

# **New Prediction Formats to Accommodate Possible Laser/Optical Transponder Measurements to the Moon and Beyond**

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## **Abstract**

While lunar ranging data formats have been standardized for many years, the prediction formats have not, due to the few stations involved. With the possibility of laser transponders being put into lunar orbit and on the moon, the opportunity for lunar ranging will be available to many of the currently artificial-satellite-only laser ranging stations. Thus the prediction formats and procedures for lunar ranging must become standardized, as they are for artificial satellites. At the same time, provision should be made for ranging to even more distant transponders in inter-planetary space and on Mars. Preliminary concepts and requirements are presented.

## **Introduction**

With the increased interest in putting laser transponders on the moon, in orbit about the moon, and elsewhere in the solar system, there is a need to develop standard prediction formats and procedures for ranging to the moon and beyond. It is also important to clarify the differences between lunar and artificial satellite predictions with their implications for the formats and procedures.

In the past, each lunar laser ranging station either developed its own software or ported packages from other stations. There were few lunar ranging stations, so the need for formal formats was minimal. (Data formats involving the world of analysts is a different case. These formats were standardized early on and have gone through several revisions[1][2], including the recent merging into the ILRS normalpoint format[3].) Transponders will open up the opportunity for almost all artificial-satellite ranging stations to range to the moon and possibly beyond. Formats presented below are derived from current lunar prediction formats, hopefully with enough flexibility to serve equally well for lunar orbiters and laser transponders elsewhere in the solar system.

Highly accurate predictions are required not only for data acquisition but also for data filtering and compression. For any station to perform lunar laser ranging and produce field generated normalpoints requires software analogous to that used for artificial satellite ranging. This includes software to produce or manipulate predictions for data acquisition and software to perform on-site filtering and normalpoint formation from the ranging data.

## **Uniqueness of Lunar Predictions**

Two complications arise in generating predictions for ranging the moon and beyond that are not inherent in those for lower artificial earth satellites: first, we cannot simply form a range from the square root of the sum of the squares of the reflector's topocentric x, y, and z coordinates. The movement of the earth and moon during the roughly 2.5 second round trip is large enough that the range must be computed as the sum of the iteratively determined lengths of the outbound and inbound legs. Because of the distances and masses involved, there is also a non-negligible relativistic correction. The difference between the true range and the square root of the sum of the squares of coordinates gives a range error of a few to hundreds of microseconds. Omitting the relativistic correction causes a range error of about 50 nsec. In addition, light aberration effects on pointing need to be considered for stations with narrow spatial filters and for any ranging beyond the moon. The effect for Mars can amount to 10s of arcseconds.

The second complication is that one usually does not have the one-arcsec absolute pointing and tracking accuracy required to acquire and track the lunar reflectors. Pointing and tracking of this accuracy is required to guarantee the greatest amount of energy will arrive at the reflector. Because the targets subtend such a small angle as seen from the laser station, and the distance is so great, we must transmit an essentially parallel beam, dispersed only by the atmosphere.

Some lunar reflector sites have few nearby features useful for optical guiding to assist pointing and tracking, and those available are in the dark for half the month. To compensate, the observer offsets the telescope from the reflector site to another lunar feature, centers the feature, and then moves back, preserving the offsets. This is often done a number of

times over the ranging session. Offset pointing requires an ephemeris for each reflector array and feature used, or an ephemeris containing all the information necessary to point to any arbitrary lunar coordinates in real time.

A complication not present in the current ranging to lunar retro-reflector arrays comes from the transponder delay - the time between the transponder receiving a signal from the laser station and its transmitting a laser pulse back. The delay is expected to be on the order of a millisecond and needs to be handled at prediction time as a delay between the outbound and inbound legs. It is reported [4] that the Selene mission is planning a nominal delay of about 50 microseconds with an upper bound of about 1 millisecond. If the data is to be reduced on site in a timely manner, this delay needs to be available when the data is taken.

Transponders sent farther from earth, where the range delay is so large as to preclude such round-trip ranging will range asynchronously[5]. In this mode the transponder will continuously range to the earth and as earth stations range to the transponder. In other words, there is no laser fire from the earth station that causes the transponder to fire back. In this case, accurate range rate and clock drift information is important for both predictions and data reduction.

A situation in which lunar ranging is less stringent than artificial laser ranging is in the realm of biases. One reason some laser stations leave the artificial satellite predictions in the form of geocentric  $x$ ,  $y$ ,  $z$  coordinates until the last step in the prediction computations is that along and cross track biases are more simply applied in this coordinate system. The moon has no such requirements because its ephemeris is well known and stable. The UTC offset due to earth rotation uncertainties has the largest impact on lunar data acquisition, and it is rarely large enough to prevent identification of returns.

### **Current Practice**

At the McDonald Laser Ranging System (MLRS), the lunar prediction program is run often enough to incorporate the latest Earth Orientation Parameter (EOP) predictions. (Once a week is sufficient, with an automated process to retrieve and process the EOS bulletin from the USNO website.) It uses the MIT PEP (or JPL) lunar and planetary ephemeris to produce tabular files each containing predictions at 900 second spacing for an entire lunar "pass". This file (similar to type 1 below) contains the ranges to each reflector, ready for interpolation, as well as all the information needed to point to the reflector or any arbitrary lunar feature whose coordinates are supplied to the ranging program.

Ranges from this process are also used for data filtering. Actual normalpoint production uses the MIT or JPL ephemeris directly, for the best possible accuracy. It is also possible to create normalpoints using the acquisition predictions, by optimizing prediction point separation for the required accuracy.

### **Possible Actions**

Currently, artificial satellite predictions are distributed in the Tuned Inter-range Vector format[6]. Due to the different reference frame and algorithms used, neither this format nor the current on-site software using this format would be able to handle the prediction requirements for transponders and lunar reflectors. Therefore, the International Laser Ranging Service's Formats and Procedures Working Group has created a study group to recommend prediction formats and distribution procedures for the moon and transponders.

With regard to distribution procedures, one could envision centralized predictions created for each station with either a generalized file format (such as Type 1 below, which is similar to that used at MLRS) or individual files for each reflector and a select group of offset features (as has been done at other stations). The latter could be in the form of a simple tabular ephemeris (Type 2 below).

Another scenario would be to hone the MLRS or OCA (Observatoire de la Cote d'Azur) prediction, filtering, and normalpointing software, make it platform independent, perhaps rewrite the FORTRAN code in C, and provide it to each station interested in ranging the moon. The complexity of the lunar ranging software is no worse than that of the on-site slr filtering and normalpointing software that stations already use. The only outside inputs to the stations would be weekly EOP updates and a new solar system ephemeris every few years. The formats discussed here could be incorporated into this scheme.

On-site data reduction would not be an option for asynchronous transponders, due to the need for data downloaded from the transponder. A central processing center would have to be set up.

In any case, each station would still need to integrate the lunar predictions into its existing ranging software. Sample code could be provided by existing lunar stations or the study group.

For transponders orbiting or sitting on another solar system body or in interplanetary space, the most likely scenario would be to have tabular predictions produced in the type 2 or similar format and distributed to the stations on a daily or weekly schedule. It is necessary to provide return as well as transmit point angles for these objects to account for aberration. The type 2 format as shown below already includes these fields.

### **A Further Consideration**

The satellite laser ranging (SLR) community has used a relatively simple prediction format since the 1970's. These Tuned Inter-range Vectors (TIVs) typically provide one state vector per day (currently updated via the internet daily) that is integrated on site using a simplified gravity field model to produce range and point angle predictions. While this continues to work well for most satellites, very low earth satellites (<600 km) suffer from a combination of problems. One is that atmospheric drag is difficult to predict in advance, and the other is that the on-site integrators do not replicate the centralized integrator's predictions accurately enough [7]. While more frequent predictions (once or twice a day) help with the former problem, the latter can be solved by using a prediction format such as the type 2 tabular ephemeris, where all the accuracy inherent in the centralized prediction system is preserved during transfer to the ranging station.

In this case it would actually be preferable to distribute a tabular prediction format with each entry containing time, x, y, z, and x, y, and z velocities (and perhaps accelerations) in a geocentric system. The advantage would be that the predictions would once again be site-independent, relieving the centers generating these predictions from tailoring predictions to each of 40 or more ranging stations. This would require more from the on-site software to interpolate the state vector, translate to site coordinates, and do a rigorous range computation that would work from low earth satellite to the edge of the solar system. Most of these software components already exist in the current lunar prediction packages and will need to be carried into the lunar/transponder prediction software mentioned earlier.

### **Conclusion**

Ranging laser transponders from slr-only stations could provide a wealth of data for lunar, solar system, and relativity research. Enabling these capabilities will require high precision predictions provided in a timely manner. Issues regarding the format and distribution of the predictions are now being worked out in anticipation of transponder launches. In the process, software and techniques previous used only in lunar ranging will be taken to the wider artificial satellite ranging audience.

### **Acknowledgements**

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### **References**

- [1] J. D. Mulholland, "Proposed Standards for Distribution and Documentation of Lunar Laser Ranging Data", COSPAR Information Bulletin, 61, London, 1972.
- [2] R. L. Ricklefs, "Revised Standards for Distribution and Documentation of Lunar Laser Ranging Data", COSPAR Information Bulletin, 108, Oxford, 1987.
- [3] "ILRS Normalpoint Format", [http://ilrs.gsfc.nasa.gov/np\\_format.html](http://ilrs.gsfc.nasa.gov/np_format.html), March 1997.
- [4] Ulrich Schreiber, private correspondence, Sep 2000.
- [5] J. Degnan, J. McGarry, P. Dabney, T. Zagwodski, M. Tierney, M. Weatherly, "Design and Test of a Breadboard Interplanetary Laser Transponder", 11<sup>th</sup> International Workshop on Laser Ranging, Deggendorf, Germany, Sep 1998.
- [6] "SLR IRV Format", <ftp://cddisa.gsfc.nasa.gov/pub/formats/tirv.format>, June 1997.

[7] Roger Wood, private correspondence, Jan 2001.

## Appendix 1: Type 1 Tabular Predictions (Lunar only)

- Tabular information at nominal 15 minute intervals from moon rise to moon set
- Includes round trip ranges and pointing vectors to all reflectors
- Vectors and ranges are topocentric (body-fixed terrestrial system of date) and corrected for all effects but refraction.
- Libration matrix (unitless) is included to allow computing the topocentric position of any arbitrary lunar feature for which coordinates are available. Positions are used for offset pointing to visible lunar features.
- Six point interpolation of all quantities will provide adequate precision for data acquisition and filtering.

### 1. Header

columns	description	example
1-12	Prediction provider	"UTMLRS"
14-36	title	"TABULAR LUNAR EPHEMERIS"
38	format type	"1"
	1=all inclusive format	
	2=simple format	
40	format revision number	
42-49	ephemeris	"PEP534"
	"PEPxxx"= MIT Planetary Ephemeris Packaga xxx	
	"DExxx"= JPL ephemeris number xxx	
51-54	Station monument	"7080"

### 2. Date and time of Prediction (UTC)

columns	description	example
2-5	Year	"1997"
7-8	Month	"08"
10-11	Day	"13"
13-14	Hour	"21"
16-17	Minute	"45"
19-20	Second	"00"
22-36	Greenwich Apparent Sidereal Time (GAST) in hours	"5.0372598076813"

### 1. Libration Matrix, Line 1

columns	description	example
2-19	Libration matrix element (1,1)	" .051492075378791"
21-38	Libration matrix element (2,1)	" .905469351070559"
40-57	Libration matrix element (3,1)	" .421276418097484"

### 4. Libration Matrix, Line 2

columns	description	example
2-19	Libration matrix element (1,2)	" -.998666150276562"
21-38	Libration matrix element (2,2)	" .048293777688336"
40-57	Libration matrix element (3,2)	" .018265577690854"

### 5. Libration Matrix, Line 3

columns	description	example
2-19	Libration matrix element (1,3)	" -.003806108902272"
21-38	Libration matrix element (2,3)	" -.421655031167009"
40-57	Libration matrix element (3,3)	" .906748337868106"

### 6. Station to Lunar Center of Mass Vector

columns	description	example
2-5		"CofM"
7-24	Vector X component (.001 au)	"-.412526615838910"
26-43	Vector Y component (.001 au)	"-2.362612673380499"
45-62	Vector Z component (.001 au)	"-.789030528840094"

7.Station to Lunar Target Vector (repeat as needed)

columns	description	example
2-5	Satellite ID Code	0103
7-24	Vector X component (.001 au)	-.412526615838910
26-43	Vector Y component (.001 au)	-2.362612673380499
45-62	Vector Z component (.001 au)	-.789030528840094
64-77	Round trip range (seconds)	2.519788657063
79-93	Tranponder delay (seconds)	0.000000000000

**Sample**

```

UTMLRS      TABULAR LUNAR EPHEMERIS 1 0 PEP534 7080
1997 08 13 21 45 00 5.0372598076813
.051492075378791 .905469351070559 .421276418097484
-.998666150276562 .048293777688336 .018265577690854
-.003806108902272 -.421655031167009 .906748337868106
CofM -.412386682737684 -2.369898488994229 -.798057131563631
0100 -.416450905031098 -2.360099066026741 -.793362954454874 2.519440332963 0.000000000000
0101 .000000000000000 .000000000000000 .000000000000000 0.000000000000 0.000000000000
0102 -.408337791768733 -2.359753750595546 -.794132096306850 2.518036416595 0.000000000000
0103 -.412526615838910 -2.362612673380499 -.789030528840094 2.519788657063 0.000000000000
0104 -.417298598872783 -2.363664651459823 -.789603441735450 2.521731950616 0.000000000000
1997 08 13 22 00 00 5.1028888518895
.049099701485988 .905582778289210 .421318230058921
-.998786626330267 .046125111316538 .017255409871696
-.003807148249024 -.421654249085708 .906748697186920
CofM -.406473472172365 -2.368103830662268 -.798357351280316
0100 -.410563708211383 -2.358313215121320 -.793667393540347 2.516906537452 0.000000000000
0101 .000000000000000 .000000000000000 .000000000000000 0.000000000000 0.000000000000
0102 -.402450590491254 -2.357950288410684 -.794428337463462 2.515501433902 0.000000000000
0103 -.406638351284641 -2.360818255856764 -.789330975322175 2.517252634412 0.000000000000
0104 -.411407457105035 -2.361880599679735 -.789908700161599 2.519196811041 0.000000000000
    
```

## Appendix 2: Type 2 Tabular Predictions

- Tabular information at nominal 15 minute intervals from target rise to set
- Includes round trip ranges and pointing angles for one reflector, surface feature or transponder.
- Pointing angles and ranges are topocentric (body-fixed terrestrial system of date) and corrected for all effects but refraction.
- Six point interpolation of all quantities will provide adequate precision for data acquisition.

### 1. Header

columns	description	example
1-12	Prediction provider	"UTMLRS"
14-36	title	"TABULAR LUNAR EPHEMERIS"
38	format type	"2"
	1=all inclusive format	
	2=simple format	
40	format revision number	
42-49	ephemeris	"PEP534"
	"PEPxxx"= MIT Planetary Ephemeris Packaga xxx	
	"DExxx"= JPL ephemeris number xxx	
51-54	Station monument	"7080"

### 2. Target Record

columns	description	example
2-5	Year	"1997"
7-8	Month	"08"
10-11	Day	"13"
13-14	Hour	"21"
16-17	Minute	"45"
19-20	Second	"00"
22-25	Satellite ID Code	"0103"
	or	
	Feature ID Code	"F075" (1st column non-numeric)
27-36	Fire Azimuth (degrees)	" 17.341919"
38-47	Fire Elevation (degrees)	" 18.353885"
49-58	Return Azimuth (degrees)	" 17.341919"
60-69	Return Elevation (degrees)	" 18.353885"
71-80	Range (seconds to 1 psec)	"2.519440332963"
82-95	Tranponder delay (1 millisec to 1 psec)"	" 0.000000000"

### Sample

```

UTMLRS      TABULAR LUNAR EPHEMERIS 2 0 PEP534    7080
1997 08 13 21 45 00 0100 179.341919 28.353885 179.341919 28.354079 2.519440332963
0.000000000
1997 08 13 22 00 00 0100 180.123456 28.678912 180.123456 28.680856 2.516906537452
0.000000000
  
```