

## **Atmospheric Effects and the Ultimate Ranging Accuracy for Lunar Laser Ranging (3055)**

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### **ABSTRACT**

In the near future, the deployment of the next generation lunar laser retroreflectors, in particular the “Lunar Laser Ranging Retroreflectors for the 21st Century” (LLRRA-21), is planned via various missions to the moon. With proper robotic deployment using the anchored technology, these LLRRA-21 arrays will support single photo-electron ranging accuracy at the 100 micron level or better. There are available technologies for the support of lunar laser ranging at this level of accuracy by advanced ground stations. However, the major question for this type of deployment to be supported is the limit on the ranging accuracy due to the earth’s atmosphere. In particular, there are questions concerning the jitter in the delay due to atmosphere fluctuations (turbulence) and the long term effects (biases) of the measured time delay. Theoretical, simulation and experimental results will be discussed that address estimates of the magnitudes of these effects and the issue of precision vs. accuracy.

**Keywords:** Lunar Laser Ranging, Cube Corner Reflectors, Atmospheric Limitations, Turbulence, Retroreflectors, Atmospheric Gradients, Gravitation, General Relativity

### **1 OVERVIEW OF CURRENT SCIENCE PRODUCTS OF LUNAR LASER RANGING**

The current Lunar Laser Ranging (LLR) Program (LLRP), started during the NASA Apollo missions, is today an international program that has, over the past four decades, produced most of the best tests of Gravitation and General Relativity and also determined many aspects of lunar physics (e. g., including the discovery, 15 years ago, of the liquid core of the moon). The importance of these measurements and the necessity of increasing their accuracy<sup>1</sup> are now becoming critical in addressing the theories being developed to replace General Relativity in order to address the incorporation of the recent discoveries of Dark Matter and Dark Energy (DM&E).

### **2 PRE-HISTORY AND HISTORY OF THE LLRP**

#### **2.1 Prehistory of the Lunar Laser Ranging Program**

In the 1950s and 1960s, Professor Robert Dicke<sup>1</sup>, of Princeton University, was one of the early proponents of developing and implementing experiments in order to test General Relativity (GR). On the theoretical side, he developed an alternative theory to GR inspired by Mach’s Principle that violated the equivalence principle<sup>2</sup>. With Carl Brans, this was later refined into a scalar-tensor theory known as the Brans-Dicke (BD) theory<sup>3</sup>. This was both a viable alternative to GR and served to provide a comparison to be able to quantitatively evaluate the accuracy of tests required to distinguish the BD theory from GR. At the stage of measurement accuracies in the early 1960s it was not possible to distinguish between GR and the BD theories. However, the earth-moon system was a

potential “laboratory” to accomplish such accurate measurements, in particular, highly accurate lunar distance measurements repeated over a long period of time.

## **2.2 History of Lunar Distance Measurements**

In the 1960s, two events were to change the situation. Maiman<sup>4</sup> invented the ruby laser, which was capable of producing coherent light emission in the form of very high energy, very short pulses. The other event was the proclamation by President John F. Kennedy to put a man on the moon by the end of the decade. This invigorated the group centered around Bob Dicke to investigate in detail the possibility of developing definitive tests of Gravitation, General Relativity and lunar physics via laser ranging to the moon. This investigation resulted in the creation of a proposal to NASA to deploy a retroreflector package on the first lunar mission, Apollo 11. After the initial success of the ranging program<sup>5</sup> and the early science results<sup>6</sup> based on using the Apollo 11 array, our proposal for further retroreflector arrays for Apollo 14 and Apollo 15 was accepted and implemented.

## **2 CURRENT OBJECTIVES OF ADVANCED LUNAR LASER RANGING PROGRAM**

The objective of the Advanced Lunar Laser Ranging Program (ALLRP) is to proceed from the current ~100 mm single shot accuracy or 10-20 mm per normal point to 1-2 mm single shot accuracy and a normal point accuracy limited by the ground station hardware, calibration and the atmosphere. Currently, the LLRP consists of regular ranging by a few stations; the APOLLO station, CERGA/MeO and MacDonald, and with new stations i.e., MLRO, and Wettzell. To seriously address the latest theories of DM&E on an acceptable time scale, one needs a quantum leap in both the accuracy of the range measurements and the number of stations which have the improved accuracy. While the APOLLO ground station has a normal point precision of a mm, it is difficult to detect systematic and calibration errors with the data from a single station. To proceed with a mm accuracy program, we need multiple stations of mm accuracy capability. To achieve this we need:

- A) Three New Retroreflectors on the Moon<sup>8</sup>
- B) Analysis and Upgrading of Ground Stations including the Current SLR Stations
- C) Improved Ground Station Hardware, that is Fast Detectors and Short Pulse Lasers
- D) Upgraded Analysis and Scientific Software to Analyze the Range Returns
- E) Geophysical Noise – Tides, Rainfall, etc.

### **F) Understanding of the limits of the atmosphere**

Only the item F) will be addressed here, that is, the atmospheric limitations on the precision and accuracy of the range measurements to the lunar retroreflectors. In particular we wish to determine if the atmosphere will support our goal of 1 mm and also if we can go beyond 1 mm.

The atmospheric properties are a relevant phenomenon in the ranging accuracy since the index of refraction (IoR) of the air is not unity so the speed of light is not equal to that in vacuum. For this reason, the atmosphere will cause an extra time delay above and beyond the delay due to the lunar distance. If the moon were at zenith this would amount to about 2.5 meters for a ranging station at

sea level. This atmospheric delay is not a constant, since there are different delays in the different atmospheric turbulence cells. For off-zenith observations, the correction due to atmospheric gradients must be very accurate, approaching 1/10,000. Unfortunately, there are no data directly addressing the magnitude of these effects, so we must separate the different effects and investigate them by reviewing theoretical analyses, simulations and experimental results.

### **3 ISOLATION OF DIFFERENT ATMOSPHERIC EFFECTS**

The effects that will limit the accuracy of the ranging measurements may be divided into two different domains. Thus, to address the different types of analysis, simulations and experimental data, the challenge will be divided into two primary domains:

#### **3.1 Turbulence Effects**

This part of the review will address the effects of atmospheric turbulence. The basis for this has been described by Tatarskii<sup>9</sup> and can be simulated by various analytic and/or computer tools. In particular, this will address the effects of inner scale (small scale) effects, small scale effects of temperature and water vapor, outer scale effects in the atmosphere.

#### **3.2 Large Scale Effects**

These effects will include gross gradients in the atmosphere, as caused by temperature differences due to weather patterns and between warm areas like cities and suburbs, gravity waves in the upper atmosphere and the effect of wind on local terrain, like mountains.

The role of precision and accuracy or “shot to shot variation” and “biases” will be addressed separately. The former results will indicate how many shots are required in order to obtain a normal point which has a 1 millimeter precision. The later biases or mean errors are best determined by the comparison of the analyses of multiple ground stations or estimated by analysis and simulations. Typically, it would be desirable to have a single shot R.M.S. of less than 2 mm since this would imply that the ground stations could obtain the 1 millimeter precision with four or more single echoes. This use of combining multiple ranges was the practice of the first author<sup>7</sup> during the early ranging at the station at MacDonald Observatory at Mount Lock in Fort Davis, Texas in 1969-1970. It will also allow Satellite Laser Ranging stations with small aperture to participate in the ALLRRP.

### **4 TURBULENCE EFFECTS**

The fundamental cause of turbulence is the motion of the air, generally seen as the wind. The outer scale vortices proceed to ever smaller scale vortices until they reach the level that viscosity converts the small scale vortices into heat. During this cascade, cells of different temperatures and humidity are generated which have different IoRs and thus different delays for the laser pulse passing through them. These changes in the optical path delay, through the cells, integrate to a statistical delay that varies from one instant to the next.

#### **4.1 Simulation R.M.S. Fluctuations for the Propagation to a Satellite**

This addresses the use of the Gardner<sup>10</sup> theory for a spherically symmetric atmosphere and the Hufnagel-Vally theory for the altitude dependence of the strength of the turbulence. The result then depends on the choice of the outer scale. At a 40 degree elevation and an outer scale of 200 meters, the R.M.S. jitter has a value of 0.75 millimeters.

#### **4.2 Conclusion w.r.t. the Limitation of the Ranging Precision Due to Turbulence**

In conclusion, the calculations based upon the Gardner theory for a spherically symmetric atmosphere indicates that the magnitude of the local turbulence will not foreclose obtaining a ranging precision of 1 mm. The main limitation on the accuracy will come with the large scale effects addressed in the next section.

### **5 LARGE SCALE EFFECTS**

The large scale effects are generally low frequency, so they affect the accuracy rather than the precision. They may be characterized by a slope or tilt of the atmosphere over the few kilometers over which the laser pulse travels to reach a satellite or the moon that is not at the zenith. This apparent tilt can be due to temperature gradients in the atmosphere (the so-called heat island effect), pressure gradients, gravity waves at the top of the atmosphere and non-equilibrium effects generated by winds or pressure gradients. There are a variety of measurements or simulations using measurements that can estimate the magnitude of these effects or at least put an upper limit on this apparent tilt of the atmosphere.

### **6 THEORETICAL ANALYSES OF HORIZONTAL GRADIENTS**

The theoretical discussions up to this point have assumed a spherical symmetric atmosphere. We now wish to address the expected magnitude of the horizontal gradients or tilts of the atmosphere from a theoretical modeling point of view. In order to obtain data on the tilts of the atmosphere, we may consider either of two approaches. The first is to obtain single point measurement around but distant from the ranging station by radiosonde measurements<sup>10</sup>. The other approach is to use satellites to measure the properties of the atmosphere in the vicinity of the ranging station<sup>12</sup>.

#### **6.1 Gardner<sup>10</sup>**

Early estimates of the biases due to gradients are due to Gardner<sup>10</sup>, Martini<sup>11</sup> and Mendes. These consist of obtaining radiosonde data at many stations in the vicinity of the laser ranging station. The radiosonde data of the temperature, pressure and humidity as a function of altitude are then used to construct a 3D map of the IoR. Following this, the value of the laser pulse delay propagated through the 3D map of the IoR is compared to the delay as it would be calculated from the ground level temperature, pressure and humidity. As an example, the computations of a single case (one laser station and two other radiosonde measurements) has a worst case value (in azimuth) of 2.64 mm at 40° and 35.3 mm at 10°. The SLR science requires observations at 10°. On the other hand, the lunar observations addressing GR and selenophysics are typically around 40°. Therefore to relate the SLR

analysis of Gardner to the lunar case, we note that the above case yields a ratio of 16.4 between the errors obtained at 10° and 40°. The above example was repeated over “428 ray traces obtained from 17 different sets of three balloon releases”<sup>10</sup>. For each set of rays they retraced 8 or 9 azimuth angles from each of the three release sites<sup>10</sup>. The result of this analysis was an R.M.S. variation of the range at a level of about 20 mm at an elevation of 10°. Converting this to 40° with factor of 16.4, this is an R.M.S. of ~1.2 mm,

## **6.2 Hulley and Pavlis<sup>12</sup>**

A more recent and more extensive investigation, similar to that of Gardner, has been conducted by Hulley and Pavlis<sup>12</sup>. Instead of linear interpolations between the radiosondes to obtain the 3D map of the IoR of the atmosphere, Hulley and Pavlis use the observations of the AIRS satellite (as well as other similar data sets) to obtain a higher resolution and more accurate 3D map. This was done with two different sets of the data for the creation of the 3D maps denoted by ART and NRT. This allows a detailed computation, using the weather conditions at many different times.

Unfortunately, there is no information in the analysis in the Hulley and Pavlis paper for the mean and R.M.S. variation for 40° elevation. In order to provide a rough estimate of the expected value at 40° elevation (the typical elevation for lunar laser ranging) we use the same factor of 16.4 obtained earlier to determine the expected R.M.S. for 40° from the value at 10°, even though this is the result for a single instance. However, it is clear from these results that the magnitude of the expected long term atmospheric effects at elevations of 40° will probably not prohibit lunar ranging precisions at the level of 1 or 2 mm.

## **7 LASER RANGING TO SATELLITES**

Laser ranging measurements to the EVISAT satellite were conducted at the GRAZ SLR station<sup>13</sup> using the two kilohertz laser system. The returns were selected to address only those that came from a single CCR in the retroreflector array. The typical R.M.S. variation in the range was 0.3 to 0.5 mm<sup>13</sup> for an elevation angle of 36.6°. These results agree with the theoretical analysis of Gardner that was discussed in 6.1.

## **9 FUTURE DIRECTIONS**

We will concentrate on those future aspects of the ALLRP that are directly or indirectly related to the limitations due to the atmosphere. One approach to improve the biases is to deploy meteorological stations placed about 7 km from the ranging stations to measure the ground based temperature, pressure and humidity. Another approach is to investigate other meteorological models that have higher spatial resolution. Such data can be used in real time to address the systematic effects described above. In order to evaluate the issues related to such corrections, it would be prudent to consider test stations in the near future. Such a program would address the effects of different altitudes and of the non-equilibrium effects in the atmosphere.

This information would be essential to take advantage of the stability that appears to be affordable by the anchored deployment<sup>8, 14</sup> at the level of 0.1 mm or less, with respect to the deep local terrain, overcoming the diurnal effects of the extreme temperature changes.

## 10 CONCLUSIONS

The Satellite Laser Ranging (SLR) science programs require data collection at elevations angles as low as 10° where the atmospheric gradient effects are severe. On the other hand, the lunar laser ranging science program typically observes at the more favorable elevation angles around 40°.

Thus, a variety of analytical studies, simulations of the turbulence and laser ranging to space targets have been described. Most are upper limits on the expected limitation due to the atmosphere. In general, they indicate that the R.M.S. of the Shot-to-Shot (StS) variation in the atmosphere has a value of less than a mm. The most definitive evaluation of the ranging precision (the R.M.S. StS variation of the measured range to a satellite) is less than a mm. Thus we see that the StS variation will allow a normal point composed of only a few shots to reach the 0.1 mm limit. The data on the systematic effects is less complete, although the simulations by Hulley and Pavlis indicate that the systematics at 40° elevation are of the order of a mm without the additional meteorological stations.

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