EARTH ROTATION FROM LUNAR DISTANCES: BASIS AND CURRENT STATUS

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ABSTRACT

The observing campaign Earth Rotation from Lunar Distances (EROLD) was organized to provide an initial test of the applicability of lunar ranging to the determination of Universal Time and polar motion in a service bureau mode. Current plans call for a two-year campaign, overlapping with similar efforts using other techniques. The first year is largely concerned with making the network of observing stations operational, with the prospect that some 5-7 stations may be participating in 1978. This paper discusses the lunar laser technique, the EROLD organization and goals, and the present status of the observing campaign.

INTRODUCTION

It has been recognized for the past several years that the presently-used techniques for routine determination of the rotational position of the Earth's crust are no longer adequate for the scientific and practical applications for which these data are required. Many of the classical instruments are now of questionable utility and will surely have to be retired from service within one or two decades. The pertinent question, then, is not *whether* they will be replaced, but with *what* will they be replaced.

There begin to be an impressive number of potential candidates for the next-generation Earth rotation service. One can, for example, imagine a network of instruments conceptually related to the classical method, such as the new giant photographic zenith tube (PZT) at the U. S. Naval Observatory, or the photoelectric astrolabes under development in France and China. It seems more likely, however, that the new network will rely primarily on completely new techniques. The present possibilities include various techniques for radio tracking of artificial satellites, radio interferometry of celestial radio sources, and laser ranging to the Moon or to artificial satellites. In principle, each of these systems presents unique advantages and capabilities not totally shared by the others; in practical application to the needs of an Earth rotation service, each of them also shows important drawbacks. We have tried to summarize both sides of this situation in Tables 1-4.

It is important to note that none of these systems was invented for the purpose of Universal Time and polar motion. Each of them had other motivations that seemed to be more important, and most of them have demonstrated in practice that they are capable of important scientific or technical tasks. But our present subject is their applicability to the daily needs of a service bureau function. The Doppler Polar Motion Service (DPMS) has shown that it can operate in this mode, but with severe disadvantages. Episodic determinations of UT0 and/or the variation in latitude have been obtained by VLBI, artificial satellite ranging, and LLR, but we believe that (excepting DPMS) *none* of the new techniques have demonstrated their utility in a daily service network mode, nor at what real cost. True, there are sensitivity studies and projections for several of them, but most of these are believed at most by their authors. It seems undeniable that the only real way to discover the utility of the new techniques as potential next-generation Earth rotation networks is to perform realistic pilot demonstrations for each one, unless there are obvious grounds on which to exclude it. If this is done, we may suspect that the resulting "best buy" will be (as now) a hybrid system incorporating two or more of the new techniques whose advantages and disadvantages are in some way complementary.

The observing campaign called Earth Rotation from Lunar Distances (EROLD) is intended to be just such a pilot demonstration. The concept was developed in discussions between us in 1974, and was proposed first to the NASA Lunar Laser Ranging Team and then to COSPAR Working Group 1 that same year. COSPAR responded by recommending that the campaign be undertaken, and the Working Group appointed a Steering Committee to work out the details and provide coordination at the international level, recognizing that no one country is capable of determining the three-dimensional rotation of Earth from entirely within its own boundaries.

BASIS OF THE TECHNIQUE

The laser ranging technique provides measures of a nature very different from classical astronomical observations. It is an *active* process, in which the observer illuminates a target and observes the illumination that he himself has provided. It is also unlike at least some of the other new techniques, in that the observed object is entirely passive, and thus is not subject to technological failure nor administrative shutdown. (The often-mentioned fact that the target *might* be destroyed by a chance collision is in fact shared with *all* techniques, and the probabilities are quite infinitesimal for all of them.) With the laser, a pulse of light is transmitted by a terrestrial station towards a reflector on the lunar surface. Because of the cube-corner design of the reflector, the light that strikes it is retransmitted towards Earth in the same direction from which it came (Figure 1). Thus, the signal is detected by a photomultiplier at the same station from which it came. The observation recorded is the time delay between the transmission of the laser pulse and the detection of the reflected signal. For convenience, one often refers to this as a distance measurement, but it is essential to understand that it is really an aberration time, more commonly called "light time". The time delay cannot be symmetric about the reflection time, because of the relative motions of the Earth and Moon during the interval of about 2.6 seconds (1).

Since 1969, five laser reflectors have been placed on the lunar surface. The reflector on Lunakhod I has been observed only a few times by the French and Soviet teams, with relatively poor accuracy. Those carried by Apollo 11, Apollo 14, Apollo 15, and Luna 21 (Lunakhod II) have been observed regularly from the McDonald Observatory since they were deposited. The typical accuracy of these ranges, expressed as an equivalent one-way distance, is now 10-15 cm, and 5-cm ranges are no longer rare. We should note here that, at least in principle, only one reflector is required for Earth rotation determinations, so there seems to be a reserve that is more than adequate to render the meteorite "problem" truly insignificant.

It does not seem necessary to give the details about the process used to analyze these data to obtain improved estimates of the physical parameters of the Earth-Moon system, as this information is already published (e.g. 2,3). The two questions that do seem to be important here are: a) are the Earth rotation parameters separable from the other parts of the physical model, and b) can the geocentric motion of the reflector be modelled with sufficient accuracy to permit meaningful Earth rotation results?

Imagine a simplified problem in which the Moon does not move, but is fixed like a star in distant inertial space. In that case, the laser time delays measured from a point fixed on the surface of Earth would vary only as a function of the Earth's motion. Neglecting the

Earth's orbital motion for the moment, the delays would vary only as a function of the local hour angle of the reflector and its minimum (i.e. meridian) zenith distance. If the rotational axis of the Earth's crust were also fixed in inertial space, then the range could be described as exactly a simple harmonic function of time, and the determination of the geocentric coordinates of the station would consist of finding the amplitude, phase and zero offset of that sine function. True enough, that is not the real world. Suppose we approach the real world a little more closely and imagine that the Moon *does* move about the Earth, that the Earth *does* move about the Sun, and that the Earth's rotational axis *does* move in inertial space, *but* that we know these motions perfectly. Then the range is no longer a sinusoid, but the residuals of the observations with respect to the perfectly-known prediction model will be, with the amplitude, phase and zero offset depending on the station coordinates. If, however, our world includes the one imperfection of a plastic, inhomogeneous, poorly-understood Earth, then problems begin to arise. The rotation axis of the crust is no longer fixed with respect to the crust itself, and the rotation rate of the crust is no longer constant or even perfectly predictable. In other words, there will be variations in the apparent longitude and latitude of an observing station. The sinusoid concept can still be used with long observation series to give some sort of mean or nominal coordinates for the station, which can then be entered into the prediction model. The slippage of the Earth's crust will then be exhibited as quasi-sinusoidal residuals, a function that is locally harmonic, but with variable amplitude and phase. If the period of these modulations is long compared with one day, as suggested by Stolz et al (4), then the sinusoid model can be applied daily to obtain an estimate of the mean values of the apparent variations in longitude (UT0) and latitude (meridian component of polar motion) for that station and that day. The data from several stations can be combined to give an estimate of UT1, x and y for that day.

How does this idealized determination of Earth rotation fit into the realities? Of course, we do not have a perfect model. Nobody has a perfect model, not for the Moon, not for optical or radio star positions, not for TRANSIT nor for LAGEOS. And as with all systems, anything that introduces an error into the predicted hour angle or meridian zenith distance of the observed object *can* be largely absorbed (rightly or wrongly) into an estimate of UT0 and variation of latitude. In *all* methods, the hope is that the physical model can be made sufficiently complete by the addition of other solution parameters that the contamination of Earth rotation results will be small compared to the values obtained. We repeat, because it is often ignore, that *no* technique for modelling a phenomenon for which there is no theory can hope to do more. What we perceive to be an advantage for LLR is that there is no known non-gravitational phenomenon that is important in the orbital motion, and the only one that exists in the lunar rotation has well-defined periods separable from the other factors. The modelling of gravity fields seems not to be a serious problem, either. That is *not* to say that there are no problems. The statement made five years ago by one of our colleagues that "we know every factor that could influence the lunar orbit at the few-centimeter level" was not justified then and probably is not now. The best indication that there are still things to discover is the fact that, with 15-cm data, the best global solutions without determination of the Earth rotation parameters give 40-cm residuals, and including the Earth rotation parameters only reduces the rms residual to about 30 cm. The disparities between different studies are still too high (about the same level as the rumored differences between different LAGEOS results), but they are at least within the BIH uncertainties. It is easy to overemphasize these problems, however, because the uncertainties in the present classical results are much smaller than the mean errors of single observations.

The conclusion that we continue to draw from this is that the best, perhaps the only, way to draw clearly justified conclusions as to the relative merits of the various techniques is to perform realistic and extended tests of each one in a service mode of operation, preferably with temporal overlap between the different methods, to detect systematic error within each.

EROLD ORGANIZATION PLAN

In recognition of the necessity that EROLD be a collaboration between observing groups and the Earth rotation services, the Steering Committee appointed by COSPAR Working Group 1 consisted of one representative from each national observing team then existing, the Bureau International de l'Heure (BIH), the International Polar Motion Service (IPMS), plus the chairman of COSPAR Panel 10 on Lunar Laser Ranging, *ex officio*. Since that time, one new observing team has been represented, as well as the group responsible for pre-processing the data from the three stations nearest operational status.

The first meeting of the Steering Committee was held at the IUGG General Assembly in 1975. As a result of strong urgings from non-members present, the BIH accepted (somewhat reluctantly) the responsibility to act experimentally as the central agency for combining results from the individual stations for the determination of UT1, x and y. This seemed a natural extension of one of the agency's fundamental activities, but it did pose a problem: the reduction of LLR data requires significantly different analysis capability and computing capacity from that then existing at BIH. This problem was solved by a collaboration between personnel of the Observatoire de Paris (BIH/OP) and the Centre d'Etudes et de Recherches Geodynamiques et Astronomiques (BIH/CERGA). A plan for the BIH participation in EROLD was presented to the Steering Committee at its June 1976 Meeting

at Austin (5). The BIH activity was defined to consist of:
--- Collection of normal points from participating observatories;
--- Calculation of residuals with respect to a uniform model;
--- Preliminary reduction of the raw residuals;
--- Calculation of UT1, x and y;
--- Regular distribution of results;
--- Study modes of combining LLR with other data types.

The *regular* distribution of results is a key factor in service bureau operations. The proposed schedule is given in Table 5. This will provide important feedback to the observing crews, as well as valuable data to the various users of LLR (and other) observations. This is, after all, the prime function of an Earth rotation service.

PRESENT RESULTS OF EROLD AND FUTURE PROSPECTS

At what stage does November 1977 find EROLD? Not a very satisfying one, unfortunately. In principle, the observing campaign was to have begun on 1 January 1977, a date chosen because it seemed likely that three stations would be fully operational at that time. The planned duration was two years, which would include one year for the stations and the BIH to "shake down" their operations, to uncover and solve the startup problems, and then another year of "production" operations. In fact, at this moment, the only station producing real observations of usable quality on a near-daily basis is the same one that has been doing so for about eight years, the McDonald Observatory. The BIH computation system, which *was* ready for experimental use last January, has never yet been tested on real data, because there have been essentially no multi-station data. The current status of the prospective stations in the LLR network is as follows:

AUSTRALIA --- Of the new stations, Orroral appears to be the closest to operation, which is a happy circumstance in view of its southern latitude. They have been firing regularly for several months and gradually isolating and fixing various problems. There have been several successful echo detections, but they are not yet obtained consistently. Experienced LLR people estimate that Orroral could become operational at almost any instant.

FRANCE --- The station at Pic-du-Midi was closed in 1974 and a new one begun on the Calern Plateau; it was to have been finished in 1976, but they have experienced severe budget delays. The 1.5 m telescope was mounted in June 1977, and optical/mechanical testing is now underway. The refurbished and upgraded laser will be installed early next year. Ranging tests *could* begin (optimistically) as early as June 1978. Lunar acquisition may be attempted with the second-generation artificial satellite station at Calern before that time.

GERMANY (Federal Republic) --- Approval and funding have been received to upgrade the operational second-generation artificial satellite station at Wettzell to lunar capability. Equipment modifications are expected to be delivered on site next June. Lunar tests might begin as early as September 1978.

JAPAN --- Considerable difficulty has been experienced in bringing the Dodaira station to operational status. Many equipment and optical problems have been found and corrected. Further attempts at lunar ranging are scheduled for November and December 1977.

USA --- The McDonald station has recently been upgraded to the point that 5-cm normal points are common, even if not yet the rule. The Haleakala station is continuing to experience great difficulty is becoming operational. Some very high-quality echos have been received, but system debugging continues to be a full-time occupation.

USSR --- Ranging operations on the 2.6 m telescope at Crimea are still permitted only 20-25 days per year, which is inadequate for full EROLD participation. The proposed new dedicated station is still several years in the future.

Thus, the situation can be summarized in the following way:

--- The data analysis and distribution system is ready;

--- One station demonstrates that near-daily operations are possible;

--- Three-station operation may become a reality at any moment;

--- Full network operation (5-6 stations) cannot be expected before late 1978 or early 1979.

Everyone will likely agree that this is not very satisfying. Is this equivalent to saying that it is a failure, or that it should not have been tried? We think that the answer to both questions is "no". Certainly, EROLD is not yet a success, but it is also not yet a failure; it still has prospects for success. It has not yet been demonstrated that LLR can serve as a cornerstone for the next-generation Earth rotation service, but no *other* high-precision technique has yet demonstrated this capacity either. Yes, it is true that satellite ranging and VLBI have been used to determine Earth rotation parameters on a few isolated days and much after the fact, just as LLR has done. What must be demonstrated is the capability for, and the cost of, daily or near-daily operations with quick turn-around of results. EROLD was the first of the formally-organized campaigns to adopt this as its prime goal. Such campaigns are now organized or in process of being organized for the other techniques, and we are pleased to see this. We hope that our own efforts have been among the stimuli for assuring that all of the new techniques receive an adequate test. We do not know which technique or combination of techniques will prove to be the most viable for an Earth rotation service, although we do have private opinions. Opinions are not important; we must all try to assure that each technique is tested in a realistic mode, so that the best decisions may be made. In that way, one does not seek that a *technique* "wins", but that science and technology win.

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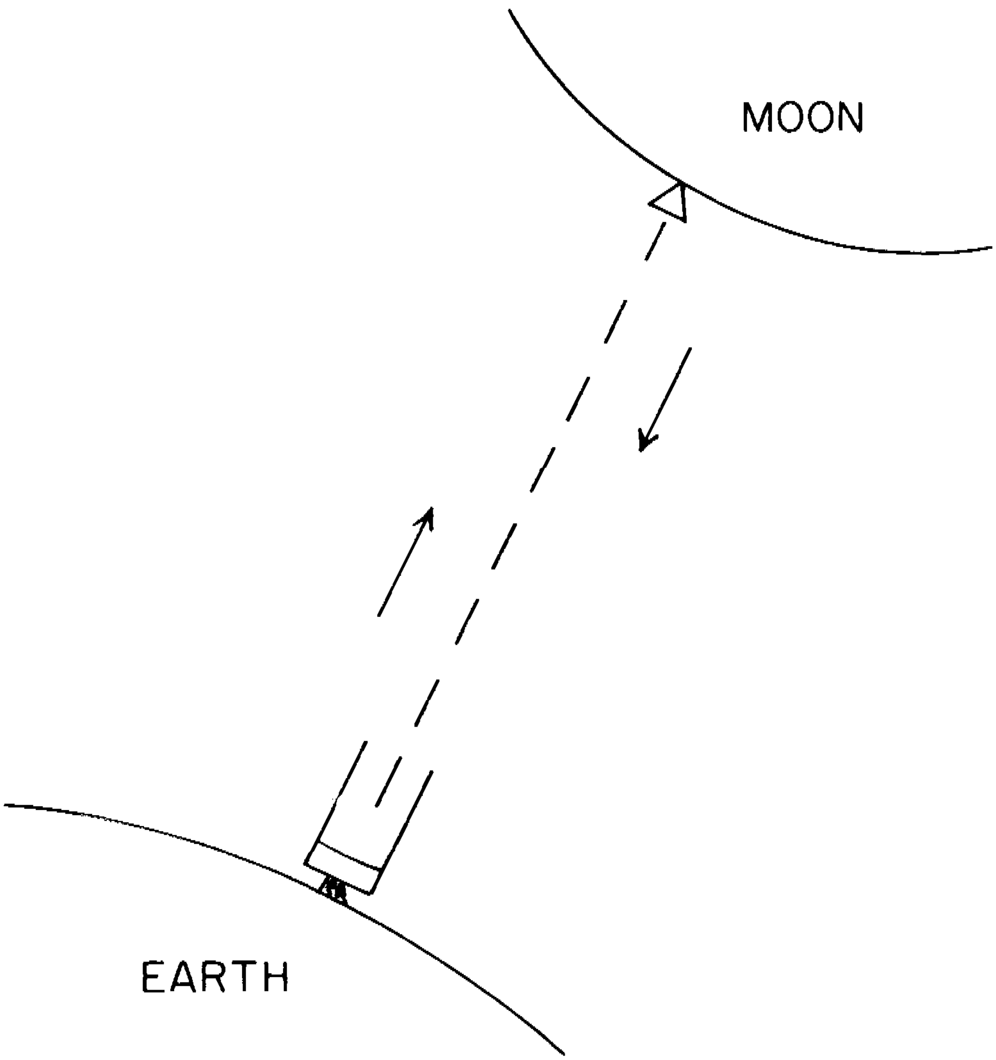

Figure 1: A schematic representation of lunar laser ranging

Table 1: Radio Tracking of Artificial Satellites

A. "Classical" doppler tracking
B. Global Positioning System (GPS), high-density network of 12-hr satellites

	A	B
Advantages		
All-weather capability	x	x
One observation requires only a few minutes	x	x
Low operational cost	x	?
High technical level not required of operations personnel	x	x
Operational network has demonstrated daily operations	x	
Disadvantages		
No tie to inertial reference system	x	x
Currently relies on data and models under military security	x	x
Produces pole position only, not Universal time	x	?
Inherent accuracy limit poorer than with other new techniques	x	?
Currently relies on TRANSIT satellites, which may be discontinued	x	

Table 2: Radio Interferometry of Celestial Radio Sources

A. Connected-element, phase-coherent interferometry
B. Very-long-baseline Interferometry (VLBI)
C. Phase-linked VLBI using satellite communications link

	A	B	C
Advantages			
Weather limit due only to extremely high humidity	X	X	X
Gives direct tie to inertial reference frame	X	X	X
Uses natural (and near-inertial) targets, not subject to failure	X	X	X
Near real-time data processing	X		X
Disadvantages			
Long integration times, each observation is several hours continuous	X	X	X
Two stations (two telescopes) required for each observation	X	X	
Four telescopes required for each observation			X
Inherent accuracy limit poorer than for other new techniques	X		
Little real-time indication of successful observation		X	
Requires large fraction of a communications satellite			X

Table 3: Laser Ranging to Artificial Satellites (LAGEOS and STARLETTE)

Advantages

- Observed object is passive, not subject to failure or shutdown
- One observation requires only about one hour (one complete pass)
- Observing network exists, largely operational
- Pointing requirements less stringent than for LLR
- Perhaps less costly per station than LLR (???)

Disadvantages

- Must have clear sky and good transparency
- No tie to inertial reference system
- Partial passes not useful for Earth rotation
- More stations required than for other techniques
- Requires highly accurate modelling of Earth's gravity field and non-gravitational forces
- Orbit rectification introduces discontinuities into Earth rotation results
- Uses limit of current technology; requires highly-skilled, dedicated personnel

Table 4: Lunar Laser Ranging (LLR)

Advantages

- Observed object is passive, not subject to failure or shutdown
- One observation requires only a few minutes
- Gives tie to inertial reference system through lunar and planetary orbits
- Low-order modelling of gravity fields sufficient, and no non-gravitational forces
- Oldest reflector shows no degradation after 8 years' use

Disadvantages

- Must have clear sky and good transparency
- Several observations required each day at each station
- New Moon gap in present data (not inherent to technique)
- Requires accurate gravitational modelling of entire planetary system
- Uses limit of current technology; requires highly-skilled, dedicated personnel

Table 5: Proposed Schedule for BIH Reduction of EROLD Data

Day j	Beginning of an observing interval
j + a	End of that observing interval
j + b	Reception of the normal points at BIH/CERGA
j + c	Reception of the residuals at BIH/OP
j + d	Transmission of the results for Universal Time and pole coordinates from BIH/OP to participating observing groups

The tentative values are: a = 7 days, (b - a) = 10-15 days, (c - b) = 3-4 days, (d - c) = 2-3 days

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QUESTIONS AND ANSWERS

DR. WILLIAM KLEPCZYNSKI, U. S. Naval Observatory:

You indicated that a study showed that you could not determine all the earth rotation parameters within any one country. Was that with just lunar laser ranging?

DR. MULHOLLAND:

No, with anything.

DR. KLEPCZYNSKI:

Even VLBI?

DR. MULHOLLAND:

I think so.

DR. TOM CLARK, NASA Goddard Space Flight Center:

I would think that the Hawaiians and Texans would certainly want to be thought of as being in the same country. In terms of the lunar laser, those are nearly orthogonal on the earth, which I think does meet the criteria. And certainly also in the case of the VLBI situation, if you regard Alaska, Hawaii, and the continental United States as all members of the same country, I believe the job can be done quite admirably on baselines involving combinations geographically deposed that way.

DR. MULHOLLAND:

I agree. I would be interested in seeing that done. I am reminded of the idea that one can model the moon's gravitational field by observations of one site only. Orthogonality is perhaps not enough. I could say very distinctly that McDonald and Hawaii are not enough. Hawaii has too low a latitude.

DR. KLEPCZYNSKI:

I believe you really must qualify to what precision you wish your quantities so that you could then determine them within one country.

DR. MULHOLLAND:

All right, that's fair enough. But I think implicit in everything we are talking about here today is the determination of all three components of the rotational position, all to a consistently and extremely high accuracy.

DR. KLEPCZYNSKI:

Next Monday, the Naval Observatory will begin observing on a monthly basis at the Greenbank interferometer to determine earth rotation parameters.

DR. MULHOLLAND:

I was under the impression, however, that the daily operation is somewhat in the future. It is the daily operation that one has to do eventually.

DR. KLEPCZYNSKI:

Well, if we can do it monthly, regularly, I think we will be ahead of the game.

DR. MULHOLLAND:

If you can do it monthly, regularly, you will be ahead of us.