RISK MANAGEMENT APPROACH FOR DE-ORBITING OF THE COMPTON GAMMA RAY OBSERVATORY

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ABSTRACT

De-orbiting of space debris into Earth is one of the methods to control and minimize the degradation of the space environment. The de-orbiting scenario poses a challenge of providing safety for the Earth population and other space-based assets below the orbit track of the spacecraft being de-orbited. Rigorous risk management is needed to provide the necessary safety margin for de-orbit operations.

These challenges were faced during the controlled de-orbit of the Compton Gamma Ray Observatory (CGRO) into the Pacific Ocean on June 4, 2000. This paper presents a risk management approach utilized at various stages of this mission; processes used to identify credible contingencies; and planned responses to contingencies for use during mission execution.

1. INTRODUCTION

CGRO was flying in low earth orbit at an altitude of 276 nautical miles (nm) (511 kilometers) circular, with an orbital inclination of 28.5 degrees to the equator, and weighed approximately 15,000 kilograms. Its orbit had been re-boosted in 1993 and again in 1997 to extend the science mission. Without such intervention CGRO was expected to re-enter the earth within two years.

On December 6, 1999, failure of one of three gyros on CGRO triggered an extensive risk management exercise. More than 5,600 kilograms of metal debris was expected to impact the earth's surface following reentry into the earth's atmosphere.

CGRO could have continued its mission with the remaining two gyros. However, loss of another gyro would have meant complete loss of attitude control. Considering the population density below the orbit track, the threat to human life and property was unacceptably high to allow a random and uncontrolled reentry. Therefore, NASA elected to de-orbit the spacecraft while it could still be controlled and directed into an uninhabited part of the Pacific Ocean.

The de-orbit activities were initiated on May 28, 2000, with an engineering test burn of the spacecraft engines. Following a successful engineering burn, a series of four maneuvers, as shown in Fig.1, were conducted, gradually lowering the perigee until the spacecraft entered the earth's atmosphere and crashed into the Pacific Ocean exactly as planned.

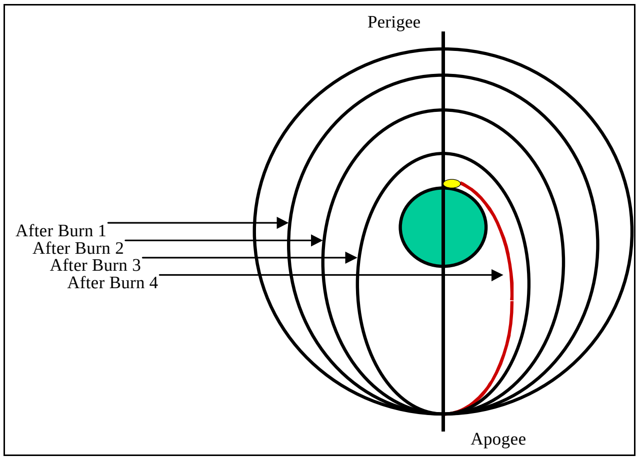

Fig. 1. De-orbiting Maneuvers

With human safety as the number one priority, risk management was exercised at every phase of the reentry mission. Mission phases can be defined as:

- Decision to de-orbit
- Selection of reentry location
- Collision avoidance with other space assets
- Constraining the mission design parameters
- Preparation for spacecraft contingencies
- Assessment of the ground system for reentry operations
- Mission execution

2. DECISION TO DE-ORBIT

2.1 General

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Although one of the gyros had failed, CGRO was still producing valuable science. The decision to terminate the mission of a functioning spacecraft could not be taken lightly. Analyses were performed to determine the threat to the population under the orbit track. Parameters involved in determining this risk included survivability of the spacecraft through the atmosphere, population density under the orbit track, and the size of the debris field.

2.2 Debris Survivability

Two independent analyses were performed to determine the number and sizes of the debris that was expected to survive reentry. These analyses were conducted using guidelines defined in NASA Tech Paper 2507 – "Procedure for Estimating Orbital Debris Risks, J. L. Crafts, JP Lindberg" and JSC Object Reentry Survival Analysis Tool (ORSAT). The analyses predicted that up to 5,600 kilograms of debris could survive the reentry, with sizes of debris fragments ranging from small (the size of a small stone) to several hundred kilograms.

2.3 Debris Footprint

The next step was to determine the debris footprint, defined as the total area of the debris field. As depicted in Fig. 2, the footprint is affected by the range of ballistic coefficients of the surviving fragments, errors in ephemeris knowledge, attitude errors, off-pulsing variation, and breakup altitude.

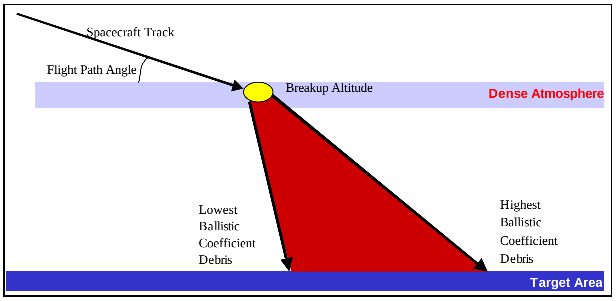


Fig. 2. Debris Footprint

With appropriate conservatism assigned to these parameters and assuming breakup at a fixed altitude (approximately 83 km), the debris was predicted to be spread over a long and narrow corridor approximately 838 nm (1,552 kilometers) in length and 14 nautical miles (26 kilometers) in width.

2.4 Threat Assessment

Based on the population density and the debris footprint, threat to human life and or property was predicted to be 1 in 1000 if the spacecraft was allowed to reenter randomly and uncontrolled. Analysis also showed that this threat would be reduced to 1 in 29,000,000 with careful design and implementation of a controlled reentry plan. Therefore, NASA elected to de-orbit the spacecraft while it could still be controlled and directed into an uninhabited part of the Pacific Ocean.

3. SELECTING REENTRY LOCATION

3.1 General

Steps involved in determining the reentry location consisted of (1) selecting an area as far away from human population as possible; (2) determining the worst case debris track; (3) overlaying the debris track within the selected area to insure that the population avoidance guidelines were met; and (4) ensuring that several consecutive opportunities existed that satisfied the above criteria.

3.2 Target Area Selection Guidelines

International sovereignty claims and NASA Safety Standard 1740 dictated that the target area should be at least 200 nautical miles from foreign lands and 25 nautical miles away from US lands. An area of the Pacific Ocean southeast of Hawaii was selected as the target area.

3.3 Debris Track

Although the debris footprint was predicted to be 838 nm (1552 km), where this footprint would land within the orbit track depended on thruster performance, accuracy of attitude control, accuracy of the ephemris knowledge, and burn initiation timing. The total range of area where the debris could impact is defined as the debris track. Appropriate uncertainties and margins were included in determining the worst case debris track. Analysis indicated that the debris track would be approximately 5,060 kilometers in length.

Fig. 3 shows the selected area with boundaries marked around populated land to indicate minimum debris avoidance distance. Predicted debris tracks for the primary and backup opportunities for June 4, 2000, are also shown.

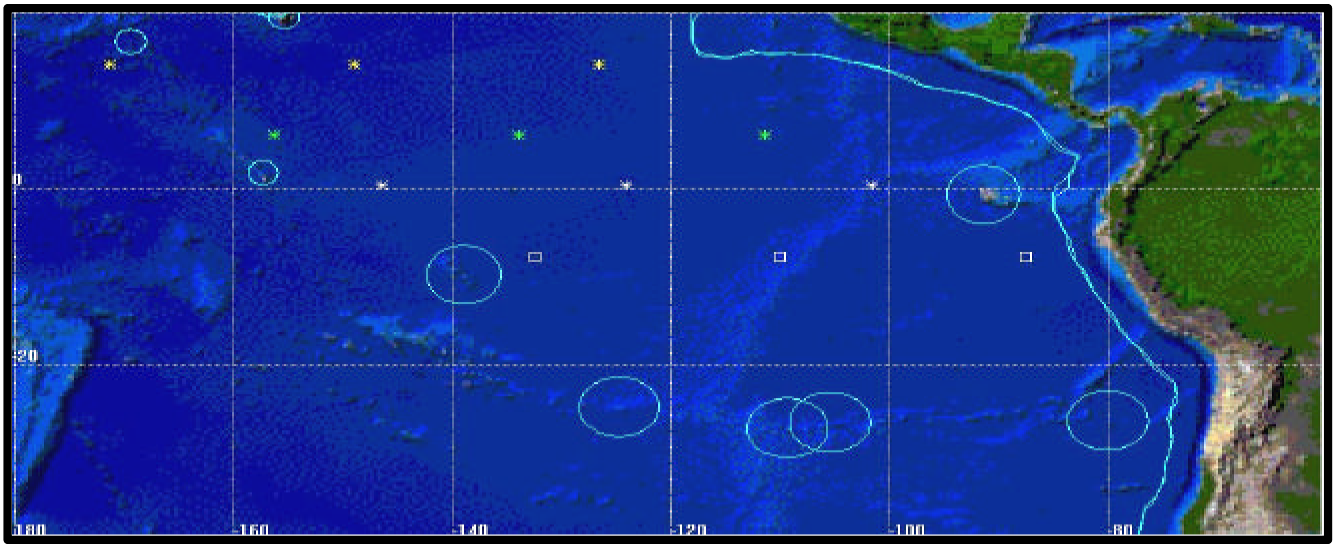


Fig. 3. Debris Track

3.4 Hazard Warning Notifications

Selection of the debris impact area away from population does not guarantee the safety of aircraft and surface vessels transiting in and near the target impact area. Methodology had to be established to provide appropriate warning to the aircraft and marine vessels without unnecessarily disrupting the schedules of these vessels. There were four days available to de-orbit CGRO starting on Sunday, June 4. On each day there were two opportunities to conduct the reentry. To minimize the loss of usable airspace and ocean area to aircraft and surface vessels, separate and unique Warning Areas ("Keep-Out Zones") were defined for each opportunity. Each area was equal to the predicted debris track, approximately 5,060 kilometers in length, and extended from the earth's surface to unlimited altitude.

The Warning Notice contained a table of latitude and longitude points that defined the centerline for each of the eight Debris Hazard Warning Areas and defined the time periods during which these areas were to be avoided. Aircraft and ships ware warned to 278 kilometers away from the Warning Area centerline.

4. COLLISION AVOIDANCE (WITH OTHER SPACEBORNE ASSETS)

4.1 General

With the descent of CGRO during the controlled de-orbit activity, the spacecraft was going to be crossing the orbital altitudes of several critical assets and many non-critical assets owned by NASA and other entities. Probabilities of conjunctions between CGRO and the critical assets were determined for each of the predicted orbits CGRO was to occupy during the de-orbit activities and a collision avoidance plan was developed.

4.2 Keep-Out Box

How close CGRO was allowed to come to the critical assets depended upon the dispersion in the thruster performance and accuracy of the ephemeris knowledge before initiating the burn. Worst case dispersion predictions dictated a keep-out-box of ± 5 x ± 30 x ± 30 km (radial x in-track x cross-track). It was agreed that after burns 1 and 2, the thruster performance would be better characterized to allow a reduction in the uncertainty. Remaining on-orbit life after burn 2 also dictated that higher priority be given to perform burns 3 and 4 in order to complete the de-orbit activities. Therefore, as a guideline for risk assessment, a keep-out-box of ± 1 x ± 3 x ± 3 km was used for burns 3 and 4. This box was based on Johnson Space Center (JSC) operational experience with debris avoidance.

4.3 Critical Assets

With so many space assets in orbits below CGRO, a decision had to be made as to which of these assets should be considered in the plan. With the size of the keep-out-box mentioned above, it was obvious that considering all assets would be impractical. Goddard Space Flight Center (GSFC) and JSC agreed to give highest priority to the manned assets, which included Mir, the International Space Station and the Space Shuttle, if it happened to be in orbit during CGRO de-orbit operations.

4.4 Implementation of Collision Avoidance Plan

With the best available ephemeris knowledge and burn parameters, JSC determined if CGRO would be inside of the keep-out-box at the completion of a burn. Both prime and backup opportunities were evaluated. If CGRO was inside the box for the primary opportunity, the backup opportunity would be used. In case both opportunities of the day showed conjunction, de-orbit activities were to stand down until the next day.

Special consideration was given to the mission phase after burn 3. At this point, the remaining on-orbit life is reduced to three days after which the spacecraft would reenter uncontrolled. It was agreed that if the analysis indicated conjunction for both opportunities for burn 4, GSFC center management could elect to give the go-ahead to continue with burn 4 and complete the reentry.

No violation of the keep-out-boxes were identified during the entire de-orbit operations.

5. MISSION DESIGN PARAMETERS

Mission design parameters were selected to maximize the probability of success of the de-orbit mission. The mission initiation dates were based on optimal windows of opportunity that provided the easiest and safest times to accurately hit the target area. The constraints that drove the optimal windows of opportunity included the target area, spacecraft power system, sun angle on the solar panels, aerodynamic heating, and propulsion fuel margins. The constraints selected by the de-orbit team were very conservative and provided very high margins of safety for all aspects of the de-orbit. Mission constraints were designed to provide a very robust, nominal environment for the spacecraft systems and for operations. The constraints were not “pushed” to widen opportunities for de-orbit. Some of the constraints are listed below:

- De-orbit burns 1, 2 and 3 to be at least 24 hours apart to provide appropriate time for post burn analyses and to respond to any contingencies.
- Duration of each burn to be the same (+/- 5 minutes of each other)
- Final perigee height to be targeted to approximately 70-80 km or lower to assures flight path angle of greater than 1.2 degrees to avoid skip-out.
- Apogee to occur at orbit noon (+/- 30°) for burns 3 and 4 to provide power margin and for the aerodynamic heating to occur during orbit night

Based on these constraints, optimum opportunities occurred every 46 days for four consecutive days.

6. SPACECRAFT CONTINGENCIES

A failure in one of the spacecraft sub-systems at the wrong time could jeopardize mission success and threaten human life. Therefore, understanding potential failure modes of CGRO as it was subjected to various mission phases, and planning appropriate responses to those failures, was an important element of risk management. Limited time was available to prepare for CGRO contingencies since any delay in initiating de-orbit proceedings caused an increased risk of further sub-system failures, decreasing the overall probability of mission success.

Failure modes and effects analysis (FMEA) is a bottom up failure analysis approach. Each component of a system is examined for potential failures. The failure impacts to the system are identified and potential handling measures are identified. The fault tree analysis is a top down failure analysis approach. System and subsystem failures are identified and examined. Component level causes and effects are then determined. System level handling measures are then identified.

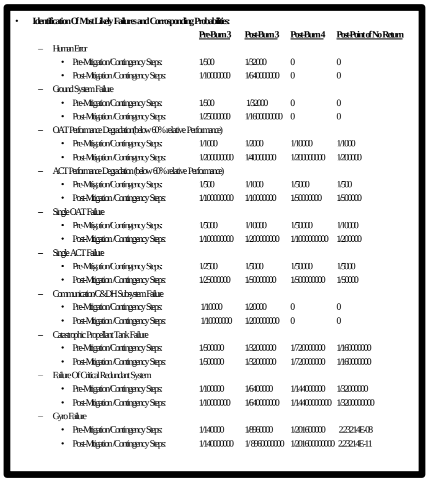
A limitation for the de-orbit mission is that FMEA analyses are typically performed early in the design process to be successful. This approach assumes that design modifications may be made to mitigate risk. Therefore, the fault tree analysis combined with the probabilistic risk assessment was found to be the best approach for CGRO de-orbit mission. This approach identifies potential failures at the system or sub-system level, assigns a probability of occurrence and evaluates the impact to the mission objective if the failure occurs. The combination of the probability and mission impact helps to prioritize the contingencies that need mitigation plans.

The CGRO de-orbit mission was divided into a series of mission events that were completed in sequence. Event based fault tree and probabilistic risk assessment approach was applied to all mission events independently to determine the probability of success of each event as well as the probability of success of the overall mission. This approach then determined the ease with which a mitigation or response to such a failure could be developed and applied. Further probabilities were applied to the success of the mitigation producer in recovering from the failure. The probability of mission success was re-calculated with a mitigation plan in place.

Major events for the de-orbit mission consisted of:

- Spacecraft re-configuration after the end of science mission, in preparation for de-orbit burns.
- Test firing of Attitude Control Thrusters (ACTs) and Orbit Adjust Thrusters (OATs) to verify performance.
- Four de-orbit burns.

Fig. 4 shows one of the matrices used to identify most likely failures, and their corresponding probabilities, during burns 3 and 4. Probabilities for a potential failure (Pre-Mitigation) and a failure with contingency procedures (Post-Mitigation) are calculated.



Identification Of Most Likely Failures and Corresponding Probabilities:

	Pre-Burn 3	Post-Burn 3	Post-Burn 4	Post-Point of No Return
Human Error				
Pre-Mitigation/Contingency Steps:	1/500	1/32000	0	0
Post-Mitigation /Contingency Steps:	1/10000000	1/640000000	0	0
Ground System Failure				
Pre-Mitigation/Contingency Steps:	1/500	1/32000	0	0
Post-Mitigation /Contingency Steps:	1/25000000	1/1600000000	0	0
OAT Performance Degradation (below 60% relative Performance)				
Pre-Mitigation/Contingency Steps:	1/1000	1/2000	1/10000	1/1000
Post-Mitigation /Contingency Steps:	1/200000000	1/40000000	1/200000000	1/200000
ACT Performance Degradation (below 60% relative Performance)				
Pre-Mitigation/Contingency Steps:	1/500	1/1000	1/5000	1/500
Post-Mitigation /Contingency Steps:	1/100000000	1/10000000	1/50000000	1/500000
Single OAT Failure				
Pre-Mitigation/Contingency Steps:	1/5000	1/10000	1/50000	1/10000
Post-Mitigation /Contingency Steps:	1/100000000	1/200000000	1/1000000000	1/200000
Single ACT Failure				
Pre-Mitigation/Contingency Steps:	1/2500	1/5000	1/50000	1/5000
Post-Mitigation /Contingency Steps:	1/25000000	1/50000000	1/500000000	1/50000
Communication C&DH Subsystem Failure				
Pre-Mitigation/Contingency Steps:	1/10000	1/20000	0	0
Post-Mitigation /Contingency Steps:	1/10000000	1/200000000	0	0
Catastrophic Propellant Tank Failure				
Pre-Mitigation/Contingency Steps:	1/500000	1/32000000	1/720000000	1/160000000
Post-Mitigation /Contingency Steps:	1/500000	1/32000000	1/720000000	1/160000000
Failure Of Critical Redundant System				
Pre-Mitigation/Contingency Steps:	1/100000	1/6400000	1/144000000	1/32000000
Post-Mitigation /Contingency Steps:	1/10000000	1/640000000	1/14400000000	1/3200000000
Gyro Failure				
Pre-Mitigation/Contingency Steps:	1/140000	1/8960000	1/201600000	2.23214E-08
Post-Mitigation /Contingency Steps:	1/140000000	1/ 8960000000	1/201600000000	2.23214E-11

Fig. 4. Failure Matrix

Fig. 5 is an example of the fault tree analysis for the time between the final burn initiation and the "Point of No Return." The ease of mitigation is included to show the impact of contingency readiness.

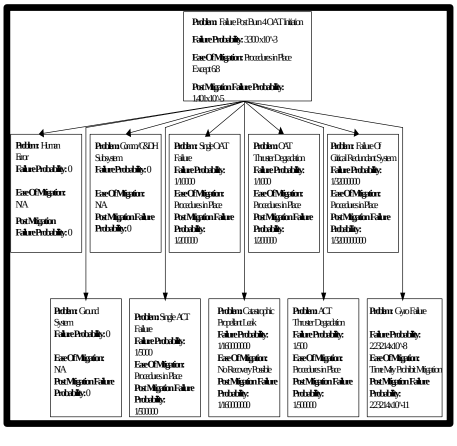


Fig. 5. Fault Tree Analysis

Each fault tree analysis was combined to give an overall probability of mission success. The de-orbit mission was dependent on all of the phases being successfully completed. Therefore, the overall mission risk assessment was determined by combining the mission phases in series.

7. ASSESSMENT OF GROUND SYSTEM

Assessment of the ground system for the de-orbit mission consisted of:

- System redundancy for conducting training and simulations while continuing with the science mission
- Verification of new commands and contingency procedures
- System redundancy for mission execution

The CGRO ground system consisted of three identical strings, each capable of executing the science program. Two of the three strings were required to provide necessary workstations for the entire reentry team. These strings were used for training and simulations of the de-orbit procedures. The third string was required to continue the real time science. A fourth string was created to mitigate the risk to schedule due to failure of one of the strings during simulations. This string was not required to demonstrate spacecraft commanding capabilities, thereby reducing the time required to certify the string for flight operations. The fourth string was not required to support the actual de-orbit mission since the third string could now be incorporated for mission execution.

There was a possibility that the shuttle mission to re-boost space station might occur during the same period as the reentry mission. A concern was raised whether the Tracking and Data Relay Spacecraft System (TDRSS) communication network was capable of handling multiple missions concurrently with sufficient backup. A delay in the reentry mission would mean standing down for 46 days. Risk assessment showed that delaying the mission had a higher mission risk for the following reasons:

- Increased probability of sub-system degradation
- Potential loss of the flight operations team members who were already looking for other jobs after the reentry mission
- Typhoon season in Guam where the ground- station for the reentry mission was located
- The TDRSS resources were found to be adequate to manage multiple missions

8. MISSION EXECUTION

8.1 Training and Verification

Not all risk mitigation was accomplished by contingency procedures alone. An area that required major risk mitigation was human error. Nominal operational procedures were defined that required multiple people to verify critical commands being sent to the spacecraft. Extensive cross-training of critical personnel and reviews were conducted early and often using independent experienced reviewers. All of this effort reduced the human error risk and was assigned a relative probability.

Once the mission design was finalized, an extensive training and verification program was initiated that consisted of several simulations using a high fidelity CGRO simulator, the ground system, and the entire reentry team. The simulations were designed to achieve the following objectives:

- Train the reentry operations team
- Verify the reentry script
- Verify that all commanding procedures are called out in the script
- Verify all network procedures and processes
- Exercise product exchange
- Exercise mission-team interaction
- Exercise contingency plans and procedures
- Demonstrate that all elements of mission operations are ready to conduct the mission

Three types of simulations were designed to meet the above objectives. Mission-team simulations were conducted within the Mission Operations Room. These simulations were designed to exercise mission team interaction and familiarize the team with the timeline and internal processes. End-to-end simulations stressed external interface coordination and exercised as many supporting elements as practical. Contingency simulations exercised time-critical and most probable contingencies.

End-to-end system verification was achieved through ongoing daily operations, end-to-end simulations, and special tests. Since the science operations were continuing until the initiation of the de-orbit mission, the ground system was exercised for:

- Command, telemetry, tracking operations,
- Generation, uplink, and verification of loads
- Orbit determination
- Generation, transmission and use of acquisition data
- Network scheduling and reconfigurations

End-to-end simulations verified specific reentry procedures and processes for interaction between different elements. Stand-alone special tests exercised and verified procedures and processes that were not capable of being incorporated into the end-to-end simulations. CGRO was reentered on the very first opportunity. The appropriate authorities were notified to lift the remaining hazard zone warnings as soon as the reentry was confirmed.

9. CONCLUSIONS

The CGRO de-orbit mission was an exemplary mission that defined a risk management approach for all aspects of a spacecraft de-orbit operation. The decision to de-orbit CGRO while it was still producing unique science was in itself an example of NASA’s commitment to safety as the number one priority.

The de-orbit mission team strived to identify potential risks during all aspects of the mission, determined appropriate methodologies to reduce the risk, and imposed constraints on the mission design such that the probability of successfully completing the mission was maximized.

Lessons learned during this mission have been carefully documented and can be useful to future missions of this nature.