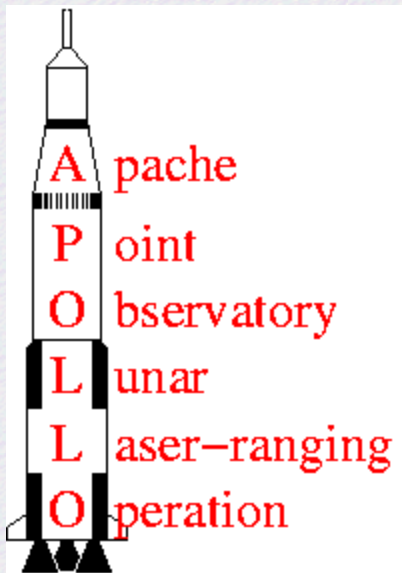


# APOLLO



**APOLLO** (the Apache Point Observatory Lunar Laser-ranging Operation) is a new initiative in [lunar laser ranging \(LLR\)](#), that utilizes the 3.5 meter telescope at [Apache Point](#) in southern New Mexico. The large aperture of the telescope in combination with the good atmospheric "seeing" at the site has launched us into the regime of recording multiple returned laser photons per pulse—in contrast to the 0.01 photon-per-pulse average experienced by previous LLR facilities.

APOLLO measures the round-trip travel time of laser pulses bounced off the [lunar retroreflectors](#) to a precision of a *few picoseconds*, corresponding to about **one millimeter** of precision in range to the moon. Using this information, we will be able to gauge the relative acceleration of the earth and moon toward the sun (like a modern-day Leaning Tower of Pisa experiment) in order to ascertain the free-fall properties of earth's gravitational self-energy.

## Science Goals

Einstein's Equivalence Principle, upon which General Relativity rests, claims that *all* forms of mass-energy experience the same acceleration in response to an external gravitational force. This is to say that the *inertial* mass and *gravitational* mass are equivalent for any form of mass and/or energy. This is very difficult to verify for gravitational energy itself, because laboratory masses have *no* appreciable gravitational binding energy. One needs bodies as large as the earth to have any measurable self-energy content. Even then, the self-energy contribution to Earth's total mass-energy is less than one part-per-billion.

If the earth's gravitational self-energy does not precisely obey the Equivalence Principle, the orbits of the earth and moon around the sun would be slightly displaced from one another (think of this as a modification of Kepler's third law), which would show up as a signal in our lunar range data. Various string-motivated theories, quintessence, and other alternatives to General Relativity almost all predict a violation of the Equivalence Principle at *some* subtle level. Given the recent hints that there may be some new and mysterious modification to the laws of large-scale gravitational attraction (as indicated by supernovae and cosmic background anisotropies), it is important that we probe every available aspect of the basic nature of gravity.

LLR also provides the *best* test of the constancy of Newton's gravitational constant,  $G$ , currently limited to a variation of less than a part in  $10^{12}$  per year. Relativistic geodetic precession is also *best* probed (currently) by LLR, now verified at the 0.35% level of precision. And the list goes on: LLR provides the *best* test of the

motional influence on gravitational attraction (called *gravitomagnetism*) at the 0.1% level, and also sets the *most stringent* limits on deviations from the expected  $1/r^2$  law of gravity.

See [this review article](#) for more information on the motivations behind LLR and some related issues.

## [The Basics of Lunar Laser Ranging](#)

### [Wikipedia Site for APOLLO](#)

### [UCSDTV video of public lecture describing APOLLO](#)

#### Millimeter Precision Measurements?! From *where* to *where*?



The points of reference for the earth-moon measurement are the earth-based telescope—in this case, the 3.5 meter telescope at Apache Point, and in particular, the intersection of the telescope mount axes—and the small, suitcase-sized retroreflector array placed on the lunar surface by Apollo astronauts (pictured is the Apollo 11 reflector at Tranquility Base). A total of four [lunar retroreflectors](#) are functional: three Apollo reflectors from Apollo 11, 14, and 15 (three times bigger than 11 & 14), and one French-built, Soviet landed (unmanned) unit from the Luna 21 mission. A significant part of the challenge of lunar range modeling is converting this point-to-point measurement into a distance between the center-of-mass of the earth and the center-of-mass of the moon. It is only after this reduction that one can consider the interesting part of the problem: the dynamics of the earth-moon-sun system. For more general information on the technique, see [this description of how the technique works](#) and why we're performing this experiment.

#### APOLLO News:





Astronomy Picture of the Day, 2014.04.18

Eclipse observations resolve [Full Moon Curse](#) anomaly

APOLLO sets limits on [Lunokhod rover azimuth](#)

APOLLO continues to set records, run after run. See the [observing-run highlights page](#) and the [monthly yield summaries](#) for more.

APOLLO has seen it's own reflection! [First Ranging Results](#) include 2,400 return photons in 30 minutes, and confirmed accuracy at the inch-level (sort-of).

APOLLO began shooting its laser at the moon in July 2005. [See pictures of the laser beam!!](#)

The laser was installed on the telescope on 6/18/03. [See pictures](#)

[Take a virtual tour](#) of APOLLO to see the layout of the equipment.

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The [APOLLO Apparatus](#) page provides details about (*and pictures of*) the hardware implementation

[APOLLO Normal Point Data](#)

[Observing Aids](#)

See screenshots from the [APOLLO Graphical Interface](#)

See the [lunar pointer tool](#) we use to assist in selecting targets and issuing track commands to the telescope

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### Published Information

- [Review Article \(PDF; 12 MB\)](#) describing the scientific motivations, technique, history, modeling, and future prospects of LLR. Published in Reports on Progress in Physics, **76**, 076901, (2013).
- [Instrument Paper \(PDF; 412 kB\)](#) detailing the as-constructed design of the apparatus. Published in PASP, **120**, 20 (2008).
- [APOLLO overview \(PDF; 132 kB\)](#) as it appears in the conference proceedings of the [12<sup>th</sup> International Workshop on Laser Ranging](#), held in Matera, Italy, 13-17 November 2000. This paper is the most general APOLLO paper, and serves as a good introduction.
- [System description \(PDF; 435 kB\)](#), a modified version of the paper in the conference proceedings of the [13<sup>th</sup> International Workshop on Laser Ranging](#), held in Washington D. C., October 2002. This paper describes at some depth the multiplexed timing scheme employed in APOLLO.
- [Improving LLR Tests of Gravitational Theory](#), Williams, Turyshev, & Murphy, International Journal of Modern Physics D, Vol. 13, No. 3 (2004) 567-582. This paper describes the science attainable by APOLLO, as well as some of the model advances required.

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**Recent Press Releases (the better ones...)**

- [San Diego Union Tribune, July 13, 2006](#), by Bruce Lieberman
  - [NASA Science Headline, May 6, 2004](#), by Patrick Barry
  - [San Francisco Chronicle](#), by Keay Davidson
  - [New York Times](#), by William Broad
  - [UW Press release](#), by Vince Stricherz
  - [ABC Online News](#), by Lee Dye
  - [New Scientist](#), by Will Knight
  - [Optics.org](#), by Jaqueline Hewett
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## Participating Scientists & Acknowledgments

- [Tom Murphy](#) (UCSD): astrophysicist; project leader
- [Eric Adelberger](#) (UW): gravitational physicist
- [Christopher Stubbs](#) (Harvard): astrophysicist
- Kenneth Nordtvedt (Northwest Analysis): gravitational theorist
- C. D. Hoyle (UW): postdoc
- Erik Swanson (UW): research physicist
- [James Battat](#) (Wellesley): Assistant Professor
- [Eric Michelsen](#) (UCSD): graduate student in physics
- [Adam Orin](#) (UCSD): graduate student in physics
- Eric Williams (UCSD): staff research associate
- Bruce Gillespie (APO): Apache Point site director
- Jim Williams (JPL): LLR modeling/analysis
- Slava Turyshev (JPL): LLR modeling/analysis; gravitational theory
- Dale Boggs (JPL): LLR modeling/analysis
- Jean Dickey (JPL): LLR modeling/analysis
- John Goodkind (UCSD): physicist/gravimetry

In addition, a number of graduate and undergraduate students have been involved with APOLLO: Jana Strasburg (now Dr. Jana!), Tristan Hromnik, Jonathan Driscoll, Jesse Angle, Evan Million, Daniel Miller, Laura Tom, Charlie Barnhart, Matias Duran-Matute, Matt Stiglianese, Justin Ryser, and Laura Bodine.

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Finally, we thank NASA for supporting APOLLO and enabling it to get "off the ground", and more recently, a joint effort by NASA and the National Science Foundation to fund APOLLO at a level that will allow project completion and production of the first science results.

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