NAAKI: A TWIN CUBESAT MISSION TO THE MOON. M. P. Milazzo[1,⋆], T. Stone[1], J. Heynssens[2], P. Flikkema[2], I. Daubar[3], A. Springmann[4]; [1]Astrogeology Science Center, U.S. Geological Survey, Flagstaff, AZ, [2]Northern Arizona University, Flagstaff, AZ, [3]NASA Postdoctoral Program Fellow; Jet Propulsion Laboratory, California Institute of Technology, Pasadena, CA, [4]University of Arizona, Tucson, AZ; ⋆moses@usgs.gov

Introduction: NASA's Small, Innovative Missions for Planetary Exploration (SIMPLEx) solicitation calls for CubeSat [1] missions for non-terrestrial and non-solar science with a lifetime cost of less than $\$5.6M$. Interplanetary missions are encouraged. Here we describe a mission concept to the Moon to improve our understanding of its surface photometry as well as to monitor the near-Earth impact flux.

The Naaki (the Navajo word for "two") mission concept is to send two identical 3U (30-cm x 10-cm x 10-cm) CubeSats (named "Ooljee" and "Muuyaw", from the Navajo and Hopi words for the Moon, respectively) into complimentary, 20,000-km orbits (for $\sim$1.7-km/pixel ground scale with a $10°$ Field of View (FOV)) of the Moon for full-disk observations. These full-disk observations would be used to meet two main science mission goals (plus others based on possible Science Enhancement Opportunities).

Science Objectives: The Naaki mission concept meets several of the 2013 Planetary Science Decadal Survey [2] (Table 1).

Table 1: Decadal Survey Science Questions/Goals addressed by Naaki:

Goal	Measurement
Characterize planetary surfaces	Surface scattering via photometric response survey
Characterize surface modification process	Photometric changes
Understand recent impact flux of inner solar system	Impact flash monitoring

Impactor Flux Monitoring: The Naaki science mission would include monitoring of the lunar impact flux via "full-disc" night-side observations. These observations would be intended to catch lunar impactor flashes. Major observing campaigns would be conducted during major meteor shower events, such as the Leonids, which have been shown to cause impact flashes [10]. The Lunar Reconnaissance Orbiter Camera (LROC) has identified at least 547 Low Reflectance Changes (LRCs) and 48 High Reflectance Changes (HRCs) that suggest a minimum impact rate of 364,000 new craters per year [11], although it is not clear how many of these are primaries and how many are secondaries. We do not propose that Naaki would be able to observe these changes but would rather help constrain the impact flux by monitoring night-time impact flash occurrences. There have been several Earth-based impact flash monitoring campaigns *c.f.* [12, 13, 14, 15], though these campaigns suffer from viewing opportunities limited to the near-side and lunar phase of 10% to 50% for various reasons. Naaki's observations would not be limited in such a manner and could observe the entire moon and during every nighttime pass and every lunar phase, as desired. Two satellites observing with different viewing geometries will greatly improve false positive rejection, location determination, and flash brightness determination and thus energy release estimates.

Photometric Observations: Photometric normalization of surface images is required to achieve highly accurate mapping of various scientifically interesting properties of the lunar surface *c.f.*, [3, 4, 5, 6]. Lunar observing geometries would be such that simultaneous observations of the illuminated (same incidence angle) disk would be taken from different phase angles. During the lifetime of the mission, the spacecraft would also migrate through varying incidence angles, for a full suite of photometric observations, providing for the first time full phase and incidence angle coverage of the entire Moon. The USGS's Robotic Lunar Observatory (ROLO) [7, 8] has obtained photometric observations of the Moon over the spectral range appropriate for Earth-observing as well as interplanetary satellites ($0.347 - 2.39\mu m$) and over solar phase angles of $1.55° - 97°$. Naaki's observations would extend these photometric studies (possibly at a slightly reduced spectral range and resolution) to the entire Moon. A wavelength-dependent visible and infrared spectrophotometric function for two lunar terrain end-members: highlands and maria was derived by [9]. Naaki's observations would allow the ground-truth-constrained ROLO observations to be extended to all regions on the far side of the Moon, thus allowing derivations such as that by [9] to be extended to more terrain types across the full surface of the Moon.

The purpose of having two satellites observing simultaneously is that never before has the entire lunar surface been mapped with simultaneous observations from two differing phase angles. Obtaining simultaneous observations at differing phase angles reduces the likelihood of losing phase angle coverage due to complications, provides incidence-angle-independence for at least two phase angles at a time over the entire photometry study, and . In addition, observations from multiple viewing geometries significantly decreases the required mission lifetime; the suite of phase angles will be covered in far shorter time with minimally increased cost (major costs will be development and operations).

Mission Design: To be consistent with CubeSat ideals and to save on costs, this mission would be designed, built, and operated by university students (graduate and undergraduate) at Northern Arizona University (NAU) in Flagstaff, AZ and The University of Arizona (U of A) in Tucson, AZ. The students would operate under supervision by professors at NAU and researchers at the U.S. Geological Survey Astrogeology Science Center (ASC) in Flagstaff, and at the Jet Propulsion Laboratory (JPL) in Pasadena, CA. The spacecraft would be launched with NASA's EM-1 mission in 2018 or with another mission as the opportunity arises. The twin spacecraft would consist of Commercial Off-The-Shelf (COTS) components modified at NAU as necessary to meet specific mission goals and requirements. The mission components will include a 3-axis (star tracker and reaction wheels) attitude and control system (ACS), an X-Band radio and antenna, an EPS and battery (40Wh), thermal control, fixed and deployable solar array, and a camera with spectral sensitivity in the visible to near infrared and with a 10° FOV.

Engineering Innovations: To date, there have been no interplanetary CubeSat or other micro-satellite missions, so simply moving a CubeSat beyond LEO could be considered innovative. However, there are several proposed or actively developed interplanetary CubeSat missions *e.g.*, [16, 17], which include innovative operations, communications, propulsion, and navigation technologies. Our mission's innovative technologies will include modifications to the reaction wheel ACS to allow momentum dumping with other than mass expulsion (NASA is understandably reluctant to allow compressed gas containers on secondary payloads such as CubeSats) or magnetic control torques (the Moon has a negligible magnetic field). That stated, if allowed by NASA, the mission would include a small store of Xe or other noble gas for micro ion drive propulsion. If an ion drive is not approved, solar sails will likely be the method used for Lunar orbit insertion.

In addition, utilizing two CubeSats in Lunar orbit may allow us to experiment with lunar communications infrastructure. For example, if one of the two satellites is placed in a polar, terminator-following orbit, while performing its science mission duties it could also act as a relay for the second satellite when the it is unable to view the Earth.

Complications for Interplanetary Missions: As already noted, there are several complications with small satellites operating in interplanetary space. These include: *Communications:* The only communications station currently readily capable of communicating with a small spacecraft at Lunar distances is the Deep Space Network (DSN), but its costs are very nearly prohibitive for a small, low-cost mission such as allowed by the SIMPLEx solicitation. The INSPIRE mission [16] design includes developing innovative communications technologies, including the potential use of Arecibo as a communications link, but it is not clear that such communications technology would be ready for a lunar-orbiting CubeSat science mission on the timescale of the SIMPLEx/Naaki's mission goals. *Navigation and Propulsion:* A 3-axis ACS is available COTS, but desaturation of CubeSat reaction wheels in lunar orbit requires a momentum dumping mechanism other than magnetic torquing or mass expulsion. We are investigating modifying a COTS reaction wheel module to allow electrical braking (and battery charge regeneration) as a mechanism for converting rotational momentum into electrical potential and ultimately using this for reaction wheel desaturation. Another reaction wheel desaturation technique may be to deploy solar sails when necessary to provide the required torques. *Radiation Protection:* The low-cost, low-mass goals for CubeSat missions requires use of COTS components that may not have been adequately proven space-worthy. It may be cheaper and more effective to shield the entirety of the spacecraft (with the exception of the camera lens and the ion drive if included) than to attempt to shield or radiation harden each component separately. We are considering this as the likely radiation shielding method for the Naaki spacecraft. Hydrogen-rich materials such as polyethylene provide effective shielding [18], though aluminum CubeSat external shielding panels are readily available. The particular shielding material used will depend on further investigations.

Conclusions: Naaki offers an unprecedented CubeSat mission concept to monitor the lunar impactor flux on both the near- and far-sides of the Moon, to provide greatly improved coverage in both phase angle and time for photometric studies of the lunar surface and for large scale photometric changes of the Moon. The CubeSat mission model offers exceptional opportunities to university students as well as early-career researchers, of which the Naaki mission concept takes full-advantage, providing multiple lunar science goals at low-cost ($< \$5.6M$).

References:

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