Mars Sample Return Direct Earth Approach Navigation Analysis

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***Abstract* – This paper describes the navigation analysis, results and filter strategies planned by the European Space Agency (ESA) and the National Aeronautical and Space Administration (NASA) navigation Teams for the joint ESA and NASA Mars Sample Return (MSR) mission, targeting a direct approach to the Earth landing site at the Utah Test and Training Range (UTTR). Direct approach strategy and navigation filter assumptions will be discussed for ESA's Earth Return Orbiter (ERO) in order to satisfy approach navigation requirements and to achieve the desired landing footprint uncertainty at the UTTR landing site for the Earth Entry System (EES). After the EES is released three days prior to atmospheric entry, alternate tracking measurements are needed since the EES cannot be tracked after release by ESA's European Space Tracking network (ESTRACK) and NASA's Deep Space Network (DSN). A navigation sensitivity analysis to the alternate tracking measurement accuracy will be presented.**

I. INTRODUCTION

Returning the samples from Mars has been priority of the scientific community for over a decade (see [1] and [2]); key objectives currently relate to the understanding of Mars climate and geology (including their evolution), the search for extinct or extant life, past habitability and preparation for eventual human exploration. There is a wide consensus that the greatest scientific return would come from returning samples from a well-characterized site, allowing their study in large dedicated facilities on Earth (see [3]).

The MSR campaign employs several missions to achieve this goal: one for sample collection (Mars 2020 with the Perseverance rover), one for sample retrieval and delivery in Mars orbit (which includes the Mars Ascent Vehicle – MAV) and one for returning them (ERO), as detailed in [4] and [5]. In the current paper, the architecture assumed entails a direct delivery of the samples to the Earth using a EES that is part of ERO's payload.

The focus is the final part of the campaign, when ERO enters the Earth Delivery Phase (EDP); this mission phase is dense with critical events and is also the most demanding from a Backward Planetary Protection (BPP) point of view. Initially ERO is on a fly-by trajectory with a safe minimum altitude of 1600 km above the Earth surface; an Earth Targeting Maneuver (ETM) places the spacecraft on a direct Earth entry trajectory and is followed by an optional Final Correction Maneuver (FCM) to fine-tune the landing target; if all requirements are satisfied, the EES is released, leading to its landing in UTTR; ERO then performs an Earth Avoidance Maneuver (EAM) that brings it back to a fly-by trajectory, followed by disposal in heliocentric orbit. A sketch of the main events during EDP is given in Fig. 1.

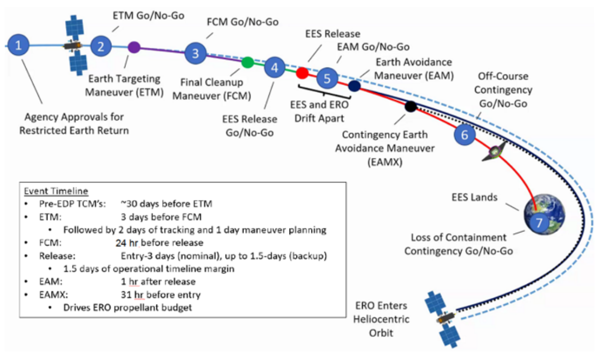

Fig. *1* EDP events timeline

II. MSR NAVIGATION REQUIREMENTS

Accurately delivering the spacecraft to the intended entry point is fundamental to all direct entry missions, including all previous sample return missions. MSR is unique, however, in its planetary protection categorization as a category V, restricted Earth return. Practically speaking, this can impose additional constraints on the acceptable landing footprint.

For these reasons, stringent requirements are given at the MSR program level for the delivery accuracy. Specifically, the ERO inertial state error at EES release is bounded by the limits reported in Tab. 1.

Timeline	Position [km]	Velocity [mm/s]
Nominal	2	10
Backup EES release	2	21.6

Tab. 1 Maximum inertial errors at EES release (with 99.7% probability and 95% confidence)

The other stringent requirement is that the landing footprint 3-s uncertainty ellipse is within the UTTR landing area and that the EES is to land within 11.25 km of the MSR program-controlled target coordinates with a 99.87% probability.

In order to check that these requirements are satisfied and to collect relevant information for the uncertainty of this final part of the campaign, navigation analyses are performed for the relevant phases, simulating the orbit determination and guidance processes with assumptions coherent with the mission design and scheme of operations. In addition to the EDP, part of the Inbound Transfer Phase (ITP) is also simulated, to sensibly initiate the dispersion and have a realistic simulation of the EDP navigation.

III. ESA NAVIGATION ANALYSIS

A. *ESA Navigation Analysis Approach and Assumptions*

The navigation analysis conducted for the ERO mission includes orbit determination and guidance. The approach used is a conventional simulation in which both aspects and their interactions are considered. The trajectory modelling and navigation simulation was done with GODOT and MIDAS software, both internally developed at ESA-ESOC flight dynamics division (see [6] and [7] respectively). The first offers low-level flight dynamics functionalities needed for efficiently simulating a trajectory and an orbit determination process, while the second was used to run the navigation analysis, taking advantage of generic modules developed for such purposes.

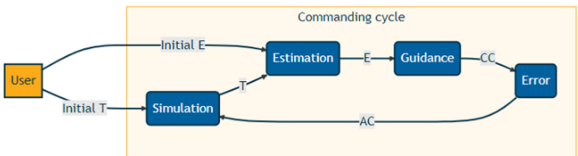

Fig. 2 Main elements of the navigation software. E is estimated state, T is true state, CC is commanded control parameters, AC is applied control parameters. Loop of the diagram is performed at each control cycle. Credits: MIDAS documentation.

A scheme of main elements of the navigation software is given in Fig. 2. In relation to this scheme, knowledge error is defined as the difference between estimated and true state, while dispersion error is defined as the difference between true state and reference state (taken from reference trajectory at the same epoch).

The trajectory considered is the reference return scenario detailed in [5], with a return to Earth in 2033. Small updates to the trajectory are included; the most relevant being the timeline of the ETM, which is moved to 7 days before arrival. Two scenarios are simulated, one with nominal release and a second with a contingency release delayed by 1.5 days (all events from ETM onwards are shifted in the future). The simulation starts 45 days before arrival, covering the last part of ITP and also the last Re-Targeting Maneuver (RTM), that lowers the fly-by altitude to 1600 km (this targeting strategy ensures that ERO would safely miss Earth, even in the unlikely event of a major spacecraft anomaly during ITP). Trajectory Correction Maneuvers (TCM) are also added to navigate the spacecraft: all maneuvers considered are listed in Tab. 2, with their execution time given with respect to the Entry Interface Point (EIP) defined as EES crossing an Earth distance of 6495 km.

Event	Nominal timeline	Contingency timeline (1.5 days delay)
RTM3	EIP – 30 days	
TCM1	EIP – 21 days	
TCM2	EIP – 14 days	
ETM	EIP – 7 days	EIP – 5.5 days
TCM3 (FCM)	EIP – 4 days	EIP – 2.5 days
EES release	EIP – 3 days	EIP – 1.5 days
EAM	Release + 1 hr	

Tab. 2 Timelines in nominal and contingency scenarios

The observations considered for orbit determination are two-way range and Doppler measurements from ESTRACK and DSN ground stations, with a minimum elevation of 15 degrees; sampling rates for the measurements are 1 per hour for range and 1 every 10 minutes for Doppler (with a noise of 2 m for range and 0.3 mm/s per 1 minute count time for Doppler, both at 1-sigma).

The estimation setup includes sources of uncertainty that are either consider biases or estimated; a summary of the uncertainties assumed is given in Tab. 3. The setup for the orbit determination is based on a sliding window approach: for each 2-week window the initial uncertainty is improved thanks to measurements. A commanding cycle approach is used for the navigation simulation: first the knowledge information at data-cut-off (DCO) of a commanding opportunity is computed, then the guidance is run and all maneuver parameters are updated, with the cycle being repeated in chronological order for all the commanding opportunities. During post-processing, the estimation is repeated to obtain detailed knowledge information at fixed intervals in time (few hours for the knowledge plots, for example).

Quantity	Treated as	Uncertainty [1-sigma]
Spacecraft state	Estimated	10^4 km in position (3 components) 0.1 km/s in velocity (3 components)
Wheels-Off-Loadings deltaV	Estimated	0.667 mm/s (3 components) every 3 days
Reflectivity coefficient	Estimated	0.3 (20% of reference)
	Consider bias	0.025 (1.67% of reference)
Range observation	Consider bias	10 m
GS location	Consider bias	0.33 m (3 components)

Tab. 3 Estimation setup for ERO

The guidance is simulated as Monte Carlo process with 10000 samples and the initial spacecraft state dispersion is injected 7 days before RTM3 (the values are guess-estimated from previous analyses, which is considered good enough since it drives only the size of RTM3, which is not the focus of the analysis). The mapping of the dispersion in time accounts for uncertainty in the reflectivity coefficient and Wheels-Off-Loadings (WOLs, as done in the estimation). The simulated maneuvers are used to keep ERO on its reference trajectory, with the 3 ΔV components of the maneuver fully determined by targeting imposed; each maneuver accounts for the uncertainty of the spacecraft state (knowledge error) at the time of maneuver execution (i.e. improved with all the measurements in the 14 days window preceding the DCO). The Monte Carlo simulation also include the mechanization error of each maneuver, which degrades the targeting precision and the knowledge error post-maneuver. The detailed assumptions for mechanization errors and DCO duration (which depends on the mission phase criticality) are given in Tab. 4 and Tab. 5, respectively.

Maneuver propulsion type		Magnitude proportional error (3-sigma)	Direction error (3-sigma)
Solar Electric (RTM3)		3%	1.5 deg
Chemical	ΔV > 0.85 m/s	0.5%	0.3 deg
	ΔV ≤ 0.85 m/s	2%	0.6 deg

Tab. 4 Mechanization errors for ERO

Mission phase	Applicable to	DCO duration [day]
ITP	RTM3	4
EDP	TCM1 and TCM2	2
EDP critical phase	ETM and onwards	1

Tab. 5 DCO duration for ERO

The targeting scheme selected for the approach first corrects the position error at pre-ETM conditions, while targets the inertial position of EES at EIP with ETM and FCM, accounting for the proper mapping between ERO and EES state after their separation.

B. Uncertainties evolution during approach

Assuming the reference timeline for the EDP phase events, the full navigation analysis is run. The evolution of the instantaneous spacecraft state knowledge is reported in Fig. 3 (position components) and Fig. 4 (velocity components). In Fig. 3 it is possible to observe how the position uncertainty decreases in all components as ERO gets closer to the Earth and improves dramatically in the last few days before closest approach where the Earth gravitational pull dominates the dynamics and constrains the orbit determination solution. In Fig. 4, other than what already mentioned, the effect of the WOLs is evident, with spikes most visible in the radial direction (the one that can be better determined thanks to direct observability through Doppler measurements); the direct effect of maneuvers execution error can also be clearly seen, as they lead to an increase in uncertainty in all velocity components, particularly when a larger deterministic component is present.

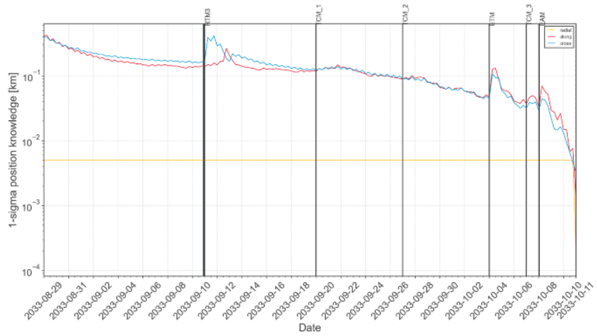

Fig. 3 ERO Instantaneous knowledge position error during EDP

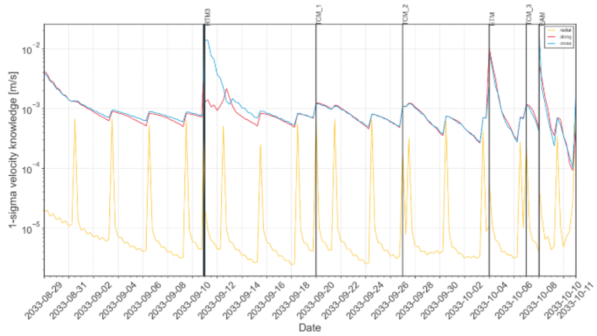

Fig. 4 ERO Instantaneous knowledge velocity error during EDP

The stochastic ΔV cost for the navigation of EDP is very limited, around 0.2 m/s at 99th percentile; note that from this estimate the RTM3 contribution is excluded since it pertains the previous phase (ITP) and in the presented setup is anyway driven by the initial dispersion assumed.

C. Position and velocity pre-release errors

The most important output of the simulation conducted is to verify the EES pre-release dispersion errors satisfy the requirements reported in section II. The requirements impose an upper bound for the position and velocity errors just before EES release; to consider a realistic estimate, the requirements are checked considering the difference between actual state and targeted state for each sample and not the absolute dispersion error with respect to the reference trajectory (which can be much larger at pre-release epoch as FCM corrects for position errors at EIP). The following steps are therefore followed to check compliance:

- A sample on the estimated state before FCM is taken, FCM is designed based on this, and the final state at pre-EES release is obtained; this is the sample-by-sample target state;
- The corresponding sample on the true state before FCM is taken, the designed FCM is applied accounting for mechanization error and the dispersed pre-EES release state sample is obtained;
- The modulus of difference in position and velocity for each sample is extracted;
- Statistics on the retrieved quantities (position and velocity differences norms) are extracted from all the samples simulated; specifically, the 99.7th percentiles at 95% confidence level are obtained.

Applying this procedure an error of 611 m in position and 5.43 mm/s in velocity are obtained (at 99.7th percentile with 95% confidence); both are well within the required upper bounds of section II.

The obtained results represent how far ERO is from the targeted conditions just before EES release. Another important aspect for the release is the knowledge error. Even this is not directly subject to constraints, it is important nonetheless as it gives a complementary information, providing the accuracy level at which we can expect to know ERO's state prior to release. During EDP operations, there is in fact the need to check that the entry corridor is achieved and all requirements are met priori to EES release; the driving factor for this is a nominal execution of the FCM. Spacecraft operators have two sources of information to check this: the on-board telemetry (out of interest in the current paper) and the tracking measurements performed after FCM; the second is something that can be analyzed with the navigation setup presented.

The scenarios after FCM are essentially two: the maneuver executed within expected uncertainty or not. In case it did, the situation is straightforward: the information provided by the tracking immediately after the FCM matches the expectations and, as proved in a previous paragraph, the requirements for the release are met. In case the FCM mis-performed, substantially exceeding the expected errors, the situation is more complicated: the initial tracking data doesn't match the expected orbit solution, leading to an increase in knowledge errors; over time, as more tracking data is cumulated, the knowledge error decreases and a new orbit solution, including the better and better estimated FCM error, arises. Of course, the tracking data required for the knowledge error to decrease to acceptable levels depends on the mechanization error of FCM: a worst-case scenario with 100% error in magnitude and 5 degrees (1-sigma) is assumed. Such worst-case covers a very wide range of possibilities, from FCM interrupted just after its start to FCM being more than double the required size, essentially being in a condition in which the post-FCM tracking data are the main source of information to determine the spacecraft state; the angular error is limited since larger errors would be unreachable: if the angular error is beyond a given threshold, a safe mode would anyway have occurred, stopping the FCM execution entirely.

A sensitivity analysis is conducted, varying the amount of tracking data collected between FCM and EES release (with ESTRACK tracking for a given time and then a second arc until release without tracking). The output of the analysis is the knowledge error achieved just before EES separation, depending on the above varied parameters. The idea is that in case FCM mis-performs, it can be checked how much tracking data is needed to still achieve a knowledge level at EES release in line with the required dispersion. Once the knowledge level is below the requirement, a decision for release can be taken, which in practice depends on the actual predicted trajectory achieved after FCM. The results of the sensitivity analysis are shown in Fig. 5.

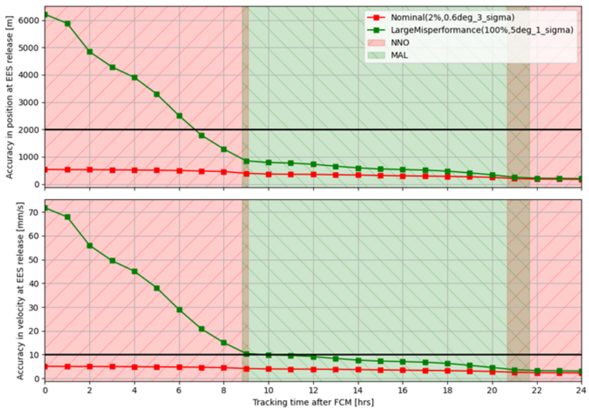

Fig. 5 Sensitivity of knowledge error at release to mechanization error and tracking data (3-sigma). Coverage from ESTRACK deep space stations over-imposed (15 deg minimum elevation assumed).

As can be seen, even in the worst case of mis-performance simulated (green curve), around 9 hours of tracking are sufficient to re-gain a 3-sigma knowledge error below the required dispersion level. This means that after 9 hours it starts being possible to decide for releasing (or not) the EES, having a good confidence on the state achieved after FCM. Note however that the dispersion of the estimated state with respect to the reference state must be factored in: the deviation of the dispersed state +/- the knowledge uncertainty will need to be within requirements to safely release.

D. *Effect of delayed timeline*

The simulation reported was repeated also for a contingency scenario in which a large portion of the timeline margin is consumed by a delay of 1.5 days of ETM. The first effect of the different timeline is an increase of deterministic size for both ETM and EAM, which in turn drives a larger mechanization error. This is partially compensated by the better possible orbit determination, being the spacecraft closer to the Earth for each of the timeline events from ETM onwards. Overall, the knowledge errors are very similar also in this contingency scenario and the total stochastic ΔV for the navigation of EDP only increases to 0.3 m/s at 99th percentile.

The dispersion errors before EES release are in line with those estimated for the nominal timeline and therefore compliant to the requirements; the velocity requirement is larger for the delayed timeline (21.6 mm/s instead of 10 mm/s) and is therefore satisfied with an ample margin.

The knowledge error prior to EES release is initially higher than the nominal timeline in case of a large FCM mis-performance (driven by the larger maneuvers during the contingency timeline). Being closer to the Earth fully mitigates the situation as the knowledge improves more rapidly.

IV. NASA NAVIGATION ANALYSIS

A. NASA Orbit Determination Assumptions

To complement the ESA navigation analysis described in section III, the NASA navigation analysis focused on the inclusion of EES release velocity errors and propagation of Orbit Determination (OD) uncertainty to a landing footprint uncertainty at UTTR. The NASA navigation analysis considered four OD cases:

1) **CReMA**: matching OD assumptions described in section III.A
2) **JPL Standard**: OD assumptions based on Mars 2020 described in [8]
3) **No Margin**: Same as 2) with parameter and measurement uncertainties based on Mars 2020 performance during flight
4) **Reqall**: OD trajectory uncertainties were set to EES pre-release requirement values described in section II

The "JPL Standard" OD case in general is less conservative than CReMA and includes uncertainties for media calibration, Earth orientation parameters instead of increased station location uncertainty in the CReMA OD case. The "No Margin" OD case represents the expected OD accuracy performance assuming the Mars 2020 performance during flight. The "Reqall" was used to establish if sufficient margin exists for the examined NASA OD cases. All NASA OD cases included EES release velocity errors which were design specification values and shown in Tab. *6*.

EES release velocity errors (1σ)	ERO Coupling	0.33 mm/sec
	ERO Pointing	0.0333 deg
	ERO Alignment	0.2033 mrad
	Deployment velocity error: lateral (x,y), axial (z)	4,4,11.5 mm/sec

Tab. 6 EES release velocity errors

Continuous ESTRACK tracking was assumed for 40 days prior to atmospheric entry. The NASA approach navigation analysis was done for 11 October 2033 and due to the southern approach only southern ESTRACK stations (Malargue and New Norcia) were selected to achieve continuous tracking. The ETM and FCM CReMA maneuver execution error specifications from III.A were used in a 5000 sample Monte Carlo analysis to determine the maneuver ΔV uncertainties. For the 11 October 2033 approach the ETM and FCM 1-σ per-axis ΔV uncertainties were found to be 64.5 and 0.8 mm/sec respectively. Finally, the CReMA wheel offloading DV uncertainties described in III.A were used.

B. EES targeting to UTTR

The first step in the NASA navigation analysis was to target ERO taking into account deterministic ΔV events prior to atmospheric entry and EES atmospheric flight to achieve the desired UTTR landing site. For the navigation analysis and propagation of ERO and EES up to atmospheric entry the Mission-analysis, Operations, and Navigation Toolkit Environment (MONTE) [9] was used. The EES atmospheric flight trajectory was modelled using the Dynamics Simulator for Entry, Descent and Surface (DSENDS) [10].

For the targeting process the NASA navigation team was provided the following for 11 October 2033 entry:

1) V_∞ vector and entry time from the mission design team
2) Desired entry flight path angle (-22º) and entry radius (6495 km)
3) Desired UTTR landing site coordinates (latitude, longitude and landing site radius)

The V_∞ vector and entry time were used to generate a 40-day backward reconstruction of the approach trajectory taking into account the deterministic ΔV events associated with the ETM and EES release. The ETM executed 7 days prior to entry is deterministic because ERO is targeted to a 1600 km periapsis Earth flyby height [5] trajectory prior to ETM due to backward planetary protection requirements. The ETM ΔV magnitude was determined to be 6.4 m/sec for the 11 October 2033 approach. The EES release also introduces a deterministic ΔV magnitude of 0.35 m/sec in the axial direction of the EES vehicle. The EES separation ΔV vector was orientated in the same direction as the EES inertial atmospheric entry velocity vector to achieve a zero angle of attack at entry for the EES vehicle.

In the iterative targeting process, the ETM ΔV vector, the EES release ΔV vector direction and the EES atmospheric flight trajectory are adjusted while the entry flight path angle, entry radius and UTTR landing coordinates are held fixed. One iteration cycle of the target processing is illustrated in Fig. *6*. In one iteration cycle the MONTE approach trajectory entry state is propagated to the ground by DSENDS and the landing site error is used to update the entry time and associated position and velocity. The ETM and EES DV vector direction are adjusted with MONTE to achieve the updated entry time, entry position and velocity.

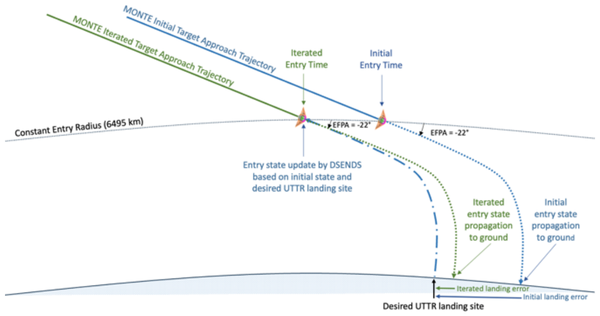

Fig. 6 EES MONTE and DSENDS iteration cycle for entry target computation

This targeting iteration process is repeated until convergence of the entry time. After convergence the MONTE approach trajectory, ETM ΔV vector and EES separation ΔV direction are used for the NASA navigation analysis.

C. *EES delivery accuracy results at entry and UTTR*

The EES delivery accuracy results for the NASA OD cases described in section IV.A are presented in the Earth B-plane and associated the linearized time of flight in Fig. 7. The B-plane 3-σ uncertainty ellipses in Fig. 7 are the result of mapping the OD covariance to atmospheric entry, which occurs at a radius of 6495 km from the center of the Earth. Fig. 7 illustrates that the entry flight path angle (EFPA) of -22° target is achieved for all ellipse centers.

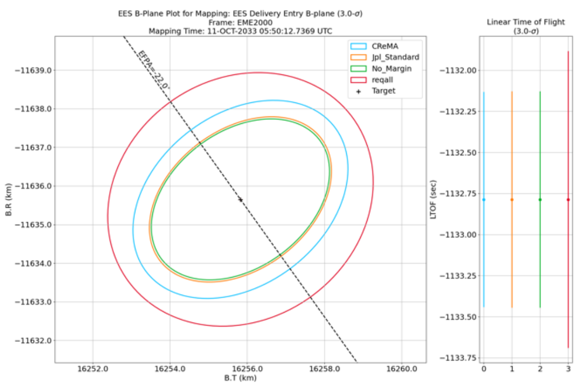

Fig. 7 EES delivery accuracy for requirement (reqall), CReMA baseline, JPL Standard and No-Margin OD Cases

For OD cases CReMA baseline, JPL Standard and No-Margin the B-plane ellipses show their OD assumptions result in smaller ellipses compared with the Reqall OD case B-plane ellipse, for which all trajectory accuracy requirements were used in the navigation analysis. As expected, the ellipses for the CReMA OD case, with more conservative OD assumptions, is larger than the two JPL OD cases. The No-Margin case ellipse is only marginally improved due to the fact that the Earth relative trajectory accuracy is very well determined with tracking assets located on Earth, resulting in only a small improvement in trajectory accuracy with improved tracking data performance.

Unlike other lander mission like Mars 2020 [8], there are no explicit requirements for EFPA and cross track uncertainty in the B-plane. For MSR landing footprint size requirements are defined such that the footprint is contained within the UTTR boundary and the center of the footprint ellipse is positioned to have the most favorable soil conditions for landing in the footprint. The UTTR landing footprint for the four NASA OD cases was computed using a DSENDS Monte Carlo analysis. For the DSENDS run 20000 samples were taken from the atmospheric entry OD covariance and propagated to the ground. The 3-σ footprint ellipses are shown in Fig. 8.

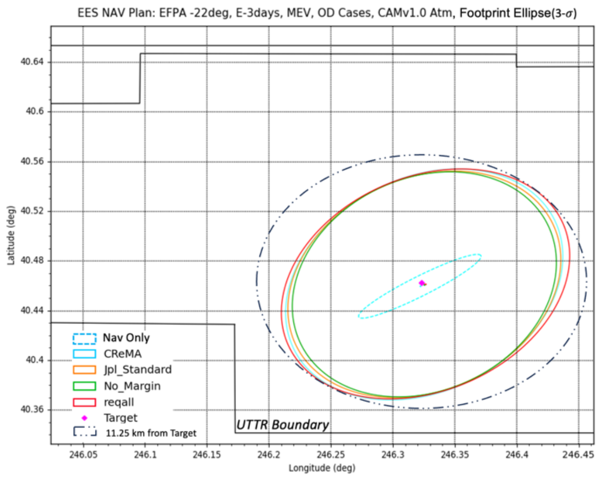

Fig. 8 EES landing footprint uncertainty ellipses for requirement (reqall) CReMA baseline, JPL Standard, No-Margin and navigation errors only OD Cases

The ellipse centers in Fig. *8* have achieved the desired landing site target coordinates and the 3-σ landing footprint size fits with margin inside the UTTR boundary and satisfies the 11.25 km radius from the target requirement.

The footprint ellipse sizes are dominated by atmospheric model errors (especially winds) in DSENDS, which is illustrated in Fig. *8* where the footprint ellipse is shown for a DSENDS propagation to the ground where only navigation OD errors are propagated and no atmospheric model errors.

D. *OD parameter sensitivity Analysis*

A series of parameterized sensitivity studies for the approach navigation was performed in order to determine the effects of changes to data assumptions and modeling uncertainties on the orbit delivery accuracies. This sensitivity study focused on the EFPA uncertainty at atmospheric entry since this parameter has the largest impact on the landing footprint size and center location. For all cases studied, only a single parameter or model is changed at a time with respect to the CReMA baseline. Fig 9. shows bar charts for the 3-σ EFPA sensitivity analysis results. In Fig. 9 the individual cases are listed along the left, beginning from the top with the CReMA Baseline, "JPL Standard" and "JPL No-Margin" (green) cases, followed by the variations of dynamic model error assumptions and data weights (blue for improved, red for degraded), followed by tracking data combinations (orange). For the improved and degraded cases, the uncertainty was changed by a factor 0.5 and 2.0 respectively. For comparison, a green dotted vertical line indicates the CReMA baseline level. Bars that extend past outer right edge of the plot have their value listed in the right of the bar.

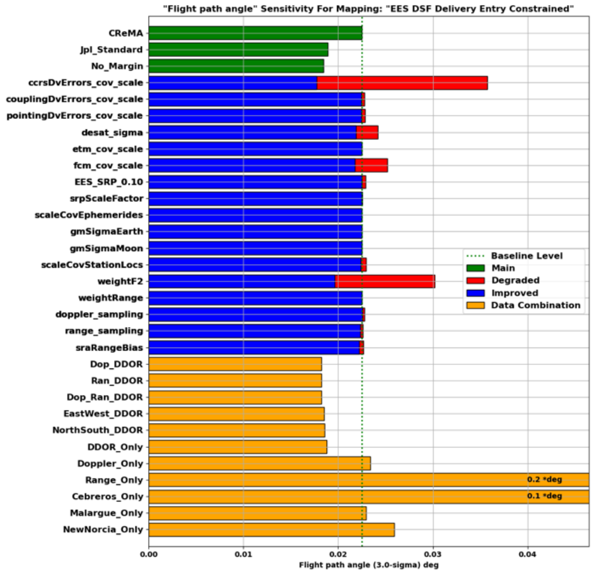

Fig. 9 Entry flight path angle OD parameter sensitivity results

As expected, events past the FCM Data Cut Off (DCO) have the largest sensitivity in EFPA delivery accuracy since no tracking data exist after the FCM DCO to reduce the covariance. The FCM DCO for this is analysis is shown in Fig. *10* and the FCM execution (FCM_cov_scale), EES release (ccrsDVerrors) and wheel offloading (desat_sigma) occur after the FCM DCO. Another significant sensitivity is the Doppler weight case (weightF2). This case has a large sensitivity due to the conservative weight assumption in the CReMA of 0.3 mm/sec (1-σ). This sensitivity would have been less if the "JPL Standard" OD case value of 0.1 mm/sec (1-σ) was used. The data variation cases demonstrate that using Delta Differential One-way Ranging (ΔDOR) [11] in the OD would be beneficial, however ΔDOR was not part of the baseline. Finally, the data variation cases also show that using only range data or only using a northern hemisphere tracking station (Cebreros) significantly degrades the EFPA accuracy performance.

V. EES POST-RELEASE ORBIT DETERMINATION

A. EES post-release alternate tracking resources

The EES was planned to be released 3 days prior to atmospheric entry with no further radio metric tracking possible. After EES release, the ERO spacecraft will provide acceleration telemetry and post EES release radiometric tracking that can confirm if the EES release was successful. For the case of an ERO contingency where telemetry and radiometric data are not available, current alternate tracking data types were identified in order to assist in confirming that the EES release was nominal and update the predicted the UTTR landing footprint. In Tab. *7* alternate tracking data types are listed that were considered in this navigation analysis. Each of the alternate data types have different constraints when measurements can be made.

Tracking Data Type	Number of Observations	Tracking Data Type Sigma (1σ)		
		Low	Medium	High
Optical RA/DEC (EME2000)	6 (2 stations)	0.05 arcsec	0.5 arcsec	0.5 arcsec
DSN Radar X-band Doppler	2 (2 stations)	0.1 Hz	1 Hz	10 Hz
DSN Radar Range	2 (2 stations)	75 m	150 m	225 m
SSN Radar Range	183 (3 stations)	10 m	100 m	1000 m
SSN Radar AZ/EL	183 (3 stations)	10 arcsec	100 arcsec	1000 arcsec

Tab. 7 Alternate tracking data types and measurement uncertainty levels

The optical measurements can be made from EES release to 12 hours prior to entry but only at night and are weather dependent. The current DSN radar that can detect the EES within the Moon's orbit is at Goldstone in the northern hemisphere which limits visibility for the 11 October 2033 southern approach. Currently a DSN radar at Canberra has only ~3% sensitivity of the Goldstone radar and can detect the EES only about 11 hours prior to entry. The Space Surveillance Network can detect the EES within Earth's geostationary orbit or about 1.75 hours prior to atmospheric entry. Based on the current alternate tracking data type constraints, a tracking schedule was developed assuming that all possible tracking opportunities listed in Tab. *7* were successful.

B. Sensitivity results based on alternate tracking data type measurement accuracy

To make an assessment on what measurement accuracy was needed to improve the EES orbit accuracy after it is released, a sensitivity studies was performed where the measurement accuracy was varied for the alternate measurement types described in Tab. *7*. In Tab. *7* three data type uncertainty levels (Low, Baseline and High) are assumed. The uncertainty levels in Tab. *7* are used to assess what measurement uncertainty is needed to improved EES trajectory accuracy and not based on actual performance. For the sensitivity study the 3-σ EFPA unertainty evolution at atmospheric entry is shown in Fig. *10* for the three measurement uncertain levels and assuming all alternate tracking data types are used.

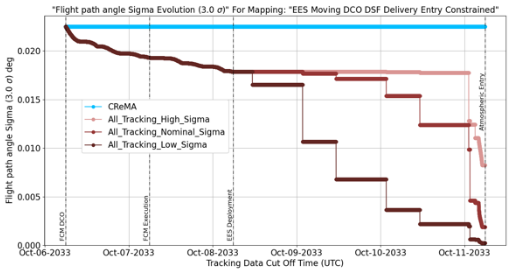

Fig. 10 EES post release entry flight path angle uncertainty evolution using all alternate tracking data types

In Fig. *10* it should be noted that for all three measurements uncertainty levels the radiometric tracking prior to EES release will reduce the EFPA uncertainty compared to the CReMA baseline delivery accuracy. The analysis for Fig. *10* does not include any ERO telemetry or post EES release ERO radiometric tracking that would improve the EFPA uncertainty. From Fig. *10* it can be seen that the "High" measurement uncertainty does not significantly improve the EFPA uncertainty until the SSN measurement are processed in the last 1.75 hours prior to EES atmospheric entry. However, the "Low" and "Baseline" levels can significantly reduce the EFPA uncertainty allowing a landing footprint update 12 hours prior to EES atmospheric entry. The alternate tracking data types could potentially allow a land footprint ellipse center update, but it should be noted that the landing footprint ellipse size would remain unchanged.

VI. Conclusion

The ESA and NASA navigation analysis for the MSR Earth direct approach showed compliance with the EES prep-release approach trajectory accuracy requirements using ESA and NASA orbit determination assumptions. The NASA analysis also showed that including EES release velocity errors resulted in landing footprints fitting within the required UTTR boundary. The NASA OD parameter sensitivity study showed that event uncertainties occurring after the FCM DCO had the largest impact on the atmospheric entry trajectory accuracy, because no radiometric tracking data is available to reduce the OD covariance. Finally alternate tracking types used after the EES release at 3 days prior to atmospheric entry could provide improved landing footprint ellipse center updates 12 hours prior to atmospheric entry using assumed "Medium" or optimistic low measurement uncertainties.

VII. Acknowledgements

As part of the NASA response to the recent MSR Independent Review Board's report and in light of the current budget environment, the MSR Program is undergoing a consideration of changes in its mission architecture. This document is based upon the previous baseline MSR architecture in which Capture, Containment and Return System (CCRS)/ERO would return the Orbit Sample container (OS) to Earth within approximately five years of landing on Mars to retrieve samples collected by the Perseverance rover. The CCRS project completed system development to a Preliminary Design Review level of maturity in mid-December 2023, after which the project was stopped indefinitely pending the results of the re-architecting effort. The decision to implement Mars Sample Return will not be finalized until NASA's completion of the National Environmental Policy Act (NEPA) process. This document is being made available for information purposes only.

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