Station coordinates from LLR analysis as contribution to the next ITRF

Liliane Biskupek[1], Manuela Seitz[2], Jürgen Müller[1] and Franz Hofmann[1]

1) Institut für Erdmessung, Leibniz Universität Hannover, Germany
2) Deutsches Geodätisches Forschungsinstitut, München, Germany

Introduction

Lunar Laser Ranging (LLR) is carried out for more than 43 years. Until the end of 2012 about 17500 measurements, so-called normal points (NP), were collected and are analysed to determine several parameters of the Earth–Moon system, e.g. lunar orbit, Earth orientation parameters, coordinates of the retroreflectors on the lunar surface and station coordinates and velocities on the Earth. Also the validation of Einstein's theory of relativity is possible.

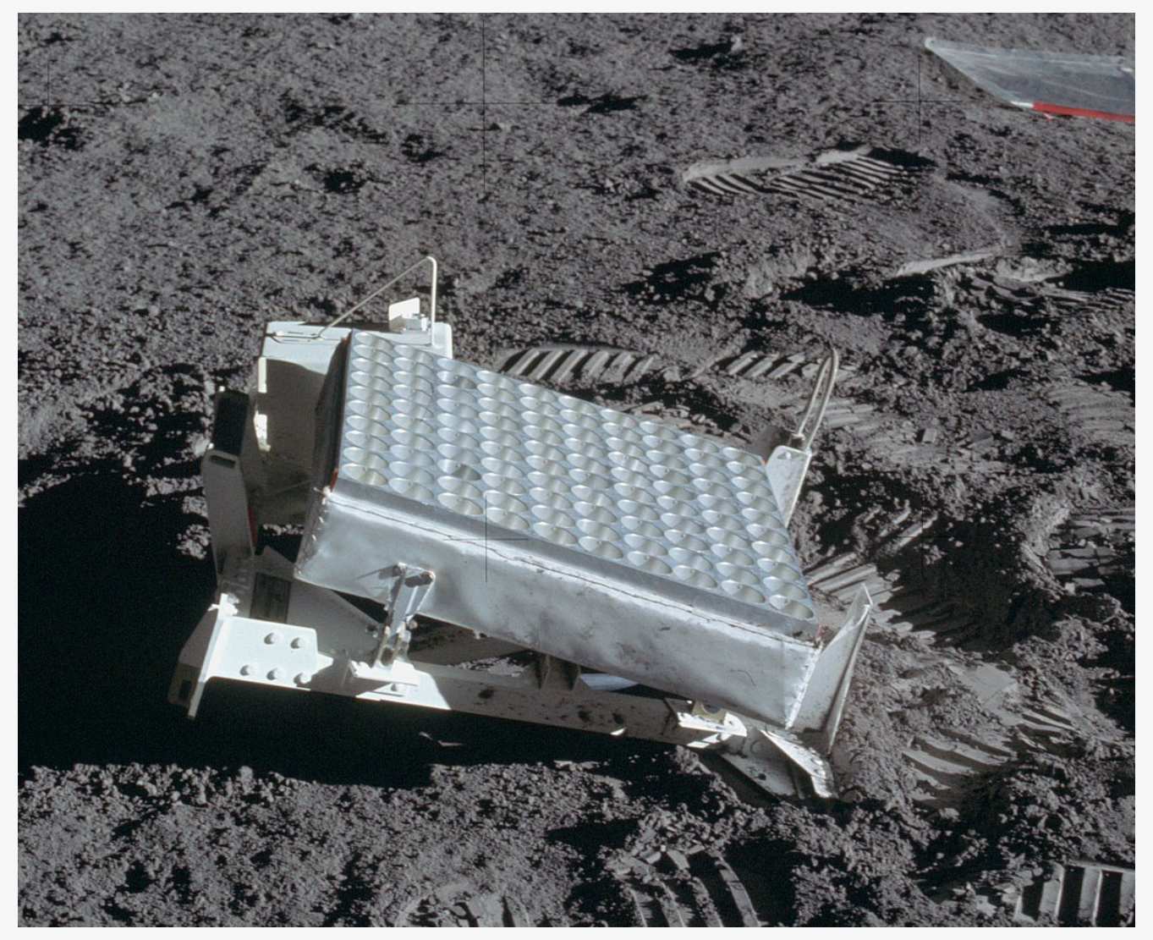

Fig. 1: Retroreflector set up by astronauts of APOLLO 14 mission

Now, the reference system transformation in the analysis of the LLR data was adapted to IERS2010 Conventions and the a priori information of the stations was transformed to ITRF2008. Thus the resulting station coordinates and velocities are more consistent to the results of the other space geodetic techniques VLBI, GNSS and DORIS provided by the corresponding IAG services and can be used for the computation of the next ITRF. Here, first results are presented, how well the LLR derived coordinates and velocities fit into the DTRF2008 solution (Seitz et al., 2012).

Analysis of the LLR observations

The LLR analysis model is based on Einstein's theory, it is fully relativistic and complete up to the first post–Newtonian ($1/c^2$) level. The observation equation is analysed with a Gauß–Markoff model in the BCRF (Barycentric Celestial Reference Frame). For the analysis, the ephemeris of the solar system bodies are integrated simultaneously with the rotation of the Moon. The station coordinates and velocities are determined in the International Terrestrial Reference Frame (ITRF).

Solution set–up

For the six LLR solutions 16732 NP are used in the time span 1970 - 2011. Tab. 1 gives the distribution of the NP with respect to the several stations. All station coordinates from LLR are referred to the intersection of the telescope axes.

Tab. 1: Used NP for combination

DOMES number	Station description	time span of NP	number of NP
40442S002	McDonald	1970 - 1985	3146
40442S001	MLRS 1	1983 - 1988	695
40442S006	MLRS 2	1988 - 2011	2734
40445S005	Haleakala	1984 - 1990	389
10002S002	Grasse	1984 - 2011	8826
49447S001	APO	2006 - 2010	942

The observations of all McDonald sites are referred to one common reference point 40442S006. Thus, the observation data for that station cover more than 40 years. The apriori values for coordinates are taken from ITRF2008, and NUVEL–1A model is used for the velocities. For the transformation between BCRF and ITRF, nutation and precession are considered according to IAU2000/2006 model. The EOP are fixed to the IERS C04 combined series. The origin is realized in the centre of mass of the Earth.

The LLR solutions are generated setting up the following parameters:

- initial values for lunar orbit and rotation
- station coordinates and velocities
- coordinates for the retroreflectors
- potential coefficients of the Moon up to degree and order four
- mass of the Earth–Moon system (in five of the investigated solutions)
- range biases for all stations
- tidal parameters for Earth and Moon

The standard deviations of the estimated station coordinates are between 0.5 and 1.7 cm and for the velocities between 0.05 and 0.4 cm/yr.

Fig. 2: Apache Point Observatory 3.5 m telescope running APOLLO LLR experiment taken by D. Long

Combination

The investigated LLR solutions include four stations. At three sites SLR–LLR colocations are available (fig. 3). At station Grasse, the observations of SLR and LLR refer to one common reference point.

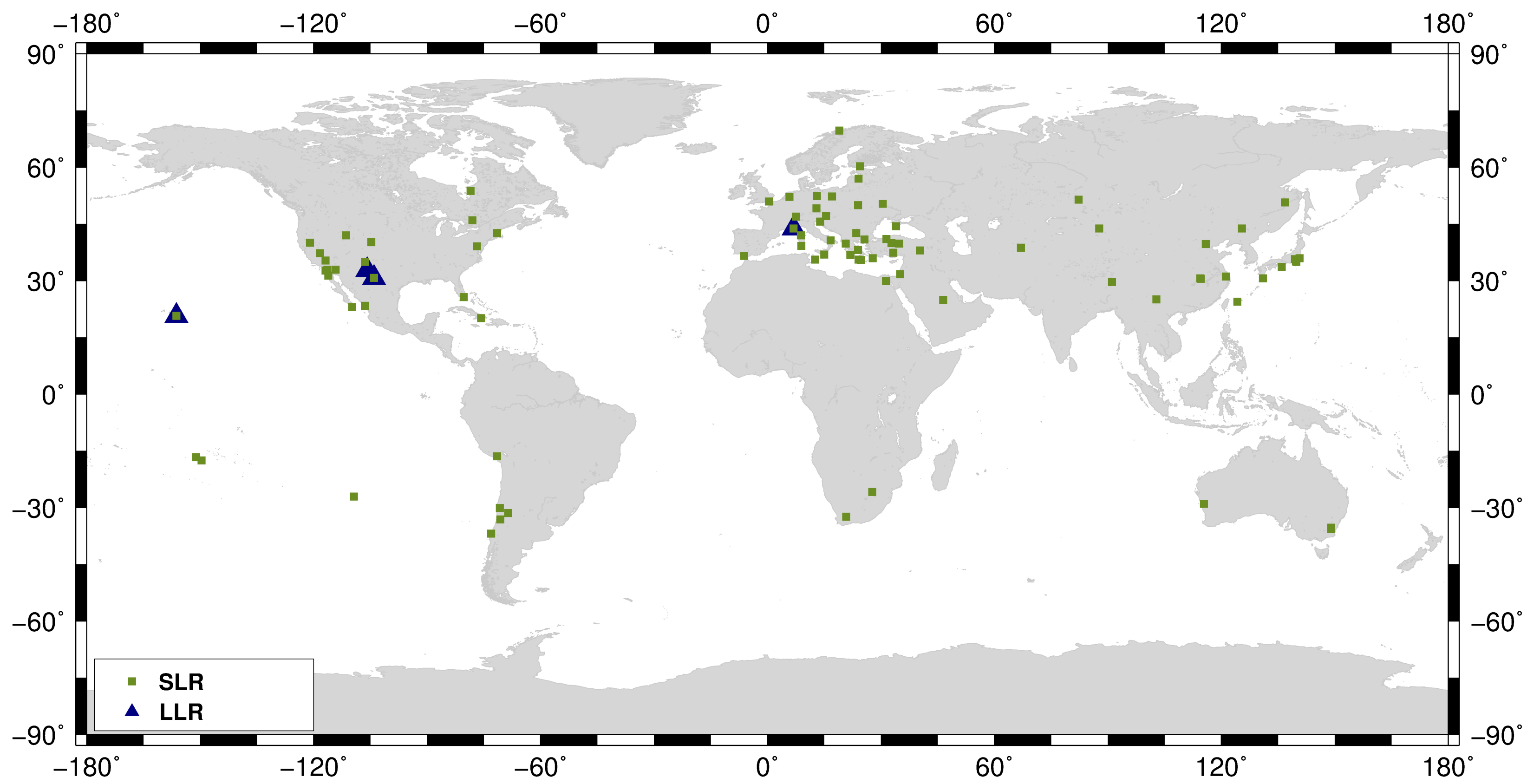

Fig. 3: SLR station network in DTRF2008 and LLR sites

At two sites, McDonald and Haleakala, local ties between SLR and LLR are introduced (tab. 2). For the combination of the two techniques, the LLR solution is introduced by setting up translation parameters and a scale parameter as well as the corresponding rates.

Tab. 2: Local ties between SLR and LLR reference points

		local ties [m]		
SLR	LLR	Δx	Δy	Δz
40445M001	40445S005	0.483	0.212	-1.003
40442M006	40442S006	0.373	1.471	-0.897

Discussion of the results

Six different LLR solutions are computed by applying different types of regularisation and by fixing or estimating the mass of the Earth–Moon system. The combination results are analysed regarding the agreement of network geometry and datum parameters. Applying no regularisation at all and fixing the mass of the Earth–Moon system, the network geometries of SLR and LLR agree within 3.5 cm for coordinates and 0.95 cm/yr for velocities. With respect to the scale (that is multiplied with the Earth radius) and its rate the agreement is within 4.4 cm and 1.0 cm/yr, respectively. For the origin, the agreement is much worse: several decimeters and about 10 cm/yr.

Estimating the mass of the Earth–Moon system, the agreement in origin is not improved and the mean discrepancy in network geometry increases to 5.3 cm, while the translation rate differences are unchanged. The agreement for the scale became also worse (7.4 cm) only the agreement for scale rate is improved to 0.2 cm/yr.

Applying regularisations the agreement in origin is improved (maximum difference of 25 cm), but the scale differences become worse (8 to 10 cm) and also the agreement of network geometry (about 8 cm).

In summary, a LLR solution without regularization and with a fixed mass of the Earth-Moon system agrees best with SLR regarding network geometry and scale. However, the origin of this frame should not contribute to an ITRF solution.

Future investigations will be made in order to further stabilize the solution as the final goal is that LLR can contribute to both, the origin and the scale of ITRF.

References and acknowledgement

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Institut für Erdmessung
Schneiderberg 50
D-30167 Hannover

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1) biskupek@ife.uni-hannover.de | www.ife.uni-hannover.de
2) seitz@dgfi.badw.de | www.dgfi.badw.de