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Earth Rotation and Polar Motion from Laser Ranging to the Moon and Artificial Satellites

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Abstract. Earth-based laser ranging to artificial satellites and to the moon is considered as a technique for monitoring the Earth's polar motion and diurnal rotation. The kinematics of Earth rotation as related to laser ranging is outlined. The current status of laser ranging as regards its measuring capabilities is reviewed. Artificial satellite laser ranging has recently yielded pole position to better than 0.02 arcseconds with 5 days averaging as the best result. In recent years single-station lunar laser ranging has produced UT0-values to better than 1 msec. The relative merits of artificial satellite and lunar laser ranging are pointed out. It appears that multistation combined artificial satellite and lunar laser ranging is likely to ultimately meet a 0.002 arcseconds in pole position and 0.1 msec in UT1 daily precision requirement.

Introduction

Although the most intriguing implications of the Earth orientation phenomenon lie in its dynamics and the geophysical effects involved, the present contribution will focus on its kinematics. This is done in relation to the use of Earth-based laser ranging to the moon and to artificial satellites as a technique to monitor polar motion and diurnal rotation. It should be pointed out, however, that such monitoring can only be performed efficiently if a dedicated program of measurement is based on a profound qualitative understanding of the phenomenon.

Earth orientation is involved where measurements connect positions of objects, related to an extra-terrestrial frame of reference, to terrestrial objects. The geometric relationships established by the measurements depend on the orientation of a conventional Earth-fixed frame of reference with respect to the extra-terrestrial one. Such situation arises in space geodesy in general and in satellite geodesy in particular, the moon conveniently being considered as a satellite. Until the advent of precise tracking means, including laser ranging, the time-dependent orientation of the Earth was numerically modelled in terms of the current theories of precession and nutation and the orientation parameters as provided by the Bureau International de l'Heure (BIH); see Veis [1963]. Noting the inherent precision of modern tracking techniques and some of their further advantageous characteristics it was realized that certain constituents of Earth orientation should be rather modelled in terms of unknown solution parameters in order to exploit the qualities of the measurement data. One of these techniques is laser ranging to the moon and to artificial satellites.

Before reviewing the current status of this technique and its foreseen development the geometry and kinematics of Earth orientation as pertaining to laser ranging will be presented. The potentialities to monitor Earth orientation by laser ranging will be assessed and results obtained from both lunar and artificial satellite ranging will be quoted. These concern the diurnal rotation of the Earth and polar motion.

Earth orientation as related to laser ranging

A meaningful approach to Earth orientation requires the operational definition of at least two frames of reference: one to which the motion of the Earth is sufficiently well modelled (the rectangular Cartesian conventioned "Earth-fixed" frame: x_1, x_2, x_3) and another rectangular Cartesian frame (z_1, z_2, z_3) with respect to which the orientation is to be monitored. The definition of reference frames in a contemporary context is not always straightforward as demonstrated by Kolaczek and Weiffenbach [1974]. Of particular relevance is the problem of fixing a reference frame to a deformable Earth. The problem of Earth orientation is essentially the problem of finding the relative orientation of two reference frames, the components of unit vectors referred to both reference frames being given as time-dependent quantities. The basic problem is thus to find both sets of components, in this case from the laser ranging.

In the classical optical stellar approach to monitor Earth orientation, the x-system is defined by a set of conventionally adopted latitudes ϕ and longitudes λ of participating observatories, these observatories measuring the time-dependent direction components of the observatory verticals with respect to a fundamental stellar reference frame adopted as z-frame. This z-frame is in fact defined by conventional positions and proper motions of fundamental stars and considered inertial. Satellite ranging is, however, what Newton [1974] called, a "blind" technique and the relation to the fundamental z-frame is less straightforward. The main complication of the satellite approach is that the orbits of the satellites with respect to which the Earth's orientation is to be monitored by Earth-based measurements, have to be monitored themselves by means of such measurements. This holds in particular for artificial satellites somewhat less for the moon. The critical issue here is that satellite orbits referenced to the z-frame cannot be determined from Earth-based tracking without the à priori involvement of the Earth's orientation. This involvement is however restricted so that Earth-based determined satellite orbits are at least in certain respects independent of à priori knowledge about the Earth's orientation, and Earth-based tracking data may thus contain signatures of Earth-orientation.

Of crucial importance to any practical approach to Earth orientation is the operationality of re-

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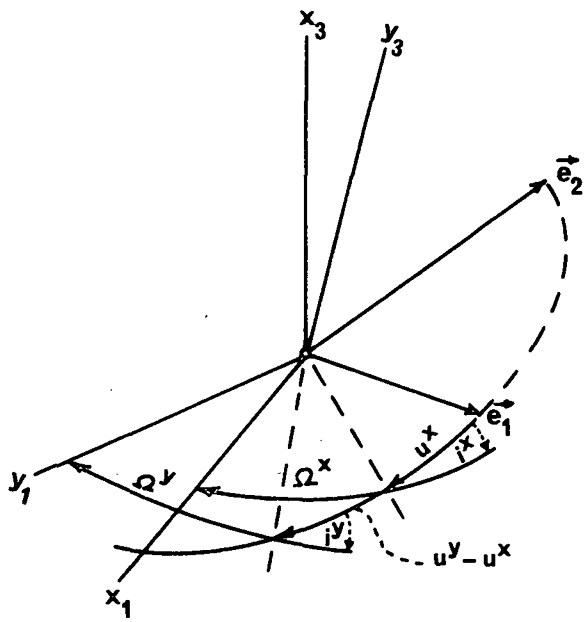

Fig. 1. Definition of reference frames by angular Keplerian orbital elements u, i and Ω.

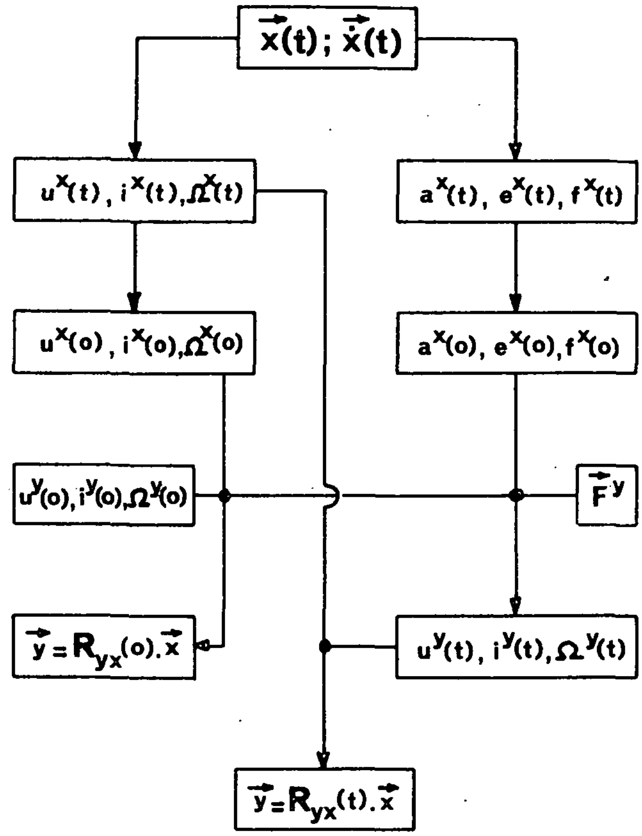

Fig. 2. Orientation of an Earth-fixed x-frame relative to an inertial y-frame by means of perturbed angular Keplerian orbital elements. $\vec{F}^y$ is the field of perturbing forces as described on the y-frame, a is the satellite orbit's semi-major axis, e its eccentricity and f its true anomaly.

ference frame definitions. The orientation of a right-handed rectangular Cartesian frame is uniquely defined by two orthogonal unit vectors $\vec{e}_1$ and $\vec{e}_2$. Any frame obtained by rotation from this basic frame, can then be specified by angles u^x, i^x and Ω^x; see Figure 1. So is a quasi Earth-fixed x_1, x_2, x_3-frame, in which laser tracking locations and their modelled motions due to tides, tectonics etc, are specified. Likewise any y_1, y_2 y_3-frame with respect to which the orientation of the x-frame is to be described: u^y, i^y, Ω^y.

Given u^y, i^y, Ω^y, the differences

$$\Delta u = u^x - u^y$$
$$\Delta i = i^x - i^y$$
$$\Delta \Omega = \Omega^x - \Omega^y$$

uniquely describe the rotation from the y-frame to the x-frame.

Now u, i and Ω respectively can be identified with the angular Keplerian orbital elements of a satellite: argument of latitude $\omega + f$, inclination and argument of the ascending node, f being the true anomaly and ω the argument of perigee. Thus the use of satellites to monitor Earth orientation seems rather obvious if u^y, i^y, Ω^y and Δu, Δi, ΔΩ can to sufficient accuracy be determined as time varying quantities. The procedure to obtain such quantities is a complicated one, to be summarized as follows. (see Figure 2).

Osculating Keplerian elements of the satellite $\Omega^x(t)$, $i^x(t)$, $\omega^x(t)$, $a^x(t)$, $e^x(t)$ and $f^x(t)$ are obtained from a state vector $\vec{x}(t)$; $\dot{\vec{x}}(t)$, determined in the x-frame from tracking data, e.g. laser ranging, in a purely kinematic way.

An inertial y-frame can be defined by adopting values $u^y(0)$, $i^y(0)$, $\Omega^y(0)$ for u^y, i^y, Ω^y at a selected epoch t_0. Together with $a^x(0)$, $e^x(0)$ and $f^x(0)$ these provide the initial state vector at t_0 of the satellite in the y-frame.

The two sets of angular elements

$$u^x(0),\ i^x(0),\ \Omega^x(0)$$
$$u^y(0),\ i^y(0),\ \Omega^y(0)$$

together define the relative orientation of the x- and y-frames at t_0: $\vec{y} = R_{yx}(0) \cdot \vec{x}$.

To track the time-dependent orientation $R_{yx}(t)$ of the x-frame relative to the y-frame, angular elements

$$u^y(t),\ i^y(t),\ \Omega^y(t)$$

are required in addition to

$$u^x(t),\ i^x(t),\ \Omega^x(t)$$

as obtained by measurement in the x-frame. Elements

$$u^y(t),\ i^y(t),\ \Omega^y(t)$$

can be extrapolated from the initial state vector at t_0 if the complete field of forces acting in the y-frame ($\vec{F}^y$) is assumed. In this extrapolation the y-frame may be considered inertial. It should be noted however that this inertial frame does in general not coincide with the fundamental stellar z-frame of reference, which was also considered inertial, but which deviates from the y-frame by a time-invariant relative orientation

$$\vec{z} = R_{zy} \cdot \vec{y},$$

the elements of which remain as yet unspecified.

The force field as referred to the y-frame will consist of two classes of contributions:

- forces depending on the time-dependent relative orientation $R_{yx}(t)$ of the x- and y-frames, e.g. non-central terrestrial gravitation including solid-Earth and ocean tides;
- forces independent of this orientation, e.g. solar radiation pressure and luni-solar gravitation.

The first class of forces poses a theoretical complication because the relative orientation $R_{yx}(t)$ to be derived has to be known in advance in order to extrapolate the initial angular elements

$$u^y(0),\ i^y(0),\ \Omega^y(0) \quad \text{at } t_0$$

to obtain instantaneous values:

$$u^y(t),\ i^y(t),\ \Omega^y(t) \quad \text{at } t.$$

It should be noted that R_{yx}-dependent inertial forces acting in the x-frame do not interfere, provided the procedure to obtain angular elements $u^x(t)$, $i^x(t)$, $\Omega^x(t)$ is indeed a purely kinematic one.

To obtain the R_{yx}-dependent force contribution with respect to the y-frame poses a complication leading to the introduction of what Lambeck [1971] called "dynamic perturbations". Although these perturbations may not be entirely negligible with future precise laser ranging to artificial satellites, this complication is disregarded here. In doing so a unique latent opportunity to verify the coincidence of the adopted x_3-axis of maximum inertia [Melchior, 1972] is likewise disregarded. On the other hand it seems unlikely that even advanced tracking precision would permit this verification in a foreseeable future [Gaposchkin, 1972; Kolaczek and Weiffenbach, 1974]. Nevertheless in a detailed discussion the formal non-coincidence should not be overlooked:

$$\vec{x} = R_{x\xi} \cdot \vec{\xi},$$

the ξ-system being the axis-of-figure (maximum inertia) system. Hence:

$$\vec{z} = R_{zy} \cdot R_{yx} \cdot R_{x\xi} \cdot \vec{\xi} = R_{z\xi} \cdot \vec{\xi}$$

$R_{z\xi}$, thus defined includes:

a. the unknown small and virtually invariable deviation of the adopted quasi Earth-fixed x-frame from the axis-of-figure ξ-frame;
b. polar motion relative to the x_3-axis, which does not necessarily coincide with the CIO, but will be close to it;
c. the Earth's diurnal rotation as measured by the siderial angle θ;
d. the small deviation termed "sway" of the Earth's instantaneous rotation axis from the direction or the total angular momentum vector; McClure [1973] found that for a deformable Earth this deviation can approach 0.01 second of arc.
e. luni-solar forced nutation and precession of the Earth's total angular momentum vector;
f. the relative orientation of the inertial y-frame to the quasi-inertial fundamental stellar z-frame.

Of these only items (b) and (c) pertain directly to the present subject. Ignoring for the sake of simplicity of the present treatment the possible deviations between the ξ_3-axis and the CIO and between the CIO and the x_3-axis and also sway, we can summarize:

$$\vec{y} = R_{yz} \cdot P \cdot N \circ R \cdot \vec{x} = R_{yx} \cdot \vec{x},$$

R, N and P being rotation matrices describing combined polar motion and diurnal rotation, forced nutation and precession respectively, in a form as presented by Veis [1963]. Writing

$$P' = R_{yz} \cdot P,$$

P' may be considered as describing precession with respect to the arbitrarily defined inertial y-frame, leading to the conclusion that satellite techniques yield the compound rotation

$$\vec{y} = P' \cdot N \cdot R \cdot \vec{x},$$

precession P' relative to the y-frame. To comply in practice with convention and to conveniently separate R from precession and nutation, when assuming the latter two, the initial angular orbital elements

$$u^y(0),\ i^y(0),\ \Omega^y(0)$$

are selected so, that the y-frame coincides with the z-frame, although because of incomplete knowledge about R(0) at epoch, this can be realized only approximately, even if N(0) and P(0) are assumed. If realized, R_{yz} is unity and P' = P, so that:

$$P \cdot N \cdot R = R_{zx}$$

and consequently:

$$R(t) = N^* \cdot P^* \cdot R_{zx}$$

If not fully realized, R(t), thus derived, will be biased by an unknown, but contstant relative orientation.

A sequence of R(t) for a sequence of instants t will provide the time-dependent orientation of the Earth's rotation axis with respect to the Earth-fixed x-frame (ψ^x, λ^x) and the siderial angle θ, see Figures 3 and 4. Finally, to comply with IPMS and BIH convention, pole position is given as x_p and y_p.

In practice [Lambeck, 1971] u^x, i^x, Ω^x may be

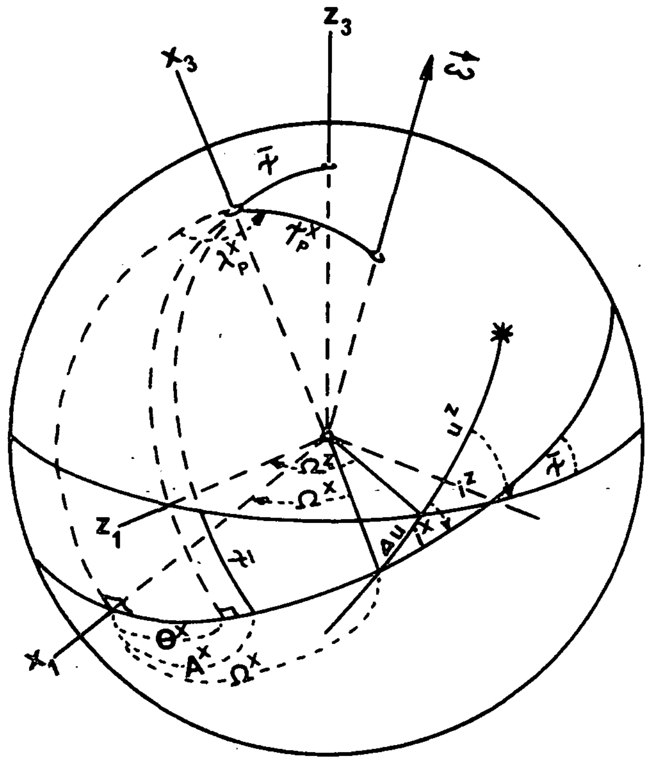

Fig. 3. Geometry of Earth orientation with respect to stellar z-frame, the orientation to be obtained from satellite orbits. λ_p^x and ψ_p^x specify the direction of the Earth's rotation axis relative to an Earth-fixed x-frame.

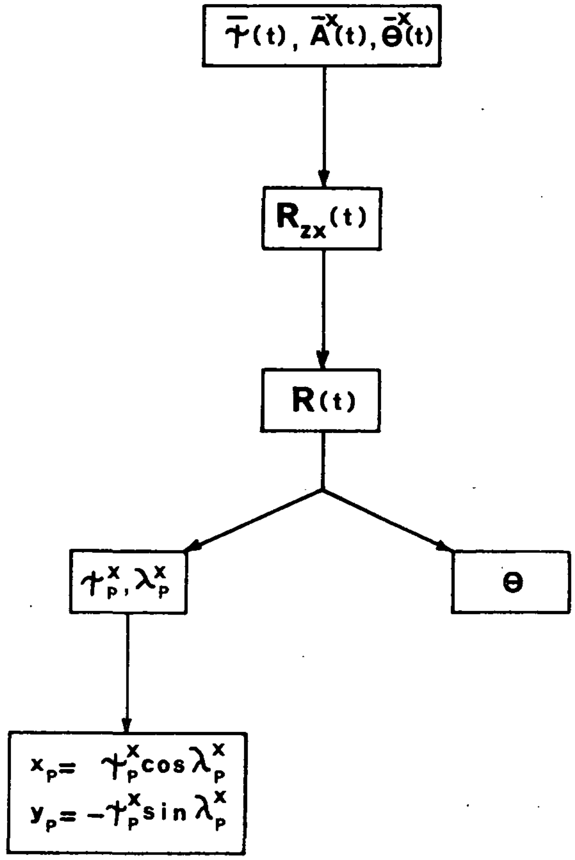

Fig. 4. From the relative orientation of Earth-fixed x- and stellar z-frames to pole position (x_p, y_p) and siderial angle Θ.

transformed to $u^{z'}$, $i^{z'}$, $\Omega^{z'}$ as referred to an intermediate quasi inertial z'-frame, which approximates the z-frame:

$$\vec{z} = D(t) \, . \, \vec{z}'$$

This is performed by approximating R(t) by $\tilde{R}(t)$, replacing Θ by an approximate value $\tilde{\Theta}$ and equating x_p and y_p to zero:

$$\tilde{R}(t) = \begin{bmatrix} \cos\tilde{\Theta} & -\sin\tilde{\Theta} & 0 \\ \sin\tilde{\Theta} & \cos\tilde{\Theta} & 0 \\ 0 & 0 & 1 \end{bmatrix}$$

Solving then for D(t), rather than for R(t) directly, yields ψ_p^x, λ_p^x and $\Delta\tilde{\Theta} = \Theta - \tilde{\Theta}$; see Figure 5.

This general approach is valid for both artificial satellites and the moon although it is primarily tuned in to the use of artificial satellites, not restricted however to laser ranging. Before pointing out special features of the lunar laser ranging case some general conclusions may be drawn:

- because the x-frame does not necessarily coincide with the conventional terrestrial reference frame as defined by the CIO and the conventional zero meridian of Greenwich, there may appear constant biases in all three determined rotatio-

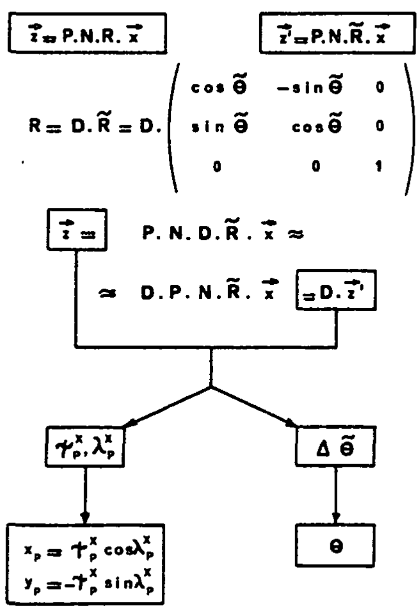

Fig. 5. Pole position (x_p, y_p) and siderial angle (Θ) from the relative orientation of the quasi-inertial z'-frame relative to the inertial z-frame. Θ is an approximated siderial angle.

nal parameters x_p, y_p, θ as derived in the classical optical stellar way;
- due to the well-known longitude-ambiguity in artificial satellite orbits such bias is so likely in θ that artificial satellite techniques are expected not to provide UT1, but rather the rotation rate ω of the Earth;
- additional not necessarily constant biases may be caused by erroneously modelled lunar-solar precession and mutation (P- and N-matrices);
- a detailed force model and a scrupulous application of that model are required.

The moon is just another satellite, kinematically differing from the others by:
- its larger mean orbital radius;
- its relatedly longer period of revolution, in fact much longer than that of the Earth's diuranl rotation;
- its more stable center of mass orbit, less effected by the Earth's graviational potential and other terrestrial perturbing forces;
- its substantial size, which requires the selenodetic coordinates of the retroreflector sites and the lunar rotation to be modelled or solved for;
- there is only one moon, hence one lunar center-of-mass orbit but the moon carries several geometrically distinct retroreflectors.

These differences entail marked differences concerning tracking-operational and data analysis aspects. These are indicated in the next two paragraphs respectively.

The status of laser ranging

The technique itself is assumed known and will be reviewed only as regards its main characteristics pertaining to Earth orientation determination. Detailed and up to date technical information on availabe instrumentation and current developments can be obtained from Pearlman and Hámal [1978].

Relevant system characteristics are:
- maximum range capacity;
- ranging precision;
- day-light ranging capability;
- repetition rate.

Speaking in general terms these characteristics are not mutually independent.

In the present context, systems can as regards their maximum range capibility be classified in broadly three catagories:
- those of lunar ranging capability;
- those able to range at Lageos;
- those restricted to closer artificial satellites, like Beacon Explorer-C, Starlette and Geos-3.

It should be noted that the operational aspects of lunar laser ranging (LLR) are quite different from those of artificial satellite laser ranging (SLR), and a system of lunar range capability will not necessarily be able to range at artificial satellites.

The most advanced SLR systems attain between 5 and 10 cm single shot precision, expressed as a distance standard deviation; 2 to 3 cm is foreseen for the next few years. LLR "normal observation point" precisions (see next paragraph) reach or are expected to reach the same level.

Day-light ranging capability is of crucial importance in order to provide a continuous record of short period Earth orientation phenomena, such resolution requiring averaging times of a fraction of a day. It is to be understood that such short averaging time is a prerequisite of future precise Earth rotation monitoring systems. Many of the operational and most of the planned SLR devices have day-light capability on the closer satellites, few on Lageos. LLR features guiding difficulties when ranging is attempted close to new moon. Because of that, the only routinely operational LLR system (at the McDonald Observatory, Fort Davis, Texas) cannot effectively range within 3 days off new moon.

The repetition rates of most SLR systems exceed 0.1 pps. The McDonald LLR performs 1 pulse per 3 seconds, but the McDonald team has made it practice to compress the data from each 5 to 20 minutes run into a single "normal point", three runs being attempted per day, leading to an equal number of daily "normal points", except around new moon.

Of paramount importance for Earth orientation work, will be station siting, considering average atmospheric conditions and the need of global deployment, the first requirement in view of data continuity, the second for "Earth-fixed" (x-) reference frame definition.

Although only part of the available facilities has been used in dedicated programs of polar motion and diurnal rotation studies, encouraging preliminary results have been obtained from both SLR and LLR.

Review of work accomplished

In the past eight years or so several types of contribution have been made to the determination of the Earth's diurnal rotation and polar motion:
- theoretical modelling;
- feasibility analysis of simulated data;
- dedicated data taking;
- analysis of actual data.

Only the latter of these will be reviewed, separately for SLR and LLR, arbitrarily, in this order. In the present context this review can only be sketchy and cannot satisfactory reflect the amount of effort spent by contributing individual or groups of investigators.

Early attempts at NASA's Goddard Space Flight Center (GSFC) to detect polar motion from artificial laser ranging were initiated in 1970 and demonstrated the capability. [Smith et al, 1972a]. First preliminary results [Smith et al, 1972b] indicated that using the data of a single 30 cm precision ranging station the variation in latitude of that station could be derived to 0.03 seconds of arc with a time resolution of 6 hours. Considering the latitude of that station at Greenbelt, MD (39^{o}N) and the inclination of the single Beacon Explorer-C satellite used (41^{o}) this satellite could be tracked near apex and i' (briefly written instead of i^{z}) be accurately determined to about 0.001 second of arc, the accuracy of $\Delta i=i'_z-i$ limited by that of i (briefly, instead of i^{z}), because of gravitational field uncertainties. What could be derived from a single station was the variation of latitude, thus polar motion projected onto the Greenbelt-meridian; not the corresponding component of polar deviation from the CIO, simply not because the Greenbelt-latitude is not known in the conventional BIH-frame. The method employed to obtain such single station polar motion results has been described to some detail in [Dunn et al, 1974] and [Kolenkiewicz et al, 1977]. It is a special version of the general approach outlined before, the angular element analysed being the inclination i, the pertinent kinematic equation reading [Lambeck, 1971]:

$$i' - i \simeq -\psi_p \sin(\lambda_N - \lambda_p) ,$$

where λ_N stands for the longitude of the satellite's ascending node. Using up to four consecutive station passes of the satellite within a time span of about 6 hours, short arc osculating inclinations i' were obtained (see Figure 6) and compared with a reference orbit, extended over the entire period of the experiment. Later this so-called "max-lat" approach was abandoned and replaced by a more flexible approach yielding both variation of latitude and length of day information [Dunn et al, 1977]. During a 3-week period in 1970 a second ranging station operated from Seneca, N.Y., 400 km North of Greenbelt, yielding also a small number of 4-pass arcs. This enabled two independent determinations of both solution parameters.

The single-station approach as just described, has several limitations:

- of polar motion only the meridional component can be measured;
- it is difficult to separate this component from dynamical perturbations of i, these to be modelled over the full time span of the investigation;
- it is impossible to separate polar motion from precession and nutation;
- the use of several satellites or interrupted arcs of the same satellite may cause discontinuities and inconsistencies in the pole path as measured.

These can completely or to a substantial degree be overcome by deploying a multi-station network. Such network enables to determine a complete set of osculating angular orbital elements from a day or less of laser tracking. A minimally perturbed reference orbit $u^z(t)$, $i^z(t)$, $\Omega^z(t)$ valid only for the same period of a day or less, say, will suffice to yield a sufficiently detailed $R_{zx}(t)$- or R_{xz}-record to derive the direction of the orientation axis for the observation period. Because of the shortness of this period incomplete modelling of precession (P) and nutation (N) and of acting forces will practically not interfere. To be more precise as concerns precession and nutation an error in P(0) and N(0) at t_o would cause a biased reference orbit, but because of the shortness of the tracking period this bias will remain constant throughout and persist as such in $P^*(t)$ and $N^*(t)$.

Polar motion results from multi-station laser tracking of artificial satellites were reported recently from two sources by Smith et al [1978b] and Schutz et al [1978b]. These results announced a break-through in polar motion determination from laser ranging.

Smith et al [1978b] reported preliminary results obtained from Lageos tracking at a total of seven GSFC- and Smithsonian Astrophysical Observatory (SAO)-stations, four of which in the U.S.A., two in South-America and one in Australia. The four GSFC-stations in the U.S.A. claim a 10 cm single shot ranging precision, the SAO-stations in South-America and Australia 1 m. First a consistent set of station coordinates was obtained from this data to define an x-frame of reference [Smith et al, 1978a]. Subsequently an iterative procedure of fitting 5-day arcs to three interlinking 30-day reference orbits yielded average pole positions, relative to the adopted x-frame, for each of the eighteen 5-day periods of October, November and December 1976. The formal standard error in the x_p-component of polar position is 0.003 arcseconds, 0.002 arcseconds in y_p. The authors believe however that a precision between 0.01 and 0.02 arcseconds is more realistic. From this experience and previous simulations [Kolenkiewics et al, 1977] it was concluded that with more stations ranging Lageos at the 10 cm level and improved modelling, in particular of solid-Earth and ocean tidal effects, ultimately daily 5-cm pole position and UT1 values to about 0.2 msec consistent over 2 to 3 months are feasible. Recently GSFC issued a first bulletin of preliminary 5-day pole positions as obtained from Lageos ranging; the period covered is May-December 1976. Standard deviations given there range on the average from about 0.01 to about 0.03 arcseconds.

Schutz et al [1978b] reported pole positions obtained from laser tracking of Geos-3, spanning a roughly one-month period in early 1976. Data was used from three GSFC 5 to 10 cm single shot precision systems located at Greenbelt, MD, Bermuda and Grand Turk. The analysis was based on a previously obtained set of station coordinates de-

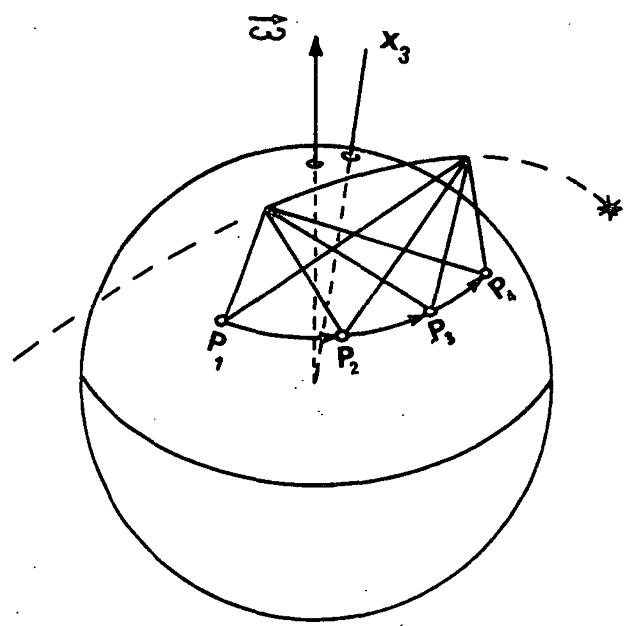

Fig. 6. A single station P (rotated to respective positions P_1, P_2, P_3 and P_4) is able to track four consecutive passes of an artificial satellite near apex and thus derive its orbital inclination.

fining an x-system and the GEM-10 geopotential model. The data span was devided into sixteen 2-day arcs. Special care was taken to model upper atmosphere effects. Weighted least squares straight line fits to the determined x_p and y_p values yielded estimated x_p and y_p standard deviations smaller than 0.07 arcseconds. The results indicate that a determination of both pole position components is possible from a regional station network, that as expected, the y_p-component is more accurately recovered than the x_p-component and that additional model improvements may be required for further analysis of Geos-3 data. The method used has been documented in more detail in connection with polar motion analysis of earlier Geos-3 data [Schutz et al, 1978a]. Although at first glance not impressive the authors consider the results from the 1976 data analysis of particular significance because this data was not used in the GEM-10 geopotential and station coordinates solution.

The LLR experiment has been outlined by Bender et al [1973]. A total of five retroflector arrays has been deposited on widely dispersed sites on the moon by the US and USSR space programs and subsequently laser ranged. Although returns have been announced by nine stations in five countries [Silverberg, 1978], LLR on a routine basis has in essence so far been a single-station operation from the McDonald Observatory. This restricted the yield of practical results as regards Earth orientation, like this was restricted in single-station SLR. Nevertheless, like single-station SLR demonstrated a capability to measure polar motion, so demonstrated the single-station LLR a capability to measure UT0 as pertaining to that station.

The lunar orbit differs most markedly from artificial satellite orbits in its much larger semimajor axis, which entails a 200 to 400 times longer period of revolution and a superior orbital covarage from a single observing station. These features have consequencies for both the data acquisition and the data analysis. Apart from a gap around new moon as caused by guiding problems which seem difficult to overcome, a geographically well selected LLR station can observe the moon daily, more or less evenly distributed over a full revolution. As compared to SLR the longer period and the high degree of predictability of the lunar orbit entail distinct differences in observation data handling. A LLR "normal point" covers about 5-15 minutes of ranging, a portion of a lunation too short to construct orbital elements. Such normal point may be regarded as an equivalent photon return representing the observation run. Over the past few years an average of 25-30 normal points have been produced at McDonald per lunation [Mulholland, 1978]. When solving for Earth orientation a normal point is fitted to a retroreflector reference orbit, obtained by taking into account the selenodetic retroreflector coordinates and the physical librations of the moon. The range residuals are then analysed in an attempt to recover Earth orientation signatures. This procedure follows the general pattern as outlined before and seems to deviate from SLR data analyses to recover Earth orientation, only in so far dictated by the kinematics of the lunar orbit and the ensuing data acquisition strategy.

Range residuals have been analysed by several authors to study various aspects of the Earth-moon system, including the Earth's diurnal rotation in terms of UT0; Stolz et al [1976], Harris and Williams [1977], Shelus et al [1977], King et al [1978], Calame [1978]. Single-station operation implies that as regards the direction of the rotation axis, only the projection of its change (polar motion) with respect to an Earth-fixed x-frame, onto the station's meridian can be measured. This, in turn, implies that not UT1, but only UT0 can be derived, since the transverse component of pole position, required to correct UT0 in order to obtain UT1, cannot be determined from a single station. Therefore Earth orientation results from LLR have up till now only been obtained in terms of UT0-corrections valid for McDonald. This nevertheless is a unique contribution, because it is a field in which reliable results from SLR are not expected in the near future, and if so, these will measure the rotation rate ω, rather than the angular position of the Earth-fixed frame in terms of the siderial angle as obtained from UT1.

First UT0-values derived from LLR were reported by Stolz et al [1976]. Using diurnal variation of range residuals they obtained, scattered over a roughly 5 years' time span, 194 single day values with a medium standard deviation of 0.7 msec if allowance is made for the uncertainty of the current lunar ephemeris. Only days with data well distributed in time were included in the analysis.

Rather than selecting the best isolated observation days of a data span, Shelus et al [1977] obtained UT0 results for a complete lunation on a daily basis, accepting all observations, as one would have to do in a routinely operating Earth rotation monitoring service. The results were obviously less precise than those of Stolz et al [1976], the standard deviation relative to the corresponding BIH data amounting to 2.6 msec in the most realistic case of analysis, but they may provide a more realistic measure of what can be expected on a continuing near real-time basis from a single station operating under normal conditions. The results obtained by Stolz et al [1976], on the other hand, demonstrate what can be done on a daily averaging basis under the best conditions. It should possibly not be overlooked that although Shelus et al [1977] did not select the best days of data within a lunation, they seem to have selected the best LLR lunation at McDonald.

King et al [1978] analysed the normal points on four retroreflectors taken at McDonald between October 1970 and November 1975 and solved for corrections to UT0 in terms of 126 "tabular points" defining a continuous, piecewise linear function of time spanning the 5-year interval. The solution was a phased one for a total of 166 parameters, only the UT0 parameters being obtained in the second phase. After removing a constant difference, the standard deviation of the tabular points as compared to BIH values is 2.1 msec. The standard deviation of a comparison of the tabular points with the results obtained by Stolz et al [1976], who analysed most of the same data, is 0.8 msec.

Calame [1978] proceeded along several lines, varying the selection of parameters solved for simultaneously with UT0, data selection criteria and averaging time (1, 2 or 5 days). Using data through January 1978, the estimated UT0 standard deviation ranges from about 1 to 3 msec.

A major break-through as regards Earth orientation from LLR is expected from the deployment of the proposed multi-station EROLD-network [e.g. Mulholland and Calame, 1978]. Such network would enable the separation of all three components of Earth orientation at a level of precision assessed by Stolz and Larden [1977]: better than measuring accuracy with an averaging time of two days. The BIH's involvement in EROLD has been outlined by Calame et al [1976].

Summarizing one could say that both SLR and LLR have already demonstrated some of their capabilities and defaults in single-station operation to measure Earth orientation. Multi-station results are available from SLR. Multi-station LLR is expected in the near future. Up till now SLR and LLR have been complementary in that SLR provided mainly polar motion, while LLR yielded information on diurnal rotation. In multi-station operation one would expect both SLR and LLR to provide complete three-parameter Earth-orientation, comprising both polar motion and diurnal rotation. Short averaging times are more likely to be achieved with SLR. On the other hand, the lunar orbit offers a more stable long term reference, in particular for the determination of UT1 and ω. Considering this, SLR and LLR should be considered complementary techniques, rather than competitive. It is important to note here that at least some of the planned LLR stations will also have Lageos-capability. Alternatively Silverberg [1978] envisions SLR stations with occasional LLR capability. In such integrated arrangements the SLR could be used to track polar motion on a daily basis, the LLR from one or more of the stations being then used to measure UT1 applying the SLR polar coordinates to correct UTO as measured. Ultimately Earth orientation to equivalent measurement precision or better with averaging times of one day or shorter is expected from integrated LR.

Concluding remarks

Figure 7 depicts types of Earth orientation results obtained or expected from laser ranging, classified according to modes of operation. As pointed out in the preceding paragraphs, only multi-station operation will be able to provide both polar motion and UT1 results. Ultimately both SLR and LLR should be able to do so independently. Up till the present time, only SLR has demonstrated multi-station operation and yielded polar motion in this mode. Once in multi-station operation, as foreseen in the EROLD campaign, LLR is more likely than SLR to provide long-term consistency of results in particular as regards UT1. On the other hand SLR may offer shorter averaging times. Considering moreover practical operational constraints, there is strong tendency to foresee SLR and LLR as operating in a complementary rather than in a competitive way when monitoring Earth orientation, allowing both techniques to contribute on their strong points. Instruments having both SLR and LLR capability seem advantageous in this respect. A future Earth orientation

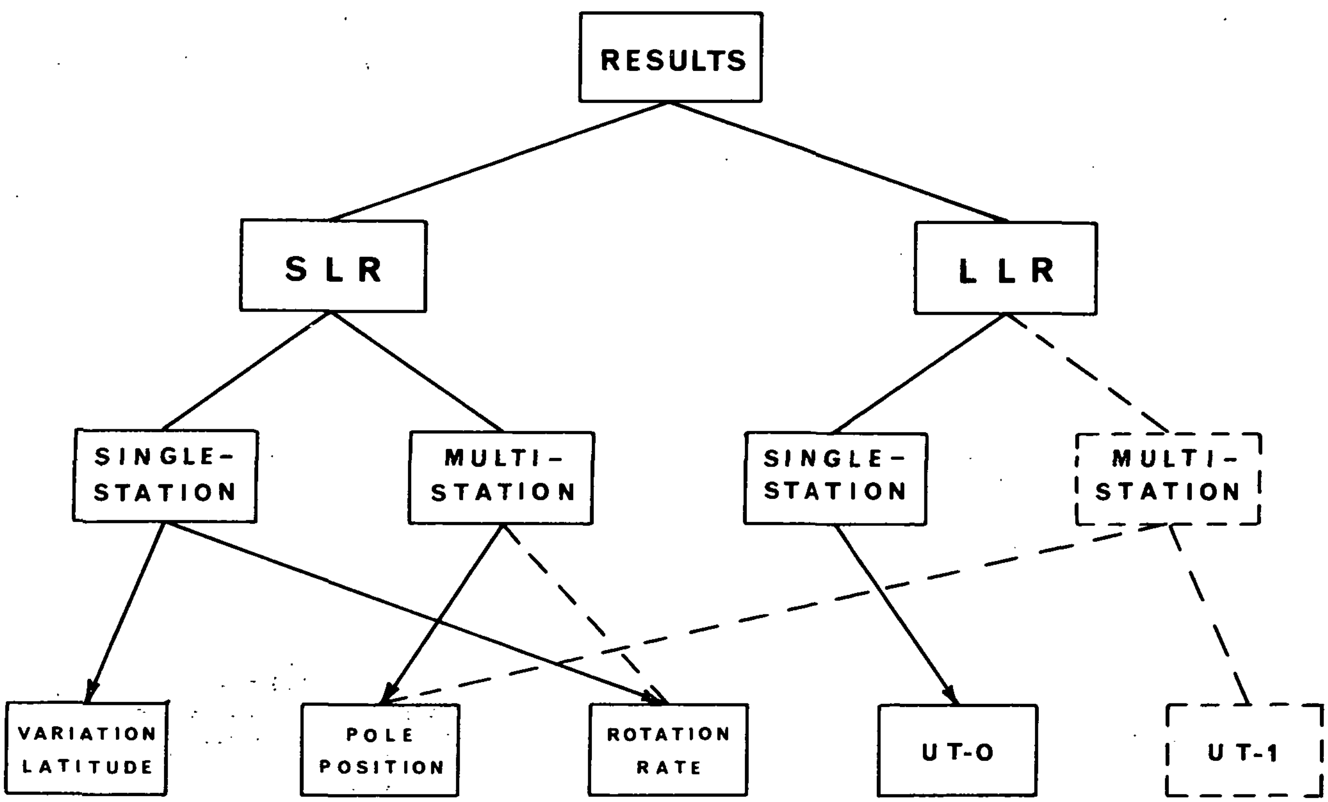

Fig. 7. Classification of Earth orientation results. Solid lines indicate demonstrated capabilities, dashed lines indicate potentialities.

service is supposed to provide pole position to 0.002 arcsec and UT1 to 0.1 msec with averaging times of one day or shorter. When extrapolating current experience into the future by means of simulation [e.g. Stolz and Larden, 1977; Smith et al, 1978b] it seems that the above requirements can be ultimately met by multi-station combined SLR and LLR. Additional requirements to be considered for a service bureau type of operation are continuity of results, quasi real time availability of results and cost-effectiveness.

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