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SPACE RIDER – The Operation Design Of The Development And Verification Drop Test Campaigns For Parachute Deployments, GNC Under Parafoil Characterization, And System Verifications)

Gianluca Curti^{a*}, Marilia de Almeida C. Matos^b, Aleix Hernandez^a, Gianluca Ascanio^a, Cinzia Cossu^a

^a European Space Agency, ESA-ESRIN, Frascati, name.surname@esa.int ; ^b Marilia.Matos@ext.esa.int

* Corresponding Author

Abstract

Space Rider will provide Europe with an affordable, autonomous, reusable end-to-end integrated space transportation system, facilitating routine access and return from space, making extensive use of new technologies and taking advantage of IXV mission expertise from 2015. Space Rider is a European project, led by the European Space Agency (ESA), in collaboration with AVIO and Thales Alenia Space Italy (TASI) as prime contractors for the Flight Segment, and ALTEC and Telespazio as prime contractors for the Ground Segment and Operations.

The program foresees a first demonstrative flight (Maiden Flight) and five more commercial flights reusing the same re-entry module and performing destructive re-entry of the orbital module. The Maiden Flight launch is foreseen from Europe’s Spaceport in French Guyana with the VEGA-C launcher, with a subsequent landing at the designated Landing Site. Each mission flight will consist of at least two months of in-orbit operations and subsequent de-orbiting, re-entry, and landing.

Space Rider can perform several kinds of missions, such as scientific experimentation or manufacturing under in-orbit environment, particularly micro-gravity and radiation, exploration, servicing, observation, telecommunication, education, and commercial services, always ensuring such Payload is safely returned to Earth.

The system will reuse technology and experience derived from IXV to re-enter the atmosphere, whereas it will rely on brand new technology to land safely on a prepared landing terrain, decelerating under a subsonic drogue parachute and finally heading to the landing spot under a parafoil. To ensure the success of this subsonic landing phase, a thorough verification test plan that relies on several drop test campaigns has been conceived.

Drop tests are complex as they include expensive means and logistics (i.e. military high lift capacity helicopter) and shall have significant level of representativeness to meet the tests’ objective. Different types of drop tests include Open Loop Drop Tests (OLDT), Closed Loop Drop Tests (CLDT), Landing Stability Test (LST) and System Drop Tests (SDT). These tests aim to characterize and verify parachutes, parafoil extraction sequences, actuation chains, aerodynamic parameters, autonomous landing algorithms, and landing dynamic stability and mechanical loads at touch-down.

Operations for each drop test campaign differ significantly due to the varying vehicles and test objectives. Real-time meteorological surveys using drone measurements with immediate result analysis determine test go-ahead. Commands are executed either autonomously on board or through remote control from the ground. Telemetry systems of various vehicles are tested on-site to verify effective reception during drop tests and flights. Data collection is crucial to meet objectives and provide necessary information for the GNC and system design.

All operations must be agreed upon with landing site authority to obtain flight permission and guarantee safety. Operations performed during drop tests refine operations logic for real flights, including real-time wind distribution information during re-entry and landing scenarios. The paper provides an overview of operations for Space Rider Parafoil-GNC phase and lessons learnt from completed tests like OLDT.

Keywords: Space Rider, Reusable Space Transportation, Drop Test Campaign, Parachute Deployments, Parafoil Characterization, GNC Systems

Acronyms/Abbreviations

ACU – Article Control Unit
ALTEC – Aerospace Logistics Technology Engineering Company
AOM – AVUM Orbital Module
CAM – Collision Avoidance Maneuver
CLDT – Closed Loop Drop Test
ESA – European Space Agency

GNC- Guidance, Navigation and Control
GWPT – Ground Wind Processing Tool
IXV – Intermediate eXperimental Vehicle
LDS – Landing Site
LSDO – Landing Site Director of Operations
LSSA – Landing Site Director of Operations
MPCB – Multi-Purpose Cargo Bay
OLDT – Open Loop Drop Test
PGNC – Parafoil phase Guidance Navigation and Control
PoP – Point of Presence
RM – Re-entry Module
ROD – Re-entry Operations Director
RX - Receiver
SDT – System Drop Test
S/S – Sub Systems
TASI – Thales Alenia Space Italia
TC – TeleCommand
TM – TeleMetry
TX – Transmitter
VCC-LC – Vehicle Control Centre – Landing Control
VCC-OC – Vehicle Control Centre – Orbital Control
WP – Way Point
WTU – Wind Table Update

1. Introduction

The Space Rider project, led by the European Space Agency (ESA) in collaboration with AVIO, Thales Alenia Space Italy (TASI), ALTEC, and Telespazio, aims to provide Europe with an affordable, autonomous, and reusable space transportation system. Building on the IXV mission expertise, Space Rider will perform various missions, including micro-gravity, radiation, exploration, and more [1], [2]. Space Rider aims at performing in-orbit payloads operations, de-orbit, re-enter, land on ground and being relaunched after limited refurbishment. This is to be achieved benefiting to the maximum possible extent from existing technologies, addressing relevant technological challenges with proper risk mitigation actions, and supporting the innovation of re-entry technologies for reusable systems.

This paper focuses on the specificities of the operations involved in the Space Rider re-entry and landing phase, particularly related to the drop test campaigns operations that are necessary to demonstrate the landing under parafoil, in view of the first flight. These tests, including Open Loop Drop Tests (OLDT), Closed Loop Drop Tests (CLDT), Landing Stability Test (LST) and System Drop Tests (SDT), are crucial for characterizing and verifying the parachutes, parafoil extraction sequences, actuation chains, aerodynamic parameters, autonomous landing algorithms, and landing dynamic stability and mechanical loads at touch-down. The detailed description of these operations will provide valuable insights into the project's success and future advancements.

2. Overview on Space Rider Re-entry & Landing Operations

When the Space Rider Orbital Phase comes to an end, the whole SR System and its payloads are configured in Preparation for the De-Orbit, Re-Entry & Landing Phase. The Ground Segment uplinks specific commands to activate a set of on-board tasks, which include the Multi-Purpose Cargo Bay (MPCB) chill-down, radiator folding and MPCB door closure, RM GNC initialization and health check together with other critical sub-systems initialization and checkout, in order to eventually proceed with the GO for de-orbit Tele Command (TC), as depicted in Figure 1. In addition, the Ground Segment uplinks the first Wind Table of a series of Wind Table Updates (WTU). These are sent after well-defined ground processes which take as inputs the real-time weather station, radio soundings and weather drones inputs measured at the Landing Site (LDS) and that generate the most recent wind information for the RM's GNC [3].

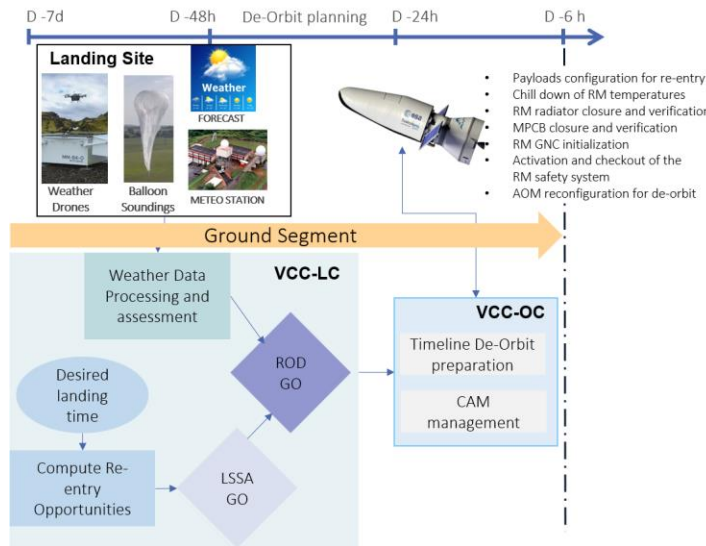


Figure 1 - De-orbit Preparation and Operations

After the GO for de-orbit is given by the Landing Site Safety Authority (LSSA) and the Re-entry Director of Operations (ROD), basing on the Flight segment status, the Ground Segment and Landing Site status and the meteorological forecasts and measurements, the GO for De-orbit TC is uploaded to the Spacecraft and a fully autonomous phase starts. Ground will however need to keep uplinking the WTU TCs during the parafoil phase, after the black-out, to update the RM GNC parameters that support its autonomous guidance until RM touch-down at the Landing Area. Additionally, it is only during this phase that the neutralization command from the LSSA becomes available. The neutralization consists in cutting the parafoil bridles and let RM fall in the sea, preventing potential hazards to people and properties on ground. The decision to neutralize the RM is taken when the RM trajectory goes outside the defined safety boundaries and is based on redundant localization data. Additionally, VCC-LC will send the TeleMetry (TM) parameters to the LDS Safety Team through a Point of Presence (PoP) and will always be in voice-loop with the Landing Site Director of Operations (LSDO). The whole process is depicted in Figure 2.

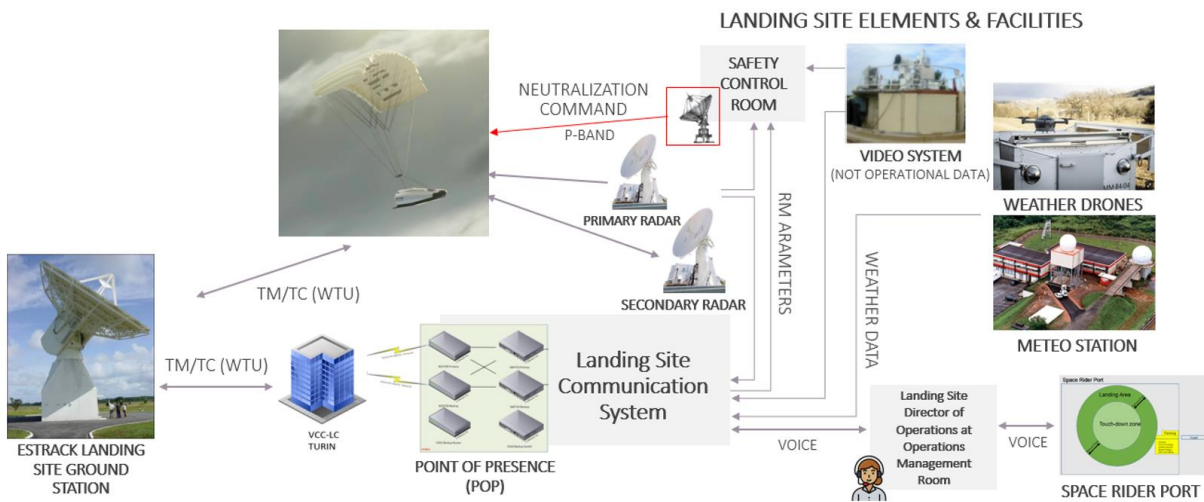


Figure 2- Operations at the Landing Site during Parafoil Phase

Of course, in order to grant the success of this critical phase several drop test campaigns have been planned on ground before the launch as described in the following sections.

3. Drop Test campaigns

3.1 Introduction

GNC development sees as prime contractor for its design, testing and qualification Thales Alenia Space Italy (TASI), which guide an industrial chain composed by DEIMOS for the re-entry trajectory design and simulation and SENER for the Parafoil GNC design, testing and qualification. Drop Test Vehicle design and preparation, as well as parafoil procurement and preparation is in charge to CIMSA, while the test Article Control Unit, called AGU is developed by TESEO.

Whereas the Re-entry Module orbital coasting and atmospheric re-entry phases are based on the flight heritage gained during the IXV mission, few differences need to be addressed in the frame of Space Rider program, pertaining to the parachutes release and the totally brand-new phase performed under parachute, with autonomous precise landing:

- Drogue parachute deployment characterization.
- Parafoil deployment characterization.
- Parafoil GNC characterization and testing.
- Landing characterization and testing.

As far as the GNC phase under parafoil is concerned, different types of drop tests are included in the development plan of the re-entry module, namely:

- Full scale parafoil drop test in open loop (OLDT)
- Full scale parafoil drop test in closed loop (CLDT)
- System Drop tests (SDT)

The most important target of the OLD T is the characterization of the parafoil aerodynamic model, that is a critical input for the simulators that are used to verify performance and manoeuvres of the vehicle during its descent phase.

3.2 Open Loop Drop tests characteristics

Open loop drop tests are performed by dropping a test article at a minimum critical altitude by making use of an helicopter. The drop position is defined respecting the area available for the drop, considering the characteristics of the terrain over which the drop is executed and taking into account the weather condition at the moment of the drop.

The test article is a metallic carriage, which hosts the packed parafoil, the control unit (AGU) and a dummy mass to represent the overall mass characteristics of the real vehicle. At the moment of the release of the test article from the helicopter, the parafoil is automatically extracted by means of a static line; after its inflation is completed, the phase starts in which a predefined set of manoeuvres is executed. The AGU unit is encompassing all the functions that are needed to control the vehicle, in particular:

- Navigation unit including GNSS and rotational kinematic.
- Simplified OBC to load and execute command profiles.
- Actuators for parafoil, i.e. EM winches representative of flight HW.
- Wind sensors, visual sensors, altimeter.
- TLM/TLC S/S including antennas, TX/RX and data storage unit.
- Batteries and power management/distribution unit.



Figure 3 - Open Loop Drop Test Trajectory

Test objectives are focused on the characterization of the vehicle kinematic response to specific open loop control commands issued, for this reason a set of precise manoeuvres are performed, in order to cover all the possible situations that can occur during the flight, like slow turns, fast turns, straight legs, flare manoeuvre.

The trajectory followed by the vehicle (Figure 3) is fully influenced by the command sequence that actuates during the test and by the weather conditions, especially the wind condition during test execution.

The test preparation is characterized by a list of checks, each one of them is allowing the execution of the test sequence, with well-established success criteria and responsibility allocation.

3.3 Open Loop Drop tests operations characteristics and criticalities

Test execution and successful completion passes through some operational main phases, such as:

- Test design and preparation and weather measurement
- Pre-flight checks
- Test execution
- Post-test vehicle recovery and refurbishment

Test design preparation: This phase involves first the identification of the desired sequence of manoeuvres, then understanding the status of the test range at the planned time of the test, with particular attention to the weather conditions. Wind conditions are checked carefully as they can significantly affect the vehicle's trajectory and landing point during the test. The wind profile is obtained through drone measurement, which is processed automatically based on the control feedback of the drone while it climbs vertically at the measurement point. The wind profile is measured accurately from ground level to an altitude of 5 km. Understanding the wind differences at various altitude layers helps determine the drop point over the test range to ensure the trajectory remains within the allowed zone. Once the measurement is completed, the flight dynamics engineers calculate the drop point and communicate it to the helicopter team just before lift-off for the mission. A wind measurements campaign is also needed to provide inputs for the test's GO-NO-GO decision.

Preflight checks: they start much before the test, with the vehicle status control, in particular a specific team is preparing the test article and checking the following:

- vehicle structural integrity (for test that implies carriage re-use)
- parafoil packaging status
- battery charging status and avionic switch on functional tests successful execution
- TLM link test with the vehicle
- status check of the ground control base

- helicopter team readiness check

Test execution: Once the pre-flight check list is completed, the test execution is authorized. The helicopter lifts off and reaches the test range, with the helicopter team in charge of grabbing the test vehicle while hovering over it and bringing it to the release point with coordinates communicated by the flight dynamics team. This phase is normally taking more than 30 minutes, from helicopter lift off to test vehicle release.

Following the release, test execution enters its critical phase. During this stage, the test conductor is responsible for monitoring the vehicle's status, ensuring the stability of the telemetry (TM) link, and overseeing the execution of telecommands. Although the telecommand sequence is pre-programmed for automatic execution, manual intervention is possible in case of anomalies. The TASI team closely monitors potential issues such as TM link loss, actuator anomalies reported in the TM, deviations from the predefined trajectory, or non-nominal evolution of control parameters during the test. In the event of these anomalies, a designated test vehicle pilot is tasked with manually sending commands to correct any trajectory discrepancies. Upon landing, the vehicle's AGU is deactivated, and the recovery process commences.

Post-test vehicle recovery and refurbishment: The vehicle touch-down position is identified through real-time telemetry data received during the test, corroborated by visual confirmation from the helicopter team. A designated recovery team then retrieves the vehicle from the test range, in order to immediately start the preparation for subsequent flights. Each carriage structure can be reused up to two times, provided that the landing did not cause damage, which also applies to the AGU unit. One parafoil unit is used for each test, and after the completion of the test, it is inspected for any damage that may have occurred due to abnormal inflation. Whereas damage to the parafoil upon touch down is possible, it does not affect the success of the test.

3.4 Closed Loop Drop tests characteristics

Closed Loop Drop tests (CLDT) are an evolution of the OLDLT and are under TASI's responsibility with the support of CIMSA for the parafoil readiness and SENER for the integration of the PGNC algorithms. This test campaign is used to test the PGNC in real flight condition. Differently with respect to the OLDLT, the full version of the Parafoil GNC algorithms is loaded on the AGU unit, and the execution of the trajectory (Figure 4) is performed on the basis of the guidance calculations executed on board, targeting the ground position of the defined landing spot.

The test article drop should occur at a minimum altitude sufficient to enable the execution of various phases of the approach to the landing spot of the actual mission, including homing, energy management, terminal guidance, and the adaptive flare manoeuvre. During the drop test preparation phase, the Flight Dynamics team from TASI is responsible for calculating the appropriate drop point and its altitude necessary to achieve the test objectives, while also taking into account the specific weather conditions expected during the test.

Regarding weather conditions, the GNC algorithms onboard are capable of calculating the trajectory, basing on the wind profile loaded onto the system. Therefore, it is crucial to obtain a wind profile measurement that is as recent as possible before the test to minimize last-minute wind variations and ensure accurate execution.

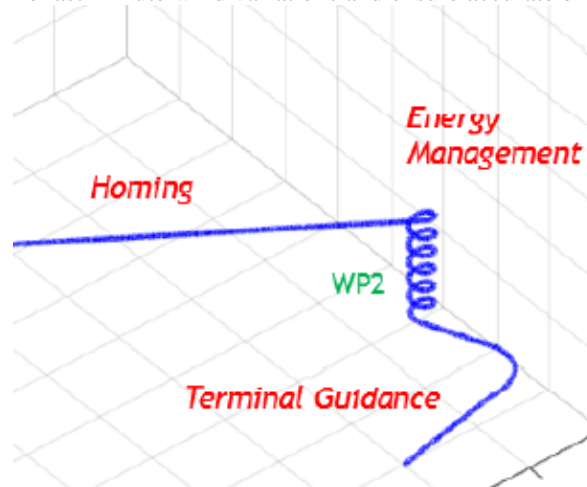


Figure 4 - Closed-Loop Drop Test Trajectory

3.5 Closed Loop Drop tests operations characteristics and criticalities

The operations to be done for the CLDT are slightly different with respect to the ones foreseen for the OLDLT, with GNC algorithms executed in real time in the AGU on board computer, there is no need to pre-load manoeuvres on board, Way Point (WP) position and landing site position is instead loaded, together with the measured wind profile.

The est preparation phase is therefore characterized by wind measurement, the decision about the release point in accordance with the wind characteristics and the calculation on ground of the possible trajectory for the test. The trajectory shall be verified against allowed overflow area and safety requirements belonging to the test range.

A major criticality is represented by the wind measurement activity that shall be as recent as possible before the test: wind variation statistics calculated by historical measurements are showing that in certain layers of the atmosphere the wind intensity and direction variation can be significant, it is therefore very important to reduce the information age of the wind table loaded on board. Before the drop test campaign, a series of wind measurements are carried on to provide the tests GO-NO-GO decision.

Pre-flight phase operations are equivalent to the ones already performed for the OLDLT, with particular emphasis on the parameters that need to be checked before flight, that shall be the guidance parameters of the landing site and way point position, as well as the wind table update on board.

Post-test vehicle recovery and refurbishment: as it is valid for the OLDLT, also in this case the carriages and AGUs can be reused for more than one test. A dedicated recovery team is in charge to recover the test vehicle at landing site, to complete structure and avionics sanity checks and functional testing for the following flight.

A total of four CLDT will be performed, using two AGUs and two carriages.

3.6 System Drop tests operations characteristics and criticalities

The objectives of OLDLT and CLDT is to provide characterization, validation and testing to the final version of the PGNC algorithms and to confirm the performance of the vehicle for its final descent and landing approach phases.

The final leg of this testing sequence is represented by the System Drop Test, that is characterized by a test vehicle representative of the flight model of space rider, not only from parafoil, actuators and mass point of view, as done for the OLDLT and CLDT, but also from shape, inertia, landing structures and critical sensors point of view. The System drop tests are not only aiming to achieve the testing confirmation of the GNC algorithms, but also to confirm the performance achieved at landing, including the aspect of actual touch-down at landing, with representative landing terrain and EM landing gears of the vehicle.

From an operations point of view, the CLDT preparation was useful to refine the procedure of Wind Table Update on board, that implies real time wind measurement, conversion of wind table in the proper format, and its upload on board during the descent phase through the use of the Ground Wind Processing Tool (GWPT) developed for the scope.

Among the SDT's objectives, the following are finally checked only in this campaign, putting at completion the list of testing campaigns to be executed before real flight in orbit:

- Demonstrate the end-to-end behaviour of the parafoil phase, from parachutes release to landing, with real Mass, Centre of Gravity and Inertia characteristics of the test vehicle;
- Wind table update from ground in real time, from measurement to table uplink and availability on board during descent phase;
- Demonstrate the capability to approach the landing spot and land with the desired heading;
- Perform separation of the parafoil after landing

4. Text execution and lessons learned

4.1 OLDLT Execution

The OLDLT campaign was successfully executed during Spring 2024, as depicted in Figure 5. A complete characterization of the parafoil aerodynamic database was possible, with the considerable amount of data collected during the tests. All the manoeuvres needed to meet the test objectives were executed, namely complete nominal inflations, turns in both directions, spiral manoeuvres, multiple flare exercises and straight flights.

Critical aerodynamic data of the parafoil has been confirmed, including time to full inflation, L/D ratio, trajectory bending radius depending on the steering lines' stroke, vertical and horizontal components of absolute velocity, efficiency of the flare manoeuvre.

Moreover, thanks to the processing of both AGU inertial measurements and of the optical imaging of the parafoil as seen from the test vehicle, the reconstruction of the dynamic behaviour of the 12 DOF system constituted by the test vehicle plus the parafoil has been carried out.



Figure 5 - OLD T Campaign

4.2 CLDT Operations lessons implemented

The above mentioned OLD T test results allowed the test vehicle design team to collect important lessons learned, useful to improve the AGU design. In particular, some instabilities of the TM/TC links have been noticed, leading to a revision of the test article configuration, with antenna positions revised to ensure more robustness of the link independent of the attitude of the vehicle. Moreover the AGU ground segment, constituted by a transmitting station and a TM/TC portable control station, has been reviewed and improved for the CLDT preparation, in order to optimize the visualization of the critical parameters to be monitored during flight, and improve position and velocity follow up in real time to cope with the safety requirements of the test range in relation to specific needs of the CLDT.

On the other hand, improvements on the PGNC design have been possible as well, including correlation of the PGNC simulators with the test results to better fit the actual vehicle dynamics that catch the relative motion of the vehicle suspended under the parafoil, which will allow improved stability and overall performance of the control, that will be verified during the upcoming CLDT drop campaign.

6. Conclusions, way ahead and system drop tests

The Space Rider project represents a significant advancement in Europe's space transportation capabilities, offering an affordable, autonomous, and reusable system for routine access and return from space. The project's success is built on the expertise gained from the IXV mission and the collaboration between ESA, AVIO, Thales Alenia Space Italy, ALTEC, and Telespazio. The Maiden Flight and subsequent commercial flights will demonstrate the system's ability to perform various missions, including micro-gravity, radiation, exploration, servicing, observation, telecommunication, education, and commercial services.

The drop test campaigns, including Open Loop Drop Tests (OLD T), Closed Loop Drop Tests (CLDT), and System Drop Tests (SDT), have been and will be crucial in characterizing and verifying the parachute, parafoil extraction sequences, actuation chains, aerodynamic parameters, autonomous landing algorithms, and landing mechanical loads. These tests have provided valuable data for the GNC and system design, ensuring the success of the complex re-entry and landing phases.

The lessons learned from the OLD T and CLDT campaigns have led to improvements in the operation definition for the final phase of the flight, from the subsonic parachute opening to the precise autonomous landing. These enhancements will contribute to the definition of the final operational procedures that will be applied to the Space Rider in orbit flight and autonomous re-entry, increasing overall reliability and performance of the re-entry module.

As the project moves forward, the focus will be on refining the operations logic for real flights, incorporating real-time wind distribution information during re-entry and landing scenarios, and ensuring the safety and success of the missions. The Space Rider project is poised to make a significant impact on Europe's space transportation capabilities, paving the way for future advancements in all re-entry and autonomous landing technologies.

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