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Lunar and interplanetary laser ranging

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There are laser retroreflector arrays (LRAs) on the Moon since 50+ years ago (deployed by Apollo and Luna missions). There were no laser retroreflectors on Mars until microreflectors (of ~25 gr mass) were recently deployed on Mars (deployed by the InSight and Perseverance missions). These instruments are positioned using specialized ephemeris software (Planetary Ephemeris Program, from the Harvard-Smithsonian Center for Astrophysics) and data acquired with the Satellite or Lunar Laser Ranging (SLR/LLR) technique by the International Laser Ranging Service (ILRS, ilrs.gsfc.nasa.gov, part of the IAG) or by orbiting spacecrafts, like NASA's Lunar Reconnaissance Orbiter (LRO, equipped with a laser altimeter). Examples of LLR station are the French station in Grasse, the US station, APOLLO (Apache Point Lunar Laser-ranging Operation) and MLRO, the Matera Laser Ranging Observatory of the Italian Space Agency. SLR, LLR and their interplanetary equivalents at the Mars system (and, in the future, beyond) enable accurate tests of relativistic gravity, establishing reliable planetary geodetic reference frames, interesting studies of planetary interiors and support planetary exploration.
For 50+ years LLR to Apollo/Lunokhod LRAs supplied accurate tests of General Relativity (GR) and new gravitational physics: possible changes of the gravitational constant Gdot/G, weak and strong equivalence principle, gravitational self-energy (post Newtonian parameter beta), geodetic precession, inverse-square force-law (Williams 2006, Dell'Agnello 2009, Currie 2013, Dell'Agnello 2018), spacetime torsion (March 2011-1, 2) and nonminimally coupled gravity (March 2017, March 2013). LLR has also provided significant information on the composition of the deep interior of the Moon, complementary to that of NASA's mission GRAIL (Gravity Recovery And Lunar Interior Laboratory). In fact, already in the later 1990s LLR first provided evidence of the existence of a fluid component of the deep lunar interior (Williams 2006), confirmed later by a re-analysis of Apollo lunar seismometry data in 2011 (Weber 2011). Therefore, lunar LRAs form the first realization of a passive Lunar Geophysical Network (LGN) for lunar science, exploration and precisions tests of GR (LGN-LPSC 2019).
In 1969 LRAs contributed a negligible fraction of the LLR error budget. Since laser station range accuracy improved by more than a factor 100, now, because of lunar librations, the lunar LRAs dominate the error due to their multi-reflector geometry and large physical size. For direct LLR by ILRS, a next-generation, single, large reflector, MoonLIGHT (Moon Laser Instrumentation for General relativity and Geodesy high-accuracy test, of kg-level mass) was developed, whose LLR accuracy is unaffected by librations (Ciocci 2017). This class of next-gen reflectors supports an improvement from a factor 10 up to a factor 100 of the space segment of the LLR accuracy (Dell'Agnello 2009) and will be deployed on the Moon with two lunar landing mission opportunities by ESA and NASA in late 2023 or early 2024.
The extension of the LLR gravitational science program to ongoing or approved missions to Mars (InSight 2018, Perseverance 2020, ExoMars 2022, Mars Sample Return 2026-2028) and to Phobos (MMX 2024) will also be described.

Primary author: MUCCINO, Marco (LNF- INFN)

Co-author: DELL'AGNELLO, Simone (LNF)

Presenters: MUCCINO, Marco (LNF- INFN); DELL'AGNELLO, Simone (LNF)

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