STATE OF SMALL INSTRUMENTS FOR NANO-SPACECRAFT APPLICATIONS – A REVIEW. J. C. Castillo-Rogez, S. M. Feldman, J. D. Baker, G. Vane, Jet Propulsion Laboratory, California Institute of Technology, 4800 Oak Grove Drive, Pasadena, CA 91109.

Introduction: Nano-platforms, in the 1-10 kg range, are gaining maturity for deep space exploration thanks to increased investments from various space agencies into miniaturized subsystems and instruments. The last decade has seen the introduction of small platforms such as JAXA's Minerva hopper and the MASCOT (Mobile Asteroid Surface Scout) [1] developed by the German Space Agency (DLR), both of which are flying on the Hayabusa 2. Rover missions to Mars developed by NASA (e.g., Pathfinder, Mars Exploration Rovers, Mars Science Laboratory) and ESA (Beagle 2, Huygens, Rosetta's Philae, ExoMars) have fostered the development of small instruments some of which can be leveraged on future nano-spacecraft. NASA's recent focus on Cubesat have led to the development of a reference 3U bus (INSPIRE, Interplanetary Nanospacecraft Pathfinder in Relevant Environment, [2]) and a 6U bus (NEAScout and Lunar Flashlight missions, MSFC/JPL [3]) developed under the sponsorship of the Advanced Exploration Systems (HEOMD). The growing interest across the community for Cubesats and other nanosatellites for deep space exploration requires the availability of small instruments that can be easily implemented on these platforms and yet remain performant.

We review the current state of the art in small instruments that may be applicable to future missions involving independent or deployable platforms in the 1-10 kg range. We first highlight instruments inherited from past missions and then address requirements and way forward for the development of future small instrument.

Framework: Nano-spacecrafts open a new dimension in planetary exploration with the introduction of new architectures that carry the potential to increase science return at low cost: distributed network, complementary vantage point between mothership and daughterships, expandable assets for the exploration of high-risk areas (e.g., cometary plumes) [4]. An obvious trade to the low scale and cost of these platforms is a degradation in science data quality and quantity in comparison to the science return of larger missions, which the planetary science community is used to.

Mass and power are obvious limitations intrinsic to nano-spacecraft. Smaller detectors and apertures generally imply degraded spectral resolution and spatial resolution; the latter may be compensated for by flying the spacecraft closer to the target.

Short lifetime and limited data rates require science to be returned shortly following acquisition. Operational complexity, associated for example with material sampling and processing, or calibration, may simply preclude the implementation of certain measurement techniques into small spacecraft. As the field of miniaturized instruments progresses, it will be important to consider new ways of implementing old techniques. This is expecially true for optical instruments which could benefit greatly from the most recent technological advances enabling miniaturization, for example computational methods, on-chip spectrometers, and new semiconductor-based devices.

State of the Art in Small Instruments: A review of instruments that have flown on past and current missions shows the availability of a spectrum of geophysical and fields and particles instruments (seismometers, penetrometers, thermal probes, particle detectors, etc.); only a few optical and spectrometer instruments are available in a small form factor, including visible cameras (e.g., NEAScout imaging system [3]), ultraviolet sensors [5], new generation of small IR-spectrometer such as the Lunar Flashlight point spectrometer [6], the LunarCubes' BIRCHES [7], as well as micro-bolometers; a few analytical chemistry instruments have already been demonstrated on small landers, such as alpha-particle X-ray spectrometer [8] and gas chromatograph-mass spectrometer [9]. More advanced spectrometers for chemical measurements, especially isotopes, typically require larger platforms, especially when solid material sampling and processing is required. However a new class of miniaturized mass spectrometers (e.g., JPL's quadrupole ion trap mass spectrometers [10]) will open up possibilities in atmospheric sampling with small probes [11]. Tunable laser spectrometers have seen a huge success in recent years, with the tunable laser spectrometer (TLS) on Curiosity, capable of measuring gas abundances and isotope ratios to extremely high precision [12]. Pathways exist for further miniaturization, and instruments targetting specific gases and isoptope ratios (e.g., D/H in H_2O) could be designed to fit on small platforms. These instruments could, for example, sample cometary plumes, or deploy mechanisms for surface heating and gas capture on icy bodies. Key technological gaps have been identified in the area of radar instruments, although novel approaches such as passive radio experiments should enable probing deep interiors with small spacecraft from orbit or even during flybys [13].

Many instruments required for addressing strategic knowledge gaps at Near Earth Asteroids and Mars' moons are already small enough to be deployed on small spacecraft as is illustrated by recent Cubesat concepts: NEAScout [3] and the Hedgehog platform currently developed under NASA's Space Technology Mission Directorate [14].

Emerging Technologies for the Next Generation of Small Instruments:

- Advanced detector technologies, for example the HOTBIRD (High Operating Temperature Barrier Infrared Detector [15]), enables instrument miniaturization without loss of performance.
- Increased aperture, for example in the context of Cubesat-based exoplanet search and characterization; origami-inspired deployable optics have been recently introduced as a promising approach [16].
- Increased on-board intelligence can help optimize science return when lifetime and downlink resources are tight and/or when observing opportunities are time constrained, e.g., in the case of a flyby or impacting experiment. Agile Science algorithms [17] can help optimize science return via on-board data processing, compression, and triage.
- Deployment mechanisms: low-cost nano-spacecraft should ideally avoid the number and complexity of internal mechanisms. However deployable booms have been recently introduced, for example for the INSPIRE magnetometer and RainCube Ka-band radar mission [18].
- Smart configuration of the lander may help optimize the shielding of electronics [19], as well as relax operational requirements, e.g., thermal control
- Low-temperature electronics would be suitable in order to relax requirements on thermal control.
- Smart packaging, for example foldable electronics, can help to significantly decrease instrument volume.
- The development of standard instrument interfaces will also be instrumental to the introduction of reference nano-spacecraft flight systems that may be considered for a variety of missions.

Environment Specific Requirements: The availability of small instruments for future small-class deployable platforms at Europa is limited to fields and particles. High-g investigations (penetrators) set requirements on instrument survivability that may be out of reach from the current generation of instruments, except for seismometers [20]. Significant tailoring to high-radiation, atmospheric, or in situ environments may conflict with the perception that nano-spacecraft, and especially Cubesats, may offer reference platforms for plug and play experiments.

Acknowledgements: This study is being developed at the Jet Propulsion Laboratory, California Institute of Technology, under contract to NASA.

References: [1] Jaumann, R. (2013) LPS 44, 1500. [2] Klesh, A., et al. (2013) *Proc. 27th Annual AIAA/USU Conference on Small Satellites*. [3] Castillo-Rogez, J. C., et al. (2016) NASA Exploration Science Forum, https://ac.arc.nasa.gov/p82b7is9fqr/. [4] Klesh, A., Castillo-Rogez, J. (2012) *Proc. Space 2012 Conference*. [5] Ishimaru, R., et al. (2016) This Conference. [6] Cohen, B., et al. (2014) NASA Exploration Science Forum. [7] Clark, P. E., et al. (2016) This conference. [8] Foley, C., et al. (2003) *J. Geophys. Res.* 108, E12. [9] Raulin, F., et al. (1989) *Origins of Life and Evolution of the Biosphere* 19, 497-498. [10] Madzunkov, S. M., Nikolic, D. (2014) J. Am. Soc. Mass. Spectrom. 25, 1841-1852. [11] Darrach, M., et al. (2015) Workshop on Harsh-Environment Mass Spectrometry, http://www.hems-workshop.org/10thWS/Talks/Durrach.pdf; [12] Webster, C.R. et al. (2014) "Tunable Laser Spectrometers For Space Science", *Instrumentation for Planetary Mission Workshop* 2014. [13] Romero-Wolf, A., et al. (2014) eprint arXiv:1404.1876. [14] Pavone, M., et al. (2013) *Proc. IEEE Aerospace Conference* 2013. [15] Ting, D. Z.−Y., et al. (2011) In: *Semiconductors and Semimetals* 84, 1–57, Eds. S.D. Gunapala, D.R. Rhiger, and C. Jagadish, Elsevier, Amsterdam. [16] Marchis, F., (2014) SPIE Astronomical Telescopes+Instrumentation Conference, #9143-128. [17] Thompson, D. R. (2012) SpaceOps http://ml.jpl.nasa.gov/papers/thompson/Thompson_2012_SpaceOps.pdf. [18] Sauder, J., et al. (2015) 29th Annual AIAA/USU Conference on Small Satellites, SSC15-VI-7. [19] Castillo-Rogez, J. C. (2013) *Low-Cost Planetary Mission Workshop*, http://lcpm10.caltech.edu/pdf/session-6/3_LCPM10-Castillo_Final.pdf. [20] Gowen, R. A., et al. (2011) *Adv. Space Res.* 48, 725-742.