A Terminal Descent Sensor Trade Study Overview for the Orion Landing and Recovery System

Catherine Dunn and Ravi Prakash
Jet Propulsion Laboratory
California Institute of Technology
4800 Oak Grove Drive
M/S 301-490
Pasadena, CA 91109
818-393-2348
catherine.dunn@jpl.nasa.gov

Abstract—This trade study was conducted as a part of the Orion Landing System Advanced Development Project to determine possible Terminal Descent Sensor (TDS) architectures that could be used for a rocket assisted landing system. Several technologies were considered for the Orion TDS including radar, lidar, GPS applications, mechanical sensors, and gamma ray altimetry. A preliminary down selection occurred by comparing each sensor's ability to meet the requirements. The driving requirements included the range of operation, accuracy, and sensor development to a technology readiness level of 6 (TRL-6) by the Orion PDR in June 2008. Additionally, Orion is very mass and volume constrained, so these parameters were weighted heavily.

Radar, lidar, and GPS applications all had potential to meet the requirements and were carried on for further analysis. Investigation into GPS led to concerns over potential loss of signal and required ground infrastructure, so GPS was taken out of the trade space. Remaining technologies included a Pulse-Doppler Radar, FMCW Radar, and a Hybrid Lidar ranger and velocimeter (termed the Hybrid Lidar). The trade boils down to the maturity and weather robustness of the radar options versus the mass, volume, power, and heat shield blowout port size advantage of the lidar. This trade study did not result in a recommended TDS. The trade of the mass and volume impact versus the development time and cost should be made at a higher level than this particular trade study.[1,2]

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1. INTRODUCTION

Orion is the next generation spacecraft that will take astronauts to space and land them safely on the surface of the Earth. Currently, three landing system architectures are being considered to attenuate the landing of the capsule for its baseline land landing: an airbag system, a retro-rocket system, and a hybrid airbag-rocket system. For the two architectures that utilize rockets, a method of sensing the horizontal and vertical velocities (velocimetry) as well as the altitude of the capsule above the surface of the Earth (altimetry) is imperative to trigger the rockets to fire at a specific altitude. Dynamics analysis determined that the use of rockets on the landing system would require a highly accurate terminal descent sensor (TDS) that could provide altitude and velocity measurements at low altitudes. To find a TDS architecture that could best meet these requirements, a broad search of various sensor technologies was conducted, including radar, lidar, GPS applications, gamma ray, and mechanical sensors. The technologies were evaluated based on a set of discriminators that included each sensor's ability to meet the requirements. This paper is a summary of the trade study final report that is being published as a NASA Technical Memo [1], and provides an in depth discussion of the steps taken in the trade study, including an overview of the various technologies, the down selection process, and the suggested TDS architecture choices for the Orion TDS.

2. TRADE STUDY OVERVIEW

Configurations

One of the two landing system configurations considered in this trade study is an airbag landing system with vertical and horizontal rockets, henceforth called the airbag-rocket landing system (Figure 1a). This configuration jettisons the heat shield to expose the airbags and vertical rockets, and allows the TDS to be placed under the heatshield. The other configuration is a rocket landing system with vertical and horizontal rockets (Figure 1b). In this configuration, the heat shield remains attached to the capsule throughout the

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[2] IEEEAC paper #1038, Final Version, Updated January 29, 2008

landing sequence to provide the secondary attenuation that the airbags provide in the previous configuration. Because the heat shield remains attached, the rockets will thrust through blowout ports in the heat shield. In addition, sensor options that require a line of sight to the ground will need to utilize blowout ports in the heat shield.

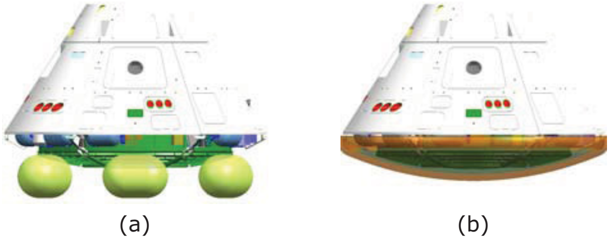
(a) (b)

Figure 1 – Landing System Configurations Considered in Trade Study. a) Airbag-rocket landing system, b) Rocket landing system

For both configurations, the horizontal rockets are all on the windward side of the capsule during entry and will be fired as necessary through blowout ports in the back shell. The vertical rockets on the landing system are the driver for the high accuracy, low operating altitude requirements for the TDS. More detailed information on these configurations and the rocket design is available in reference [1].

Nominal Landing Sequence

The nominal landing sequence for Orion is shown in Figure 2. The sequence of events is separated for the airbag-rocket configuration and the rocket configuration. The concept of operations assumed for the purposes of this study is based upon a pre-design analysis cycle-1 (DAC-1) design. Differences in the concept of operations for the current DAC-1 design do not affect the selection of the TDS. For this study, main parachute deploy occurs at around 14,000 ft above ground level (AGL). The main parachutes are assumed to be fully inflated by 7,000 ft AGL. To allow the system to damp out oscillations and to ensure the parachute is fully inflated, the blowout ports or heat shield (depending on the configuration) will separate between 7,000 ft and 5,000 ft AGL.

For the airbag-rocket configuration, the airbags will begin inflating around 1,000 ft AGL. Shortly thereafter (or even before, depending on the desired method of sensing the altitude to begin airbag inflation), the TDS will begin operation no later than 750 ft AGL. This will allow the capsule enough time to accurately determine its altitude and heading so that it can begin rolling the capsule with the RCS thrusters to align the horizontal rockets with the horizontal velocity vector (since all of the horizontal rockets are on one side of the capsule). Then, depending on the descent velocity, the flight computer will determine the optimal altitude at which to fire the rockets. Once the flight computer reads from the TDS that the capsule has reached the appropriate altitude, the signal is sent to fire the rockets and the TDS is no longer needed. When the capsule touches down, the parachute cluster is disconnected so that it will not drag the capsule. It is assumed that the landing sites are relatively flat and smooth with varying surface roughness and reflectivity between the sites. Furthermore, there can be slopes of up to 5° in any direction and a terrain uncertainty of 6 inches (3σ).

Off Nominal Scenarios

Off nominal scenarios are countless for a mission such as the Orion mission. Some of the notable off nominal scenarios include launch pad aborts, parachute deploy failures, and landing in off nominal landing sites. Off nominal scenarios such as landing away from the nominal landing sites or aborts where the capsule would land on water were not considered because of the uncertainty in firing the rockets over unknown or potentially hazardous terrain. Operating the TDS at higher descent velocities due to a single parachute failure to inflate was considered, but was not found to be a driver. For the off-nominal cases (emergency entry mode), it was assumed that the landing system would have power, a single backup IMU, and the ability to use the backup flight computer. The landing system cannot rely on the navigation software.

Trade Study Process

This trade study followed the procedure outlined in this section. First, TDS performance requirements were determined through various 10,000 run Monte Carlo simulations of the rocket landing system [2]. Once the requirements were determined, a Technology Summit was held to immediately down select to the best candidates for purposes of keeping the trade study's resources focused on the most promising sensors. Ball Aerospace conducted a survey of existing options for the remaining sensors. All options were made to be dual fault tolerant so that a consistent comparison could be made. The remaining options were compared and another down selection was made so that more detailed performance, configuration, and development analysis could be performed on fewer options.

TDS Requirements

The TDS requirements flow down from the higher-level Landing and Recovery System (LRS) requirements. The requirement set used are from the LRS Requirements dated March 14, 2007. The driving requirements for the TDS are shown in Table 1. A complete set of requirements is given in [1].

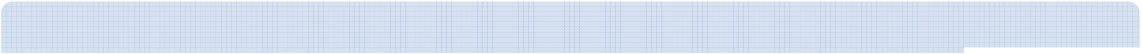

Figure 2 – Nominal Sequence of Events

The requirement that specifies the amount of dust or moisture in the air has not been fully defined for the possible landing sites for the Orion vehicle. This characteristic of the TDS was taken into account during the trade study even though a number to which to design was not available. This requirement is especially relevant to architectures that use optical sensors like lidar and cameras because the optics can be contaminated by dust, precipitation, or moisture in the air.

Other design discriminators were taken into account during the trade study to thoroughly understand how each technology compared with one another. These include mass, volume, power, field of view (FOV), complexity of operation, human qualifiability, and operational reliability. The allocations of mass, volume, and power are maintained at a system engineering level. Although specific allocations were not assigned, Orion is currently mass and volume constrained so these two discriminators were significant drivers in the trade space. For the rocket landing system with a retained heat shield, the TDS FOV is a driver since small FOV translates to a small blowout port in the heat shield for the sensor to see the ground. The remaining discriminators were considered, but were not drivers for the trade study.

Table 1. Driving TDS Requirements

Parameter	Requirement
Altitude (range) accuracy (3σ)	2.5% of AGL at altitudes > 20ft AGL; 0.5ft at altitudes ≤ 20ft AGL
Vertical velocity accuracy (3σ)	0.33ft/s for duration **OR** 5% of mean vertical velocity at altitudes > 20ft AGL 0.33ft/s at alt ≤ 20ft AGL
Horizontal velocity accuracy (3σ)	0.65ft/s to 2ft/s **OR** 5% of mean horizontal velocity at altitudes > 20ft AGL 0.65ft/s at alt ≤ 20ft AGL
Instrument altitude range of operation	6ft to 750ft
Dust/fog/moisture	TBD
Water	Meet requirements while operating over water at landing sites
Technology Readiness	TRL-6 by June 2008