AUTONOMOUS LOW COST PRECISION LANDER FOR LUNAR EXPLORATION. J. N. Head[1], G. V. Hoppa[1], T. G. Gardner[1], K. S. Seybold[1], and T. Svitek[2], [1]Raytheon, 1151 E Hermans Rd., P.O. Box 11337, Bldg. 848, M/S 6, Tucson, AZ 85734. [2]Stellar Exploration, 4574 Spanish Oaks Dr., San Luis Obispo, CA 93401.

Introduction: For 60 years the US Defense Department has invested heavily in producing small, low mass, precision guided vehicles. The technologies matured under these programs include terrain-aided guidance and navigation, closed loop terminal guidance algorithms, robust autopilots, high thrust-to-weight propulsion systems, autonomous mission management software, sensors, vehicle state estimation, and data fusion. These technologies will aid NASA in addressing the requirements flowing from the Vision for Space Exploration articulated in January 2004 as well as New Millennium Science and Technology. Establishing and resupplying a long term lunar presence will require automated landing precision not demonstrated to date. Precision landing (CEP < 10 m) will allow the targeting of scientifically interesting locations heretofore off-limits due to vehicle safety and mission success concerns. In the DOD world, precision guidance and the associated enabling technologies are used routinely and reliably. Hence, it is timely to generate a point design based on these mature technologies for a precise planetary lander useful for lunar exploration. In this design science instruments amount to 10 kg, 16% of the lander vehicle mass. This compares favorably with 7% for *Mars Pathfinder* and less than 15% for *Surveyor.*

Mission Design: The mission chosen for this point design is a landing at the lunar South Pole. The scientific rationale is the analysis of the putative volatiles such as H_2O, D/H, CO, CO_2, NH_3, CH_4, HCN, and other molecules including organics. Such an analysis would provide insight into asteroid or comet composition and the delivery of volatiles throughout the inner solar system. The engineering rationale include 1) airless bodies are easier to manage from a control standpoint, 2) the moon's proximity minimizes operations in the space radiation environment, and 3) choosing a landing zone achievable only with precision landing.

Cruise and Landing. The mission design entails sending the lander with a Star-17A solid motor and a cruise stage (with the lander in an inert configuration) to the moon. The cruise stage is used for power and TCMs. The total mass of the stack at TLI is ~260 kg, current best estimate (CBE). The lander activates about a minute before impact. The CBE lander mass at separation is approximately 64 kg. A solid booster burn reduces the vehicle speed to 300-450 m/s. The lander is now about 2 minutes from touchdown and has 600 to 700 m/s delta-v capability, allowing for ~10 km of vehicle divert during terminal descent. The lander propulsion system is derived from missile defense systems. Terminal guidance is optical, allowing the vehicle to navigate independently of the geodetic grid, thus countering the deleterious effects of the known large errors in the lunar grid (up to 15 km). Inertial navigation and a radar altimeter provide the data required to guide the vehicle to a safe landing in a permanently shadowed crater. The vehicle concept is depicted in Figure 1.

The concept of operations outlined here closely mimics missile operational timelines used for decades and is chosen for that reason: the vehicle remains inert in a challenging environment, and then must execute its mission flawlessly on a moment's notice. The vehicle mechanical design consists of a re-plumbed propulsion system, using propellant tanks and thrusters from exoatmospheric programs. A redesigned truss provides hard points for landing gear, electronics, power supply, and science instruments. A radar altimeter and a Digital Scene Matching Area Correlator (DSMAC) provide data for the terminal guidance algorithms. DSMAC—fielded on DOD platforms for decades—acquires high-resolution images for real-time correlation with a reference map. This system provides ownship position with a precision proportional to the reference map resolution and does not require global mapping at high resolution. Assuming the reference map is derived from *Clementine* data, the expected landing precision is 100 meters. LRO maps of the poles would improve this precision considerably.

Since the DSMAC can sample at 1.5 mrad, any imaging acquired below 70 km altitude will surpass the resolution available from previous missions. The DSMAC has an operational mode where image data are compressed and downlinked. This capability could be used to downlink live images during terminal approach and landing. Approximately 500 kbps telemetry would be required to provide 100% overlap for stereo. The downlinked data would comprise the first live descent imaging sequence since *Ranger*. This would provide unique geologic context imaging for the landing site.

Science Operations: The DSMAC has the flexibility to acquire timed exposures after landing. A 100 second exposure should be adequate to produce a good image of the landing crater illuminated only by the crescent earth. Science operations are powered by a Li-ion battery pack providing over 700 W-hr after landing. This can provide 10 hours of science operations in darkness at 40 K.

Development: The development path to produce such a vehicle is that used to develop tactical missiles. First, a pathfinder vehicle is designed and built as a test bed for hardware integration including science instruments. Second, a hover test vehicle would be built. Equipped with mass mockups for the science payload, the vehicle would otherwise be an exact copy of the flight vehicle, but flown on Earth to demonstrate the proper function and integration of the propulsion system, autopilots, navigation algorithms, and guidance sensors. There is sufficient delta-v in the proposed design to take off from the ground, fly a ballistic arc to over 100 m altitude, then guide to a precision soft landing. Hover testing already is done in an enclosed volume for DOD exoatmospheric vehicles. Once the vehicle has flown safely on earth, then the validated design would be used to produce the flight vehicle.

Extensibility: The vehicle described above is a point design for a lunar mission. A choice of an illuminated landing site would allow the substitution of solar power for batteries. In addition, the optical guidance system could acquire images all the way to touchdown.

Europa. Since Europa is similar in size and mass to the moon, this lander concept is directly applicable. The baseline mass is consistent with the JIMO payload.

Mercury. The proposed landing vehicle is modular and scalable. Doubling the lander fuel tanks increases the lander delta-v by ~400 m/sec (Figure 2.) Though the delta-v from the solid motor burn is reduced, this combination would allow a precision landing from low (300 x 300 km) Mercury orbit. Hence, a slightly more massive stack delivered to such an orbit would be capable of a precision landing at the Hermian poles.

Mars. Uncertainties in the atmospheric density at the time and location of entry contribute greatly to the landing error ellipse at Mars. If the atmosphere can be well characterized, or the entry can be guided to a 10-20 km precision, then the proposed design should prove readily adaptable to the Martian environment. With guided entry precision landing would be achieved by increasing the divert capability of the lander itself. Given the high resolution maps available for potential Martian landing sites, it should be possible to target such interesting locations as volcanic calderas, canyon bottoms, or the cut bank of a meandering channel. Specific outcrops could be targeted, lowering the mobility requirements for the landed system. All that is required is a small landing zone certified clear of hazards near the scientific target.

Small Bodies. Asteroids and comets could be targeted with the same precision, though the reference maps would likely be made during a reconnaissance phase of the mission (*cf.* NEAR).

Conclusion. Mature exploration enabling technologies exist and are adaptable to the precision landing problem. Besides allowing crewed mission support such as automated prepositioning, precision landing opens new regions of planetary bodies for scientific exploration. We have shown this with a point design for landing in a permanently shadowed crater on the moon. Since this leverages the billions of dollars DOD has invested in these technologies, it should be possible to land useful science payloads precisely at relatively low cost.

Acknowledgements: Greg Longerich, Joseph Garcia-Alfieri, Thomas Lee.

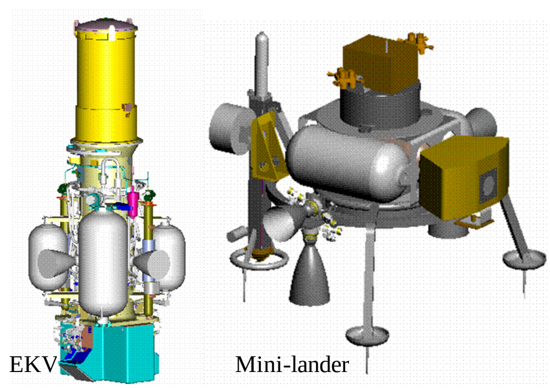

Figure 1. Raytheon concept for a missile defense-derived lunar lander. Common components include tanks and thrusters. Lander science payload of 10 kg includes optical and radar guidance sensors.

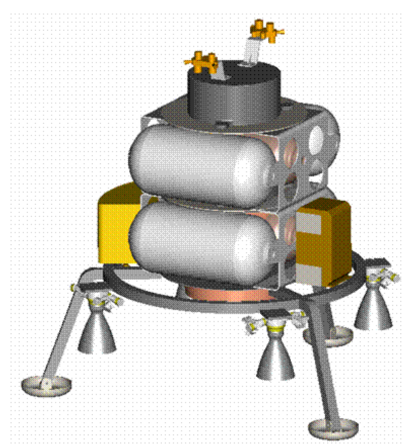

Figure 2. Scaled-up lander with ~1100 m/sec delta-v.