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HUMAN SAFETY ANALYSIS FOR THE GENESIS SAMPLE RETURN MISSION

Geoffrey G.Wawrzyniak[*] and Tom E. Wahl[†]

In order for the Sample Return Capsule from the Genesis spacecraft to return to Earth, it had to be determined that the casualty risk of the capsule's return would be minimal. Under stringent NASA and USAF requirements, JPL engineers developed a statistical analysis of the collective and individual casualty risks based on a regional population survey and Gaussian landing distributions. Additionally, other assessments of property damage and unacceptable zones were studied. These analyses were updated through the final hours of the mission as the navigation team produced new assessments of the landing distributions based on updated orbit-determination solutions and maneuver designs.

This analysis showed that the capsule was targeted to a region of minimal casualty risk: northeastern Nevada prior to the capsule release sequence and the Utah Test and Training range in northwestern Utah before the final maneuver and after the capsule-release sequence. Had this analysis not been performed, NASA would not have allowed the capsule to return.

INTRODUCTION

Launched in August of 2001 to a Lissajous orbit around the Earth-Sun L1 point, the Genesis spacecraft collected solar-wind particles during its two-year science phase. On April 1, 2004, its collector arrays were stowed and the Sample Return Capsule (SRC) was closed, and the spacecraft began it journey back to Earth.

On the morning of Wednesday, September 8, 2004, the SRC came tumbling through Earth's atmosphere and crashed into the Utah desert at 300-kph, approximately 8.31 km south of the target and well within the 99% nominal landing ellipse. While the capsule was badly damaged, scientists have determined that most of the samples inside are usable. These samples should be able to fulfill mission goals to learn about the Sun and the history of the solar system.

While the return of Genesis to Earth was not an unqualified success, the SRC was the only casualty. Aside from the emotions of the engineers, scientists, and well-wishers, there were no injuries due to the spacecraft. Furthermore, aside from the SRC, no

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property was damaged. The probability of these events was well known by JPL and NASA well before atmospheric entry. If the risk had been unknown or unacceptably high, NASA would not have allowed the SRC to re-enter.

After the ninth trajectory correction maneuver (TCM), Genesis was targeted to a 250-km flyby of the Earth. The next TCM, TCM-10, moved the instantaneous impact point (IIP)[*] through Texas from the Gulf of Mexico to the Utah Test and Training Range (UTTR), located in northwest Utah. The safety analysis of that path was performed by Mendeck at JSC.[1] TCM-11 took the spacecraft to an IIP in northeast Nevada so that the ΔV from the SRC-release events (spin-up from 1.6 rpm to 10 rpm, 117° precession to attitude for release, spin-up to 15 rpm, and the release of the SRC) would target the SRC back to the UTTR. After the release, a divert maneuver sent the spacecraft bus on a flyby trajectory for later disposal. The purpose of the analysis described in this paper was to quantify the risk the entering capsule and/or bus posed to the public after TCM-10, excluding the divert maneuver events.

The analysis described in this paper is similar to the efforts to characterize the landing sites for the NASA's Mars Exploration Rover (MER) mission. Whereas Genesis used population data and casualty-risk thresholds, regions in the MER landing sites were characterized by levels of lander survivability.[2] The MER project used a Matlab-based suite of software called MarsLS. Since Genesis was returning to Earth, the Mission Design and Navigation Team (MDNAV) felt the name was inappropriate, so, after a few bug fixes and minor additions, MarsLS became EarthLS.[†]

REQUIREMENTS

Safety Analysis Customers and Deliverables

The primary customers of the human-safety-analysis results before and during Genesis entry events were NASA and JPL management and the Genesis project team. Decision authority existed at each of these levels regarding authorization for the Genesis SRC to return to Earth. Months prior to entry, a set of contour analyses was used to convince all parties that Genesis would likely be safe. These contour analyses incorporated a grid of evenly spaced probability distributions, based on large and small ellipses to represent bounding cases, laid over population data in northeastern Nevada and northwestern Utah. These products are recorded in the Earth Targeting and Entry Safety Plan (ETESP), Volume 1, a document now required for all such Genesis-class NASA missions returning to Earth. Review and approval of the ETESP and a series of major Genesis project reviews on the topic contributed to a pre-certification by NASA and JPL of the safety of Genesis. This ultimately allowed a small group of experts on the flight operations team to make time-critical rapid go/no-go decisions without the

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[*] The IIP is where the spacecraft (consisting of the SRC and the spacecraft bus) would impact Earth if the TCM were stopped and nothing further was done.

[†] MarsLS/EarthLS was developed to work with any spherical body, so a general name would be more appropriate; however, since the lead author is responsible for the software, he is primarily to blame for the lack of an appropriate name.

logistical burden of involving a larger group of managers or other authorities.

Final delivery of analysis results was made at three briefings in the last thirty-six hours prior to entry. At the last of these briefings, at eight hours prior to entry (E–8 hours), the analysis constituted the best and final test of the performance of the flight team and spacecraft performance regarding delivery of the SRC to UTTR. The short, fifteen-minute turnaround between the end of the EDL-dispersion simulation (the final leg of the trajectory-estimation-and-propagation process) and the preparation for the final briefing placed a requirement on software (EarthLS) used in this analysis to be quick at producing results. The turnaround also required the results be quickly understood both by humans preparing for the briefings and by humans participating in the briefings. A series of operational readiness tests ensured that everyone knew what he or she was looking at during these briefings. The table and graphics used in the E–8 hour briefing are discussed in the Results section.

Collective and Individual Risk

It is the policy of NASA to protect the safety of the public, mission-essential workforce, and property during range operations; NASA's range-safety requirements delineate this policy.[3] The UTTR also has a set of safety requirements that must be met as long as the SRC and/or spacecraft bus is targeted to the range.[4]

Both entities have different levels of acceptable risk for mission-essential and general-public populations. Individual or collective risk must be assessed for both populations. UTTR and NASA also have different levels of acceptable risk associated with property. The Genesis project had the obligation to comply with the more stringent requirements wherever both requirements apply. Table 1 identifies the levels of acceptable risk.

Table 1
RANGE-SAFETY PROBABILITY-RISK THRESHOLDS

REQUIRED RISK ASSESSMENT	UTTR POST LAUNCH	NASA POST LAUNCH
Individual Risk Mission Nonessential: Probability of casualty per hazard (debris, far-field blast overpressure, and toxic material release) for individual members of the public outside NASA property and for visitors and personnel located on NASA property who are not directly involved in the mission, exclusive of people on any waterborne vessel or aircraft	1e–07	1e–06
Mission Essential: Probability of casualty per hazard for individuals who are directly involved in the mission, but not onboard the vehicle, exclusive of people on any waterborne vessel or aircraft.	3e–06	1e–05

REQUIRED RISK ASSESSMENT	UTTR POST LAUNCH	NASA POST LAUNCH
Collective Risk Mission Nonessential: Probability of casualty per hazard for the public outside NASA property, exclusive of people on any waterborne vessel or aircraft	3e–07	3e–05
Mission Nonessential: Probability of casualty per hazard for the population that consists of visitors and personnel located on NASA property, who are not directly involved in the mission, exclusive of people on any waterborne vessel or aircraft	N/A	3e–05
Mission Essential: Probability of casualty per hazard for all personnel who are directly involved in the mission, but not onboard the vehicle, exclusive of people on any waterborne vessel or aircraft	3e–04	3e–04
Probability of impact that debris could cause casualty Probability of impacting any inhabited waterborne vessel Non-Mission Ship Mission Essential Ship	 1e–06 1e–05	 1e–05
Probability of impacting any inhabited aircraft Non-Mission Aircraft Mission Essential Aircraft	 1e–07 1e–06	 1e–07
Probability of impacting any property in the vicinity of the flight	N/A	1e–03

Interpretation of Risk Requirements for the Final Briefings

When EarthLS was used to test compliance with the collective and individual risk limits, a certain amount off-nominal spacecraft performance was assumed. The bounding case assumed is failure to achieve any separation velocity between the SRC and the remaining spacecraft bus, resulting in delivery of the SRC up to 35 km uptrack of the targeted location in UTTR, potentially along with surviving pieces of a non-diverted spacecraft bus. To that end, the maximum risk from a line of seven ellipses stretching from the nominal ellipse uptrack 35 km was reported in the final briefings.

Additional restrictions were placed on the Genesis project in order to ensure safety, requiring the authors to investigate more than casualty and property risk. The SRC had to have a 99% probability of landing within a 2.5-nautical-mile (4.63 km) inset from the border of the southern restricted airspace at the UTTR, also known as the "green fence". The SRC delivery performance also had to include the effect of on-board spacecraft fault recovery activities, which could cause delays resulting in up to a 14-km uptrack shift in the SRC delivery. Therefore, the nominal and 14-km uptrack ellipse each had to have a 99% probability of landing within the green fence. This protects against impacts outside what is essentially a bombing range (a place that expects and accepts impacts, as opposed to nearby civilian land which rightfully should not expect to experience an impact).

Another requirement stated that the center of the nominal impact ellipse must fall farther than 1 nautical mile (1.852 km) away from five sensitive sites identified within UTTR. This is a traditional UTTR requirement, intended to decrease the chance of damage to these UTTR facilities. Due to the relatively large Genesis impact ellipse, the increase in protection was slight, but the requirement was honored nonetheless. EarthLS was also required to determine if the impact-ellipse center would fall on or outside a "warning track", which was the area between 3-σ and 6-σ ellipses centered on the targeted and based on covariance studies. If the center was found to be outside this warning track, which corresponded to a greater than 6-σ event, that would have indicated something unusual had occurred and require confident explanation to avoid aborting the entry attempt. A landing predicted to be "on" the warning track would be treated as a negative, but not decisive, factor during real time go/no-go decisions made close to entry.

Finally, although no requirement existed, the authors used EarthLS to determine the probability of landing in areas where population data existed. This set an upper bound on the calculation of the risk to humans in that area, because, as is later discussed, the probability of landing in an area is multiplied by the percentage of space that people take up in that area and then summed to obtain the risk of that landing distribution. Due to the layout of the areas, only one cluster of areas could conceivable affect the probability of landing in any area with population data at the expense of other clusters. For instance, if the 35-km line of ellipses approached I-80, north of the restricted airspace, the probably of landing in any area with population data would be dominated by the areas along I-80. The same would be true if the ellipses were closest to the five sensitive sites in the UTTR, a dry lakebed in the northwest corner of the restricted airspace, US-93 in eastern Nevada, or Fish Springs National Wildlife Refuge in the southern part of the restricted airspace.

Regional Population Data Sets

JPL was provided with two sets of population data in the UTTR region. The UTTR region is shown in Figure 1. The first data set was provided by UTTR. This data set comprises 2004 population data on the UTTR, specifically, the regions R6402A, R6402B, R6404A, R6405, R6406A, R6406B, R6407, SEVIER A MOA, and SEVIER B MOA. In all, there were over 100 locations labeled mission nonessential. There were two locations (Wig Fallback Complex and TPQ-39) labeled Mission Essential. For each site, the central geodetic latitude and longitude, geometric area, and population data were given. This information was converted to geocentric latitude for use in EarthLS and an EarthLS-area file was created. This area file assumed triangular shapes for the locations that did not give any other geometric shape (usually less than 10,000 sq-ft in geometric area) and set vertices as such. For areas where a shape was given (circle or rectangle), that shape was used for the vertices at that site. The EarthLS-area file also contains geometric area and population data for each site.

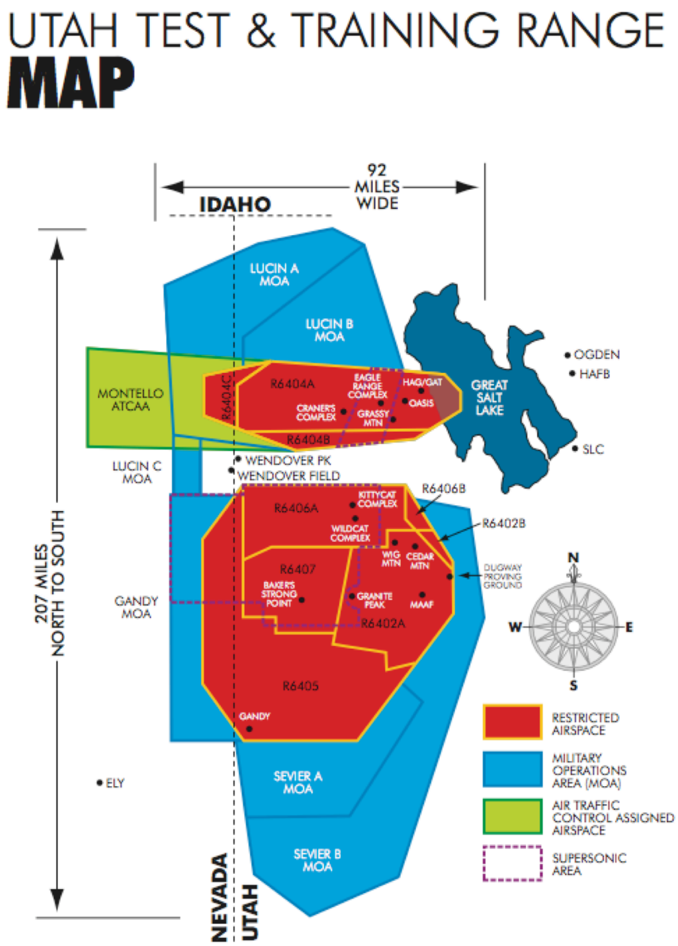

Figure 1. UTTR map and associated restricted airspace (red) and military operated airspace (blue). Map courtesy of UTTR (http://www.hill.af.mil/uttr/).

JPL received another set of population data for northeast Nevada and northwest Utah from the Oak Ridge Laboratory, by way of the Johnson Space Center. These data are from a database of global population information (LandScan), which was last updated in 2002. The data are a Matlab array, where each cell corresponds to a geodetic latitude and longitude value and the value of the cell is the population of that cell. The cells are 1/120° geodetic latitude by 1/120° longitude, about 0.64 km^2 at this latitude. JPL converted these cells into geocentric latitude and created an EarthLS-area file from the four corners of each cell. Figure 2 is a contour of the original data set, with contours at each level of person per cell (0–2674) for maximum resolution.

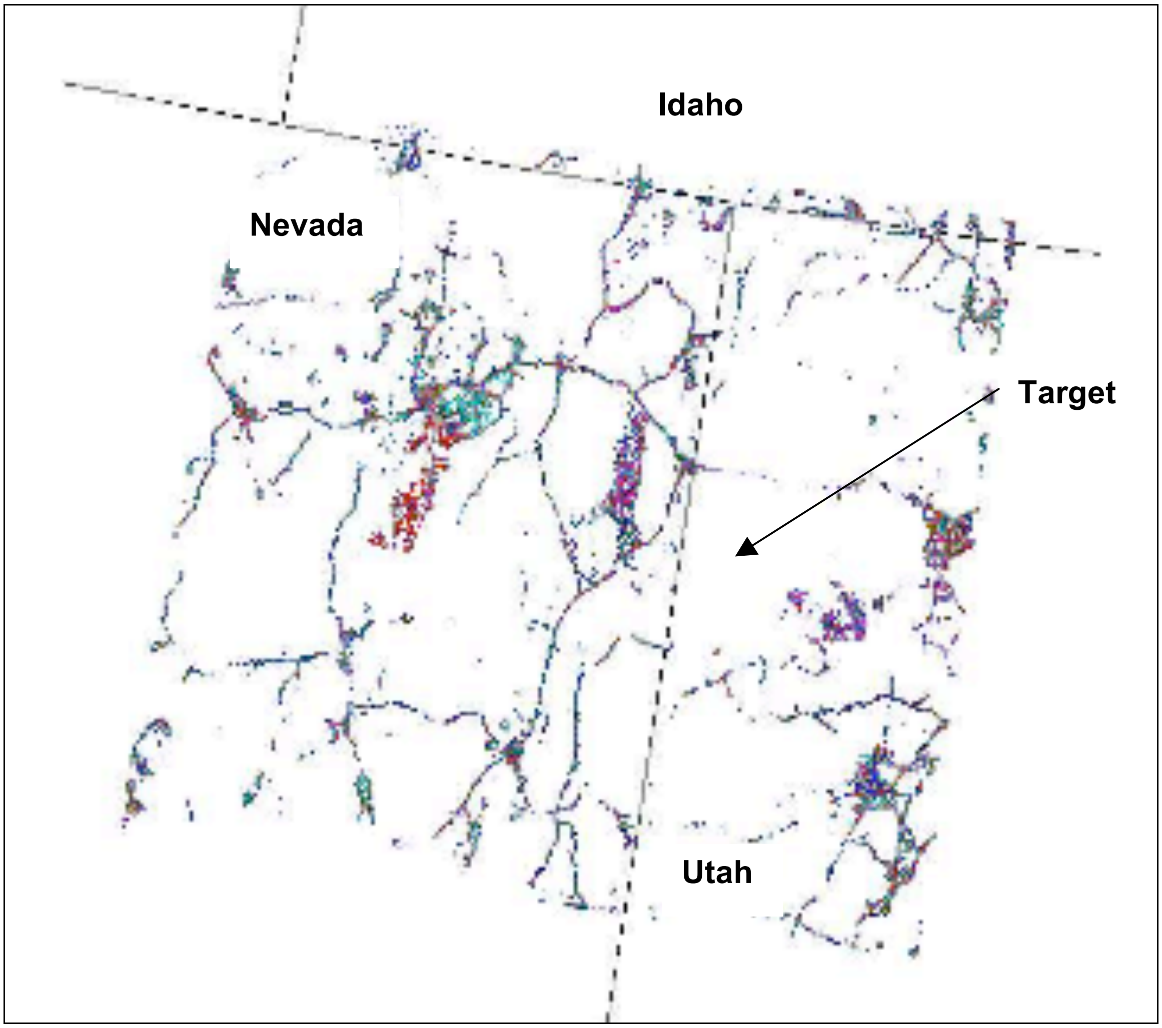

Figure 2. Contours of population density going from blue to red. White is no data or no population.

METHODOLOGY

Probability of Landing in a Site

Using entry and descent simulation software, such as JPL's AEPL or Langley Research Center's POST, the landing point of a trajectory started at atmospheric entry can be found. By sampling the orbit-determination covariance before atmospheric entry and varying the atmospheric and drag parameters of the entry body in a Monte-Carlo analysis, these simulation programs can generate a dispersion of landing points. The resulting dispersion of points is best characterized as a two-dimensional Gaussian distribution and can be represented by an ellipse.

In reality, a large sample of re-entries might not be perfectly Gaussian, with only a first and second moment (mean and variance). There may be higher-order moments (skew and kurtosis) that are not taken into account in the Monte-Carlo analysis.

Alternatively, a distribution based on real data might be better described as some other kind of distribution (i.e., a beta distribution). There also could be errors in the entry-and-descent modeling that are not accounted for in the Monte Carlo analysis (i.e., an unknown bias in a parameter or an unaccounted for parameter) making the distribution noncontinuous.* The analyses do not account for spacecraft malfunction (as occurred with Mars Observer and Mars Polar Lander) or severe and highly unexpected modeling error (as with Mars Climate Orbiter).

Additionally, there might be a nonzero floor to the probability-distribution function beyond a certain distance from the central point, to account for modeling error and unknown unknowns. (For example, the probability of any 5-σ or greater event occurring is less than 3.727e–06. Integrations by EarthLS of small, discrete areas this far away have been calculated as less than 1e–100, which is likely an unrealistically small probability.) That value is unquantifiable: based on in-flight experience, no credible option exists but to assume that the orbit-determination and atmospheric-entry models are sound and that the spacecraft will not malfunction beyond statistical variation in maneuver ΔVs (i.e., the probability of a failure such as a stuck thruster is not computed). Integrating the probability over a small area under this floor value will yield a small result. Nonetheless, based on the orbit-determination and entry-and-descent analysis to obtain a landing-point dispersion, a Gaussian distribution was used—and should suffice—for this probabilistic analysis. (Because the surface is fairly "flat" for the region in question, negligible error was also introduced by assuming a flat surface in the probability calculation instead of accounting for terrain or global curvature.)

To determine the probability of landing in a region, or site, EarthLS can integrate the (Gaussian) bivariate-probability distribution function (BVPDF) over that site. The integration of the BVPDF,

$$P_S(i) = \frac{1}{2\pi|\Sigma|^{1/2}} \iint_{\substack{polygonal \\ region,\, i}} \exp\left[-\tfrac{1}{2}(\mathrm{X}-\mu)^{\mathrm{T}} \Sigma^{-1}(\mathrm{X}-\mu)\right] dx\, dy, \qquad (1)$$

where Σ is the two-dimensional covariance described by the ellipse centered at μ=[μx, μy]T and X is the vector [x, y]T, is non-trivial to perform. Fortunately, an innovative approach to integrate this function was developed by John Michel, a professor at Marietta College in Ohio who spends a few weeks at JPL in the summers, and is used by EarthLS.[5]

The integral of the BVPDF for each site, $P_S(i)$, is stored in memory to be combined with the probability of casualty in that area later in the process. The probability of landing in a site can also be summed to find the overall probability of landing in any populated region. This can be a conservative approximation of the probability of

* The debris field of the *Columbia* tragedy offers some insight into re–entry distributions. As it broke up about 60 km above the surface, fragments of differing shape, mass, and size traveled through the atmosphere. However, these fragments are not analogous to a distribution of drag coefficients in a Monte Carlo simulation. The orbiter broke up over several minutes; smaller debris pieces separated from larger debris pieces. The debris field does, however, illustrate that atmospheric-entry uncertainty translates into primarily a downtrack distribution. In *Columbia's* case, neither a normal nor a beta distribution best describes the downtrack debris field; a combination of beta distributions does. A Gaussian distribution, however, can be used to describe the crosstrack debris field (Mendeck email, Aug 6, 2004).

impacting property.

Probability of Casualty in a Site

The probability of casualty in a specific site is a function of the following parameters:

A_H = Area of one human (varies by interested party, described more in the next section)
$A_S(i)$ = Area of manned location/site "i"
$C(i)$ = Population of site "i"
$P_S(i)$ = Probability of landing in site "i" based on integration of the BVPDF

The risk to humans in these sites is separated into two categories: collective and individual. Collective risk can be described as the probability of anyone suffering from a casualty resulting from flight-project activities. Collective risk for a site can be mathematically described as:

$D(i)$ = $C(i) / A_S(i)$, Population density of site "i"
$P_C(i)$ = $C(i) * (A_H / A_S(i))$, Collective probability of adverse contact with any human being in site "i" based on a uniform distribution of humans
P_{DC} = $\sum [P_C(i) * P_S(i)]$, Overall collective risk

A uniform distribution of humans is used because there is no simple way to approximate for the random motion of humans within a site. If the area of the site is small enough or if the population density is small enough, a uniform distribution is an appropriate approximation. Data in this analysis are used at their highest fidelity to support this assumption.

Individual risk is from the point of view of the individual, where the individual is concerned with only his or her own safety. One of the features of individual risk is that it exposes some cases of risk where collective risk does not. Individual risk is calculated:

$P_H(i)$ = $1 * (A_H / A_S(i))$, Probability of adverse contact with a specific individual human being in site "i"
P_{DH} = $\max[P_H(i) * P_S(i)]$, overall individual risk

The maximum is used in calculating the overall individual risk because no individual can be in more than one site at a time.

Area of a Human

UTTR is clear on what they define as the area of a human (0.278 m^2). NASA has different metrics for a human, depending on whether the human is standing (0.36 m^2) or sitting (0.6 m^2). The authors examined the risk associated with 0.278 m^2, 3.51 m^2, and 3.8 m^2 humans, but the authors elected to use 3.8 m^2 as the area of one human in all reported analyses. This number is the area of a circle, which has a radius equal to the radius of a NASA human (sqrt[0.36/π] = 0.339 m) plus the radius of the SRC (0.76 m). For the UTTR criteria, the human plus SRC area is 3.51 m^2, so the NASA human is larger. This did introduce conservatism when addressing UTTR risks, but using the NASA-based area retained to the philosophy of meeting the toughest requirement. Also, the resulting reduction in complexity when reporting results from EarthLS proved to be a noticeable benefit during reviews and in time critical briefings.

RESULTS

The aforementioned methodology applied to two sets of analyses. The first was a contour analysis used in the ETESP to pre-certify the safety of the capsule return. The second set was used in the final briefings at E–35, –15, and –8 hours for the MDNAV's contribution to those meetings.

Contouring

While the preceding formulations are appropriate for specific landing ellipses, the authors also characterized the risk based on the nominal landing point over the entire region to pre-approve the landing re-entry strategy. Since the two data sets, LandScan and UTTR-provided, were different enough, two sets of analyses were performed. The process of performing each analysis is identical.

A grid of nominal landing ellipses was spread over the region in which population data existed (northeast Nevada and northwest Utah for the LandScan data, UTTR for the UTTR-provided data). The ellipses were spaced at 0.05° and were 41.71 km by 26.61 km, with an azimuth of 133.91° clockwise from north. This ellipse resulted from predicting the SRC-release sequence; it was based on a covariance study assuming a tracking-data cutoff before the SRC release.

The probability of landing in each area for each ellipse, $P_S(i)$, was then calculated. The probability of collective and individual casualty for each area was also calculated and combined with $P_S(i)$ to get the overall probability of collective (total) and individual (maximum) casualty for each ellipse.

At this point, contours could have been made for the risk levels, showing where risk levels were exceeded. However, these points were interpolated to better approximate the contours at a finer resolution. Figure 3 contains contours based on the UTTR-provided data and on a grid of post-SRC-release landing ellipses. The NASA property threshold (blue contour) is exceeded around Blue Lake (northwest circular region), Fish Springs NWR (central rectangular region), and the five UTTR keep-out zones, but this is artificial in that the analysis assumes the entire region is covered in property, which is not true in these two regions. The NASA requirement related to property was eventually disregarded following consultation with NASA. The intent of the requirement was not clear in its parent document; it is actually intended to address specific high-value properties near launch or landing ranges that are identified on a case-by-case basis by NASA. No such properties were identified for the Genesis mission. It was further noted by NASA that UTTR was the appropriate party to have concern regarding Genesis entry on to property, and UTTR was satisfied with their own requirements already levied on the project.

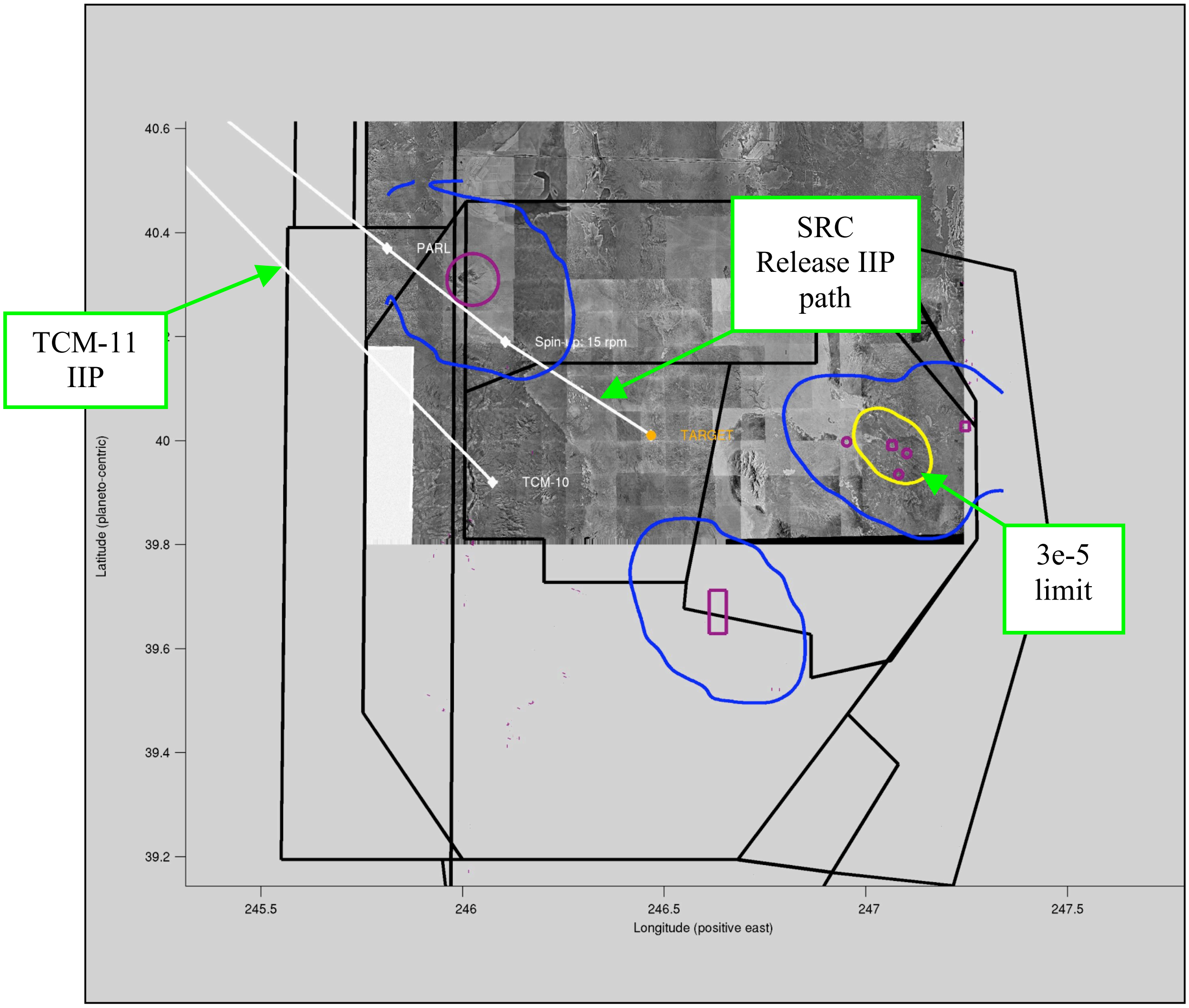

Figure 3. Contours based on UTTR-provided data (purple). The only criteria that are exceeded based on the locations of nominal landing point for a grid of ellipses are the UTTR-collective risk for mission nonessential (3e–5, yellow), and NASA property (1e–3, blue), which was disregarded.

Figure 4 contains contours based on the LandScan data and on a grid of nominal, post-SRC-release landing ellipses. The areas where population data existed are shown in black. The NASA collective risk (3e–5, yellow) would be exceeded in areas that are more "metropolitan"; however, the IIP path does not cross through any of these areas. The contours within the UTTR, based on LandScan data, differ from the contours based on the UTTR data.

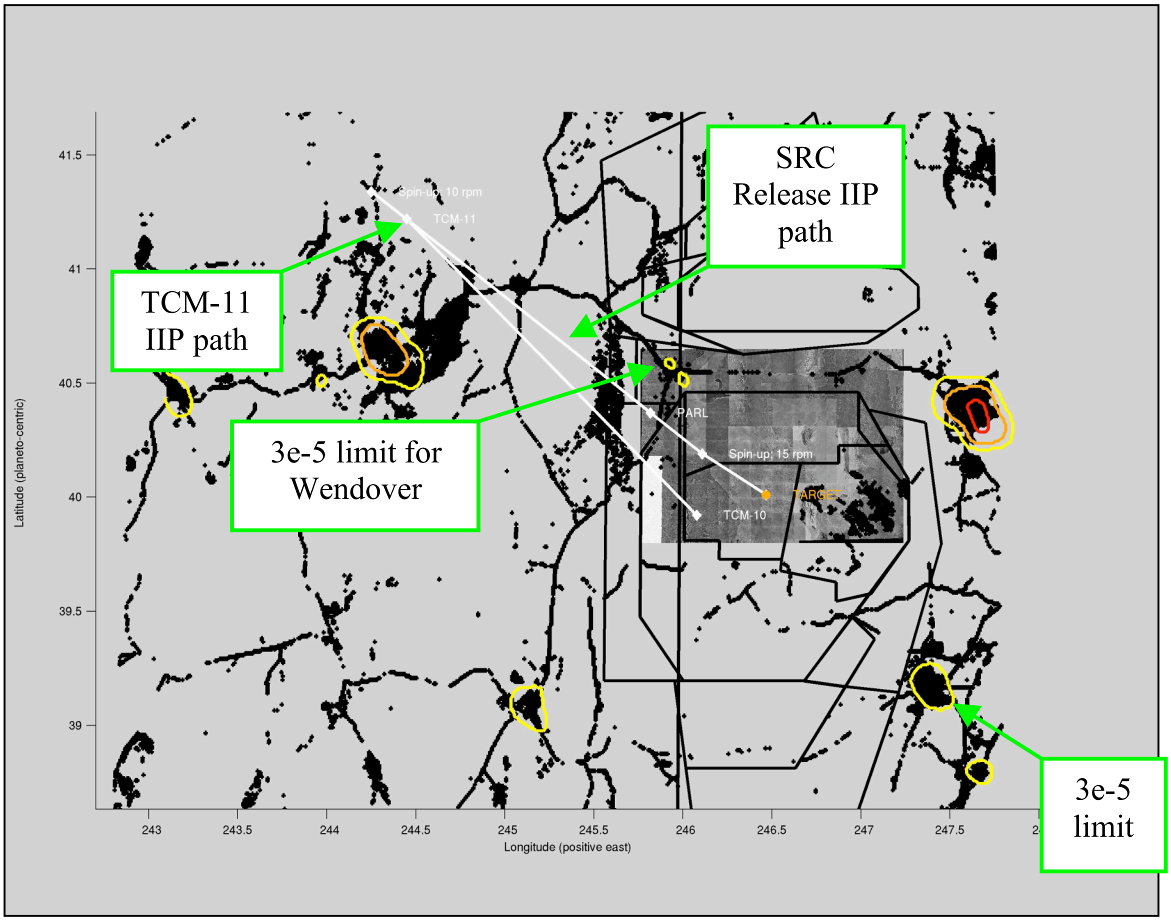

Figure 4. Contours of NE Nevada and NW Utah based on LandScan data and a grid of post-SRC-release ellipses. No thresholds are exceeded. Contours are 3e–5 (yellow), 1e–4 (orange), and 3e–4 (red).

Figure 5 displays contours of LandScan data, based on a grid of post-TCM-10 ellipses where orbit determination has shrunk the ellipse as much as possible. The contours are further from the populated regions because the ellipse is bigger.

Like most common contours, these probability contours describe a three-dimensional surface. The topography of the surface is a function of the ellipse size and the percent of each data cell covered with people or property. As the ellipse gets smaller, the surface has more relief and variability. A larger ellipse acts as a low-pass filter, smoothing the surface. The height of the surface above a cell is at a maximum when the entire cell is considered as a probable event. If the cell is partially covered (by population or property—both vary based on the area assumed for a person or property), the height of the surface is reduced.

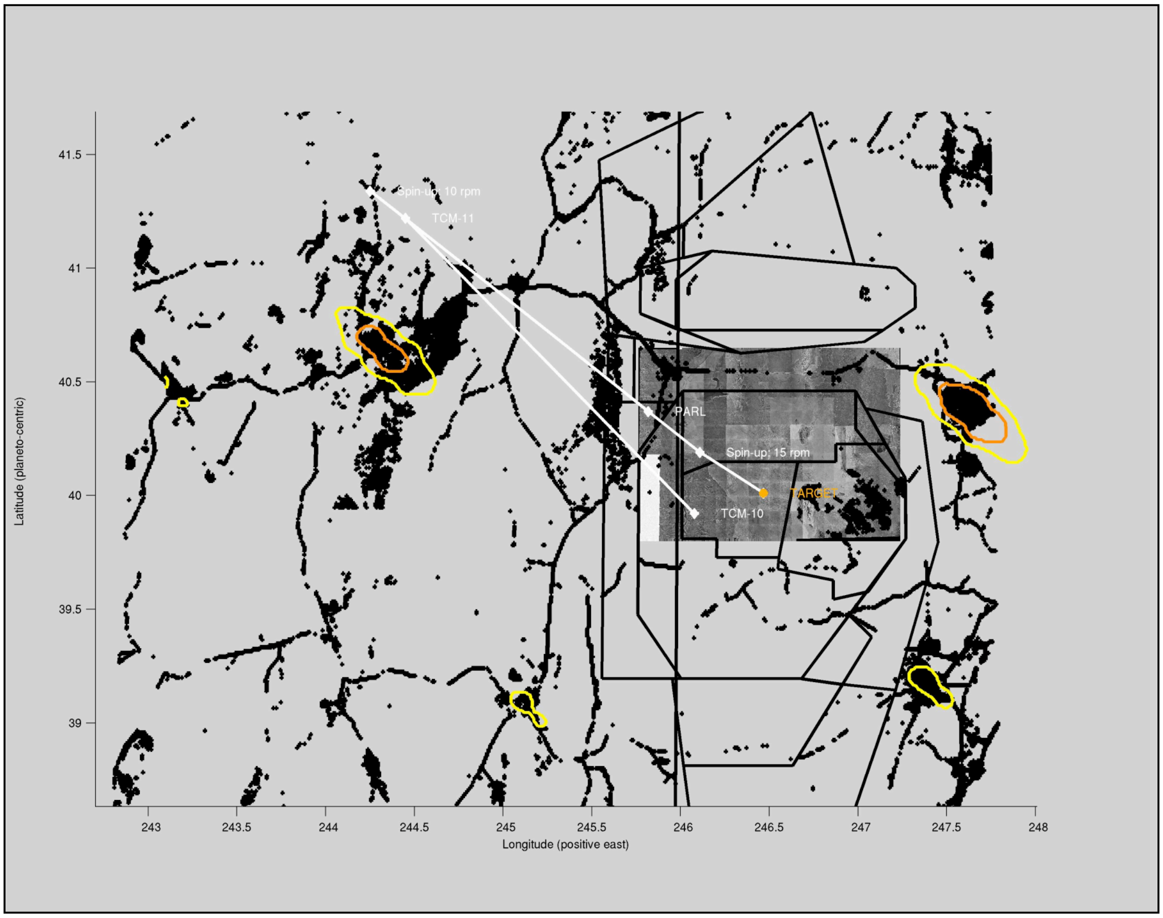

Figure 5. Contours of NE Nevada and NW Utah based on LandScan data and a grid of post-TCM-10 ellipses. No thresholds are exceeded in the IIP path. Contours are 3e–5 (yellow), 1e–4 (orange), and 3e–4 (red).

Contouring also mitigates concerns about issues arising from assuming Gaussian distributions. If a floor were assumed for cases beyond a 4- or 5-σ ellipse, the effect would be negligible, because the contours are dominated by regions near the center of the ellipse. The preceding figures show that even if an ellipse is centered on a small, sparsely populated region, the concerns about human safety do not exceed the threshold criteria.

Final Briefings: E–35, –15, and –8 hours

At 35, 15, and 8 hours prior to entry, the Genesis flight team met to share the status of each subsystem. The final TCM, TCM-11, had executed at E–2 days, so the only remaining event was the SRC-release sequence. At each meeting, the MDNAV team chief had to report on the latest state of the navigation, which included the entry-and-descent analysis performed by both AEPL and POST (discussed in Ref. 6). Table 2 was provided to the MDNAV team chief for the E–8 hour meeting and incorporated into his presentation of the MDNAV-team status. Similar tables were used in the E–15 and E–35 hour meetings. These values, found in the "Navigation Decision Factors" of this table, were the maximums taken from a string of ellipses generated along a 35-km line uptrack from the nominal landing point.

Table 2
MDNAV assessment for the E–8 hour go/no-go meeting

```
FILENAME: ellipse_files/uttr/od154_srcInspec.txt
 CREATION TIME: 07-Sep-2004 22:36:54 PDT
 RELATIVE TO ENTRY: -10.3 hours

 NOMINAL     GEOCENTRIC    POS-EAST
 ELLIPSE     LAT(mean)     LON(mean)      MAA(99%)      MIA(99%)      AZ from N
    POST      40.0196      246.4819       41.9586       27.1214       137.0899
    AEPL      40.0257      246.4834       40.7757       26.7246       135.2940
    DIFF      -0.0061       -0.0015        1.1828        0.3968         1.7959

    POST-AEPL DIST:   0.6892 km

 NOMINAL     GEODETIC      POS-WEST                GEOCENTRIC DIST
 ELLIPSE     LAT(mean)     LON(mean)                  TO TARGET
    POST      40.2093      113.5181                    1.6499 km
    AEPL      40.2153      113.5166                    2.2162 km

 NOTE: Values for Pc are based on the maximum probability from a set of 8 evenly spaced ellipses
       from both POST and AEPL results. The ellipses start at the nominal ellipses for both POST
       and AEPL and span along the azimuth vectors, northwest, for 35 km.

 NAVIGATION DECISION FACTORS                 CRITERION    POST        AEPL     POST VIOL  AEPL VIOL
 ==========================================  =========  ========    ========   =========  =========
 Impact points NOT in Nav Delivery Zone        < 1e–02
                           Nominal Ellipse:             0.00e+00    0.00e+00       0          0
                       14km Offset Ellipse:             0.00e+00    0.00e+00       0          0

 IPs meet NASA Pc for Public Individual        < 1e–06
                  LandScan-Population Data:             3.52e–10    3.22e–10       0          0
                      UTTR-Population Data:             7.46e–10    9.16e–10       0          0
 IPs meet NASA Pc for Public Collective        < 3e–05
                  LandScan-Population Data:             5.93e–09    6.62e–09       0          0
                      UTTR-Population Data:             3.98e–09    4.89e–09       0          0
 IPs meet NASA Pc for Mission Individual       < 1e–05
                      UTTR-Population Data:             2.46e–10    3.02e–10       0          0
 IPs meet NASA Pc for Mission Collective       < 3e–04
                      UTTR-Population Data:             1.72e–09    2.12e–09       0          0

 IPs meet UTTR Pc for Public Individual        < 1e–07
                      UTTR-Population Data:             7.46e–10    9.16e–10       0          0
 IPs meet UTTR Pc for Public Collective        < 3e–05
                      UTTR-Population Data:             3.98e–09    4.89e–09       0          0
 IPs meet UTTR Pc for Mission Individual       < 3e–06
                      UTTR-Population Data:             2.46e–10    3.02e–10       0          0
 IPs meet UTTR Pc for Mission Collective       < 3e–04
                      UTTR-Population Data:             1.72e–09    2.12e–09       0          0

 Nominal points enter Dugway keep-out zone       0                                 0          0

 IPs enter UTTR-provided areas (BL,FS,DPG,etc): N/A     1.90e–02    2.34e–02      N/A        N/A
 NW IPs enter LandScan areas (Wendover,I-80):   N/A     3.87e–06    4.66e–06      N/A        N/A
 +++++++++++++++++++++++++++++++++++++++++++++++++++++++++++++++++++++++++++++++++++++++++++++++++
 NUMBER OF APPLICABLE CRITERIA VIOLATED ABOVE:                                     0          0
 +++++++++++++++++++++++++++++++++++++++++++++++++++++++++++++++++++++++++++++++++++++++++++++++++

 Valid Navigation Solutions                  CRITERION     OD          MNVR       POST       AEPL
   Concurrence from Navigation Advisory Group    1          1           1          1          1
 =================================================================================================
```

The MDNAV-team chief was also provided with two figures for each meeting. (Figures 6 and 7 were used in the E–8 hour briefing; figures for the E–35 and E–15 hour briefings were very similar to the figures used in the E–8 hour briefing, which indicates that the orbit determination was stable.) One of the figures (Figure 6) was an EarthLS image of what the landing-dispersion ellipses would look like if the SRC release completed successfully. The POST (white) and AEPL (blue) ellipses for each meeting were in good agreement. In this figure, the smaller orange ellipse centered on the target represented a nominal execution; it also served as the inner race of the warning track described in a previous section. The larger orange ellipse is the outer race of the warning track. The POST and AEPL ellipses 14-km northwest represent the landing dispersion if there were a delay in the SRC release due to potential autonomous actions taken by the spacecraft in the presence of a detected fault. A 35-km white line on the figure represents the locus of points used to compute the values found in the "Navigation Decision Factors" in Table 2. This line addressed the case of a weak separation velocity between the SRC and the spacecraft bus.* Yellow contours on the plot are the 3e–5 collective risk thresholds based on both LandScan and UTTR data and using a grid of nominal, post-SRC-release ellipses; they were put on the plot for reference. The red circles are the five UTTR keep-out zones.

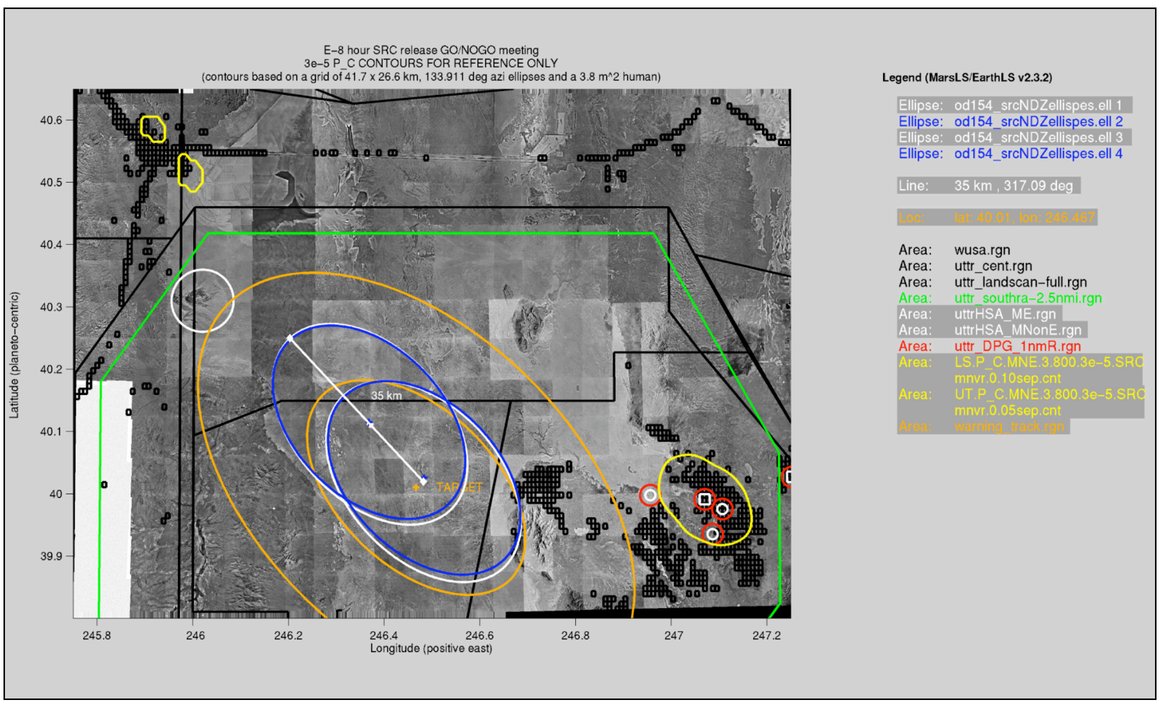

Figure 6. This graphic was used in the Genesis E–8 hour status briefing. It is zoomed into the nominal landing area in the UTTR.

* Other failure cases (beyond the two mentioned here) were not examined by EarthLS because the go/no-go decision could have been exercised by the flight operations team, which would have aborted the SRC-release events, effectively filtering out all other off-nominal SRC deliveries to UTTR.

The other figure (Figure 7) provided to the MDNAV-team chief was similar to Figure 6, but it was expanded to the whole northeast Nevada and northwest Utah region. The features on it are identical to Figure 6, except that the POST and AEPL ellipses are what the dispersions would be if the SCR-release sequence was not executed and the spacecraft failed to perform a planned maneuver to divert away from targeting Earth. The POST ellipse (white) is larger because that analysis modeled the trajectory of the expected largest piece of the spacecraft after burn-up in the atmosphere. AEPL (blue) modeled the EDL of the SRC intact.

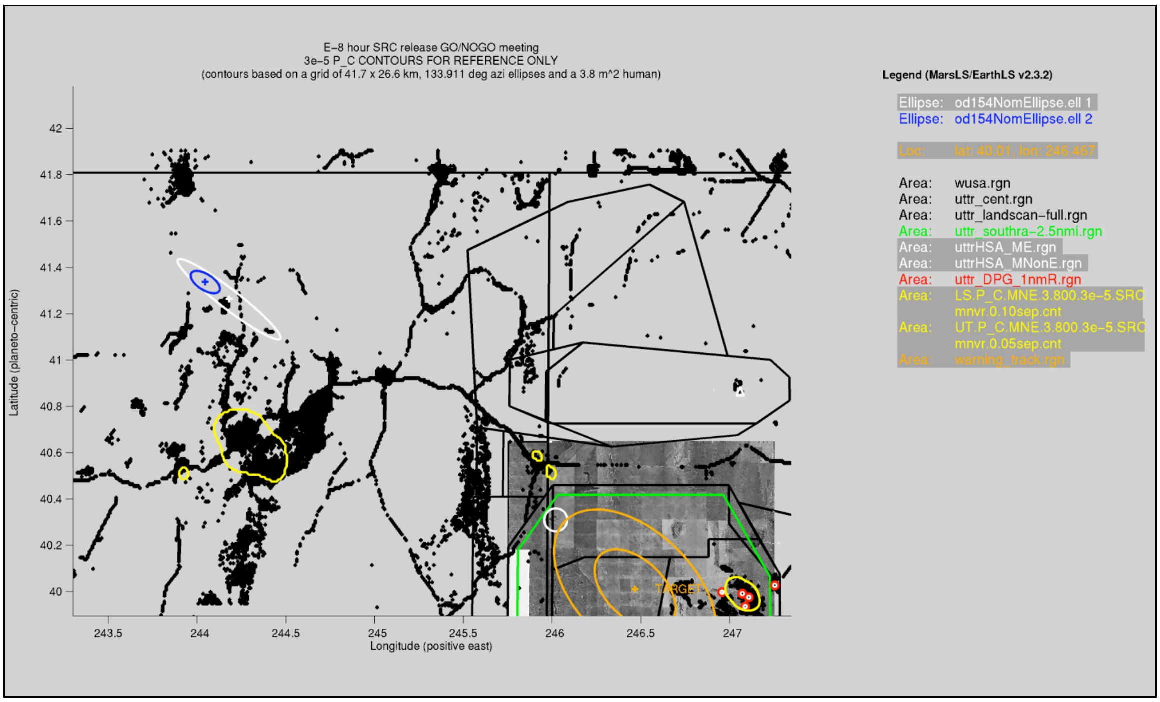

Figure 7. A regional view of the landing area. The blue and white ellipses are what would have occurred if no future events occurred.

UNEXPLORED ANALYSES

Better assumptions on property distribution could have been tested. In the analysis in this paper, the assumption was that that each cell is 100% covered with property. One new method would be to assume that only the percentage of a region for which there are population data is covered by property. Another method would be to use a conservative ricochet parameter and state that the property coverage in a populated area is proportional to the population density of human inhabitants.

A further analysis could also account for the probability of spacecraft malfunction and percentage of the IIP over the contour. Trials not discussed in this paper have shown the risk to property is negligible, or less than the threshold criteria. In summary, contours produced by EarthLS are de-rated by the chance that the spacecraft will suffer the catastrophic failure required to end up landing on or in said contour. For example, a 1e–2 contour can be taken as equivalent to a 1e–3 contour if the spacecraft is assumed to have 90% reliability. Additionally, if only 10% of an IIP segment crosses into a 1e–2 contour, then the contour can be treated as if it is actually 1e–3. This de-rating factor can be applied together with the above mentioned reliability factor. In the case of Genesis, both factors can be applied to this degree, resulting in a hundredfold de-rating. With the assumption that property actually covers no more that 10% of the occupied LandScan data cells, the full de-rating is a factor of 1000. Since the NASA property requirement is 1e–3, application of the thousand-fold de-rating implies Genesis met the 1e–3 limit everywhere.

In the analysis described in this paper, only two ellipses were considered: post-TCM-10 (or pre-TCM-11) and the SRC release ellipses. Since the maneuver errors would cause the landing ellipse to grow, the post-TCM-11 ellipse without tracking data would be large. Subsequently, the pre-SRC release ellipse will be small, since orbit-determination uncertainties after TCM-11 will decrease with more tracking data. These two ellipses could also be used to create contours. Additionally, a series of ellipses whose orientation and size are interpolated could give a more accurate representation of what happens along the IIP path.

Because of the nature of the spin stabilized Genesis spacecraft, the IIPs during and between TCMs are very deterministic and confined. EarthLS focused on the more complicated SRC release events. Missions with dead-banding attitude control can have IIPs that are random walks between TCMs. For example, Stardust, the next mission returning to Earth and landing in UTTR, has such random walks. When done for Stardust, the analyses described in this paper should include more of the LandScan database so its contour maps can show acceptable regions farther outside UTTR for random walking IIPs to exist.

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