two items separately and mating them accurately complicate this method. More durable mating alignment schemes should have been designed into the system to protect against this possibility.

If rapid integration and processing is required due to a tight launch schedule, the use of a "simple" SRM mass simulator representing the flight SRM can be used if: 1) can demonstrate sufficient margin between the resultant worst case unbalance conditions of separately balanced components and the ACS static and dynamic unbalance requirements; 2) repeatable and accurate mating of separate components is demonstrated; and 3) durable and accurate alignment schemes are designed into the system. If these three items are not addressed, then provisions should be built into the processing schedule to correct for any unbalance found to be out of tolerance during the final unbalance measurement of the processed vehicle.

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