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]

TABLE OF CONTENTS

1

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

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 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.

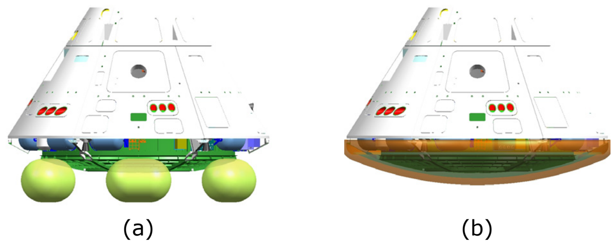

Figure 1 – Landing System Configurations Considered in Trade Study. a) Airbag-rocket landing system, b) Rocket landing system

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].

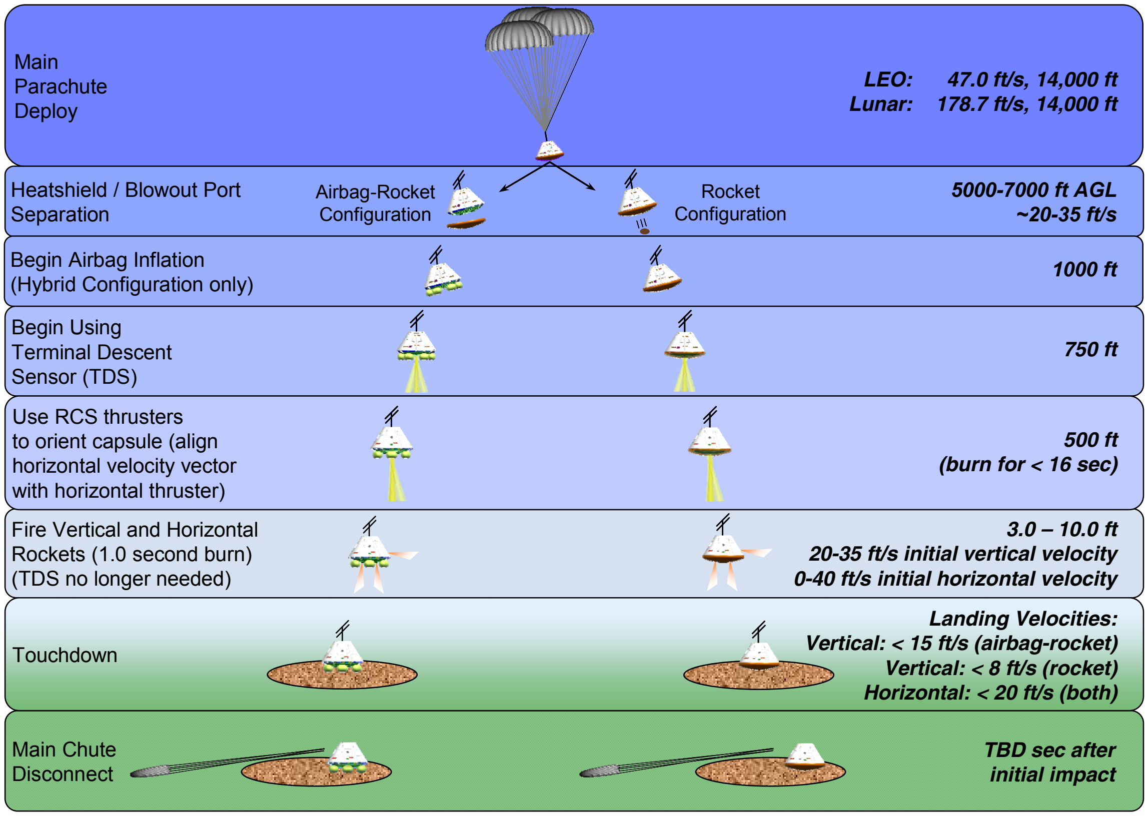

Figure 2 – Nominal Sequence of Events

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

Fault Tolerance

Both Orion and the TDS are required to be dual fault tolerant. If a single fault occurs on Orion that affects the landing (i.e. single parachute failed to inflate), or if any single TDS component fails (i.e. loss of a single antenna), the Orion requirement is to maintain capsule reusability and crew safety. This means that the TDS must continue to meet the performance requirements listed in Table 1. If two faults occur on Orion that affect the landing, or if any two TDS components fail, the Orion requirement is to maintain crew safety without regard for capsule reusability. This relaxes the TDS requirements because only the altitude of the vehicle is needed to fire the vertical rockets between 10 and 11.6 ft AGL.

3. Terminal Descent Sensor Heritage

Terminal descent sensors have been tested and used for rocket landing systems on human-rated spacecraft in the past. This section gives a brief overview of these sensors and why they are not adequate for use on Orion.

Mechanical Sensors

Mechanical sensors (or contact sensors) have been used to measure a vehicle's altitude. Mechanical sensors have heritage from the Gemini and Apollo capsule landing studies where hardware was fabricated and tests were conducted, all the way up to capsule drop tests where the mechanical sensors initiated rocket motor firings (Figure 3) [3, 4]. Although the final decision on both programs went to splashdowns in the ocean, the Apollo moon landings used contact sensors mounted on 5.6 foot booms attached to all but one of the landing pads that provided capsule support after landing [5].

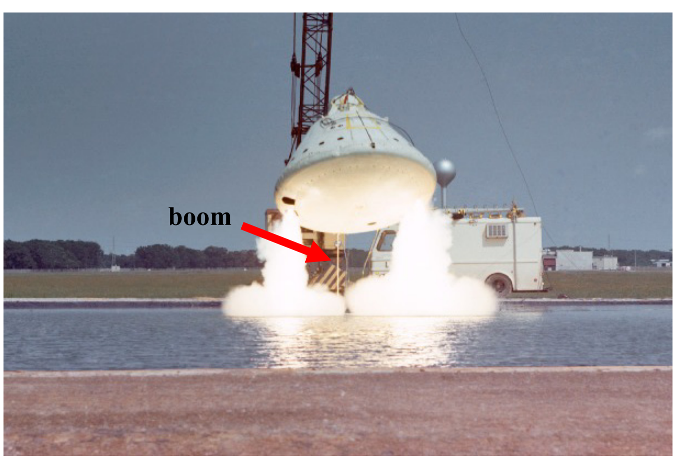

Figure 3 – Apollo CM Rocket Test with Contact Sensor [4]

Although the mechanical sensor testing on Gemini and Apollo was successful, the mechanical sensor technology does not meet the architectural requirements of the Orion landing system mainly because a position and velocity profile is not generated from the sensor. Generally, mechanical sensors only provide a single measurement when the probe contacts the ground unless multiple sensors are used. Although the simple approach of taking a single measurement using a contact probe is appealing, the added complexity of a position and velocity profile provides the vehicle with added knowledge and therefore information to fire the rockets at a more optimal altitude. The use of a mechanical sensor as a backup sensor that provides redundancy is ideal because it is simple and reliable. The mechanical sensor research was concluded at this point in the trade study so resources could be concentrated on the primary sensor study.

Gamma Ray Altimetry

The use of reflected radioactive particles off a given surface is a technology used currently by the Russian space agency on the Soyuz vehicle. Soyuz is one of the vehicles used to take cosmonauts and astronauts to the ISS and return them safely to the Earth. The altimeter used onboard the vehicle is called the Kaktus and contains a radioactive source that is used to determine the vehicle's distance above the ground. This sensor technology has been the primary TDS on Soyuz vehicles since the program began in 1966.

The Cesium-137 radioactive source onboard Soyuz is placed internal to the heat shield with a small hatch for retrieval after the capsule has landed. A collimator directs the flow of particles coming from the radioactive source toward the ground. The source is always "on," so it requires no electrical initiation, but it can be hazardous to the crew or ground recovery team because it cannot be turned "off". Because of this risk, the radioactive source is transported and housed in a lead container which is installed in the vehicle just prior to crew boarding. The hatch for the radiation source can be seen in the picture below of a Soyuz capsule after reentry (Figure 4).

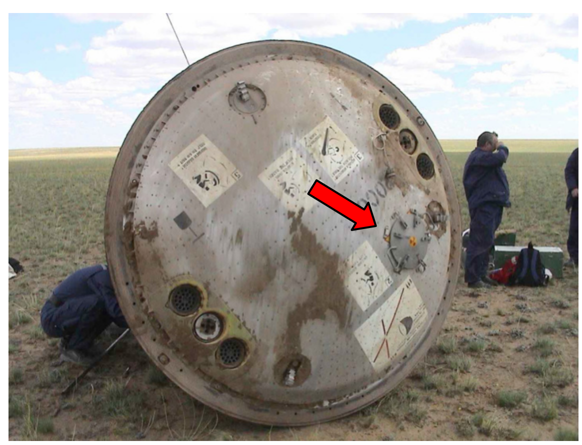

Figure 4 - Landed Soyuz capsule showing heat shield and Kaktus instrument placement

There are three receivers onboard that detect the intensity of the reflected particles and determine the vehicle's height above the ground. When two of the three receivers reach the pre-determined intensity level, the signal to fire the rockets is sent. The intensity threshold is configurable on descent to account for variation in descent velocity in real time. Vertical velocity is determined by integrating the output of the radiation detectors over time [6].

Gamma ray altimetry was not considered as a viable TDS option for Orion for several safety and political reasons. The use of a radioactive source onboard a spacecraft that is launching into and reentering the Earth's atmosphere would require extensive safety precautions to be taken so no radioactive material escapes the capsule in any event. Also, in order to build a gamma ray altimeter instrument, agreement between NASA and the Russian Space Federation would need to be established as well as with the Russian contractor, Energia. If an agreement is possible, this would lead to International Traffic in Arms Regulations (ITAR) and contract issues that could inhibit the cost and development schedule of the instrument. There is also a negative public perception of using radioactive material on spacecraft that could make use of this sensor difficult for political reasons.

Because the gamma ray altimetry technology does not meet the requirements and involves political challenges, it was dropped from the trade study's consideration.

4. Terminal Descent Sensor Options

Additional TDS options such as radar, lidar, and GPS applications were considered. An overview and the down selection process for these sensors are provided in this report. Other options were analyzed and are given in [1].

Radar

In general, radar options can operate in most any weather conditions day or night. Radars also have the most heritage of any TDS option as radars have been used successfully on all the Mars Landers. However, radars tend to have high mass, volume, and power. The three high-level radar technologies considered for the TDS are Pulse-Doppler, Frequency Modulated Continuous Wave (FMCW), and Ultra-Wideband (UWB).

To determine the best radar technologies to carry forward for this trade study, a comparison of dual fault tolerant radar architectures was put together and is shown in **Table 2**. The performances stated in the trade table represent point-of-departure expectations based on best estimates of available components and demonstrated technologies. The items in this table are color coded to indicate if the value poses a high risk (red), medium risk (yellow), or meets the requirements (green).

Of these options, the Pulse-Doppler Radar is the only sensor that would not require development by Orion since it is being developed by the Mars Science Laboratory (MSL) project [7]. However, the mass of this system is the highest among the listed options. In addition, the Pulse-Doppler Radar does not meet the minimum operating range requirement of 6 ft. However, this radar could be used in tandem with an IMU to integrate the additional time necessary to signal the rockets to fire at the proper altitude. Using the IMU adds additional error and risk into the system, but permits this option to be a viable candidate.

The remaining options require some development to get to TRL-6 by June 2008. The risk to TRL-6 for these options is considered high because these options cannot be at TRL-6 by the Orion PDR. In addition, the UWB Radar would require either a significant amount of power increase (more than 100 times!) or a redesign of the antenna to meet the maximum operating range requirement. This design is the least mature among the listed options and was discarded for the above reasons. The FMCW sensor meets all the requirements but requires some development to reach TRL-6. Since this option provides some mass savings over the Pulse-Doppler Radar and the development risk is considered low to medium, the FMCW Radar was considered a viable candidate. Thus, the two options carried forward in the trade study for more detailed analysis were the Pulse-Doppler Radar as an existing option, and the FMCW Radar as a potential development option.

Lidar

Lidar technologies have a low mass and volume when compared many of the other options in this trade study. Most lidar technologies are not highly developed and would therefore take considerably more time and money to achieve the required TRL. Weather is also a driving factor for lidar technology because it can adversely affect the performance of the instrument.

Three technologies were considered for the lidar sensor: FMCW Doppler Lidar, Hybrid Range and Doppler Lidar, and Flash Lidar. A separate sub-trade was performed for the ranging portion of the Hybrid Lidar between the Pseudo Random Noise (PRN) Ranging Lidar, Pulse Diode Laser Lidar, and Microchip Diode-Pumped Solid-State Laser Lidar (DPSS) technologies to obtain the ranging technology that best fit the requirements.

The relative performance of these technologies is tabulated in Table 3. The performances stated in Table 3 represent point-of-departure expectations based on best estimates of commercially available components and demonstrated technologies. The Pulse lidar is given in Table 3 because it was chosen as the ranging component of the Hybrid Lidar systems.

Table 2. Summary of Radar Technologies

Dual Fault Tolerant System Specs	Pulse-Doppler	Hybrid FMCW Altimeter and FMCW Velocimeter	Hybrid UWB Altimeter and FMCW Velocimeter	Hybrid UWB Altimeter and UWB Pseudolite System (flight receiver)
Mass (lbs)	78.4	50	33.1	11.0
Volume (L) Heatshield Mounted	3 * 250x220x180 mm + 4 * 220 mm diax20mm thick Total Vol = 32.7	3 * 354x91x84 mm + 4 * 220 mm diax20mm thick TBR 20	3 * 150x83x62 mm + 2 * 373x346x50 mm + 7 * 220 mm diax20mm thick TBR 20.5	3 * 150x83x62 mm + 2 * 150x83x62 mm + 7 * 220 mm diax20mm thick TBR 9.2
Power (W)	300†	90	34	6
Vertical Velocity Accuracy (ft/s) 3σ	Better than 0.20	0.20% of V_V + 0.16	0.20% of V_V + 0.16	< 0.33
Horizontal Velocity Accuracy (ft/s), 3σ	Better than 0.39	0.25% of V_h + 0.16	0.25% of V_h + 0.16	< 0.33
Min-max Range (ft), 3σ	19.7 – 11,975	0 – 8000	3.3 – 302	3.3 – 302
Range Accuracy (ft), 3σ	Better than 1.4%	2%	1 ft	1 ft
Dust, clouds, precip	Very Robust	Very Robust	Very Robust	Very Robust
System TRL (components)	6 (6+)	3 (6)	3 (5)	3 (4)
Risk to TRL6	None	Low to Medium	Medium	Medium
Dual Fault Tolerance Method	3 * Electronics + 4 * antennas	3 * combined altimeter and velocimeter units with 4 * antennas	3 * UWB Altimeters with 3 * antennas + 2* FMCW Velocimeters with 4 *antennas	3 * UWB Altimeters with 3 * antennas + 2* UWB Receivers with 4 *antennas
Blow-out dia. (in)	14.6	Bigger than Pulse-Doppler	Bigger than Pulse-Doppler	Bigger than Pulse-Doppler

† Power may be lower depending on the redundancy strategy, 300 W is for all three electronics units on simultaneously.

High Risk   Medium Risk   Meets requirements

Table 3. Summary of Lidar Technologies

Dual Fault Tolerant System Specs	Pulse-only	FMCW	Hybrid (4 stick system)	Hybrid (3 stick system) *	Flash (if also used for rendezvous & docking)
Mass (lbs) Backshell / Heatshield mounted	4.2 / 4.2	NA / 24.3	8.2 / 10.6	6.2 / 7.9	May exist in crew cabin: ~2 extra for mirrors + 1.3 range only TOF stick LIDAR
Volume (L) - BS / HS	1.7 / 1.7	NA / 12.7	3.3 / 3.5	2.5 / 2.6	0 + 0.6 extra TOF range
Power (W)	12	92	64	48	64
Vertical Velocity Accuracy (ft/s), 3σ	0.33	0.52	0.23	0.23	0.16
Horizontal Velocity Accuracy (ft/s), 3σ	N/A	0.92	0.52	0.52	0.66
Min-max Range (ft)	3 - 6560	3 – 8200	3 - 3280	3 - 3280	3 - 13100
Range Accuracy (ft), 3σ	0.15	0.16	0.079 (alt < 20 ft) 0.4% or range (alt > 20 ft)	0.079 (alt < 20 ft) 0.4% or range (alt > 20 ft)	0.11
Dust, clouds, precipitation	Only unbroken thick obscuring clouds (optical depth [OD] >2)	Moderate cloud, dust, and serious precip velocity and range issue. Must have 3 TOF range LIDARs to back up. Only unbroken thick obscuring clouds (OD>2) to surface can stop pulse TOF range	Moderate cloud, dust, precip issue only for Doppler velocity, but dR/dt can substitute Unbroken thick obscuring clouds issue for both (OD>2) to surface can stop pulse TOF range	Moderate cloud, dust, precip issue only for Doppler velocity, but dR/dt can substitute Unbroken thick obscuring clouds issue for both (OD>2) to surface can stop pulse TOF range	Only unbroken thick obscuring clouds (OD>2) to surface can stop pulse TOF range
System TRL (compnts)	2 (4)	2 (4)	2 (4)	2 (4)	4 (4 - 9)
Risk to TRL6	Low	Low	Medium	Medium	Medium, in progress
Dual Fault Tolerance Method	3 * pulse TOF range only "stick"	2 * Doppler FMCW + 3 simple pulse TOF range	4 * hybrid "stick"	3 * hybrid "stick"	2 * Flash, 1 pulse TOF range only "stick"
Blow-out dia. (in)	1 * 7.9†	6 * 5.1 +7.9=33.1	1 * 4.8†	1 * 4.4†	1 * 7.9†

* 3-stick system with simple data filtering does not meet velocity accuracy requirement with failed Doppler element
† "Stick" systems can be backshell mounted with no heatshield blow-out necessary

High Risk   Medium Risk   Meets requirements

The FMCW Lidar architecture meets the majority of the requirements except for the horizontal and vertical velocity accuracy requirements. An important note that is not captured by Table 3 is that the FMCW range and velocity measurements are coupled. If a failure occurs in the range or velocity component, the system will suffer the loss of the other component as well. Lastly, the mass and power of the FMCW Lidar is more than that of the Hybrid Lidar system. It was for these reasons that the FMCW architecture was not recommended as a viable sensor for the Orion TDS.

The Flash Lidar was another possible TDS option for the Orion vehicle because it could also potentially be used for rendezvous and docking. The horizontal velocity accuracy does not quite meet the defined Orion TDS requirement although it may be sufficient. The Flash Lidar technology obtains the horizontal velocity based on feature correlation of sequential range images. This characteristic is hard to test to specific precision and therefore, can only be estimated on statistical scene properties. Additionally, this method in which the instrument obtains horizontal velocity is highly risk averse because of the uncertainty in landing site terrain. Like the FMCW system, the Flash Lidar also has the range and velocity measurements coupled, so if a failure occurs in one measurement component, the other component is lost as well. For these reasons, the Flash Lidar option was taken out of the trade space.

The final lidar technology in Table 3, and the lidar technology recommended for the Orion TDS, is the Hybrid Lidar option. This option is the only lidar candidate that meets all of the performance requirements. One of the main advantages of this option is the velocity measurements are decoupled. If the range portion of the measurement is lost, the velocity measurement will remain in tact. Additionally, the Hybrid Lidar option has lowest mass and power of all of the options. Refinement of the requirements may allow for a graceful degradation of the performance requirements for a single fault case, allowing three lidar sticks to meet the requirements. Therefore, both three and four stick lidars are shown in Table 3. Drawings of the recommended lidar configuration are shown in Figure 5.

The effect of the local environment (dust, clouds, precipitation, etc.) on all of the lidar technologies could be significant enough to take the lidar option out of the trade space. The quantity of dust increases exponentially as the vehicle descends to the ground and may adversely affect the Doppler velocity measurements and to a lesser degree, the Pulse TOF ranging lidar. Similar to the effects of dust on the Doppler velocity measurements, water and ice clouds can cause invalid data returns due to reflection off the particles in the air. Precipitation in the form of heavy rain or falling snow could also be a problem for the Doppler sensor. Heavy precipitation in the form of blowing snow may prevent the Pulse TOF return signal from the surface until approximately 10m altitude, and will definitely corrupt the Doppler measurement. To determine if weather constraints will eliminate lidar technologies, the landing sites for the Orion vehicle need to be fully characterized and their environments understood. Furthermore, if a lidar system is chosen, its performance in these weather conditions needs to be tested to characterize its performance.

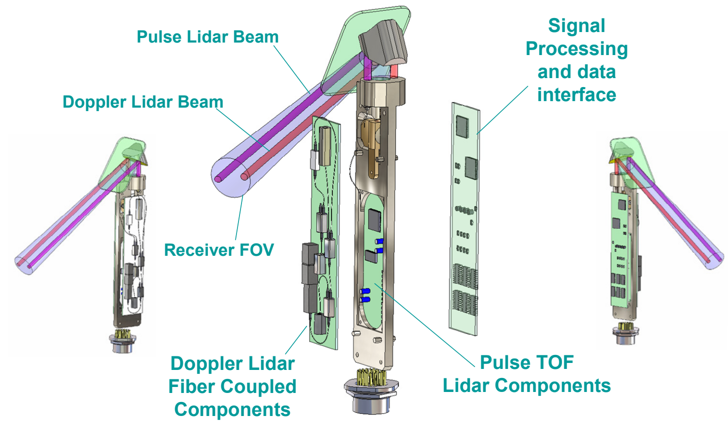

Figure 5 – Hybrid Lidar Concept Drawing

Global Positioning System (GPS) Applications

Earth and space based vehicles have come to rely on GPS to obtain position and velocity. GPS was considered for use on the Orion vehicle both on its own and augmented with pseudolites and differential signals.

GPS and GPS with Global Differential Corrections—GPS is a network of satellites that continuously transmits coded information, which makes it possible to precisely identify locations on Earth by measuring distance from the satellites. A receiver on the spacecraft receives the GPS signals broadcast from the geostationary orbiting satellites. These signals are decoded on the spacecraft and used to determine the vehicle's inertial position and velocity. There are two levels of accuracy that can be obtained using GPS. Civilian GPS is the less accurate of the two and can be accessed by the entire planet with the proper receiver. The position is accurate to approximately 30 ft relative to the geoid. The second level of GPS is used strictly by the military and is not available to the general public. One way to increase the accuracy of the GPS receiver is to use global corrections. The ability to use global corrections is intrinsic to the receiver. Currently, there are no space-qualified receivers that have the ability to use global corrections. A receiver that uses global corrections and is space rated would have to be developed.

Ground Based Correction—GPS can be used in conjunction with ground based stations to increase the accuracy. Examples of ground based corrections include differential ground stations, psuedolites, and the wide area augmentation system (WAAS). Differential GPS uses one ground station that receives data from the GPS satellites and calculates a correction for the vehicle based on its own position knowledge. The ground station then broadcasts the correction back to the spacecraft.

Pseudolites (termed from pseudo-satellite) are ground beacons that transmit a GPS-like signal with carriers and ranging codes. The use of pseudolites to determine altitude and velocity involves placing multiple transmitters within range of the desired landing site. The GPS receiver onboard Orion collects the signals broadcasted from the pseudolites and the vehicle's current position and velocity is estimated. The pseudolite provides additional GPS satellite like signals to the spacecraft that have decreased error because of the close proximity (atmospheric effects are reduced and satellite geometry is improved).

The WAAS is a series of satellites and ground stations in North America that provide corrections to GPS receivers. The WAAS infrastructure consists of a master station on each coast that broadcast corrections through geostationary satellites. A WAAS enabled GPS receiver must be used to read the signal [8]. However, a GPS plus WAAS architecture does not meet the vertical velocity accuracy requirement or the range requirement, so it was taken out of the trade space.

One of the main disadvantages to using an architecture with a ground-based station is if the spacecraft lands outside of the range of the ground station, the accuracy will not be improved from ordinary GPS and the system will not meet the performance requirements. Although off site landings are not in the scope of this study, the requirement placed on the TDS to land in a specific place is enough of a driver to mention it here as a disadvantage. A second disadvantage of using a ground station is they require maintenance and check out with each landing. In addition, if ground based stations are used, there must be GPS transmitters and receivers on the bottom of the vehicle, depending on the architecture (with differential GPS, a receiver and transmitter are required on the vehicle; with just pseudolites, only a GPS receiver is required on the vehicle). Architectures using GPS are shown in Figure 6.

The GPS architectures are shown in Table 4. GPS and GPS with WAAS do not meet the vertical velocity or range accuracy requirement as shown by the red shading. The GPS architecture that is augmented with global differential corrections does not meet the range accuracy. These three architectures were no longer considered viable options for the Orion TDS because they did not meet the requirements. The two architectures that do meet the requirements are the GPS augmented with pseudolites and GPS augmented with local differential corrections. The GPS augmented with pseudolite technology has had limited heritage and therefore, has medium risk in achieving a TRL-6 by the Orion PDR. GPS augmented with local differential corrections meets the requirements and is therefore the recommended GPS application for the Orion TDS.

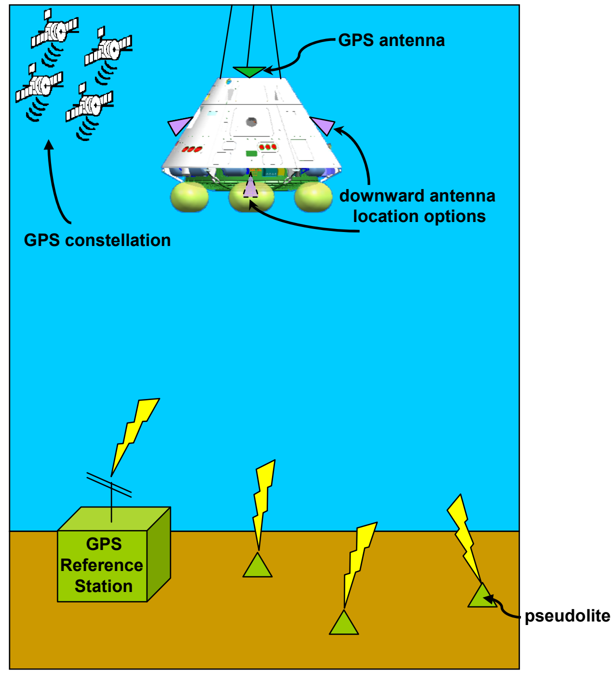

Figure 6 – GPS Architectures

Despite the many advantages of a GPS-based system, there are several drawbacks to using a GPS architecture. In addition to the need for ground infrastructure, ground maintenance would be required to maintain accurate Digital Elevation Maps (DEMs) to ensure high accuracy of each landing site. Another concern that is not well understood for GPS applications is the reacquisition of the GPS and/or ground signal after plasma blackout during reentry. However, this is not expected to be a major problem since the capsule will have ample time on the parachute before the signal needs to be reacquired. Perhaps the most concerning problem with a GPS architecture is that the accuracy requirements will not be met if the constellation of satellites (whether ground based or space based) is upset or loss of signal occurs. There is built-in redundancy in the space-based constellation with over 40 GPS satellites orbiting the Earth and any ground infrastructure could be redundant. However, loss of the GPS signal in a single receiver would possibly mean loss of the signal in all receivers, and thus, the single fault requirements cannot be met. It was for these reasons that GPS architectures were taken out of the trade space and not recommended as a final architecture for the Orion TDS. However, it is noted that if the reliability of GPS is better understood, GPS architectures could provide a valuable solution.

Table 4. Summary of GPS Technologies

Dual Fault Tolerant System Specs	GPS with no corrections	GPS + WAAS	GPS + Pseudolite	GPS + Global differential correction	GPS + Local differential correction
Mass (lbs)	8.8	8.8	8.8	8.8	8.8
Volume (L) Shell / Bottom	3 * (152 x 132 x 43) = 2.6 L	3 * (152 x 132 x 43) = 2.6 L	3 * (152 x 132 x 43) = 2.6 L	3 * (152 x 132 x 43) = 2.6 L	3 * (152 x 132 x 43) = 2.6 L
Power (W)	14	14	14	14	14
Vertical Velocity Accuracy (ft/s), 3σ	0.6	0.6	0.1	0.2	0.02
Horizontal Velocity Accuracy (ft/s), 3σ	0.4	0.4	0.05	0.1	0.01
Min-max Range (ft)	0 – LEO	0 – LEO	0 – 3000+	0 – LEO	0 – LEO
Range Accuracy (ft), 3σ	30, relative to geoid	10 , relative to geoid	0.2	2 (vertical position uncertainty wrt geoid)	0.2 (vertical position uncertainty wrt geoid)
Dust, clouds, precip	Very Robust	Very Robust	Very Robust	Very Robust	Very Robust
System TRL (components)	9 (9)	6 (6)	5 (5)	≥8 (aircraft demo)	8 (aircraft demo)
Risk to TRL6	None	Low	Medium	None	None
Dual Fault Tolerance Method	3 GPS receivers	3 GPS receivers	3 GPS/Pseudolite receivers multiple pseudolite beacons on ground	3 GPS receivers	3 GPS receivers
Blow out dia.	GPS antennas	GPS antennas	GPS antennas	GPS antennas	GPS antennas

High Risk   Medium Risk   Meets requirements

5. ANALYSIS OF ARCHITECTURES

With three remaining architectures, a Pulse-Doppler Radar, FMCW Radar, and Hybrid Lidar, a more complete analysis was performed to determine an optimal TDS for Orion. This analysis included a close look at the concept of operations and the performance to have a better understanding of how the sensors would operate and as to the capabilities of the sensors. In addition, potential design improvements to make the sensor a better candidate for Orion were considered. Furthermore, integration with the CM was considered to ensure that the sensor would have adequate room for packaging. Finally, the development risk for the sensors to meet the TRL requirement was considered. Because of the similarity between the Pulse-Doppler Radar and the FMCW Radar, and due to time constraints, the Pulse-Doppler Radar was looked at more closely than the FMCW Radar. Details of this analysis can be found in [1]. The remainder of this paper will focus on the configuration options and provide only a brief summary of the rest of the analysis.

TDS Configuration Options

The radar and lidar architectures were integrated into the Orion CM to determine if there would be accommodation concerns. The rocket landing architecture with the retained heat shield was considered to determine the size of the blowout port to satisfy the FOV requirement. The airbag-rocket landing architecture was considered to ensure that the airbags would not interfere with the TDS signal. Possible configurations for the radar and lidar architectures are shown in this section. All configurations shown can be used for both landing system options. Higher system level trades would need to be performed to narrow the choices to a single configuration.

Radar Configuration Options—The radar consists of 4 antennas and 3 electronics boxes. Because the electronics boxes do not have location restrictions, only the antennas were placed in the model. To calculate three-dimensional velocity, at least three of the antennas require an off-nadir angle between 15° to 50° off-nadir, with no two antennas looking at the same point on the ground. The off-nadir angle is defined as the angle the center of the beam makes with the gravity vector. The radar emits a beam of 3° emanating from the outer diameter of each antenna. In addition, there is a 25° half cone near field keep out zone, also emanating from the outer diameter of each antenna, for the beam pattern to form. The 25° requirement is a conservative value and should be updated as the MSL radar is better understood. The beam width and keep out zone are illustrated in Figure 7.

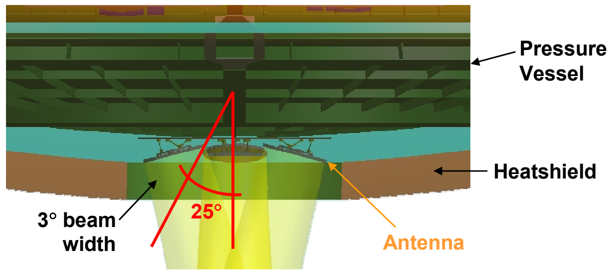

Figure 7 – Radar Beam Width and Keep Out Zone

One option for the antenna placement is directly underneath the center of the heat shield (Figure 8). In this configuration, the antennas have a high probability of "looking" where the capsule will be landing since there is a measurement directly beneath and slightly in front of the capsule. Also, all the antennas are looking through the same area in the heat shield, so only a single blowout port needs to be made for the retained heat shield configuration. The blowout port size is looked at in greater detail at the end of this section.

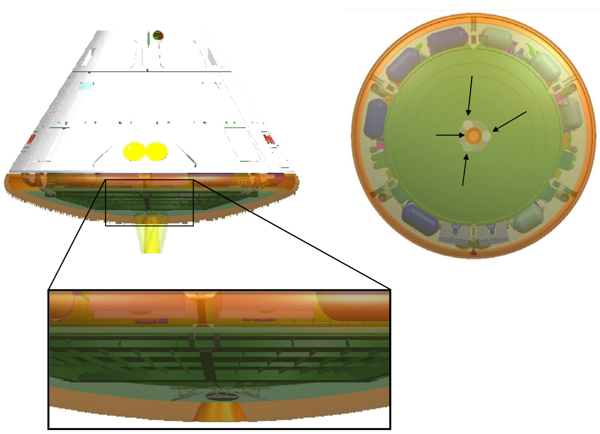

Figure 8 – Radar Configuration – Heat Shield Center

However, the antennas are more exposed to damage upon landing since the CM will probably rest on its center. Furthermore, there is not much clearance between the antennas and the inner mold line of the heat shield, so there may be contact concerns with the heat shield and thermal concerns if there is no room for insulation.

Another configuration option is to place the radar antennas on the leeward side of the capsule Figure 9. This area has less heating during entry and would reduce the thermal protection mass associated with the system. Furthermore, there is less concern in this area about the antennas contacting the heat shield as well as a smaller chance of the capsule damaging the antennas upon landing. However, in the case of a retained heat shield, this configuration would require multiple blowout ports. The antennas were placed so that the airbags would not interfere with the 25° keep out zone requirement.

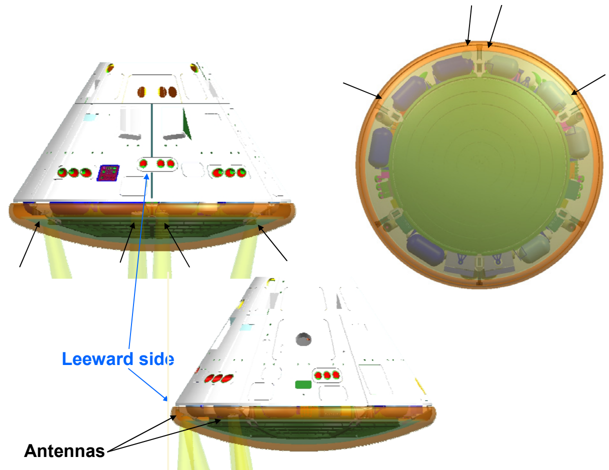

Figure 9 – Radar Configuration – Leeward Side

While the potential number of configurations is countless, these two configurations were deemed the most promising. Other configuration options are possible. It should be noted that the radar antennas cannot be placed on the back shell because it would impinge the back shell due to the radar's 25° keep out zone requirement.

Lidar Configuration Options—The lidar consists of 4 sticks. To calculate three-dimensional velocity, at least three of the sticks require an off-nadir angle between 25° to 55°, with no two sticks looking at the same point on the ground. The lidar beam can be approximated as a cylinder of 2 inch diameter, and does not require any additional space for FOV reasons.

The same two configurations that were shown for the radar can be applied to the lidar, and are shown in Figure 10 and Figure 11 for comparison purposes. The same advantages and disadvantages apply, but it should be noted that much smaller blowout ports are required for the lidar architecture.

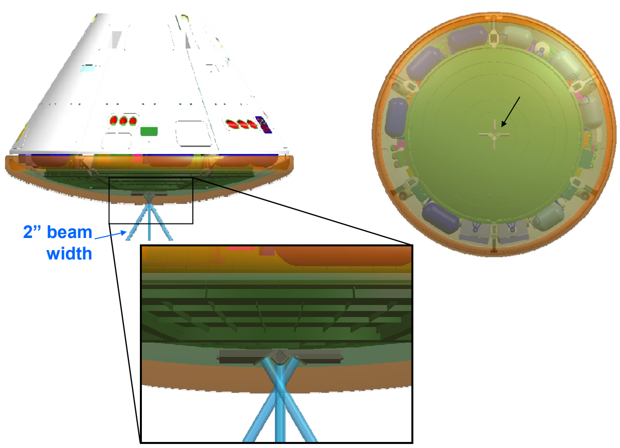

Figure 10 – Lidar Configuration – Heat Shield Center

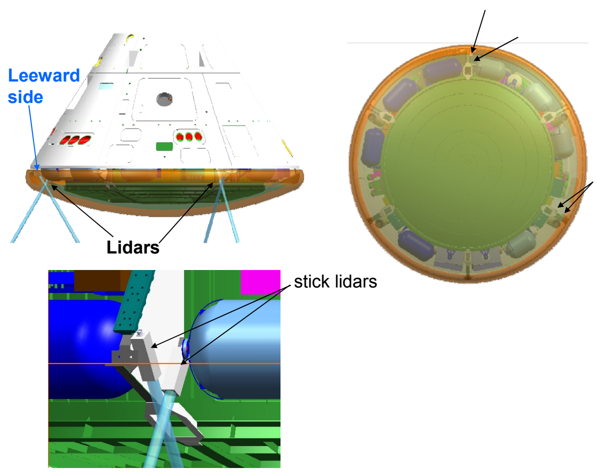

Figure 11 – Lidar Configuration – Leeward Side

For the leeward option, the lidar sticks were split up because there was not enough room for all sticks to be on the same structural longeron. Thus, two blowout ports would be required based on this configuration.

Since the lidar has a very small FOV requirement, it can be placed behind the back shell without impinging on the back shell as it senses the ground. This configuration option is shown in Figure 12. An advantage of this configuration is that there is no need for a blowout port since the sensor could see through "windows" in the back shell. However, there are potential issues with precipitation running along the capsule and distorting the optics as well as the RCS plumes distorting the optics.

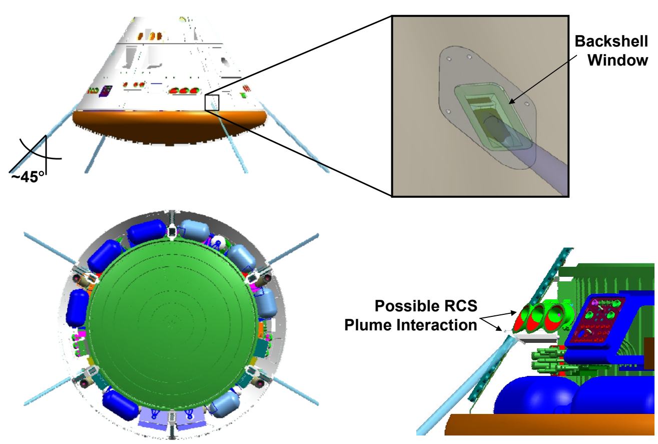

Figure 12 – Lidar Configuration – Back Shell Penetrating

Heatshield Blowout Port Size Comparison

For the rocket landing system, heat shield blowout ports would be needed for the radar architecture, and may be needed for the lidar architecture. If the TDS is placed underneath the center of the capsule, the radar architecture would require a 14.6 inch blowout port, while the lidar architecture would require a 4.8 inch blowout port. A scaled image of the radar and lidar blowout ports is shown in Figure 13. A concern with having blowout ports is that the blowout port debris could obstruct the antenna or optics. This issue is not expected to be a showstopper, but is mentioned so that it will not be overlooked.

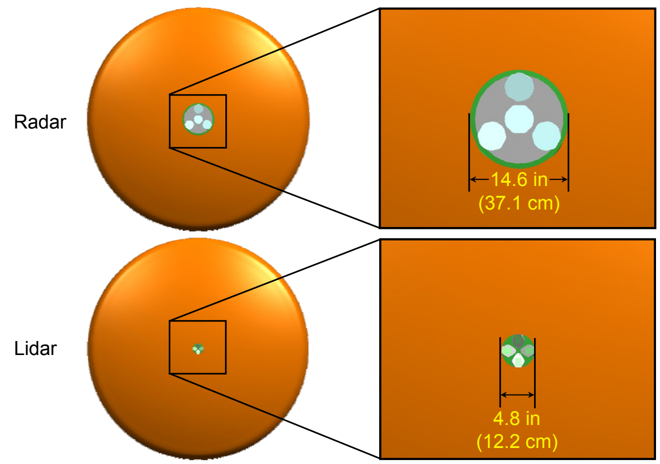

Figure 13 – Blowout Port Size Comparison

Additional Analysis

Additional analyses were performed to obtain higher fidelity mass estimates and to ensure that the remaining sensor options could meet the requirements. In addition, the development risk for the sensors to meet the TRL requirement was also considered. The Pulse-Doppler Radar is virtually identical to the radar being flown by MSL in 2009. This technology is already at TRL-6, and MSL will develop the radar to TRL-8 by 2008 and TRL-9 by 2010. Development of the FMCW Radar to TRL-6 is considered low risk because there are no technological hurdles that stand in the way of its development. However, an aggressive development timeline for the FMCW Radar would take a minimum of 14 months, exceeding the Orion PDR date by about a year (assuming an optimistic start date in early to mid 2008). The Hybrid Lidar is a high risk development option because there are more unknowns in the development of the Doppler portion of the Hybrid Lidar. In addition, an aggressive development timeline of 25 months to TRL-6 exceeds the Orion PDR date by about two years.

6. CONCLUSIONS

The trade study evaluated the TDS options for a rocket landing system and an airbag-rocket landing system on Orion. After an initial survey of various options, the trade down selected to three sensors that can meet the Orion TDS requirements: Pulse-Doppler Radar, FMCW Radar, and Hybrid Lidar. The trade boils down to maturity and weather robustness of the radar options versus the mass, volume, power, and heat shield blowout port size advantage of the lidar. A comparison table of these sensors is shown in Table 5.

Table 5. Comparison Table of Down Selected Sensors

	Pulse-Doppler Radar	FMCW Radar	Hybrid Lidar
Mass	78.4 lbs	50 lbs	10.6 lbs
Power	300 W	90 W	64 W
Volume	29.7 L	20 L	3.5 L
Operating Range	19.7 – 11,975 ft	0 – 8000 ft	3 – 3280 ft
Weather Robustness	Operable in all weather conditions	Operable in all weather conditions	Limitations in dense fog, dust, etc
Aperture	14.6 in diameter, shared between 4 antennas	Larger than Pulse-Doppler Radar	4.8 in diameter, shared between 4 units
TRL (components)	6 (6+) (MSL will take to TRL-8 by 2008)	3 (5)	2 (4)
Development time to TRL 6	None	≥ 14 months	≥ 25 months

Based on the analysis, it was determined that the Pulse-Doppler Radar with an IMU is the only existing option that could meet the requirements. Although the Pulse-Doppler Radar is the most technologically mature option, it has the highest mass, volume, and power of the three options. Furthermore, use of the IMU introduces additional errors and faults into the system.

Two potential developments were also identified: FMCW Radar and Hybrid Lidar. Of these options, the FMCW Radar is the lowest risk option based on a better technological understanding of the design and its shorter development timeline. Furthermore, it provides the weather robustness of a radar, but is a lower mass option with a lower operating range than the Pulse-Doppler Radar. However, development of the FMCW Radar to TRL-6 would exceed the Orion PDR date by almost a year.

The Hybrid Lidar provides an even greater mass, volume, and power savings over the radar options. In addition, for the rocket landing system option with a retained heat shield, the lidar option results in a smaller FOV than the radar, which results in a smaller blowout port. However, dust, dense fog, and heavy rain may disrupt the Doppler velocity measurement, and blowing snow may disrupt both the altitude and velocity measurements. Furthermore, the lidar is the highest risk development option because there are more unknowns in the development of the Doppler portion of the lidar. In addition, the development timeline to TRL-6 exceeds the Orion PDR date by well over a year. It should be noted that since the completion of this trade study, the Orion PDR has been pushed back to September 2008. Despite the additional time, neither the FMCW radar or Hybrid Lidar can be developed in time, so the conclusions of this trade study still apply.

The trade between these three options is dependent on three main drivers:

(1) Orion mass and volume constraints

(2) Orion funding and schedule

(3) Atmospheric and weather requirements

Because of the larger scope of these issues, 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. If there is not flexibility in the TDS being a TRL-6 by the Orion PDR, then the only option available is the Pulse-Doppler Radar. However, if there is some flexibility with this as well as available funding for technology development, then lower mass options like the FMCW Radar and Hybrid Lidar can be added to the trade space. In addition, definition of atmospheric and weather requirements such as dust and fog opacity during descent is required to understand the impact it may have on the Hybrid Lidar sensor.

ACKNOWLEDGEMENTS

This report is a compilation of work performed by many people at NASA Jet Propulsion Laboratory (JPL) and Ball Aerospace in Boulder, CO. Team members at JPL include Dan Chang, Ed Konefat, Curtis Padgett, Brian Pollard, George Purcell, and John South. Team members at Ball Aerospace include Jim Masciarelli, Ian Gravseth, Chris Grund, Tim Morris, and Matt Verbeke. The authors would also like to thank the Orion retro-rocket landing system team members at JPL (Josh St. Vaughn, Colleen Marrese-Reading, Guru Singh, Bob Frisbee) for their help throughout this trade study, Dave Pierce of ATK for the CAD drawings, and Jim Corliss of NASA Langley Research Center for his oversight during the trade study.

The research described in this publication was carried out at the Jet Propulsion Laboratory, California Institute of Technology, under a contract with the National Aeronautics and Space Administration.

References

[1] Prakash, R., Dunn, C., *Orion Landing System Terminal Descent Sensor Trade Study,* NASA TM in print, 2007.

[2] St. Vaughn, J., Singh, G., Prakash, R., Frisbee, R., Corliss, J., Tutterow, R., *Design of a Retro Rocket Earth Landing System for the Orion Spacecraft*, IEEE 1513, IEEE Aerospace Conference, Big Sky, MT, March 3-10, 2007.

[3] Wilkins, F., et al., *A Study to Select Optimum Altitude Sensing Devices*, Sylvania Report No. A58-4-5. 0-17, Volume 1 of 2, May 1963.

[4] Lands, J.F., *Development of a Terminal Landing Rocket System for Apollo-Type Vehicles*, Journal of Spacecraft, Vol. 4, No. 3, pg. 333-338, March 1967.

[5] Rogers, W.F., Apollo Experience Report – Lunar Module Landing Gear Subsystem, NASA TN D-6850, June 1972.

[6] Petro, A., *Soyuz TM and Progress M Spacecraft Technical Summary*, NASA Johnson Space Center (Contains Russian Proprietary Information).

[7] B. Pollard, A. Berkun, M. Tope, C. Andricos, J. Okonek, and Y. Lou, *Ka-band Radar Terminal Descent Sensor*, NASA Tech Brief NPO-44462.

[8] Garmin: *What is WAAS?*, http://www8.garmin.com/aboutGPS/waas.html, visited June 11, 2007.

Biography

Catherine (Katie) Dunn *is a Systems Engineer in the Surface Systems Engineering Group at the Jet Propulsion Laboratory. She has worked on the Multi-Mission System Architecture Project (MSAP), an effort at JPL to create a reusable spacecraft bus. She switched gears and began working on the Orion vehicle while participating in this study. Continuing her work on Orion, she went on to work on the Thermal Protection System (TPS) Verification and Validation Plan for the TPS Advanced Development Project (ADP). Most recently, she has switched gears again and joined the Surface System Engineering team on the Mars Phoenix project at JPL. She looks forward to the spacecraft's touch down on Mars in May of 2008. When not at work, Katie enjoys singing with the CalTech Glee Club and climbing mountains in the Sierra Nevadas.*

Ravi Prakash *is a Systems Engineer at the Jet Propulsion Laboratory working in the Entry, Descent, and Landing Systems and Advanced Technologies group. He participated in the NESC Land vs. Water landing study for the Orion spacecraft and was involved in the design of various aspects of the Orion vehicle including the heatshield separation system and retro-rocket landing system. Currently, Ravi is on the Mars Science Laboratory team working on various aspects of the EDL system. He has a B.S. in Aerospace Engineering from The University of Texas at Austin and a M.S. in Aerospace Engineering from the Georgia Institute of Technology.*