direction). There is no zero internal check, unless the test masses themselves are physically swapped on the balance; which inevitably perturbs the measurements. A way to overcome this limitation came in the 1960s from Princeton [12] when another subtle idea was put forward: if the UFF is tested for the same test bodies in the gravitational field of the Sun rather than the Earth, the effect on the balance of possible deviation from the UFF (although slightly weaker for the same value of η) would have a modulation with the period of the day, as we have shown in Sec. 2. This modulation naturally provides an internal zero check of the experiment with no need to modify the apparatus: a balance aligned in the East–West direction should give zero twist at sunrise and sunset and maximum twist (in modulus) at noon and midnight. Such a modulation proved very successful, yielding an improvement by almost 3 orders of magnitude in sensitivity, to about 10^{-11} [12]. Another torsion balance was designed and manufactured in Moscow a few years later, also referring to the Sun as the source mass of a possible violation of Equivalence. The experiment was carried out in the basement of the Physics Department (on a deeply rooted rock, for reduced seismic noise); special care was devoted to improving the mechanical quality of the suspension wire and to reducing the effects of the local mass anomalies. The sensitivity reported was about one order of magnitude better, to about 10^{-12} [13], again demonstrating the vital importance of a frequency modulation of the expected signal.

4 Equivalence Principle tests by Lunar Laser Ranging

Test bodies of laboratory size have a negligible fraction f of their mass coming from gravitational binding energy:

$$f \equiv -\frac{3}{5}\cdot\frac{GM^2}{R}\Big/ Mc^2 \tag{17}$$

while for the Earth and the Moon this fraction is:

$$f_{earth} \cong -4.64\cdot 10^{-10} \qquad f_{moon} \cong -1.9\cdot 10^{-11} \tag{18}$$

The Equivalence Principle which Einstein puts at the basis of General Relativity requires that all bodies fall with the same acceleration in an external gravitational field, with the gravitational binding energy contributing equally to the gravitational and the inertial masses. With the Moon orbiting the Earth and both moving in the gravitational field of the Sun, a violation of the Equivalence Principle would cause the orbit of the Moon around the Earth–Moon center of mass to be “polarized” in the direction of the Sun (as sketched in Fig. 2). This effect would have the synodic period of 29.53 *days* and is usually referred to as the Nordtvedt effect [14, 15]. It adds up to the classical variations of the lunar orbit which result from the Sun’s tidal acceleration of the Moon relative to the Earth, first estimated by Newton himself. Laplace later found that Newton’s distorted orbit was also slightly polarized towards the Sun, with the center of the Earth shifted in the direction of full Moon. It is the so called *parallactic inequality*, named in this way because it is proportional to the ratio of lunar to solar distance, and therefore its measurement could be viewed as a way of determining this ratio. Should the Earth and the Moon accelerate at different rates toward the Sun, this would result in a small *additional* polarization of the orbit. For it to be observed, the motion of the Moon should be very accurately monitored.

On 21 July 1969, during the Apollo 11 first manned mission to the Moon, the first retroreflector array was placed on the surface of the Moon enabling highly accurate measurements of the Earth-Moon separation by means of laser ranging.

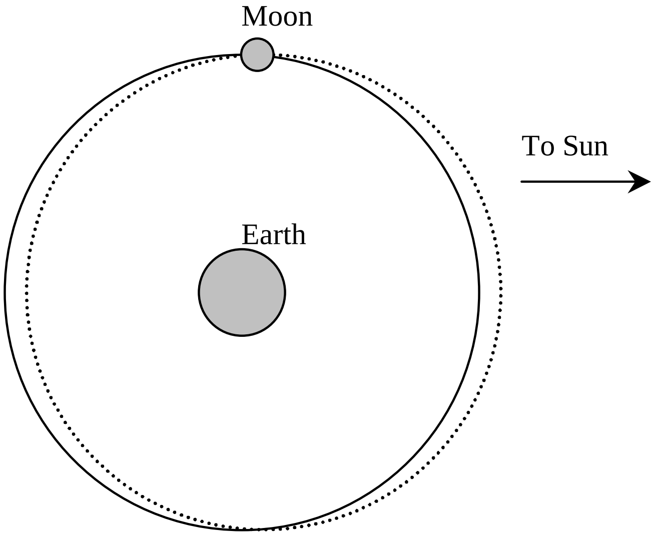

Fig. 2. – Schematic representation (figure not to scale) of the polarization of the lunar orbit toward the Sun. The polarization is mostly due to a classical effect known as the *parallactic inequality* (the Earth–Moon system is not an isolated 2–body system, because of perturbations by the Sun), first pointed out by Laplace. However, the amplitude of the polarization would be sligltly larger than calculated by Laplace should the Earth and the Moon accelerate differently toward the Sun because of a violation of the Equivalence Principle. A violation might occur either because of the different gravitational binding energy of the Earth and the Moon (as given by (18)) or because of their different composition, or both (see text).

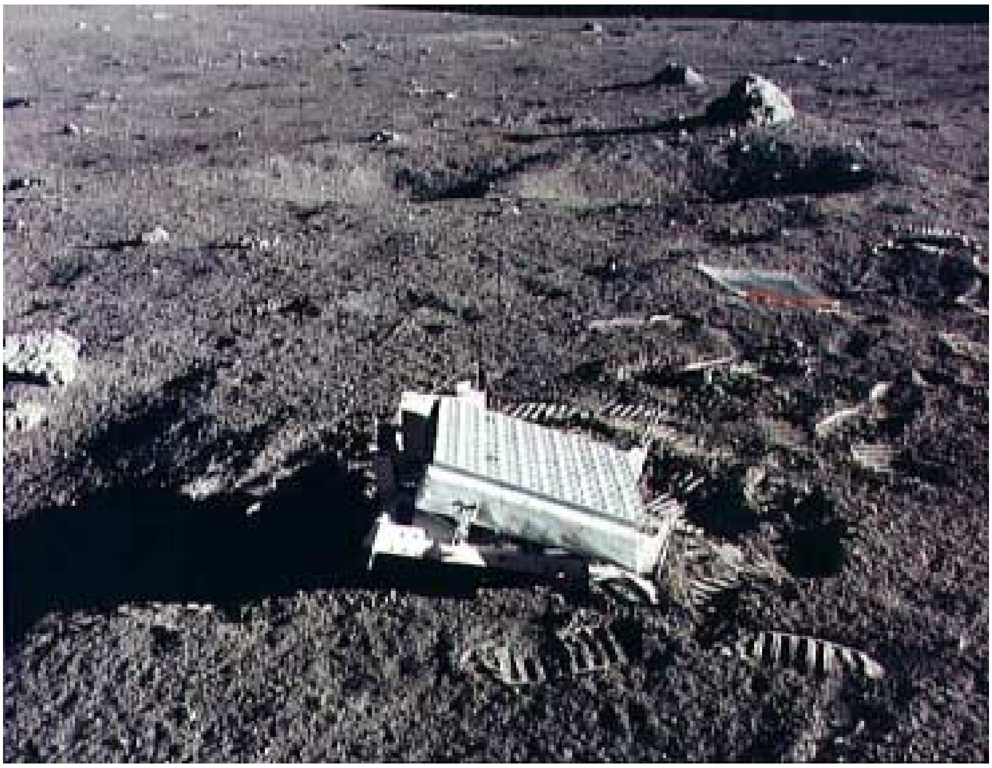

Fig. 3. – Photograph of a retroreflector array that astronauts from the Apollo 14 left on the surface of the Moon (100 corner cubes of 3.8 cm diameter mounted in an aluminum panel).

Within the next two years, two more retroreflectors were brought to the Moon by astronauts from Apollo 14 and Apollo 15 (see Fig. 3). A fourth one came in 1973 with the Soviet Lunakhod II spacecraft. Since then, laser stations on the ground can fire to these reflectors and get enough photons back (in spite of an overall signal loss of about 10^{-21} !) to be able to measure the separation distance from measurement of the round–trip travel times (photons are received about 2.6 *s* after they are sent). The accuracy currently achieved for a range measurement observing session (corresponding to tens of minutes of photon returns) is of 2–3 cm. After almost 30 years of ever–improving quality of data and data analysis, the amplitude of the parallactic inequality relevant for testing the Equivalence Principle is measured to a precision of 1.3 cm, allowing scientists to conclude that any deviation of the Earth and the Moon from the Universality of Free Fall (i.e. any fractional difference of their accelerations toward the Sun) must be less than $5{\cdot}10^{-13}$ [16, 17].

If one could rule out any composition–dependent violation of Equivalence for the Earth and the Moon, then this result could only be interpreted as proving that the gravitational binding energies of the Earth and the Moon contribute equally to their gravitational and inertial masses to about 1 part in 10^3. However, the Earth and the Moon do have different composition. The average composition of the Earth is dominated by its iron–nickel core, while the composition of the Moon is closer to that of the (less dense) Earth mantle, primarily made of silicates. Unless iron–nickel on one side and silicates on the other do accelerate the same in the gravitational field of the Sun (and to an accuracy comparable to that of the laser ranging test), Lunar Laser Ranging data cannot be interpreted without ambiguity as a test of how equally gravitational binding energies of the Earth and the Moon contribute to their gravitational and inertial masses

This ambiguity has recently been removed thanks to experiments carried out at the University of Washington, in Seattle, with "miniature" earths and moons placed on a continuously rotating torsion balance whose twist data have been analyzed for any deviations from the Universality of Free Fall with respect to the Sun [5]. The composition of the test bodies was chosen for them to resemble, to the best of current knowledge, the core of the Earth and its mantle. Improvements in the apparatus have allowed a sensitivity of a few 10^{-13} in the measurement of fractional differences in the acceleration of the test bodies toward the Sun, which is good enough for the ambiguity of Lunar Laser Ranging data to be resolved

5 Recent and ongoing laboratory experiments

A re–analysis of the Eötvös experiments carried out by [18] in 1986 has had the merit to draw the attention of a large number of scientists from all over the world to the Equivalence Principle and to the measurement of the universal constant of gravity. In relation to the Equivalence Principle the authors made the point that the most accurate tests available at the time –those carried out in Princeton [12] and in Moscow [13]– had checked for violation of Equivalence in the gravitational field of the Sun, thus over a range of 1 *AU*, while the old Eötvös tests at the turn of the century were still the most accurate ones as far as tests in the gravitational field of the Earth are concerned.

Since then, the most systematic and successful experiments on the Equivalence Principle are the so called “Eöt–Wash” experiments carried out by the group of E. Adelberger at the University of Washington in Seattle. The *Eöt–Wash* apparatus is a torsion balance operated at room temperature