# Real-Time EDL Navigation Performance Using Spacecraft to Spacecraft Radiometric Data

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**A two-year task sponsored by NASA's Mars Technology Program's Advanced Entry, Descent and Landing (EDL) work area includes investigation of improvements to EDL navigation by processing spacecraft-to-spacecraft radiometric data. Spacecraft-to-spacecraft navigation will take advantage of the UHF link between two spacecraft (i.e. to an orbiter from an approaching lander for EDL telemetry relay) to build radiometric data, specifically the velocity between the two spacecraft along the radio beam, that are processed to determine position and velocity in real time. The improved onboard state knowledge provided by spacecraft-to-spacecraft navigation will improve the performance of entry guidance by providing a more accurate state estimate and ultimately reduce the landed position error. A previous paper documented the progress of the first year of this task, including the spacecraft definitions, selection and documentation of the required algorithms and analysis results used to define the algorithm set. The final year of this task is reported here. Topics include modifications to the previously selected algorithm set for implementation, and performance of the implemented algorithms in a stand-alone filter, on an emulator of the target processor and finally on a breadboard processing unit.**

## I. Introduction

The National Aeronautics and Space Administration (NASA) Mars Technology Program is sponsoring research and development efforts in several areas, including Advanced Entry, Descent and Landing (EDL). The focus of this work area is pinpoint landing, defined as landing within $1km$ of a pre-selected target landing site. One aspect under investigation is the improvements to EDL navigation by processing spacecraft-to-spacecraft radiometric data. A two-year task within this program will implement an EDL navigation system using spacecraft-to-spacecraft radiometric data. A previous paper documented the progress of the first year of this task, including a more detailed description of the motivation, the spacecraft definitions, selection and documentation of the required algorithms and analysis results used to define the algorithm set.[1]

Spacecraft-to-spacecraft navigation for EDL involves forming radiometric data with a radio link using the UHF band ($300-3000Mhz$) between the approaching lander and an orbiting spacecraft, as shown in Figure 1 for MSL. The UHF link will be made between the two spacecraft before atmospheric entry, but the focus of this effort is processing this data after cruise stage separation (roughly 10 minutes before entry). These data are available throughout EDL with the exception of periods during hypersonic flight where the ionizing plasma around the entry body makes closing the communication link difficult. Even with these outages, enough data can be collected and processed onboard in real time to significantly improve the onboard state knowledge during hypersonic flight.[2]

The Electra Program at JPL has developed and produced a software defined radio (SDR) which is manifested as baseline equipment on future Mars missions beginning with Mars Reconnaissance Orbiter

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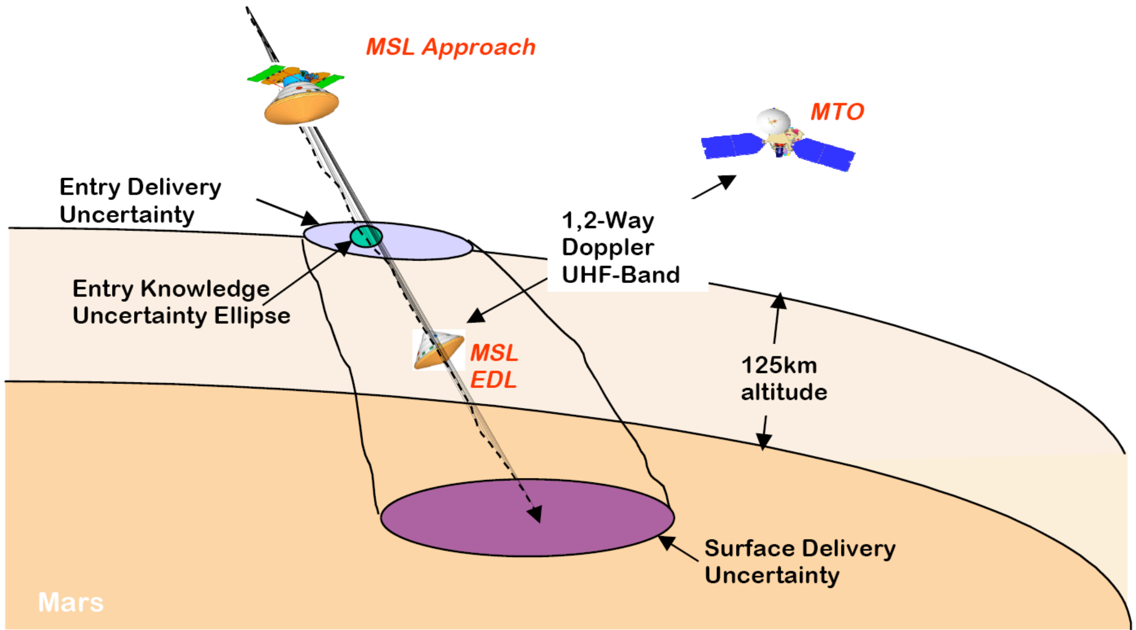


**Figure 1. Schematic of spacecraft-to-spacecraft navigation as used for EDL. The entry delivery and knowledge uncertainties for the approaching lander are depicted, as is the surface positioning error. Spacecraft-to-spacecraft navigation data will be processed throughout EDL, including other external sensor data such as radar altimeter measurements.**

(MRO) scheduled for launch in August 2005. These SDRs are nominally configured for Mars-local UHF operation for data relay in the vicinity of $437MHz$ and are also capable of making high precision radiometric measurements in Doppler and range.

By design, Electra SDRs have excess computing capacity and memory sufficient for hosting an on board, real time navigation filter. The current Electra design features a space qualified Sparc V-7 processor running at $25MHz$ and several megabytes of available memory. Over half of each of these resources is available for applications such as real time navigation filtering under direction of the RTEMS (Real-Time Executive for Multiprocessor Systems) operating system. (Electra is a single processor application for RTEMS.)

Utilizing spare Electra capacity for on board navigation frees other resources, such as the main spacecraft housekeeping computer, from involvement in such a computationally intensive, time critical task. Also, the radiometric data is locally available inside Electra and need not be transferred over the spacecraft bus.

In the present work a navigation filter task will be demonstrated on prototype Electra baseband hardware with the goal of showing that Electra resources are sufficient to host a sophisticated navigation algorithm with reasonably low latency in terms of data input to updated state output times.

Topics covered here from the final year of this task include modifications to the previously selected algorithm set for implementation and performance of the implemented algorithms in a stand-alone filter, on an emulator of the target processor and finally on a breadboard processing unit.

## II. Scenario Update

The scenarios developed in the first year of this study and documented in the previous paper have been modified based on review feedback. Mars Science Laboratory (MSL) is still the approaching spacecraft, but the relay orbiter has been changed from the cancelled Mars Telecommunications Orbiter (MTO) to Mars Reconnaissance Orbiter (MRO). This change reflects the latest MSL relay strategy and the cancellation of MTO. The scenarios used here will incorporate realistic trajectories for all assets used, including the MSL approach and EDL trajectories and MRO orbits. While MSL is not planning to do pinpoint landing, it does have the required hypersonic guidance that will most likely be used for any future pinpoint landing mission.[3] The MSL EDL baseline up to chute deploy is a likely candidate for the hypersonic strategy to be used for pinpoint landing, so analysis of the MSL scenario through this regime applies to pinpoint landing. Although other entry guidance options are available (including hypersonic guidance approaches not derived from Apollo and approaches optimized for higher L/D entry bodies), all will benefit from improved onboard knowledge.

Updated covariance analysis results for the MSL/MRO scenario will be reported. Similar results for the MSL/MTO scenario are shown in Figure 2, DSN tracking of the approaching lander from 30 days before entry to 6 hours before entry and a single UHF tracking pass beginning about 40 minutes before entry and ending at landing. In focusing on the immediate decrease in the position estimate errors and uncertainties, it is clear that the largest improvement is with the first minutes UHF Doppler data, decreasing from a mapped RSS position error of nearly $2.5km$ to under $100m$ within a few minutes and decreasing to nearly $10m$ before entry (defined as $t = 0$ in the figure). These results clearly show the benefits of collecting spacecraft-to-spacecraft UHF Doppler and processing with a fit covariance from DSN radiometric data processing.

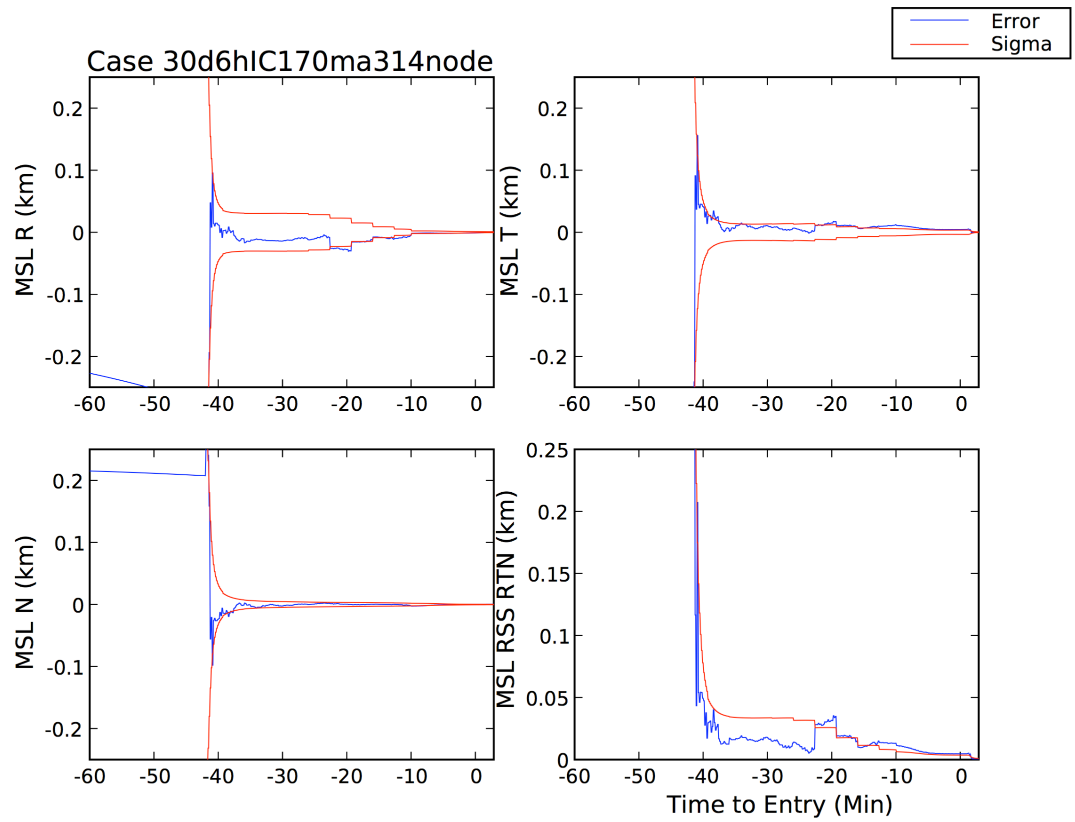


**Figure 2. Simulated UHF data processing results with DSN tracking to 6 hours before entry, focusing on the last hour before entry. Note that with only a few minutes of collecting UHF Doppler the estimates and uncertainties drop below 50m ($1\sigma$) and continue to improve as more data are collected.**

## III. Algorithm Selection Implementation and Performance

As reported previously, the selection of algorithms is separated into three main areas. The first area is dynamic modeling, which includes all forces and moments acting on the spacecraft. The second area is measurement modeling, which includes all incoming data that are to be processed with this filter. The third area is the selection of a filter algorithm. Updates, if any, to the algorithm set will be reported.

## IV. Algorithm Implementation and Performance

The final goal of this task is to demonstrate the implemented algorithms processing data on the Electra SDU. In order to reach this goal, a three-step implementation process is under way. The first step is to implement the algorithms in a stand-alone filter. While this step is free of any hardware constraints, coding practices consistent with the limitations of the final platform are enforced. These include language limitations and processor speed limitations that require small and fast algorithms. This step allows implementation that is close to the final software but utilizes a more diverse suite of optimization and debugging tools than are available for the target processor. The results generated here will serve as the baseline for the navigation performance.

The second step is to execute the above filter using an emulator of the Electra processor. The emulator will provide a platform that is theoretically the same as the final hardware target while having more diagnostic output options than the hardware. The emulator also can be run much faster than real time, allowing the analysts more insight into the execution of the implemented algorithms. The implementation here includes not only the filter itself, but includes the input interface, data buffering, output interface and housekeeping functions of the Electra SDU. The goal is to be able to build an executable that runs in the emulator and requires no modification to run on the hardware. Navigation performance will be evaluated here and compared with the stand-alone results. The run-time of the navigation algorithms will be evaluated here and any speed issues are addressed at this stage.

The final step is execution on the Electra SDU. Care has been taken to minimize the amount of modification to go from step two to step three: in reality, there will be differences between the emulator and Electra SDU that require modification of the navigation software. Once these modifications are made and the filter is operational on the Electra SDU, similar navigation performance and processing speed analysis will be performed.

## References


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