TEST OF GENERAL RELATIVITY USING LUNAR LASER RANGING DATA AND THE PLANETARY EPHEMERIS PROGRAM

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Introduction: Since 1969 Lunar Laer Ranging (LLR) to the Apollo Cube Corner Retroreflectors (CCR) arrays has supplied several significant tests of General Relativity (GR): it has evaluated the geodetic precession, probed the weak and strong equivalence principle, determined the Parametrized Post Newtonian (PPN) parameter β, addressed the time change of the gravitational constant G and $1/r^2$ law.

Over the past 40 years, LLR from a variety of observatories to CCR arrays on the Moon, have increased our understanding of gravitational physics. Nowadays technological improvements in the ground based segment of LLR are futile due to the 40 years old arrays on the Moon.

The main problem that affects the Apollo arrays consist of the lunar librations in longitude, that result from the eccentricity of the Moon orbit around the Earth. Because of the libration tilt, the array increase the dimension of the pulse coming back to the Earth.

General Relativity with LLR: In table 1 we show the GR test that have been carried out using LLR [1]. In the first column is shown the parameter under estimation, the timescale indicates the approximate data campaign length for achieving the scientific goal and in the last two columns are shown the estimation of the parameters using the accuracy of 1 mm and 0.1 mm.

We are using the software called Planetary Ephemeris Program (PEP) developed by Center for Astrophysics (CfA). This software is designed not only to generate ephemerides of the planets and Moon, but also to compare models with observations [2]. One of the early use of the PEP software was the first measurements of the geodetic precession of the Moon [3].

We have performed a preliminary analysis of real LLR data from station and dummy observations.

The parameters considered are the variation of the gravitational constant G, the Nordtvedt parameter η, the geodetic precession K_{GP} and the PPN parameter β. Each parameter is shown with successive columns including the assumed accumulation of future data, obtained with a cadence of 30 days for APOLLO station, 20 days for McDonald station, 14 days for Grasse station and 8 days for Matera station. Every observation include each available array plus three proposed ones (Astrobotics at 45N 27.2E, Israel IL at 50S 35E and Moon Express at 65N 40W).

Table 1 GR science objectives

Science Measured	Time scale	Accuracy (cm)	1 mm	0.1 mm
PPN, β	Few years	$1.1x10^{-4}$	10^{-5}	10^{-6}
WEP	Few years	$1.4x10^{-13}$	10^{-14}	10^{-15}
SEP	Few years	$4.4x10^{-4}$	$3x10^{-5}$	$3x10^{-6}$
Time variation of G	5 years	$9x10^{-13}$	$5x10^{-14}$	$5x10^{-15}$
$1/r^2$	10 years	$3x10^{-11}$	10^{-12}	10^{-13}
K_{GP}	Few years	$6.5x10^{-3}$	$6.5x10^{-4}$	$6.5x10^{-5}$

The proposed CCR are available when the Moon elevation is 30° or more, as long as the Sun is at least 10° below the horizon, with one exception: two different version of Israel IL are considered one without sun shield (available only in darkness) and one with sun shield (available whenever conditions). In table 2 the first row of each parameter shows the shieldless version and the second row shows the shielded version.

Table 2 Preliminary analysis using PEP

	2013	2016	2018	2020	2022	2025	2030
Gdot/G	1.586E-14	7.731E-15	5.432E-15	3.779E-15	2.744E-15	1.722E-15	1.100E-15
		7.663E-15	5.246E-15	3.593E-15	2.554E-15	1.582E-15	9.927E-16
eta	2.550e-03	1.648e-03	1.093e-03	8.216e-04	7.364e-04	5.882e-04	4.900e-04
		1.536e-03	9.707e-04	7.184e-04	6.264e-04	4.930e-04	4.157e-04
KGP	3.383E-04	2.099E-04	1.554E-04	1.152E-04	1.009E-04	7.831E-05	6.273E-05
		1.921E-04	1.304E-04	9.539E-05	8.018E-05	6.486E-05	5.302E-05
beta	6.425E-04	4.156E-04	2.729E-04	2.113E-04	1.881E-04	1.490E-04	1.223E-04
		3.861E-04	2.417E-04	1.854E-04	1.606E-04	1.255E-04	1.044E-04

For the simulated observations the round trip timing uncertainties are 16 ps for APOLLO station and 33 ps for other stations on existing CCR, and 3 ps for APOLLO and 7 ps for other stations on te proposed CCR.

References: [1] Williams J.G., Turyshev S.G. and Boggs D.H. (2004) *PRL 93,* 261101.
[2] Reasenberg R.D., Shapiro I.I., et al. (1979) *Astrophysical Journal Letters, 234,* L219.
[3] Shapiro I.I., Reasenberg R.D. and Chandler J.F. (1988) *PRL 61,* 2643-2646.