Title:

Landing and Population Hazard Analysis for Stardust Entry in Operations and Entry Planning

Authors:

Jeff Tooley (corresponding author)
California Institute of Technology
Jet Propulsion Laboratory
4800 Oak Grove Ave.
M/S 301-220
Pasadena, CA 91109-8099
Voice: 818-393-7925
Email: jeffrey.tooley@jpl.nasa.gov

Prasun Desai
NASA Langley Research Center
1 North Dryden Rd., MS 489
Hampton, VA 23681-2199
Voice: 757-864-2986
Fax: 757-864-8675
Email: prasun.n.desai@nasa.gov

Daniel T. Lyons < daniel.t.lyons@jpl.nasa.gov >
Ed Hirst, < Edward.A.Hirst@jpl.nasa.gov >
Tom Wahl < Tom.E.Wahl@jpl.nasa.gov >
Mark Ivanov < Mark.C.Ivanov@jpl.nasa.gov >
Geoffrey G. Wawrzyniak < Geoffrey.G.Wawrzyniak@jpl.nasa.gov >

California Institute of Technology
Jet Propulsion Laboratory
4800 Oak Grove Ave.
Pasadena, CA 91109-8099

Short Abstract

Stardust is a comet sample return mission that successfully returned to Earth on January 15, 2006. Stardust's targeted landing area was the Utah Test and Training Range in the Northwest corner of Utah. Requirements for the risks associated with landing were levied on Stardust by the Utah Test and Training Range and NASA. This paper describes the analysis to verify that these requirements were met and and includes calculation of debris survivability, generation of landing site selection plots, and identification of keep-out zones, as well as appropriate selection of the landing site. Operationally the risk requirements were all met for both of the GO/NO-GO polls, so entry was authorized.

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Jeffrey Tooley (Corresponding Author)
818-393-7925, Email: jeffrey.tooley@jpl.nasa.gov

Daniel T. Lyons, Edward Hirst, Tom Wahl and Mark Ivanov
California Institute of Technology, Jet Propulsion Laboratory, 4800 Oak Grove Drive, Pasadena CA 91109

Prasun Desai
NASA Langley Research Center, 1 North Dryden Rd., MS 489, Hampton, VA 23681-2199

Geoffrey.G.Wawrzyniak
Purdue University, School of Aeronautics & Astronautics, Grissom Hall, West Layfayette, IN 47907

Stardust is a comet sample return mission that successfully returned to Earth on January 15, 2006. Stardust's targeted landing area was the Utah Test and Training Range in the Northwest corner of Utah. Requirements for the risks associated with landing on the range or in areas around the range were levied on Stardust by the Utah Test and Training Range and NASA. These requirements were expressed in terms of the probability of landing on the range and the probability of injuring any population surrounding the Range. The requirements not only had to be met for a nominal impact but also for the most likely failure scenarios that could occur once the spacecraft was targeted to Earth. In order to make the operations go smoothly, extensive analysis was done before entry to ensure that these requirements would be met for any scenario on the day of entry. This analysis included calculation of debris survivability, generation of landing site selection plots, and identification of keep-out zones. Results from this analysis were also fed into the selection of the landing site. Operationally the risk requirements were all met for both of the GO/NO-GO polls.

Nomenclature

A_p	=	projected area
A_{sc}	=	sheltered casualty area
C_{Dhc}	=	hypersonic continuum drag coefficient
C_{Dsub}	=	subsonic continuum drag coefficient
cr	=	crossrange
E_c	=	casualty expectation
$f(dr,cr)$	=	probability density function
P	=	population count
P_{cs}	=	probability of casualty for s^{th} shelter type
PD	=	population density
P_f	=	probability of failure
σ_{cr}	=	crossrange standard deviation

*

I. Introduction

The 385 kg Stardust mission was launched on Feb 7, 1999 on a mission to collect dust samples from the tail of comet and from interplanetary space. Stardust flew within 236 km of comet Wild-2 on January 2, 2004 and collected dust samples in high purity aerogel collectors. It also took pictures as it flew by the asteroid Anne Frank on November 2, 2002. Stardust returned to Earth in the early morning of January 15, 2006 After passing through the maximum deceleration and heating phases, the entry capsule used a deceleration sensor to trigger deployment of a drogue chute to maintain attitude stability until the main chute could be deployed. Stardust descended all the way to the ground on a circular, disk band gap chute during a night entry. . The 46 kg sample return capsule landed in the Utah Test and Training Range Southwest of Salt Lake City. It was then loaded into a helicopter and flown back to the UTTR facilities. The main spacecraft bus performed a propulsive deflection maneuver after releasing the entry capsule, 4 hours before entry, and is now in orbit around the Sun. Stardust was designed and built by Lockheed Martin Astronautics in Denver, Colorado.

Further information about this exciting NASA mission can be found at http://www.jpl.nasa.gov/

II. Requirements

To orient the reader Figure 1 shows the Utah test and Training Range (UTTR) in Green and a predicted 99% impact ellipse at the target in magenta. Stardust approached UTTR from North of West (over Nevada) in a direction parallel to the long axis of the ellipse.

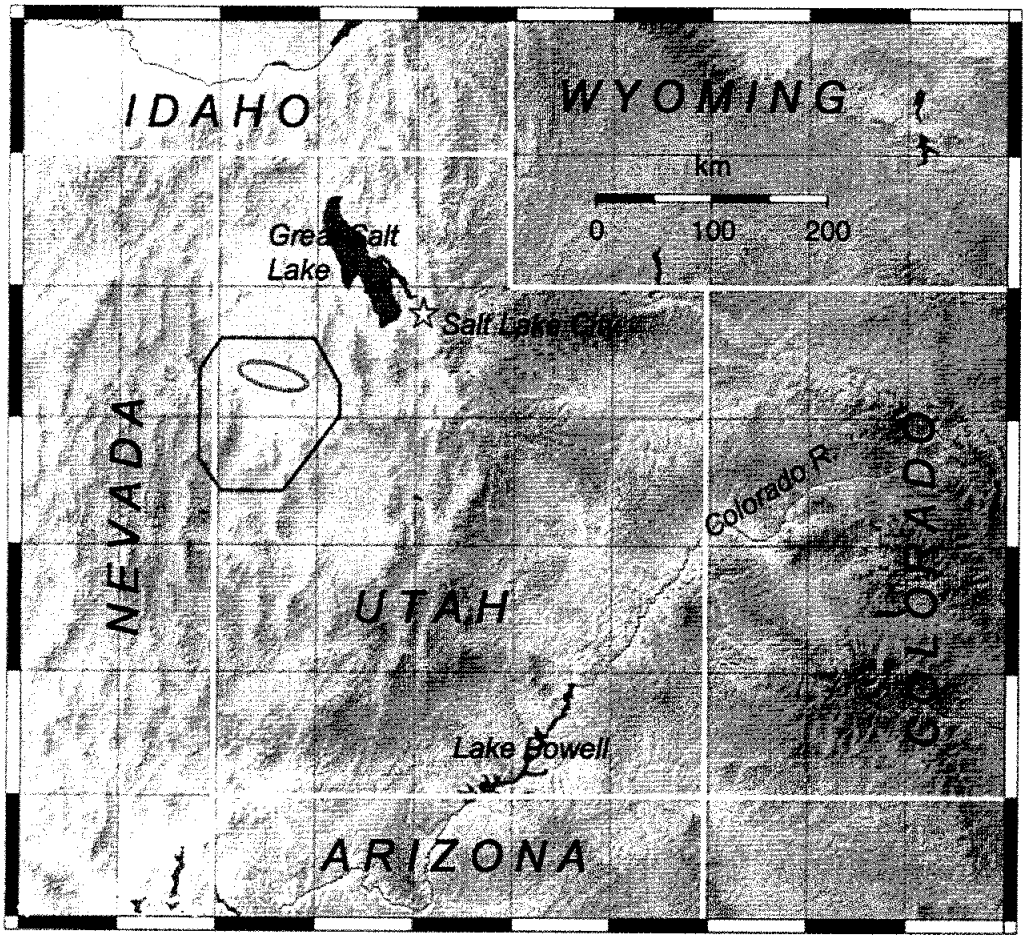

Figure 1. Illustration of Utah Test and Training Range Location.

In order to establish requirements, the definitions of probability of impact, casualty expactation and probability of casualty need to be establish. These terms, and the requirements associated with them will be described in the paper.

Figure 2 shows the an example of the calculation based on population centers. The probability of landing in a given region had to be convolved with the population distribution to generate a probability of violating the safety requirements.

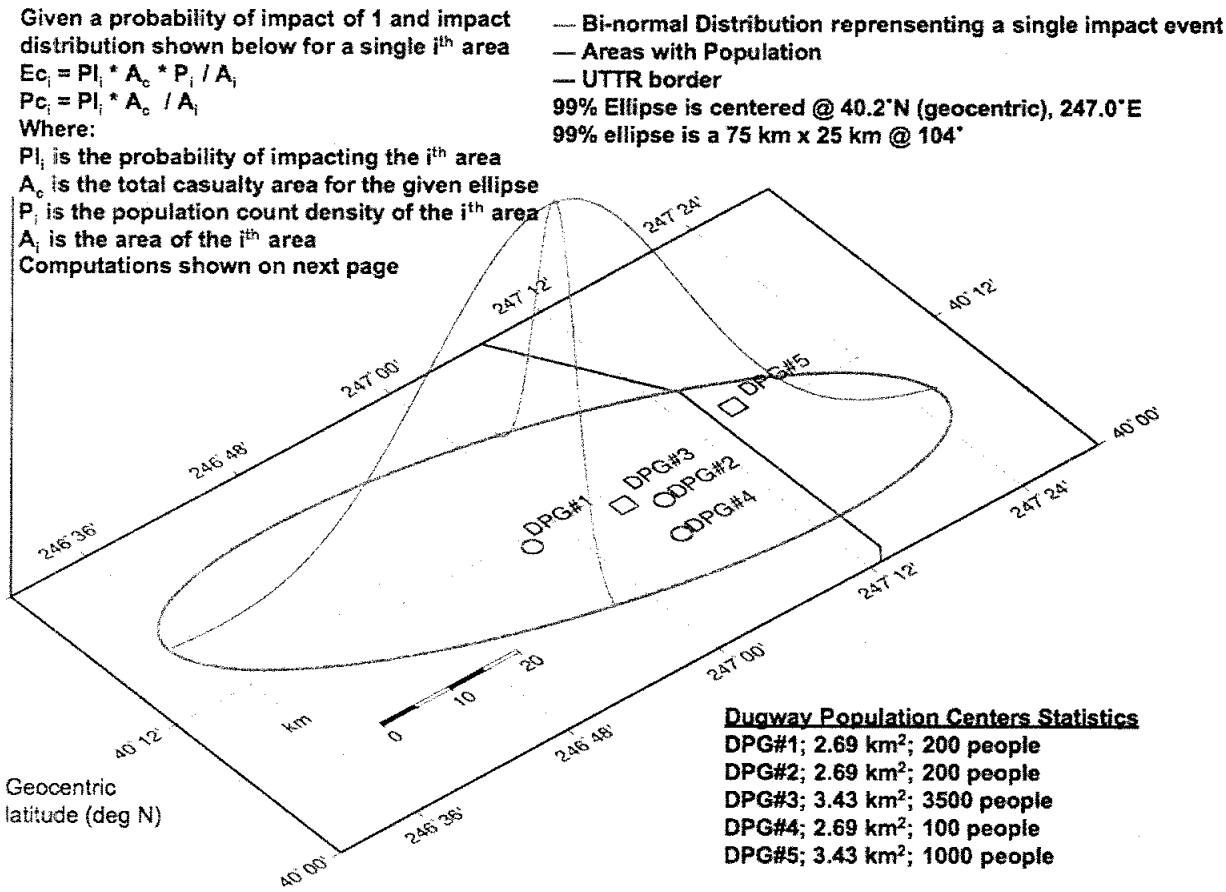

Figure 2: Probability Distributions

For the risk calculations two sets of population databases are used. The LandScan database is shown in Figure 2, and the UTTR database is shown in Figure 3. The paper will describe how each of these data bases were used to satisfy the hazard requirements. The requirements for both UTTR and NASA are listed in Table 1.

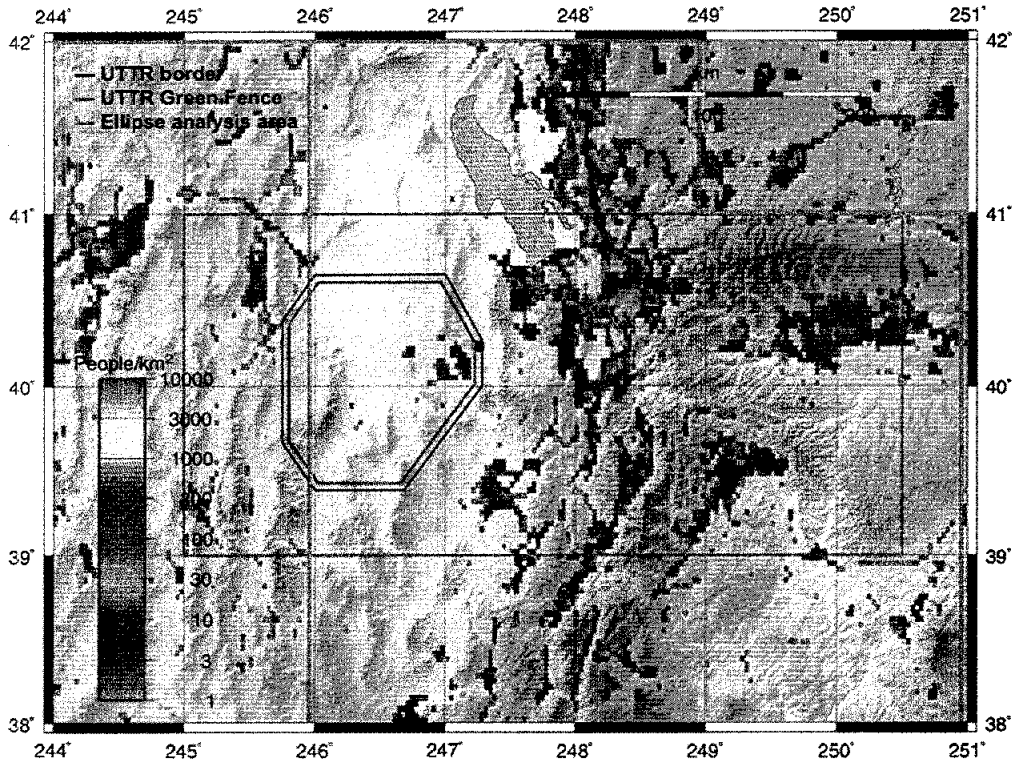

Figure 3. LandScan population

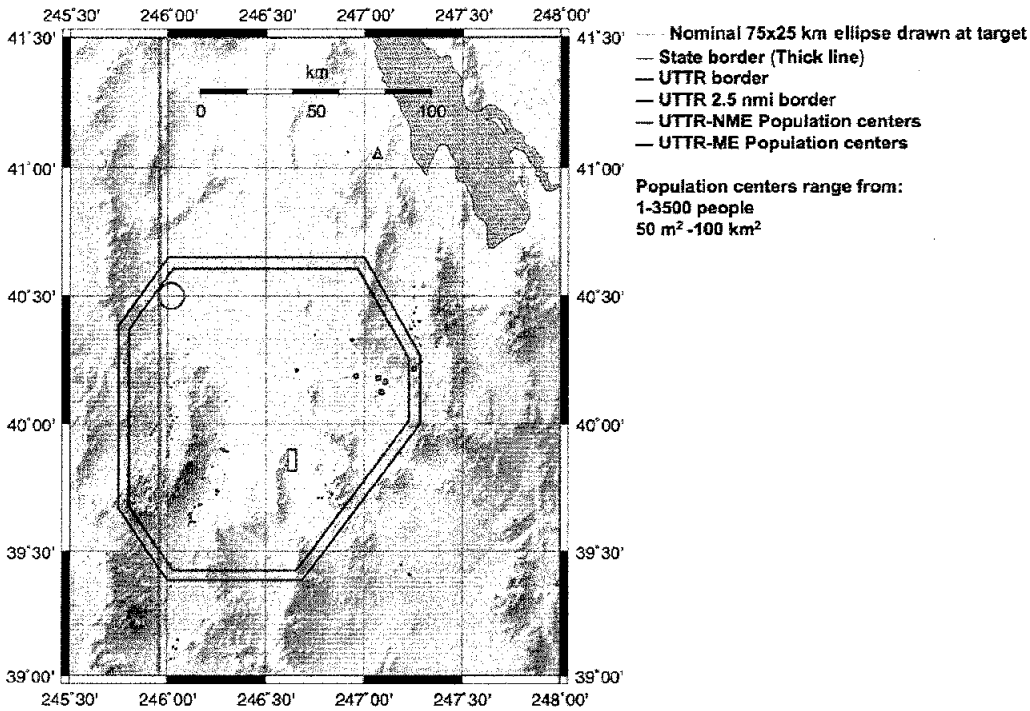

Figure 4. UTTR population

Table 1: REQUIREMENTS.

	Criterion
Human Safety	
1.1 Landing points meet UTTR Pc, public individual	< 1e-07
1.2 Landing points meet UTTR Ec, public collective	< 3e-05
1.3 Landing points meet UTTR Pc, mission individual	< 3e-06
1.4 Landing points meet UTTR Ec, mission collective	< 3e-04
1.5 Landing points meet NASA Pc, public individual	< 1e-06
1.6 Landing points meet NASA Ec, public collective	< 1e-04
1.7 Landing points meet NASA Pc, mission individual	< 1e-05
1.8 Landing points meet NASA Ec, mission collective	< 3e-04
Human Safety – Yellow Divot	
1.9 Landing points meet UTTR Pc, public individual	< 1.67e 6
1.10 Landing points meet UTTR Ec, public collective	< 5e 4
1.11 Landing points meet UTTR Pc, mission individual	< 5e 5
1.12 Landing points meet UTTR Ec, mission collective	< 5e 3
1.13 Landing points meet NASA Pc, public individual	< 1.67e 5
1.14 Landing points meet NASA Ec, public collective	< 1.67e 3
1.15 Landing points meet NASA Pc, mission individual	< 1.67e 4
1.16 Landing points meet NASA Ec, mission collective	< 5e 3
Property Damage	
1.17 Center of landing dispersion is outside of all 1 nmi radius UTTR property zones	Yes
Landing Site	
2.1 Landing points in Acceptable Landing Region above 95% below 75% - NO GO between above - ANOMALY PANEL	>95%
SRC Capability	
3.1 Entry Flight Path Angle within [-8.05°, -8.35°] to 99% beyond [-7.83°, -8.57°] to 99% - NO GO between above - ANOMALY PANEL	> 99% > 99%
Warning Track	
4.1 If center of landing dispersion is: within 3-sigma NAV ellipse – GO between 3- and 6-sigma NAV ellipse - PM DISCRETION beyond 6-sigma NAV ellipse – ANOMALY PANEL	GO

III. Failure Scenarios

Two major failure scenarios were studied. The paper will describe how these failure scenarios factored into the decision process prior to entry. The failure scenarios determined the size of the region that had to be evaluated during the tight timeline available for the "Green Button" analysis just prior to the Go/NoGo decision to release the entry capsule from the main spacecraft.

IV. Site Selection

Figure 5 shows some of the natural hazards, such as mountains and lakes near the selected landing site. These hazards and the population hazard both factored into the selection of the final target site.

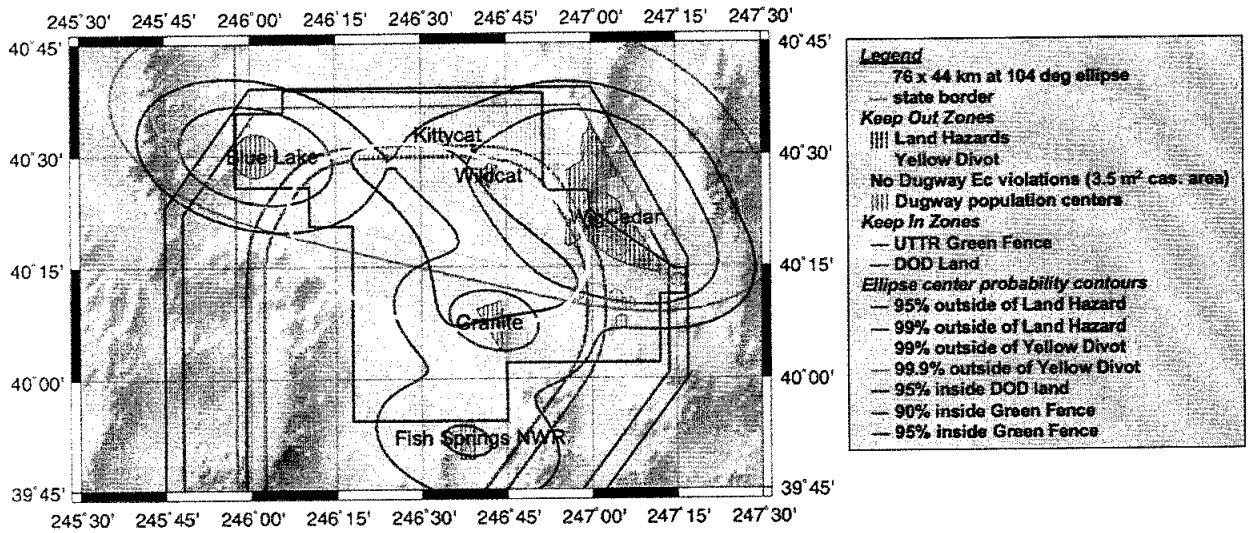

Figure 5: Natural Hazards around the targeted site.

V. Conclusions

Stardust successfully met all of the requirements needed to authorize release and entry. In spite of very strong winds following a severe winter storm that passed through UTTR only hours before entry, Stardust landed successfully inside of the 99% ellipse predicted at the time that release was authorized. The final landing location was less than 10 km from the target location. The proposed paper will describe the extensive hazard analysis that preceded the successful conclusion of the Stardust mission.