THE MEASUREMENT OF THE SHAPE AND ROTATION OF APOPHIS.

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Introduction: At the Apophis T-9 Years Workshop in 2020 we presented a mission concept [1] that would rendezvous with Apophis prior to Earth encounter, conduct a series of range measurements to the body with a Swath Mapping Lidar and surface reflectors, and continue making measurements in the proximity of Apophis for several years. In this paper we describe the primary instrument, the Small All-Range Lidar (SALi) [2, 3] that is currently under development.

The SALi Instrument: SALi is a small lidar with a ranging ability of 10 cm and a 2x8 swath with a footprint beam divergence of 60 urad (0.6 m from 10 km) specifically designed for missions to small planetary bodies for topographic mapping and support of sample collection or landing. The instrument has a wide dynamic range with several modes of operation for different distances to the target, from 500 km to near zero. The laser transmitter consists of a fiber laser that is intensity modulated with a return-to-zero pseudo-noise (RZPN) code. The receiver detects the coded pulse-train by correlating the detected signal with the RZPN kernel enabling the use of a low peak-power, high pulse-rate fiber laser for long-distance ranging. (Table 1).

Av. laser power	2 W
Laser wavelength	1.5 µm
Beam divergence	120x480 µrad
Transmit efficiency	90%
Receiver telescope	6.4 cm diam
Receiver instantaneous field of view	60x60 µrad
Number of pixels	2x8
Receiver bandwidth	1.8 µm
Optical transmission	60%
Detector quantum efficiency	50%
Detector dark count	250,000/s
Estmated instrument size	29x28x11 cm
Estmated instrument mass	10 kg
Estimated power	70 W

Table 1 *SALi Instrument Parameters* [2].

The laser power and the internal gain of the detector can both be adjusted to give a wide measurement dynamic range. The laser modulation code pattern can also be reconfigured in orbit to optimize measurements to different measurement environments. The receiver uses a multi-pixel linear mode photon-counting HgCdTe avalanche photodiode (APD) array with near quantum limited sensitivity at near to mid-infrared wavelengths.

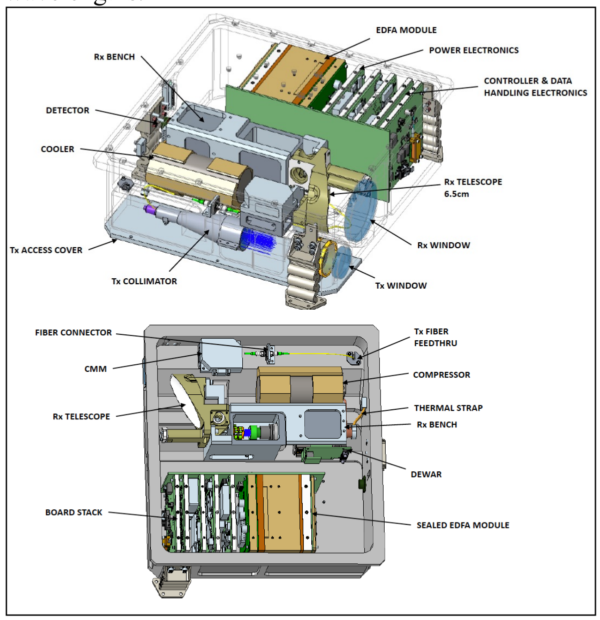

Figure 1. *Small All-Range Lidar (SALi).*

Lidar Parameter	Initial Survey	Mid-Altitude Mapping	Descent and landing
Operation Mode	Single pixel coarse ranging	8-16 pixels precision ranging	16-pixel flash lidar
Range	500-50 km	5-10 km	10 km -1 m
Apriori Uncertainty	±20 km	±200 m	±20 m
Max range rate uncertainty from orbit prediction	<0.25m/s	<0.1 m/s	<0.5
Range rate from topography	1 m/s	1 m/s	-
Measurement rate	0.1 to 1 Hz	1 to 100 Hz	10 to 100 Hz
Range precision and accuracy	10 m	0.2 m	0.05 m
Laser footprint diameter	<100 m from 500 km	6 m at 50 km	N/A
Surface reflectance accuracy	±20%	±5%	N/A

Table 2 *Performance capabilities of SALi for 3 example operational modes* [3].

The parameters describing the performance in three different operational modes shown in Table 2 are examples of how the instrument can be used, depending on the goal of the measurements.

The range precision and probability of detection of measurements that SALI is designed to achieve are shown in Figure 2 for various distances from Apophis and lighting conditions. Further, the ability of SALi to operate down to the surface makes it possible to deploy instruments and equipment to a precise location on the surface at minimal impact velocity.

For Apophis, we propose the deployment of a number of reflector arrays that would help define its basic shape and Apophis's rotation at the centimeter level, detect any small (1 cm) displacements as a result of the encounter; and be able to conduct these measurements from distances up to 500 km with SALi.

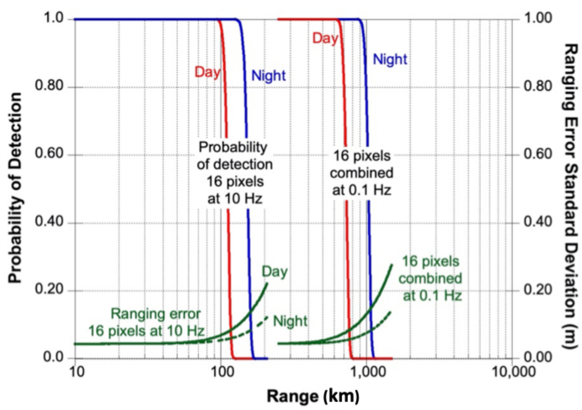

Figure 2. *Probability of detection and ranging error.*

Figure 2 indicates observations will be achievable from 1000 km altitude at the 5-10 cm level precision. If small reflectors [4] are deployed to the surface as described below they will provide a much stronger than the surface of the asteroid. Therefore, the ranging performance will be much better than shown in Fig. 2, making it possible to achieve cm level precision after averaging a number of measurements from 10's km distance.

Small Reflectors: The deployment of small reflectors as shown in Figure 3 from a spacecraft, such as OSIRIS-REx [5] with close approach capability, would significantly improve the ability to monitor the dynamical behavior of Apophis at the centimeter level. Deployed several months ahead of closest approach SALi could derive the detailed shape of Apophis well before the encounter and continue to observe the asteroid's behavior during and after encounter for several years as it orbits the Sun.

NASA is currently providing the reflector arrays shown in Fig.3 to many commercial and international lunar landers. If deployed on Apophis they would act as stable geodetic markers for decades, enabling tracking for the foreseeable future, and from much larger distances. Single-beam laser tracking system would be sufficient to achieve a high level of precision, limited primarily by the knowledge of the spacecraft hosting the laser system.

Figure 3. *The small low mass reflector arrays that are presently being deployed on international and commercial landers to the Moon* [4].

Conclusions: The SALi instrument currently in development has been designed to operate in the vicinity of small bodies and asteroids. Its ability to make distance measurements from ~1000 km to near zero range enables the host spacecraft to continuously monitor its approach to the surface and deploy many small laser reflectors or other equipment to desired locations, enabling the precision tracking of Apophis from large distances and monitor Apophis' behavior.

References:

[1] Smith, D. E. et al., (2020) Apophis T–9 Years: Knowledge of Opportunities for the Science of Planetary Defense. Abs #2003. [2] X. Sun, D. R. Cremons, E. Mazarico, G. Yang, J. B. Abshire, D. E. Smith, M. T. Zuber, M. Storm, N. Martin, J. Hwang, J. D. Beck, N. R. Huntoon, and D. M. Rawlings, "Small All-range Lidar for asteroid and comet core missions," Sensors, Vol. 21, 3081, May 2021, https://doi.org/10.3390/s21093081. [3] D. R. Cremons, X. Sun, J. B. Abshire, and E. Mazarico, "Small PN-code lidar for asteroid and comet missions -receiver processing and performance simulations," Remote Sensing, Vol. 13, 2282, June 2021, https://doi.org/10.3390/rs1312228. [4] Sun, X., et al. Applied Optics, (2019) https://dx.doi.org./10.1364. [5] NASA Press Release 11-163, (2011).