CONTROLLED DEORBIT OF THE DELTA IV UPPER STAGE FOR THE DMSP-17 MISSION

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ABSTRACT

The Delta IV Medium Upper Stage performed a controlled deorbit after delivering DMSP-17 to its mission orbit. This marked the first time a Delta IV vehicle was used to launch a DMSP spacecraft and the first time that such a deorbit maneuver was undertaken by a launch vehicle upper stage. The previous two DMSP spacecraft were injected into ballistic transfer orbits by Titan 2 launch vehicles, and the Titan 2 upper stages were left in ballistic trajectories that lead to immediate reentry into the Earth's atmosphere. The spacecraft used imbedded apogee kick motors to circularize their orbits at the mission altitude. Unlike the Titan 2, the Delta IV Medium launch vehicle has more than enough performance to directly insert the payload into its mission orbit. This paper examines the configuration of the launch vehicle and the characteristics of the mission that made the deorbit maneuver possible. The various analyses that contributed to the decision to perform the immediate deorbit maneuver are discussed.

1. INTRODUCTION

The Defense Meteorological Satellite Program uses a constellation of two satellites operating in 849 km (458 nmi) sun synchronous orbits to collect weather information for the U.S. military. Orbiting the globe about 14 times per day, the vehicles provide full Earth coverage twice daily. The primary sensor obtains visible and infrared imagery of cloud cover that helps in weather forecasting. Important products include detections of severe thunderstorms, hurricanes and typhoons in remote areas. The program has been in operation for over forty years.

In recent years, Titan 2 launch vehicles were used to inject DMSP-15 and 16 satellites into their respective transfer orbits, and their upper stages were left in ballistic transfer orbits and reentered the Earth's atmosphere after spacecraft separation. These spacecraft used apogee kick motors to circularize their orbits, but had no propulsive capability to adjust or maintain their orbital altitudes. Therefore, the spacecraft with their attached apogee kick motors will decay naturally from their respective mission orbits and reenter many years in the future.

A Delta Medium IV was used to launch DMSP-17. The higher performance of the Delta IV launch vehicle enabled it to place the DMSP-17 payload directly into a Sun synchronous 849 km (458 nmi) circular orbit inclined at 98.7 degrees. Unlike the upper stages for the Titan 2's used for the DMSP-15 and 16 missions, the Delta IV upper stage could have been left in a circular orbit after separation from DMSP-17. At this altitude the spent upper stage would drift through space, posing a collision risk with other operational spacecraft and debris objects for over one hundred years. This violates U.S. Government Orbital Debris Mitigation Guidelines[1], which calls for a maximum of 25 years in orbit before reentry.

The Delta upper stage generally performs a contamination and collision avoidance maneuver to lower the perigee and move the stage out of the payload's orbital plane to minimize collision risk.

Initial planning for the DMSP-17 mission called for a perigee lowering maneuver using some of the remaining propellant on the booster to achieve reentry in less than 25 years. However, such a maneuver would result in a random reentry, and US guidelines recommend that reentering spacecraft and upper stages have casualty expectation values equal to or less than one in ten thousand per reentry event. An analysis of the amount of survivable hardware of the Delta IV upper stage indicated that the associated casualty area would be very large and would result in a casualty expectation greatly exceeding US guidelines. Fortunately, there was enough

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propellant remaining after payload deployment to achieve a controlled deorbit of the upper stage

Several issues needed to be resolved before a decision to deorbit the upper stage could be made, and it was quickly determined that there were no practical reasons why a deorbit maneuver could not be performed. Several deorbit opportunities were identified and checks were made to ensure that battery life was sufficient and the engine could be restarted without undo risk.

The ability of the control system to stabilize the vehicle during powered flight without the mass and inertia of the payload was also a consideration. Without a payload, the value of transverse moment of inertia was greatly reduced and this changed the dynamics of the vehicle, possibly invalidating control system parameters. Secondly, the much lighter weight of the vehicle resulted in a high axial acceleration during the engine burn. In addition, dispersions or malfunctions associated with the deorbit burn might result in the upper stage impacting populated regions.

Risk assessments were performed to ensure that the casualty expectation associated with the controlled deorbit was less than one in ten thousand. Furthermore, the liability of the launch vehicle contractor in the event of a vehicle malfunction or performance anomaly needed to be established, since such an event could potentially result in casualties or property damage. The Office of the USAF Director of Air and Space Operations clarified the following responsibilities:

- Space and Missile Systems Center/Launch & Range Systems Wing (SMC/LRSW) was responsible for verifying the launch contractor's planning, execution, and safety procedures for the Upper Stage re-entry, including impact.
- 30th Space Wing (SW) was responsible for conducting a normal impact assessment and issuing appropriate notifications (NOTAMs, etc.) for the reentry based on data/information supplied by SMC/LRSW. 30th SW was not responsible for Upper Stage re-entry safety issues.
- 14th Air Force (AF) was responsible for assessing and monitoring launch planning and execution through Upper Stage reentry and reporting the results through the Air Force Space Command (AFSPC) Center.

After successful completion of these analyses, results indicated that a controlled deorbit could go forward. Therefore, a controlled deorbit was incorporated into the launch plan.

The launch and orbit injection sequence would remain essentially the same as before the modification, and a contamination and collision avoidance maneuver would be executed after payload separation to move the upper stage away from the payload. Once the upper stage was sufficiently far from the payload, the upper stage would perform an attitude adjust maneuver in preparation for the deorbit burn. The main engine on the upper stage, also known as the Delta Cryogenic Second Stage (DCSS), would be restarted and the burn continued until the propellant was depleted.

The event timeline was adjusted so that any upper stage components that survived atmospheric reentry heating environment would impact a broad Pacific Ocean area. The impact location was selected so that the deorbit burn would be visible from the AFSCN Hawaii Tracking Station. In addition, the IIP (instantaneous impact point) was required to be mostly over ocean and sparsely populated land areas. The large size of the deorbit burn results in a very steep descent and relatively small impact footprint.

2. ORBITAL DEBRIS MITIGATION

In recent years, space faring nations have recognized the hazards posed by space debris that originates from expired satellites, rocket upper stages and associated jettisoned mission hardware. On orbit fragmentations have compounded the problem by generating hundreds of new debris objects with each fragmentation. Collisions with space debris objects are suspected to be the root cause of some of the fragmentations. Satellite operators are concerned with the growing space debris population and the need to occasionally maneuver their vehicles to avoid collisions. As the debris population increases, the frequency of such maneuvers increases.

The random reentry of the larger pieces of space debris also poses a hazard because a significant fraction of spacecraft components survive the reentry heating environment and impact the Earth's surface[2, 3]. The vast sizes of the Earth's land and ocean areas have kept this hazard small thus far. Nevertheless, the hazard will only grow with time as more pieces of space debris reenter.

The US Government has adopted debris mitigation guidelines[1] to help control the growth of space debris. The guidelines not only address the hazard of space debris, but also promote the utility of space by attempting to keep the very useful operational orbits free of debris. Thus at the end of mission life, space vehicles should be moved out of mission orbits and into less populated graveyard orbits. If a graveyard orbit is not attainable, the vehicle can be allowed to decay naturally as long as its orbital lifetime is less than 25 years and its casualty expectation is less than one in ten

thousand. Otherwise a controlled deorbit is recommended. Vehicles that remain in orbit should be safed by depleting propellants and pressurants, as well as discharging batteries and removing all energy sources. Complying with these guidelines can be difficult or impossible for space programs that are already in existence. However, new space programs should design their space vehicles to satisfy debris mitigation guidelines to promote safe use of the space environment.

The Delta IV launch vehicle is part of the Air Force's relatively new Evolved Expendable Launch Vehicle program. The policy of this new program is to minimize the generation of space debris whenever possible based on cost and schedule impacts to each mission. The deorbit of the Delta IV upper stage for the DMSP-17 mission has the benefit of removing the upper stage from the mission orbit, removing it from the low Earth altitude regime, and removing the casualty risk associated with a random reentry. The deorbit maneuver clearly complies with the U.S. Government debris mitigation guidelines.

3. ORBITAL COLLISION RISK

The orbital collision risk associated with the initial plan to lower perigee of the upper stage after payload separation was found to be very small. The atmospheric drag at perigee quickly lowers the booster's apogee from the mission orbit altitude, thereby eliminating risk to numerous satellites at the apogee altitude. Other debris objects in low Earth orbit are at risk as the upper stage quickly decays from orbit. A rough estimate was made of the cumulative collision risk throughout the orbital decay process based on a very quick computational method[4]. Results indicate that the cumulative risk was on the order of one in a million. Thus, the deorbit maneuver provides only a slight benefit in the area of orbital collision risk.

4. CASUALTY EXPECTATION FOR ORBITAL DECAY REENTRY

A detailed analysis was performed to determine the casualty area of components that survive the reentry heating environment associated with a random reentry resulting from orbital decay. These orbits tend to circularize and enter the atmosphere with shallow flight path angles[5]. The most likely scenario results in a breakup at roughly 68 km and a debris casualty area of 70 m^2. Figure 1 illustrates the casualty expectation per meter of casualty area as a function of orbital inclination based on the global population in 1995[2, 3, 6, 7]. The casualty expectation for an orbit of 98.7 degrees is the same as that of 81.3 degrees due to symmetry considerations. Therefore from Fig. 1, the casualty expectation per square meter of casualty area is 7.57 x 10^{-6}. The casualty expectation for 70 square meters is (70) x 7.57 x 10^{-6} or 5.3 x 10^{-4}. This value is updated to the 2006 reentry date by using a population growth rate of about one percent per year, yielding a value of 5.91 x 10^{-4}. This is more than five times greater than the US Government recommended value of 1 x 10^{-4}. This result provides very strong motivation to perform a controlled deorbit of the Delta IV upper stage.

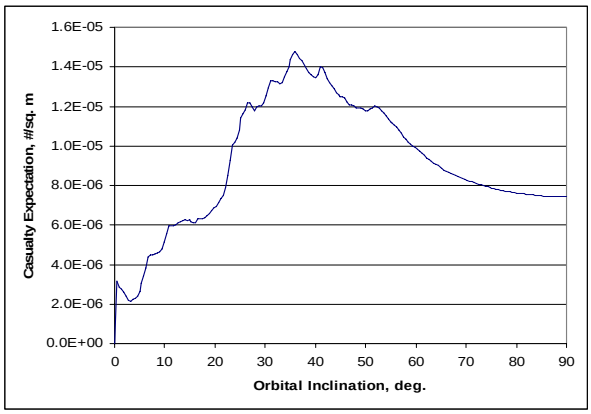

Figure 1. Casualty expectation for a random reentry as a function or orbital inclination based on global population in 1995.

5. VEHICLE PERFORMANCE AND TRAJECTORY SIMULATION

The Delta IV Medium launch vehicle maximum payload performance to a sun synchronous orbit altitude of 849 km (458 nmi) is approximately 6580 kg (14,500 lbs)[8]. The relatively light payload mass of the DMSP spacecraft compared to the maximum capability resulted in a large amount of excess propellant remaining in the upper stage after spacecraft insertion. The Aerospace Corporation independently simulated the Delta IV-Medium / DMSP trajectory as part of a launch vehicle verification process to ensure that the vehicle satisfied mission and range safety requirements. Results of the trajectory simulation quickly determined that the amount of delta-velocity remaining in the upper stage, after payload separation, was beyond the amount needed to complete an additional burn of the upper stage to deorbit the stage and perform a controlled re-entry.

Three initial impact regions shown in Fig. 2 were identified as good candidates to perform a controlled reentry: South of Madagascar, South of Alaska and South Pacific Ocean regions. Reentry trajectory simulations were generated for each region featuring a Contamination and Collision Avoidance Maneuver (CCAM), coast period, and reentry burn (the upper stage performs a CCAM to avoid re-contact between the spacecraft and upper stage). All trajectory timelines from liftoff to reentry were within the lifetime of the vehicle battery. After a coast period, the upper stage

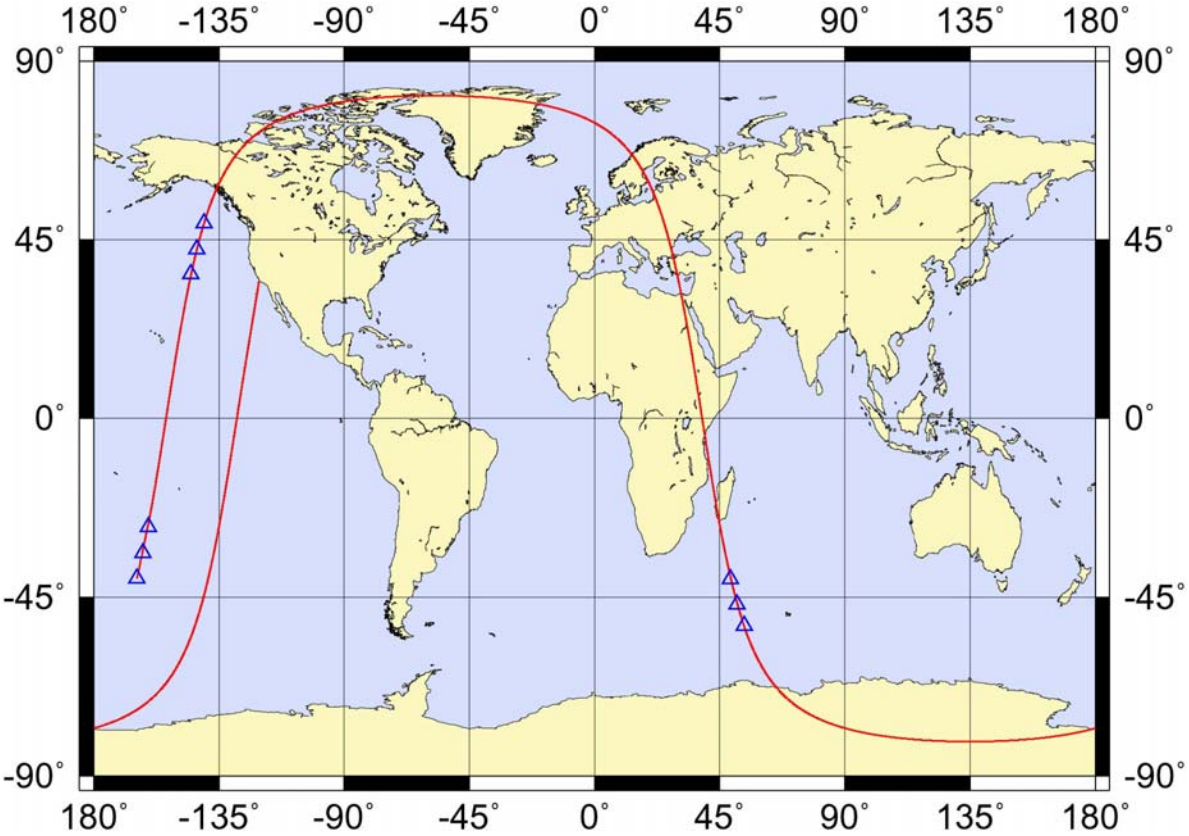

Figure 2. Groundtrack depicting three deorbit regions.

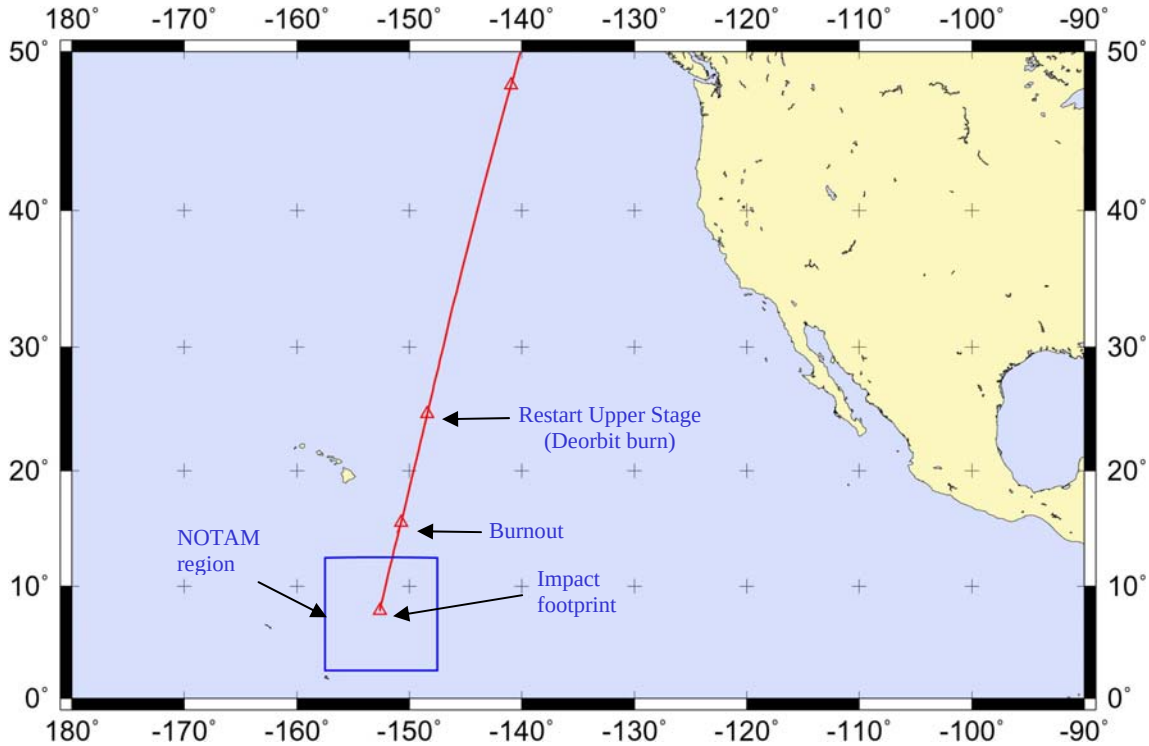

Figure 3. Location of the NOATM region and deorbit groundtack

was restarted to deplete remaining propellants. The attitude of the vehicle at re-start was optimized such that the ground range from burnout to impact was minimized. A preliminary size of the impact footprint was determined by varying coast time, burn time, reentry attitude and ballistic coefficient. The large amount of excess propellant caused the reentry angle to be significantly steeper than that of random shallow reentry, resulting in a relatively small footprint.

Several deorbit opportunities consistent with the launch and ascent timeline were identified. The impact footprint was constrained by the NASA Safety Standard 1740.14 that requires that the impact footprint be at least 370 km (200 nmi) from foreign territory and 46 km (25 nmi) from the U. S. territory[9]. The dwell time over land areas of the instantaneous impact point was minimized.

The South Pacific Ocean area was selected because telemetry coverage from the Hawaii tracking site was large, re-entry ground trace crossed a limited amount of land, and there was minimal impact to shipping lanes and commercial aircraft routes. The area of the "Keep Out" zone was 1111 x 1111 km (600 x 600 nmi) centered at latitude of 7.5 deg north and longitude of 152.5 degrees west, which is located northeast of the Christmas Islands and South of the Hawaiian Islands.

The Commander of the Delta IV Launch Systems Group provided this location, plus other necessary information such as Nominal Impact date/time, to the 30th Space Wing Flight Analysis Office (30th SW/SEL). After review by the 30 SW/SEL Office, all the required information was provided to the 30th SW/DOS Office for notification to several agencies responsible for issuing Altitude Reservation Approval Requests, HYDROPACS, and NOTAMS to alert the international shipping and air carrier communities of the potential debris impact hazard. Figure 3 illustrates the deorbit trajectory groundtrack and the NOTAM region.

On November 4, 2006 the Delta IV Medium inserted the DMSP spacecraft within its desired orbit and performed a re-entry burn targeting the center of the stay-out zone. Post-flight analysis indicated the actual impact point was very close to the pre-flight predicted value.

6. DEORBIT CASUALTY EXPECTATION

A successful DCSS deorbit results in a casualty expectation, $E_C = 0^+$ (nearly zero) since the targeted impact region is uninhabited. Only a wayward boat or aircraft that strayed within the "keep-out" zone would be at risk. However, a deorbit failure or anomaly does have the potential to impact a populated region. This type of hazard is different from the aforementioned orbital decay risk because it involves an "active" event as opposed to the passive event of a random reentry. Therefore, it requires different consideration in terms of risk acceptance and is more in-line with launch risk which is generally defined as a casualty expectation of less that 30 per million. The approach described next was followed to evaluate the deorbit risk.

All failure scenarios and anomalies can essentially be split into two categories:

1. Risk of an impact considerably further downrange from the targeted zone due to a propulsive failure. Typically, this would be caused by an early engine shut-down between 23 and 175 seconds.

2. Risk of impact in a widespread region due to a vehicle attitude failure. This the result of an incorrect initial burn attitude and/or anomalous steering rates during the depletion burn.

Casualty expectation (E_C) is calculated by multiplying the probability of impact (P_I) by the casualty-causing area (A_C) of the debris, multiplied by the population density (D) of the region of interest.

$$E_C = P_I A_C D$$

A Monte Carlo trajectory technique was used to determine a probability of impact density function (P_I pdf). The downrange probability, which is characterized by randomly selected propulsive failures, is directly related to the rate of change of the impact points as they approach the targeted zone. The crossrange probability, characterized by random attitude and rate failures, is assumed to be Gaussian, centered on the instantaneous impact point (IIP) with a varying standard deviation estimated according to the Monte Carlo impacts. Figures 4 and 5 display the impact probability contours for 20 x 20 arc-minute grid cells. The E_C calculation tool developed by Aerospace, implements a 2.5 x 2.5 arc-minute gridded world population database[7] along with the P_I pdf, and then sums E_C over all the grid cells at risk. In this case, the population at risk includes parts of Oceania, Africa and Europe.

The probability of impact is weighted by the likelihood of each failure occurring. The authors agreed to the following assumptions based on conservatism and similar values used by Boeing[10] in the ascent phase of collective risk analysis:

- Probability (DCSS failure) = 0.1
  - Probability (propulsive failure) = 0.8
    - Probability (ignition failure) = 0.5
    - Probability(early shutdown) = 0.5
  - Probability (attitude failure) = 0.2

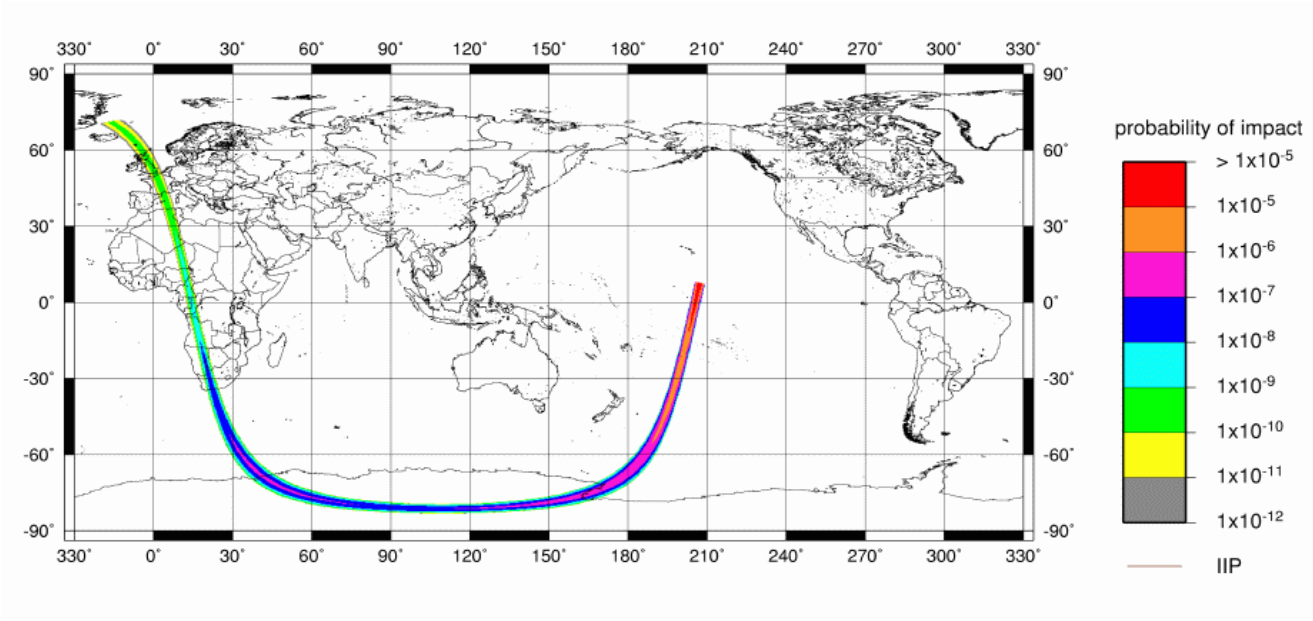

Figure 4. Probability of Impact for Propulsive Failure

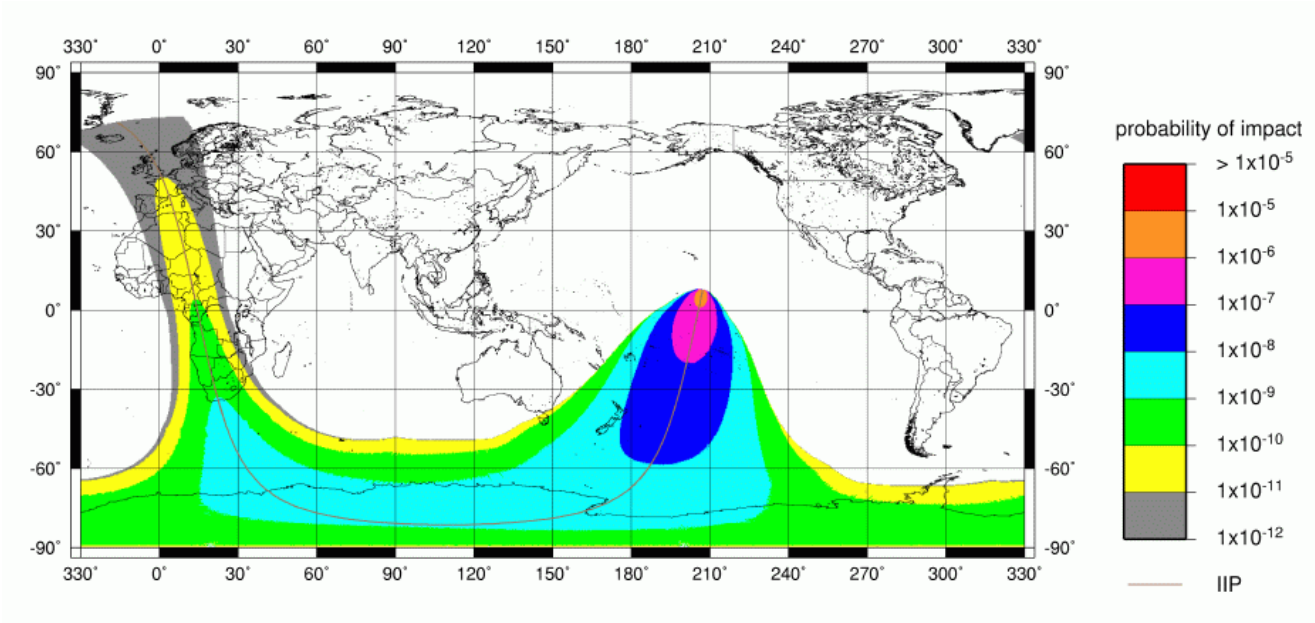

Figure 5. Probability of Impact for Attitude Failure

Thus, for example, 80% of DCSS failures are propulsive with 50% of those being at engine ignition. So the probability of ignition failure is (0.1) (0.8) (0.5) = 0.04 which will result in a DCSS random reentry at some future date. The Monte Carlo study showed that approximately half the attitude failure cases also result in a future random reentry.

7. EXPECTED CASUALTY RESULTS

Comparisons have been made within this report to the E_C for random reentry of greater than 1 in 10,000 based on a comprehensive analysis of the DCSS by NASA that predicted an A_C of 70 m^2 and an E_C exceeding 5.9 in 10,000. For the deorbit hazard calculation, it is presumed that with the lower reentry velocity there will be less material demise due to aero-thermal heating. An A_C of 114 m^2 is used to determine E_C for the deorbit mission phase. This is the same value applied to the ascent phase and is conservative and assumes all components survive reentry to impact.

Figures 6 and 7 graphically show the E_C calculated for the Oceania and Africa/Europe regions. The value is the sum for all the population at risk

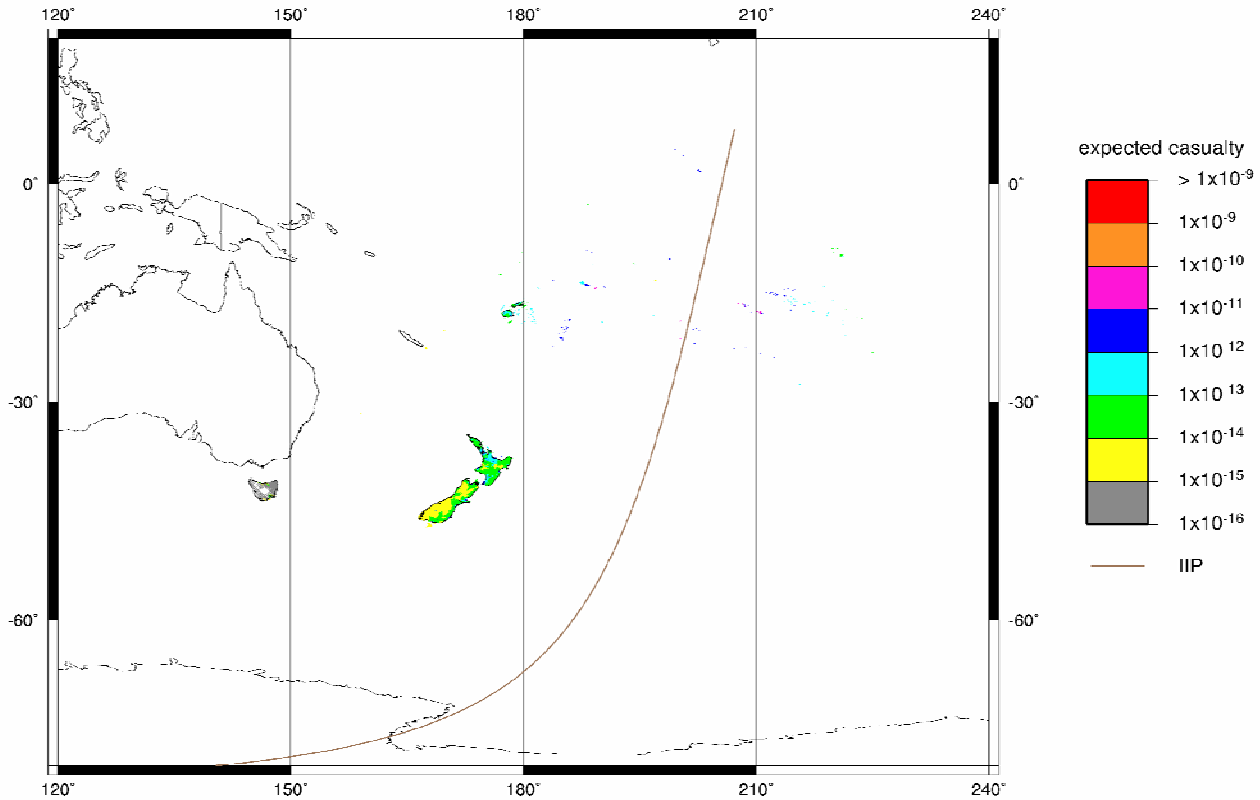

Figure 6. Ec [Oceania] = 22x10^{-9}

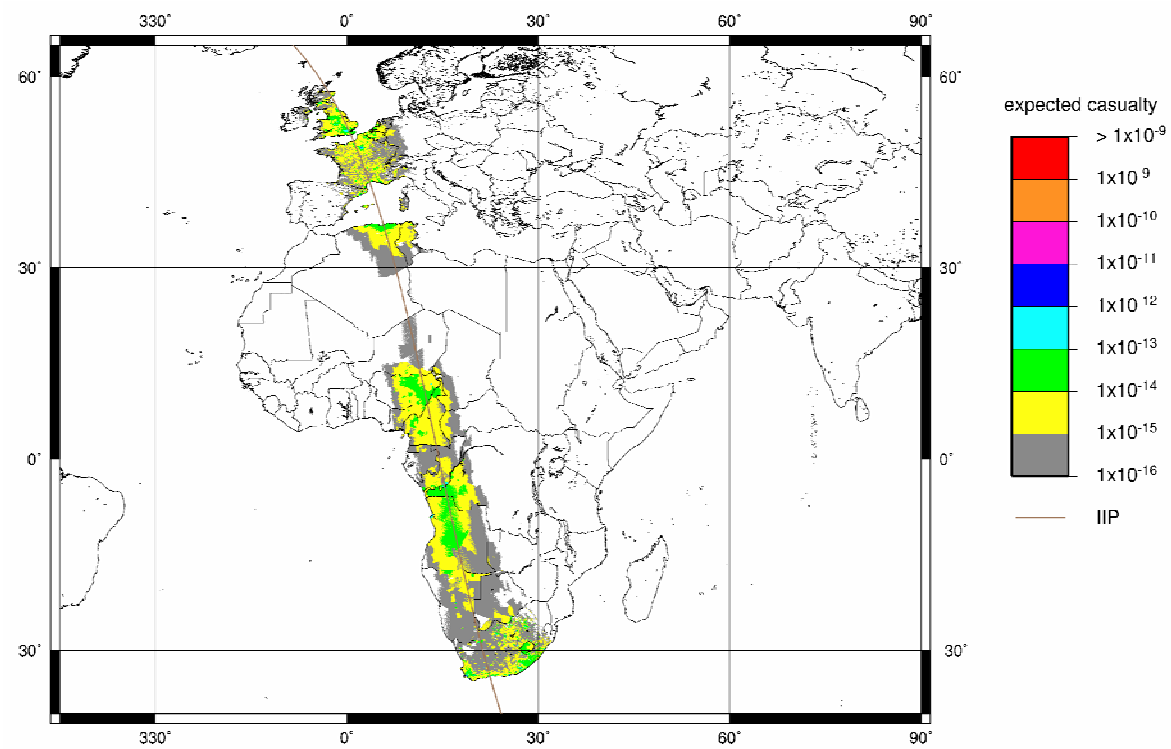

Figure 7. Ec [Africa/Europe] = 13x10^{-9}

The quantitative risk analysis and calculation of the E_C of 35 x 10^{-9} for the controlled reentry mission phase following ignition and second burn of the DCSS provides another level of assurance of acceptable risk. This is orders of magnitude less than the established flight analysis maximum acceptability standard of 30 x 10^{-6} for the pre-orbital ascent phase.

It should be noted that the 35 per billion calculation accounts for failures that result in an immediate (within one rev) ground impact of the DCSS. As was mentioned earlier, there exist failures that would result in a random reentry occurring many months or years in the future. By simply applying the Aerospace value of 5.9 per 10,000 to the conditional probability for those type of failures, the result is an expected casualty for an immediate deorbit with future random reentry of 29 per million (29 x 10^{-6}). Hence, in summary:

E_C [future orbital decay reentry] = 6 x 10^{-4}
E_C [immediate deorbit] = 35 x 10^{-9}
E_C [attempted deorbit resulting in future random reentry] = 29 x 10^{-6}

It is clear, based on the data contained within this report, that the controlled reentry of the DCSS is safer than an orbital decay reentry.

8. CONCLUSION

The launch of DMSP-17 on November 4, 2006 provided several firsts. It was the first time that the Delta IV Medium launch vehicle was used to launch a DMSP satellite. It was the first time that a DMSP spacecraft was directly injected into its mission orbit. It was the first time that an upper stage was deorbited immediately after placing its payload in orbit.

The mission was possible because the launch vehicle had a significant amount of extra performance. Analyses were done to determine if a deorbit was necessary. Analyses were also conducted to ensure that the mission was achievable and that controlled deorbit does not present unacceptable risk to populated areas should an anomaly occur.

The planning and execution of this mission helps pave the way for other deorbit missions when significant vehicle performance is available. In addition, it provides a very good example of a how space faring nations can reduce space debris and reentry casualty risk.

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