

# Interfacing with USSTRATCOM and UTTR During Stardust Earth Return

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The Stardust Sample Return Capsule separated from the main spacecraft four hours prior to atmospheric entry. Between this time and the time at which the SRC touched down at the Utah Test and Training Range, two organizations external to JPL were involved in tracking the Sample Return Capsule. Orbit determination for the Stardust spacecraft during deep space cruise, the encounters of asteroid Annefrank and comet Wild 2, and the final approach to Earth used X-band radio metric Doppler and range data obtained through the Deep Space Network. The SRC lacked the electronics needed for coherently transponded radio metric tracking, so the DSN was not able to track the SRC after it separated from the main spacecraft. Although the expected delivery accuracy at atmospheric entry was well within the capability needed to target the SRC to the desired ground location, it was still desirable to obtain direct knowledge of the SRC trajectory in case of anomalies. For this reason U.S. Strategic Command was engaged to track the SRC between separation and atmospheric entry. Once the SRC entered the atmosphere, ground sensors at UTTR were tasked to acquire the descending SRC and maintain track during the descent in order to determine the landing location, to which the ground recovery team was then directed. This paper discusses organizational interfaces, data products, and delivery schedules, and the actual tracking operations are described.

## I. Introduction

THE Stardust spacecraft was launched February 7, 1999 from Cape Canaveral Air Station in Florida. The primary objective of the mission was to collect samples of material within the coma of comet Wild 2 and return the samples to Earth. The Wild 2 encounter occurred on January 2, 2004. The next encounter was at Earth on January 15, 2006. Planning for Space Surveillance Network tracking of the sample return capsule began early in 2005. This included submitting the USSTRATCOM Form 1 specifying all aspects of the support request, defining the data products that would be required and determining the delivery schedule for these products.

## II. Technical Challenges

### A. USSTRATCOM Tracking and Orbit Determination

USSTRATCOM, one of nine unified commands within DoD, is responsible for the operation of the Space Surveillance Network, a network of radar and optical sensors used to track artificial Earth satellites and Earth orbiting debris. Two SSN sensor locations were well placed for tracking the incoming SRC. These were the optical sensor facility at Mt. Haleakala, Maui, and the ALTAIR radar at Kwajalein atoll in the western Pacific. Both are capable of long range tracking. Use of DoD resources in support of NASA projects is covered under an agreement between NASA and DoD<sup>1</sup>. Figure 1 shows the SRC descent trajectory, the Stardust spacecraft flyby trajectory, and the locations of ALTAIR and Maui.

Unlike the Genesis entry trajectory, the Stardust entry trajectory was hyperbolic with respect to Earth. This required the development of new software at USSTRATCOM to enable orbit determination using SSN observations

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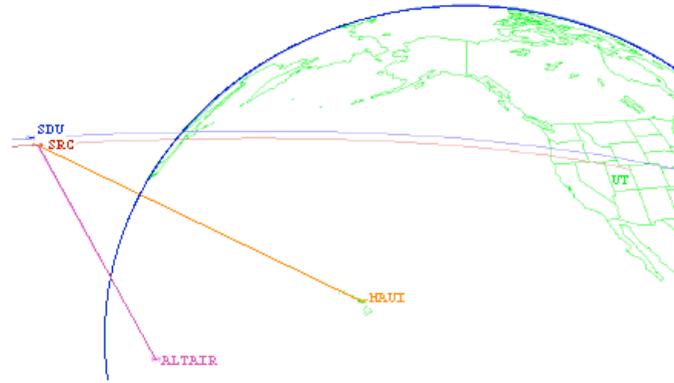
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of the SRC. Three additional factors which made the Stardust entry trajectory a challenging proposition were that the separation from the spacecraft bus occurred at a slant range of 105,000 km, the cross-sectional area of the conical SRC was 0.5 m<sup>2</sup>, and the phase angle from Maui was near 90 degrees for most of the time from separation to the end of the pass.

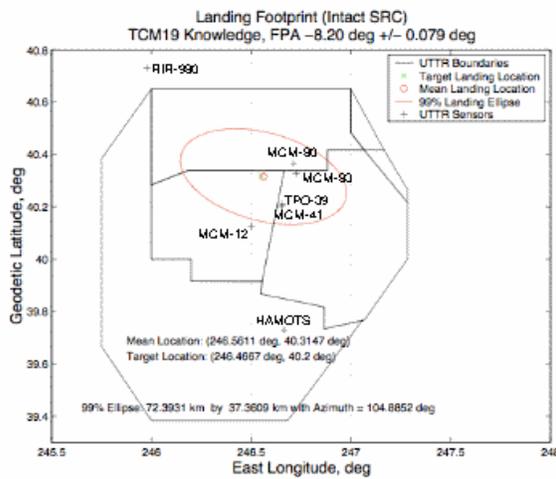
### B. SRC Acquisition at UTTR

The primary objective at UTTR was to achieve acquisition of the SRC by the radar and optical sensors as early as possible, and to track the SRC as long as possible in order to determine the landing location and thereby facilitate a rapid recovery of the SRC by the ground recovery team. As the Genesis experience showed in September 2004, if there is an unobstructed view from UTTR to the atmospheric entry point near the U.S. west coast, the infrared sensors can easily detect the incoming SRC due to the heat signature as the SRC approaches the peak heating point about 50 seconds after atmospheric entry. Alternatively, if weather prevents a distant acquisition using the IR sensors, then it falls on the radars to perform the acquisition. This presents a difficulty because of the limited acquisition range of the radars (less than 50 km) and the very large pointing uncertainty that develops as the SRC descends through the atmosphere. In order to define a search space along the incoming trajectory as the SRC descends through the atmosphere, it is necessary to account for topocentric pointing variations along the descent.

A further consideration is illustrated by the fate of the Genesis SRC, which was destroyed after the drogue and main parachutes failed to open. While the UTTR radar operators are capable of finding the SRC as it descends on the main chute without any prior knowledge of the descent point, a full horizon search takes time. If the chutes fail to open then an acquisition strategy based on a horizon search may also fail due to lack of time to perform the search. For both Genesis and Stardust the goal was to achieve a radar lock on the SRC prior to the time of drogue deployment, in order to have the SRC in



**Figure 1. Stardust Spacecraft and SRC Trajectories.** The SRC was acquired by radar and optical sensors at USSTRATCOM's ALTAIR and Maui tracking stations.



**Figure 2. Tracking Sensors at UTTR.** Shown are the two radars (RIR-980, TPQ-39), four telescopes (MCMs), and the HAMOTS reference station. Courtesy P.N. Desai.

track by the radars whether the chutes opened or not, and whether or not the radio acquisition aids worked (GPS, beacon signal).

To address this issue, a Monte Carlo trajectory propagation was used to generate topocentric range and look angle statistics at intervals spanning the period from entry plus 50 seconds to entry plus 470 seconds, near the time of main chute deployment. The software, called POST, is operated by NASA/Langley Research Center. It provides high fidelity atmosphere modeling for trajectory propagation to the ground. The drogue deployment and main chute deployment are also modeled. The Monte Carlo look angles were used to define search lines in azimuth or elevation for each of the UTTR radars and optical sensors. There were two radars and four tracking telescopes, called cinetheodolites. Apart from the radar at Wendover, the other sensors were located at different places on the range. This created quite different search characteristics due to the location, size and orientation of the uncertainty ellipsoid relative to individual sensor locations. It was necessary to track the uncertainty ellipsoid over the span of interest to properly define the search space for each sensor. Twenty acquisition points were provided for each of the UTTR

sensors, with search intervals around the nominal time and search lines around the nominal points in either azimuth or elevation.

In the actual event it was not necessary to use the search lines, as the weather, although mostly bad, cleared sufficiently near the time of the descent of the SRC through the atmosphere that the infrared sensors easily achieved a distant acquisition. All the UTTR tracking sensors are connected to a central system which enables correct pointing for all sensors based on tracking from any radar or any two cinetheodolites. The radars also have optical and infrared sensors mounted on the antennas, so pointing can be established without a radar return if the object is visible in either sensor. A sufficiently clear sky enabled UTTR to achieve an early acquisition in the infrared and optical sensors, after which the correct pointing enabled radar acquisition once the radar return was strong enough. Radar and optical tracking at UTTR through drogue deployment, main chute deployment, and then nearly to the ground enabled the ground recovery team to get to the SRC within about forty-five minutes after landing.

### **III. Operational Interfaces**

#### **A. Documentation, Communication and Personnel**

The first step was to submit an Orbital Data Request (also known as the Form 1) to USSTRATCOM requesting their support for the Earth return phase of the Stardust mission.<sup>2</sup> The Form 1 was submitted in December, 2004. It included a description of the Stardust mission, plans for Earth return and landing, and a summary of requested data.

Following approval of the Form 1, operational interface agreements between the Stardust Project and USSTRATCOM were written and approved.<sup>3-5</sup> Additional OIAs were established between the Stardust Project and UTTR.<sup>3,5-8</sup> The OIAs specified the contents of the Stardust navigation trajectory files, the USSTRATCOM state vector file, and the look angle and search line products for UTTR. The OIAs were stored on secure servers accessible to users during SRC return operations.

Voice communication was available throughout the Earth return phase using the Voice Operational Communications Assembly system provided by the Stardust Project. One of the VOCA channels was designated for direct communication between the Stardust navigation at JPL and Cheyenne Mountain. VOCA communication with UTTR was conducted over the primary project channel. Data products were delivered by performing file uploads to a computer server. The files were also sent by e-mail.

Coordination of the use of UTTR for landing the SRC began prior to spacecraft launch. Planning for UTTR sensor acquisition of the Stardust SRC was essentially identical to the plan used for Genesis SRC acquisition in September 2004.<sup>9</sup>

Three members of the orbit determination group of the Stardust navigation team at JPL were responsible for providing support to USSTRATCOM and UTTR. Responsibilities included the delivery of trajectory products to USSTRATCOM, responding to USSTRATCOM special requests, studying the SRC acquisition problem at UTTR and delivering the search lines and look angles to UTTR. In addition, a member of JPL navigation section staff was located at the USSTRATCOM facility at Cheyenne Mountain as an on-site liaison. Responsibilities included handling VOCA communications with Stardust flight operations at JPL and serving as an on-site knowledge source regarding Stardust mission operations. In turn, USSTRATCOM delivered SRC trajectory data to Stardust navigation prior to entry and informed UTTR of their assessment regarding SRC trajectory accuracy.

#### **B. Data Products Delivered by Stardust Navigation to USSTRATCOM**

In order to enable nominal SSN sensor pointing, as well as nominal and dispersed trajectory analysis by USSTRATCOM, an ensemble of trajectory products were generated by Stardust navigation for use by USSTRATCOM. These trajectory products fell into two groups. One group of trajectories was intended for use at Cheyenne Mountain to prepare for SSN tracking and general trajectory analysis. These trajectories were based on the nominal Earth return trajectory, and will be described further below. The second group of trajectories was based on the determined orbit of the Stardust spacecraft during the final days of the approach to Earth. These were the best estimates of the Earth return trajectory at the time of delivery. There were three SRC trajectories in this group, corresponding to the three deliveries that were made. The first delivery was based on the orbit determination solution that was generated for the purpose of designing the final trajectory correction maneuver (TCM-19). This trajectory modeled the nominal TCM-19 maneuver and the SRC separation impulse to propagate the trajectory to atmospheric entry, defined as occurring at a geocentric radius of 6503.14 km. The second and third trajectories were based on orbit determination solutions that were generated following execution of TCM-19. These trajectories also modeled the SRC separation.

In addition to the three SRC trajectories ending at atmospheric entry, three post-separation trajectories for the spacecraft bus were also delivered to USSTRATCOM. The bus trajectories were initialized from the pre-separation trajectory for the two attached spacecraft at an epoch shortly before separation. The SRC separation impulse as experienced by the bus and the subsequent nominal divert maneuver were modeled, giving the nominal Earth flyby trajectory for the bus. The bus trajectory was propagated to one day past the Earth flyby.

The method of delivery of all trajectories involved the generation of Earth-centered inertial J2000 state vectors at 20-second intervals, delivered in text format. This method preserved the original dynamic modeling used by Stardust navigation. The trajectory data could either be transferred to USSTRATCOM tools without loss of trajectory accuracy if used verbatim, or USSTRATCOM state vector propagation could be performed with a check against the original trajectory data for verification.

Ten days before SRC separation, trajectories based on the nominal Earth return trajectory were delivered to USSTRATCOM. In addition to the nominal SRC entry trajectory, four dispersed entry trajectories were included. The dispersed trajectories were defined by having the separated SRC fall ballistically (no chute modeling) to Earth at four locations, two uprange and two downrange of the nominal ground target location. The four points consisted of the plus and minus three-sigma ground ellipse points along the major axis, and an additional 100 km beyond these two points. The outer two points were well outside UTTR. The two outer trajectories could only occur following loss of spacecraft control, possibly with thruster anomalies included in the scenario. If the spacecraft was under control a descent outside UTTR could not occur, as the flight plan required that the spacecraft divert without releasing the SRC in the event of a severely dispersed entry trajectory. The purpose of providing these two extreme trajectory cases to USSTRATCOM was to define limits beyond which an anomalous Earth return trajectory would be detectable with high confidence based on SSN-only tracking.

An additional product for USSTRATCOM, which was included with both groups of trajectories, was a trajectory file giving the path of the SRC from atmospheric entry to a time near the deployment of the main chute. This file, which was generated by NASA/Langley Research Center using POST, consisted of the geodetic latitude, longitude, and geodetic height of the SRC at one-second intervals. This file was also delivered to UTTR.

Stardust orbit determination based on coherently transponded Doppler and range data continued up to SRC separation. The SRC separation impulse was not estimated due to the lack of sufficient post-separation Doppler data prior to the resumption of attitude control thrusting. Therefore the separation impulse uncertainty (10 mm/s RSS) was considered as a constant error source when propagating the trajectory uncertainty past separation to entry and beyond. This OD result, which was the best estimate of the entry trajectory obtained by Stardust navigation during the Earth return operation, yielded three-sigma uncertainties in the radial, in-track and cross-track directions of 150, 30, and 125 m at the time of atmospheric entry, with a three-sigma event time uncertainty of 0.1 second. Further details of Stardust Earth return orbit determination are given in Ref. 10. The RSS position differences between this best estimate trajectory and the three trajectories delivered to USSTRATCOM were 1.2, 0.2 and 0.2 km at atmospheric entry, showing that the three trajectories were both consistent and accurate.

### **C. Data Products Delivered by USSTRATCOM to Stardust Navigation**

Data products delivered to the Stardust Project by USSTRATCOM were in two forms. Each of the three pairs of operational trajectories for the SRC and the bus described above were used to perform a screening against the catalog of known Earth orbiting objects to check for close approaches of the SRC and the bus to these objects. No close approaches were identified.

SSN optical tracking of the attached SRC and spacecraft bus began at Maui following evening twilight about one hour before separation. The nominal separation velocity was 35 cm/s, so that by the time the divert burn began twenty minutes later the distance between the two spacecraft was about 400 m at a slant range of 97,850 km. The angular offset as seen from Maui at the time of divert burn start was less than 1.5 mrad. By the time the divert burn ended the angular offset between the two objects had increased sufficiently to allow Maui to confirm separation. Thereafter only Maui tracked the SRC until radar acquisition occurred at ALTAIR about fifty minutes before entry. Following the acquisition of about fifteen minutes of radar data, USSTRATCOM generated an orbit solution for the entry trajectory using the combined radar and optical data arcs. From this orbit solution a set of Earth centered inertial J2000 state vectors spanning 45 minutes and ending at atmospheric entry was generated and delivered to Stardust navigation. The state vectors were delivered about 25 minutes before entry. In the time remaining prior to entry, Stardust navigation compared the USSTRATCOM trajectory with the Stardust navigation trajectory based on DSN data up to separation. The comparison showed that the USSTRATCOM trajectory was in good agreement with the Stardust navigation trajectory. In addition, NASA/Langley propagated the USSTRATCOM trajectory to UTTR.

The results were in good agreement with the final Stardust navigation trajectory propagated to UTTR. These results were uploaded to the server at about the time the SRC entered the atmosphere.

#### **D. Data Products Delivered by Stardust Navigation to UTTR**

To enable UTTR to acquire the SRC during the descent through the atmosphere, JPL delivered look angle files for each of the six UTTR sensors used to track the SRC. A seventh look angle file was also provided for a fictitious reference station which is used by UTTR range control to enable coordinated tracking involving different sensors. Each look angle file contained azimuth, elevation, and slant range at one-second intervals. The look angle files were generated by NASA/Langley based on the propagation of the post-entry trajectory through drogue and main chute deployment to the ground.

The Monte Carlo look angle results generated by NASA/Langley included three-sigma dispersion values in range, azimuth and elevation for each UTTR sensor. These were used to define the three-sigma limits in azimuth or elevation at twenty times spanning entry to a time near main chute deployment with respect to each individual sensors. For simplicity of operation the search lines were defined in azimuth or elevation only at each time step. The length of each search line was twice the three-sigma uncertainty in azimuth or elevation at that time. The corresponding start, midpoint, and stop times for which the search line was to be used were also provided. This information enabled each sensor to perform a constrained search for the SRC, stepping from search line to search line, during the descent over UTTR.

Due to the large lengths of the three-sigma search lines toward the end of the approach to UTTR, they were divided into thirds in some cases, with a few degrees of overlap, and the three segments were assigned to different cinetheodolites. This could be done because of the relative proximity of three of the cinetheodolites to each other. The radars were separated by 80 km, and the difference in radar look angles on the final approach to UTTR did not permit this division of labor. In general the optimal approach from the point of view of optimizing search operations would have been to place the ground ellipse in a location that would minimize the lengths of the search lines. This is accomplished when the length of the search line corresponds to a minor axis of the uncertainty ellipsoid. Unfortunately the ellipsoid was so large for Stardust (as compared to Genesis for example) that satisfying this condition would not produce much advantage. A more significant obstacle to a successful search near the end of the descent over UTTR was the fact that only the radar at Wendover was not located either inside the ground ellipse or close to it. For a sensor located inside the three-sigma ground ellipse (no other was used), the three-sigma search lines toward the end of the descent include the entire horizon. In this case a constrained search becomes a full horizon search. Clearly it is better to acquire the SRC before this becomes necessary.

The use of three-sigma statistics in defining the search lines implies that the search strategy was designed to the three-sigma level. If the incoming trajectory was dispersed by more than three-sigma, then the search space would have to be redefined using updated look angles.

While twenty different sets of search lines were provided for each sensor, it was not expected that each sensor would use every search line. It was left up to the sensor operators to decide how to use this information to optimize their search operations.

It was fortunate that the weather at UTTR cleared just before atmospheric entry. The use of search lines for a radar-only acquisition was not tested beforehand. It is difficult to do this without actually flying an entry trajectory to perform the test. Use of the search lines for a radar-only acquisition would have been a significant challenge.

#### **E. Summary of Scheduled Deliveries**

The three trajectory product deliveries to USSTRATCOM and UTTR are given in Table 1.<sup>11</sup>

**Table 1. Timetable of JPL deliveries to USSTRATCOM and UTTR (UTC)**

<b>Product Set</b>	<b>OD Delivery / Data Cutoff</b>	<b>Scheduled Delivery Time</b>	<b>Actual Delivery Time to USSTRATCOM</b>	<b>Actual Delivery Time to UTTR</b>
deliv_0 Pre-TCM19	s06013c / 13-JAN-2006 10:45	13-JAN-2006 17:00	13-JAN-2006 14:45	N/A
deliv_1 Green Briefing 1	s06014c / 14-JAN-2006 10:30	14-JAN-2006 12:45	14-JAN-2006 04:35	14-JAN-2006 06:44
deliv_2 Green Briefing 2	s06015a / 15-JAN-2006 00:00	15-JAN-2006 03:15	14-JAN-2006 17:54	14-JAN-2006 18:00

All the trajectory products were uploaded to the server for retrieval by USSTRATCOM and UTTR. Once the file upload was completed, the trajectory products were e-mailed to USTRATCOM and UTTR. Delivery using backup FTP servers and fax machines was also available if needed.

USSTRATCOM reported the results of conjunction analyses, spacecraft bus and SRC acquisition, and the SRC state vectors at the times shown in Table 2.<sup>11</sup>

**Table 2. Timetable of STRATCOM deliveries to JPL/Stardust Project (UTC)**

<b>Product Set</b>	<b>Scheduled Delivery Time</b>	<b>Actual Delivery Time to JPL or Tracking Status Report</b>
Pre-TCM19 Conjunction Analysis	13-JAN-2006 18:00	13-JAN-2006 17:28
Conjunction Analysis #1	14-JAN-2006 14:00	14-JAN-2006 13:36
Conjunction Analysis #2	15-JAN-2006 04:30	15-JAN-2006 03:48
Status – Nominal S/C Acquisition	15-JAN-2006 05:00	15-JAN-2006 05:27
Tracking Status	15-JAN-2006 06:30	Two objects being tracked at Maui
Tracking Status	15-JAN-2006 07:00	Optical tracking at Maui only
Tracking Status	15-JAN-2006 07:30	Optical tracking at Maui only
Tracking Status	15-JAN-2006 08:00	15-JAN-2006 08:04 ALTAIR tracking BUS only
Tracking Status	15-JAN-2006 08:30	No change in tracking status at Maui and ALTAIR
Tracking Status	15-JAN-2006 09:00	ALTAIR has acquired SRC
SRC Trajectory	15-JAN-2006 09:00	15-JAN-2006 09:30:00

#### **IV. Conclusion**

The Stardust sample return capsule was safely returned to Earth on target. From a navigation perspective, the Stardust Earth return operation left little to be desired in terms of entry targeting and performance. Had there been a significant anomaly, such as loss of spacecraft control resulting in a severely dispersed and unknown entry trajectory, USSTRATCOM tracking and orbit determination would have provided a determination of the entry trajectory. Based on DSN tracking of the spacecraft bus up to separation, knowledge of the entry trajectory was known so precisely that SSN tracking did not improve SRC trajectory knowledge.

The tracking sensors at UTTR succeeded in tracking the SRC from shortly after atmospheric entry to just before landing, enabling the SRC recovery team to find the SRC promptly.

All data exchanges between JPL, USSTRATCOM, and UTTR were complete and on time. The elements of a viable contingency operation were in place had the sequence of return events not been nominal. This interagency effort was essential in bringing the Stardust mission to a successful conclusion.

### Acknowledgments

We thank USSTRATCOM personnel at Cheyenne Mountain and at the SSN stations for their diligence and cooperation during Stardust Earth return operations, and we congratulate them on their accurate determination of the inbound SRC trajectory under challenging circumstances. We thank Dr. Prasun N. Desai at NASA/Langley Research Center for providing the Monte Carlo look angles needed to define a realistic search strategy for the UTTR sensors, in addition to the other products that were needed. We also extend our thanks and recognition to the sensor operators at UTTR for their experience and dedication in acquiring and tracking the Stardust sample return capsule, enabling prompt recovery of the capsule and its treasure trove of cometary particles.

This work was carried out at the Jet Propulsion Laboratory, California Institute of Technology, Pasadena, California under contract to the National Aeronautics and Space Administration.

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