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J. GAIGNEBET

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D-5300 Bonn 1
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PREFACE

Within the progress span of Laser Ranging the Fifth International Workshop on Laser Ranging Instrumentation, held at Herstmonceux Castle in September 1984, is an interesting bench-mark.

Unfortunately the premature death of Frank ZEEMAN has hit our community. These proceedings are dedicated to his memory.

Satellite Laser Ranging achieves now a remarkable level of accuracy and operational efficiency. Measures are at the few centimeter level and are obtained regularly in such an amount that reduction to normal points is mandatory. Thes improvements are the results, to a large extent, of the fruitful cooperation between the technical and scientific communities.

This progress must be continued. It is well known that the week point of the Laser Ranging is its sensitivity to the weather. This handicap could be minimized only if the accuracy of the method were superior to other space techniques. The potentialities will achieve their full meaning only if calibrations and refraction correction are determined with a centimeter or sub-centimeter uncertainty.

Calibration is a fast moving domain. Today the necessity of cautious and frequent determination is well rekognized. For many stations, ranging on targets at known distance is still the basic method. This is progressively complemented or replaced by internal calibrations. A new concept of station construction allows a zero calibration value. Also a mobile device able to compare the various constants directly could be used.

Two-wavelenth experiments were presented for the first time at the workshop. Tested on short ranges, this technique prepares the direct determination of the refraction correction. The preliminary results are very promising and involve the use of very impressive and accurate time measurements methods, i.e. streak cameras.

New stations will soon join the network. Some of them are highly mobile and automated. This trend allows, with reduced manpower, the development of original programs (Wegener..).

Important objectives have been achieved by Lunar Ranging people. For the first time, two stations obtained measures simultaneously and quite regularly. The accuracy of Lunar-devoted stations is following the path of satellite ones. The introduction of new sites in the network, expected soon, will enhance this evolution and will open interesting fields of research.

This brewing of ideas was made possible thanks to the organisation of the Royal Greenwich Observatory under the responsability of our host G.A. Wilkins and the participation of the Special Study Group 2.81 of the IAG. The Worshop was sponsored by the International Association of Goedesy.

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J. GAIGNEBET

PREFACE

Dans l'évolution de la télémétrie laser, le cinquième "International Workshop on Laser Ranging Instrumentation" qui s'est tenu au château d'Herstmonceux en Septembre 1984, marque une étape intéressante.

En effet, la télémétrie sur satellite artificiels a atteint un degré remarquable de performances et d'efficacité opérationnelle. La précision est de l'ordre du centimètre et les mesures obtenues de façon régulière sont si nombreuses que la génération de points normaux est devenue obligatoire. Ce progrès est en grande partie dû à la bonne coopération entre le personnel responsable de la mise en oeuvre des stations et les scientifiques chargés du traitement des données.

Il est évident que cette amélioration de l'efficacité opérationnelle et de la précision doit se poursuivre. Nous savons que le point faible de la télémétrie laser est sa sensibilité à l'état du Ciel. Cet handicap ne peut être surmonté que si l'exactitude des mesures est supérieure à celle obtenue par les autres méthodes spatiales. Cet avantage potentiel ne peut acquérir sa pleine signification que si les calibrations et les corrections de réfraction sont réalisées avec une précision centimètrique.

La calibration est un domaine en pleine évolution. La nécessité de veiller au sérieux de sa détermination et à la fréquence de sa mesure est maintenant reconnue. Les tirs sur cible à distance connue restent la méthode de base pour beaucoup de stations mais sont progressivement complétés par des systèmes de calibration internes en cours de poursuite. Une nouvelle conception de stations permet d'obtenir une constante de calibration nulle de construction. Enfin, la sation de calibration LASSO permet de disposer d'un moyen de comparaison des télémètres.

Les premiers rapports sur les études de la télémétrie en deux couleurs ont été présentés au colloque. Cette technique, testée jusqu'à ce jour sur des distances faibles, doit permettre la détermination directe de la valeur de la correction de réfraction. Les résultats de ces études sont très prometteurs et actualisent des méthodes de mesure du temps impressionnantes de précision, telles les caméras à balayage de fente.

Le colloque à d'autre part permis de se rendre compte que de nouvelles stations sont bientôt entrer en activité. Par ailleurs, le développement de systèmes extrêmement mobiles et automatisés permet, d'une part de réduire le potentiel humain d'exploitation, d'autre part de développer les programmes originaux (Wegener).

La télémétrie de la Lune a atteint des objectifs importants. Pour la première fois, deux stations ont obtenu des données assez régulièrement et simultanément. La précision de ces stations suit une progression similaire à celle mentionnée plus haut. L'introduction prochaine de nouveaux sites dans le réseau va accélérer cette évolution et accroître les retombées scientifiques.

Malheureusement, cette même période a vu la disparition prématurée de Frank ZEEMAN, nous lui dédions ces quatrièmes compte-rendus.

Ces échanges d'idées ont été possibles grâce à l'organisation mise en place par le Royal Greenwich Observatory, sous la responsabilité de nôtre hôte G.A. WILKINS, avec la participation du SSG 2-81 sous les auspices de l'Association Internationale de Géodésie.

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J. GAIGNEBET

FIFTH INTERNATIONAL WORKSHOP ON LASER RANGING INSTRUMENTATION

AT ROYAL GREENWICH OBSERVATORY ON 10-14 SEPTEMBER 1984

LIST OF PARTICIPANTS

ABSHIRE, J B
NASA/Goddard Space Flight Center
Mail Code 723
Greenbelt, MD 20771, USA (Wish Tower)

ALLEY, C O
Department of Physics & Astronomy
University of Maryland
College Park, Maryland 20742, USA (Castle)

APPLEBY, G M
Royal Greenwich Observatory
Herstmonceux Castle
Hailsham, East Sussex

BANNI, A
Stazione Astronomica
Via Ospedale 72
09100 Cagliari, Italy (Castle)

BEEK, W
Observatory for Satellite Geodesy
P O Box 581
7300 AN Apeldoorn, Holland (Castle)

BENDER, P L
Joint Inst. for Laboratory Astrophysics
University of Colorado, Campus Box 440
Boulder, CO 80309, USA (Mansion)

BERTOTTI, B
Faculty of Science
Universita Degli Studi
Corso Strada Nuova 65
I-27100 Pavia, Italy (Castle)

BOLOIX, M
Instituto y Observatorio de Marina
Observatorio de Marina
San Fernando, Cadiz Spain (Castle)

BOWMAN, S
Department of Physics and Astronomy
University of Maryland
College Park, Maryland 20742, USA (Castle)

CALAME, O
C.E.R.G.A.
Av. Copernic
F-06130 Grasse, France (Woolpack)

CAPORALI, A
Department of Physics
University of Padova
via Marzolo n. 8
I-35131 Padova, Italy (White Friars)

CECCHET, G
University of Pavia
V. Bassi 6
I-27100 Pavia, Italy (Castle)

CENCI, A
Telespazio, Via Bergamini 50,
Rome, Italy (Wish Tower)

CHEN DAONAN
North China Research Institute of
Electro-Optics
P O Box 8511, Beijing, China

COHEN, A
Atmospheric Sciences
Hebrew University
Jerusalem
Israel

CUOT, E
C.E.R.G.A.
Av Copernic
06130, Grasse, France (Albion)

DACHEL, P R
Bendix Field Engineering Corp
1 Bendix Road
Columbia MD 21045, USA (Mansion)

DASSING, R
Satellitenbeobachtungs-station Wettzel
8493 Kozting, West Germany (Mansion)

DEGNAN, J J
NASA Goddard Space Flight Center
Greenbelt, MD 20771, USA (Mansion)

DICKEY, J O
JPL/Caltech MS 264-781
Jet Propulsion Laboratory
Pasadena, CA 91109, USA (White Friars)

DUMOULIN, C
C.E.R.G.A.
Av Copernic
06130, Grasse, France (Albion)

DUNN, P J
EG/G, WASC
1707 Mitchell Road
Silver Spring, MD 20903, USA (Castle)

EANES, R
Center for Space Research
The University of Texas at Austin
W.R. Woolrich Laboratories 402
Austin, TX 78712 USA (Mansion)

ECONOMOU, G
Contraves Goerz Corporation
610 Epsilon Drive
Pittsburgh, Pennsylvania 15238, USA

EDGE, D R
Bendix Field Engineering Corporation
1 Bendix Road
Columbia, MD 21043, USA (Mansion)

FEISSEL, M
Observatoire de Paris
61 avenue de l'Observatoire
F-75014, Paris, France (Castle)

GAIGNEBET, J
C.E.R.G.A.
Av. Copernic
06130, Grasse, France (Mansion)

GAMBIS, D
Bureau International de l'Heure
61 avenue de l'Observatoire
F-75014 Paris, France (Cleavers Lyng)

GARDNER, C C
University of Illinois
Department of Electrical
& Computer Engineering
1406 W. Green Street
Urbana, IL 61801, USA (Wish Tower)

GOMEZ, F
Instituto y Observatorio de Marina
Observatorio de Marina
San Fernando, Cadiz, Spain (Castle)

GREENE, B A
Division of National Mapping
P O Box 31 Belconnen
ACT 2616, Australia (Mansion)

GRIFFIN, S G
Royal Greenwich Observatory
Herstmonceux Castle
Hailsham, East Sussex

GUISO, C
Stazione Astronomica
Via Ospedale 72
09100 Cagliari, Italy (Albion)

GU JIANGUO
North China Research Institute of
Electro-Optics
P O Box 8511, Beijing, China

HAMAL, K
Faculty of Nuclear Science
& Physical Engineering
Czech Technical University
Brehova 7, 115 19 Prague 1
Czechoslovakia (Castle)

HATAT, J L
C.E.R.G.A.
Av Copernic
06130, Grasse, France (Albion)

Hide R
Meteorological Office
London Road
Bracknell
Berkshire RG12 2SZ

HOPFL, R
Satellitenbeobachtungs-station Wettzel
8493 Kozting
West Germany (Mansion)

HYDE, R L
Ald Optics
267 Rue du Chateau du Roi
38220 Vizille
France, France

KIELEK, W
Warsaw Technical University,
Department of Electronics
Institute of Radioelectronics
Nowowiejska Street 15/19
00-665 Warsaw, Poland (Castle)

KIRCHNER, D
Observatory Graz Lustbuhel
Institute for Space Research
Lustbuhelstrasse 46
A 08042, Graz, Austria (Sussex)

KIRCHNER, G
Observatory Graz Lustbuhel
Institute for Space Research
Lustbuhelstrasse 46,
A 08042, Graz, Austria (Castle)

KLOECKLER, P
Astronomisches Institut
Sidlerstrasse 5
CH-3012 Bern (Castle)

LAPLANCHE, M
C.E.R.G.A.
Av Copernic
06130, Grasse, France (Albion)

LI, YU-HUA
Deptartment of Physics
University of Maryland
College Park, MD 20742, USA (Woolpack)

LISTER, M J
Naval Research Laboratory
4555 Over Look Ave
Code 7966
Washington, DC 20375, USA (Albion)

MANGIN, J F
C.E.R.G.A.
Av Copernic,
06130 Grasse, France (Albion)

MATTHEWS, W E
Royal Greenwich Observatory
Herstmonceux Castle
Hailsham, East Sussex

MILLER, J J
Bendix Field Engineering Corporation
1 Bendix Road
Columbia, MD 21043, USA (Mansion)

MOORE, T
Department of Civil Engineering
The University
Nottingham NG7 2RD, England (Castle)

MUELLER, I I
Department of Geodetic Science
The Ohio State University
1958 Neil Avenue
Columbus Ohio 43210, USA (White Friars)

NOVOTNY, A
Faculty of Nuclear Sciences
& Physical Engineering
Czech Technical University
Brehova 7, 115 19 Prague 1
Czechoslovakia (Castle)

OTTEN, K H O
Observatory for Satellite Geodesy
P O Box 581
7300 AN Apeldoorn, Holland (Castle)

PALUTAN, F
Telespazio
Via Bergamini 50
Italy (Wish Tower)

PAUNONEN, M V
Finnish Geodetic Institute
Jlmalankatu 1A
00240 Helsinki 24, Finland (Cleavers Lyng)

PEARLMAN, M R
Smithsonian Astrophysical Observatory
60 Garden Street
Cambridge MA 02138, USA (Mansion)

PESEC, P
Observatory Graz Lustbuhel
Institute for Space Research
Lustbuhelstrasse 46,
A-8042, Gras Austria (Castle)

PIERRON, F
C.E.R.G.A.
Av Copernic
06130, Grasse, France (Albion)

PILKINGTON, J D H
Royal Greenwich Observatory
Herstmonceux Castle
Hailsham, East Sussex

PROCHAZKA, I
Faculty of Nuclear Science
& Physical Engineering
Czech Technical University
Brehova 7, 115 19 Prague 1
Czechoslovakia (Castle)

RAYNER, J
Department of Physics & Astronomy
University of Maryland
College Park, UD 20742, USA (Castle)

SCHUTZ, B E
The University of Texas at Austin
College of Engineering
Center for Space Research
Austin, TX 78712-1085, USA (Castle)

SEEGER, H
Geodatisches Institut
Nussallee 17
D-5300 Bonn 1, West Germany (Castle)

SINCLAIR, A
Royal Greenwich Observatory
Herstmonceux Castle
Hailsham East Sussex

SMITH, D E
NASA/Goddard Space Flight Center
Code 921
Greenbelt, MD 20771, USA (White Friars)

STEGGERDA, C A
Department of Physics & Astronomy
University of Maryland
College Park, MD 20742, USA (Castle)

SU DEXING
North China Research Institute of
Electro-Optics
P O Box 8511, Beijing, China

TORRE, J M
C.E.R.G.A.
Av Copernic
06130, Grasse, France (Albion)

VEIS, G
National Technical University
K Zographou 9
Athens 624, Greece (Castle)

VERMAAT, E
Observatory for Satellite Geodesy
P O Box 581
7300 AN Apeldoorn, Holland (Castle)

VISSER, H
Observatory for Satellite Geodesy
P O Box 581
7300 AN Apeldoorn, Holland (Castle)

WANG, B C
Department of Physics & Astronomy
University of Maryland
College Park, MD 20742, USA (Woolpack)

WANNG, N H
Department of Physics & Astronomy
Unversity of Maryland
College Park MD 20742, USA (Woolpack)

WHITE, M L
University of Hawaii
P O Box 209
Kula, Hawaii 96790, USA (Mansion)

WIANT, J
University of Texas
McDonald Observatory
Fort Davis, TX 79723, USA (Albion)

WILKINS, G A
Royal Greenwich Observatory
Herstmonceux Castle
Hailsham, East Sussex

WILSON, P
Institut fur Angewandte Geodasie
Richard-Strauss-Allee 11
D-6000 Frankfurt am Main 70
Federal Republic of Germany

REFERENCE COORDINATE SYSTEMS AND FRAMES CONCEPTS AND REALIZATION

I.I. Mueller
Dept. Of Geodetic Science and Surveying
Ohio State University
Columbus, Ohio 43210-1247 USA

Telephone (614) 422 1773
TWX 810 482 1715

ABSTRACT

Geodynamics has become the subject of intensive international research during the last decade, involving plate tectonics, both on the intra-plate and inter-plate scale, i.e., the study of crustal movements, and the study of earth rotation and of other dynamic phenomena such as the tides. Interrelated are efforts improving our knowledge of the gravity and magnetics fields of the earth. A common requirement for all these investigations is the necessity for a well-defined reference coordinate system (or systems) to which all relevant observations can be referred and in which theories or models for the dynamic behavior of the earth can be formulated. In view of the unprecedented progress in the ability of geodetic observational systems to measure crustal movements and the rotation of the earth, as well as in theory and model development, there is a great need for the theoretical definition, pratical realization, and international acceptance of suitable coordinate system (s) to facilitate such work. This article deals with certain aspects of the establishment and maintenance of such a coordinate system.

IDEAL AND CONVENTIONAL REFERENCE SYSTEMS AND FRAMES

In order to clarify some of the conceptual aspects of various reference systems and frames, we propose to use specific terms proposed in [Kovalevsky and Mueller, 1981] that have been used somewhat inconsistently in the past.

The purpose of a reference frame is to provide the means to materialize a reference system so that it can be used for the quantitative description of positions and motions on the earth (terrestrial frames), or of celestial bodies, including the earth, in space (celestial frames). In both cases the definition is based on a general statement giving the rationale for an ideal case, i.e. for an *ideal reference system.* For example, one would have the concept of an ideal terrestrial system, through the statement that with respect to such a system the crust should have only deformations (i.e., no rotations or translations). The ideal concept for a celestial system is that of an inertial system so defined that in it the differential equations of motion may be written without including any rotational term. In both cases the term "ideal" indicates the conceptual definition only and that no means are proposed to actually construct the system.

The actual construction implies the choice of a physical structure whose motions in the ideal reference system can be described by physical theories. This implies that the environment that acts upon the structure is modeled by a chosen set of parameters. Such a choice is not unique: there are many ways to model the motions or the deformations of the earth; there are also many celestial bodies that may be the basis of a dynamical definition of an inertial system (moon, planets, or artificial satellites). Even if the choice is based on sound scientific principles, there remains a part of imperfection or arbitrariness. This is one of the reasons why it is suggested to use the term "conventional" to characterize this choice. The other reason is related to the means, usually conventional, by which the reference frames are defined in practice.

At this stage, there are still two steps that are necessary to achieve the final materialization of the reference system so that one can refer coordinates of objects to them. First, one has to define in detail the model that is used in the relationship between the configuration of the basic structure and its coordinates. At this point, the coordinates are fully defined, but not necessarily accessible. Such a model is called a *conventional reference system.* The term "system" thus includes the description of the physical environment as well as the theories used in the definition of the coordinates. For example, the FK4 (conventional) reference system is defined by the ecliptic as given by Newcomb's theory of the sun, the values of precession and obliquity, also given by Newcomb, and the Woolard theory of nutation. Once a reference system is chosen, it is still necessary to make it available to the users. The system usually is materialized for this purpose by a number of points, objects or coordinates to be used for referencing any other point, object or coordinate. Thus, in addition to the conventional choice of a system, it is necessary to construct a set of conventionally chosen (or arrived at) parameters (e.g., star positions or pole coordinates). The set of such parameters, materializing the system, define a *conventional reference frame.* For example, the FK4 catalogue of over 1500 star coordinates define the FK4 frame, materializing the FK4 system. Another example is the BIH Conventional Terrestrial Frame, whose pole is the origin of the polar motion derived (and published) by the BIH, and whose longitude origin is the Greenwich Mean Astronomical Meridian, in reality the point on the equator of the above pole, used by the BIH for deriving UT1. This frame materializes the BIH Conventional Terrestrial System (CTS), which itself until recently was defined by the FK4 frame, Newcomb's constants of precession and obliquity, Woolard's series of nutation, and by all the assumptions made regarding the reference coordinates of the participating observatories and their relative weights, etc. The current BIH system is based on the IAU 1976 precession constant and the IAU 1980 (Wahr) series of nutation.

Another way of defining the CTS for the deformable earth is through the time varying positions of a number of terrestrial observatories whose coordinates are periodically reobserved by some international service. The frame of this CTS could then be derived from the changing coordinates through transformations containing rotational (and possible translational) parameters. These transformation parameters computed and published by the service would then define the frame of the system. The service, as part of the system definition, thus would have to make the assumption that the progressive changes of the reference coordinates of the observatories do not represent rotations (and translations) in the statistically significant sense. This mode seems to be the consensus for the establishment of the future CTS frame.

It is also necessary to point out that celestial reference systems may be defined *kinematically* (through the positions of extragalactic radio sources), or *dynamically* (through the geocentric or heliocentric motions of artificial satellites, moon, planets). Stellar systems, such as the FK5, are hybrid. Furthermore, approximations must be introduced in the model so that it is not true to say that these systems are realizations of an ideal inertial system. This is why it is appropriate to use the term conventional "quasi" inertial system (CIS) as a common term for all such celestial systems. The corresponding frames would be defined by either the adopted positions of a set of radio sources (kinematic frame) or the adopted geocentric or heliocentric ephemerides (dynamic frames), all serving the materialization of the CIS with greater or lesser success (accuracy).

There seems to be general agreement that only two basic coordinate systems are needed: a Conventional Inertial System (CIS), which in some "prescribed way" is attached to extragalactic celestial radio sources, to serve as a reference for the motion of a Conventional Terrestrial System (CTS), which moves and rotates in some average sense with the earth and is also attached in some "prescribed way" to a number of dedicated observatories operating on the earth's surface [Mueller, 1981]. In the latter, the geometry and dynamic behavior of the earth would be described in the relative sense, while in the former the movements of our planetary system (including the earth) and our galaxy could be monitored in the absolute sense. There also seems to be a need for certain interim systems to facilitate theoretical calculations in geodesy, astronomy, and geophysics as well as to aid the possible traditional decomposition of the transformations between the frames of the two basic systems.

As we will see later, there already seems to be understanding in principle on how the two basic reference systems should be established; certain operational details need to be worked out and an international agreement is necesary. There are, however, a number of more or less open questions which will have to be discussed further. These include the type of interim systems needed and their connections to both CIS and CTS, the type(s) of observatories, their number and distribution, whether all instruments need to be permanently located there or only installed at suitable regular intervals to repeat the measurements; how far the model development should go so as not to become impractical and unmanageable; and how independent observations should be referenced to the CTS, i.e., what kind of services need to be established and by whom. This discussion deals only with questions related to the CTS.

CONVENTIONAL TERRESTRIAL SYSTEMS (CTS) OF REFERENCE

As mentioned, the frame of the CTS is in some "prescribed way" attached to observatories located on the surface of the earth. The connection between the CTS and CIS frames by tradition (to be preserved) is through the conventional rotations expressed as [Mueller, 1969]

$$[\ \underline{CTS}\ ] = SNP\ [\ \underline{CIS}\ ]$$

where P is the matrix of rotation for precession, N for nutation, and S for earth rotation (polar motion and sidereal time). Polar motion thus is defined as the angular separation of the third axis of the CTS, the Conventional Terrestrial Pole (CTP), and the axis of the earth for which the nutation (N) is computed (e.g., instantaneous rotation axis, Celestial Ephemeris Pole, Tisserand mean axis of the mantle (see [Mueller, 1981]).

Geodynamic requirements for a CTS may be discussed in terms of global or regional problems. The former are required for monitoring the earth's rotation, while the latter are mainly associated with crustal motion studies in which one is predominantly interested in strain or strain rate, quantities which are directly related to stress and rheology. Thus for these studies, global reference systems are not particularly important although it is desirable to relate regional studies to a global frame.

For the rotation studies one is interested in the variations of the earth's rotational rate and in the motions of the rotation axis both with respect to space (CIS) and the crust or the CTS. The problem therefore is threefold: (1) to establish a geometric description of the crust, either through the coordinates of a number of points fixed to the crust, or through polyhedron(s) connecting these points whose side lengths and angles are directly estimable from observations using the new space techniques (laser ranging or VLBI). The latter is preferred because of its geometric clarity. (2) To establish the time-dependent behavior of the polyhedron due to, for example, crustal motion, surface loading or tides. (3) To relate the polyhedron to both the CIS and the CTS. For the global tectonic problems only the first two points are relevant although these may also be resolved through point (3).

In the absence of deformation, the definition of the CTS is arbitrary. Its only requirement is that it rotates with the rigid earth, but common sense suggests that the third axis should be close to the mean position of the rotation axis and the first axis be near the origin of longitudes. An arbitrary choice, such as the one presently defined by the BIH-published polar coordinates and UT1 is appropriate.

In the presence of deformations, particularly long periodic or secular ones, the definition is more problematical, because of the inability to separate rotational (and translational) crustal motions of the crust from those of the CTS. This is why the consensus seems to be the CTS described earlier. If such a system is adapted, the secular type motions mentioned above will be absorbed in the future CTS, by definition. Residuals with respect to such a CTS will provide estimates of relative motions between stations, i.e., of the deformations.

One geophysical requirement of the reference system is that other geophysical measurements can be related to it. One example is the gravity field. The reference frame generally used when giving values of the spherical harmonic coefficients is tied to the axes of figure of the earth. This frame should be simply related with sufficient accuracy to the CTS as well as to the CIS in which, for example, satellite orbits are calculated. Another example is height measurements with respect to the geoid.

The vertical motions may require some special attention, because absolute motions with respect to the center of mass have an immediate geophysical interest and are realizable. Again, if the center of mass has significant motions with respect to the crust, such a motion will be absorbed in the future CTS, if defined as suggested above. At present there is no compelling evidence that the center of mass is displaced significantly at least at the decade time scale.

Apart from the geometrical considerations the configuration of observatories should be such that (1) there are stations on most of the major tectonic plates in sufficient number to provide the necessary statistical strength, (2) the stations lie on relatively stable parts of the plate so as to reduce the possibility that tectonic shifts in some stations will not overly influence, at least initially, the parameters defining the CTS frame.

Finally one should realize that the problem of the geometric origin of the CTS frame is linked to that of a geocentric ephemeris frame. The center of mass of the earth is directly accessible to dynamical methods and is the natural origin of a geocentric satellite-based dynamical system. But, as such, it is model dependent. And, unless the terrestrial reference frame is also constructed from the same satellites (as is the case in various earth models such as GEM, SAO, GRIM), there may be inconsistencies between the assumed origin of a kinematically obtained terrestrial system and the center of mass. A time-dependent error in the position of the center of mass, considered as the origin of a terrestrial frame, may introduce spurious apparent shifts in the position of stations that may then be interpreted as erroneous plate motions. To avoid this problem the parameters defining the CTS frame should include translational terms as suggested earlier.

Current Situation

Until 1984 the internationally accepted Woolard series of nutation was used to compute the position of the instantaneous rotation axis of the rigid earth, and the CTP was the Conventional International Origin (CIO), defined by the adopted astronomic latitudes of the five International Latitude Service (ILS) stations [Mueller, 1969].

From 1984 onward the IAU 1980 [Wahr, 1981] series of nutation for the nonrigid earth gives the space position of the Celestial Ephemeris Pole (CEP). The CTP officially remains the same as before. Thus, conceptually, polar motion should be determined from latitude observations only at the ILS stations. This has been done for 80 years, and the results are, the best available *long-term* polar motions, properly, but not very accurately, determined. The first axis of the CTS, the Greenwich Mean Astronomical Meridian, is defined by the assigned astronomic longitudes of time observatories participating in the work of the Bureau International de l'Heure (BIH).

For reasons explained elsewhere (e.g., [Mueller, 1981]), the use of the CIO is no longer a reality. The common denominator being the series of nutation, observationally the CTP is defined by the coordinates of the pole as published by the IPMS or by the BIH. Thus it is legitimate to speak of IPMS and BIH CTP's. The situation recently has become even more complicated because Doppler and laser satellite tracking, VLBI observations, and lunar laser ranging also can determine earth rotation parameters, some of which are incorporated in the BIH computations. Further confusion arises due to the fact that the BIH has two systems: the BIH 1968 and the BIH 1979, the latter due to the incorporation of certain annual and semiannual variations of polar motion determined from the comparisons of astronomical (optical) results with those from Doppler and lunar laser observations [Feissel, 1980].

Though naturally every effort has been made to keep the IPMS and BIH pole of the CTS as close as possible to the CIO, the situation cannot be considered satisfactory from the point of view of the geodynamic accuracy requirement of a few parts in 10^8.

The Future Conventional Terrestrial Reference Frame

There seems to be general agreement that the new CTS frame conceptually be defined similarly to the CIO-BIH system [Bender and Goad, 1979; Guinot, 1979; Kovalevsky, 1979; Mueller, 1975, 1981; Kovalevsky and Mueller, 1981], i.e., it should be attached to observatories located on the surface of the earth. The main difference in concept is that these can no longer be assumed motionless with respect to each other. Also they must be equipped with advanced geodetic instrumentation like VLBI or lasers, which are no longer referenced to the local plumblines. Thus the new transformation formula may have the form

$$[\underline{OBS}]_j = \underline{L}_j + [\underline{CTS}]_j + \underline{v}_j \tag{2}$$

where $\underline{L}_j$ is the vector of the "j" observatory's movement on the deformable earth with respect to the CTS.

The $[\underline{OBS}]_j$ is related to the observatory coordinates ($\overline{X}^\circ_j$) determined in the terrestrial frame inherent in the observational technique (e.g., SLR) "0", through the well-known transformations involving three translation components ($\overline{\delta}^\circ$), three (usually very small) rotations ($\overline{\beta}^\circ$) and a differential scale factor (c):

$$[\underline{OBS}]_j = \overline{X}^\circ_j + \overline{\delta}^\circ + R_1(\beta_1)\ R_2(\beta_2)\ R_3(\beta_3)\ \overline{X}^\circ_j + c\overline{X}^\circ_j \tag{3}$$

Naturally in case of techniques which observe directions only (e.g., astrometry), the terms containing translation and scale will be omitted. Eqs. (2) and (3) together with (4) below (and possibly others) may form the observation equations to be used when realizing the future CTS. The latter equation [Zhu and Mueller, 1983] relates an earth rotation parameter (ERP) series (x_p, y_p, and UT1) determined by the technique "O", within its own frames of reference, with the parameters of rotation above:

$$\begin{aligned} x_p - \beta_2^\circ + \alpha_1^\circ \sin \theta + \alpha_2^\circ \cos \theta &= x_p^\circ + v_{x_p} \\ y_p - \beta_1^\circ - \alpha_1^\circ \cos \theta + \alpha_2^\circ \sin \theta &= y_p^\circ + v_{y_p} \\ \omega_c \, \mathrm{UT1} + \beta_3^\circ - \alpha_3^\circ &= \omega_c \, \mathrm{UT1}^\circ + v_{\mathrm{UT1}} \end{aligned} \qquad (4)$$

where α_1, α_2, α_3 are the small rotations between the frames of the CIS of the technique "O" and that of the service, θ is the sidereal time, ω_c the conversion factor between sidereal and solar times, and v the residuals.

The unknowns in the above system of equations to be solved for, in a least squares solution minimizing the square sum of the residuals v, are $[\underline{CTS}]_j$ and $\underline{L}_j$ for the observatories; $\overline{\delta}^\circ$, $\overline{\beta}^\circ$ and c° for the terrestrial frames of the techniques; $\overline{\alpha}^\circ$ for their inertial frames; and finally, the ERP parameters (x_p, y_p and UT1) for the service. If, however, in eq. (3) the ERP's (x_p°, y_p°, UT1°) are mean values averaged over intervals longer than a day, α_1° and α_2° cannot be determined, because the sin θ and cos θ terms average to zero in one sidereal day.

As mentioned, the parameters pertaining to the observatories ($[\underline{CTS}]_j$ and L_j) define the CTS. The others give the relationships of the CTS to the technique "O" terrestrial frame ($\overline{\delta}^\circ$, $\overline{\beta}^\circ$, c); to the CIS (x_p, y_p, UT1); and the latter's relationship to the technique "O" inertial frame ($\overline{\alpha}^\circ$).

The rotations in eq. (3) can either be determined from the Cartesian coordinates (e.g., [Moritz, 1979]) or, for possible better sensitivity, since the rotation is least sensitive to variations in height, only from those of the horizontal coordinates (geodetic latitude and longitude) (e.g., [Bender and Goad, 1979]). It is, however, unlikely that the rotations will continue to be determined (as presently) from astronomical coordinates, i.e., from the direction of the vertical, for the reasons of inadequate observational accuracy. Note that when using this method, the deformations (and the residuals) by definition cannot have common rotational (or translational) components.

As far as the origin of the CTS is concerned, it could be centered at the center of mass of the earth, and its motion with respect to the stations can be monitored either through observations to satellites or the moon, or, probably more sensitively, from continuous global gravity observations at properly selected observatories [Mather et al., 1977]. For the former method, the condition

$$\sum_D w_D \, \overline{\delta}_D^\circ = 0$$

could be imposed on the above adjustment. The summation would be extended to all the above dynamic techniques D with given relative weights w_D. A similar condition could also be imposed on the scale extended to techniques defining the best scales (probably VLBI).

The above method of determining ERP or some variation thereof needs to be initialized in a way to provide continuity. This could be done through the IPMS or BIH poles, and the BIH zero meridian, at the selected initial epoch (or averaged over a well-defined time interval, say 1-1.2 years), uncertainties in their definition mentioned earlier mercifully ignored.

It is probably not useless to point out that if such a system is established, the most important information for the users will be the ERP and the transformation parameters, but for the scientist new knowledge about the behavior of the earth will come from the analysis of the residuals after the adjustment.

It is hoped that the IAU and IUGG will make practical recommendations on the establishment of such or a very similar Conventional Terrestrial System, including the necessary plans for supporting observatories and services. One of the recommendations ought to be that due to the fact that the ultimate goal is the determination of the total transformation between the CTS and CIS, the future service must publish not only the ERP's determined from the repeated comparisons (the situation at present), but also the models and parameters discussed above, i.e., the parameters defining the whole system.

In conclusion, there is little doubt that the terrestrial reference frame presently adopted is of very little practical use because of its insufficient accessibility. Further, the astronomical observations should be replaced by methods which are not tied to the direction of the vertical but rather to directions tied to the crust. Such methods are the laser observations to satellites and to the moon, and VLBI. Portable systems can establish the polyhedron(s) discussed earlier, while permanent stations at suitably chosen locations would become the observatories for the maintenance of the CTS using the method described above.

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FIFTEEN YEARS OF LUNAR LASER RANGING ACCOMPLISHMENTS AND FUTURE CHALLENGES

J.O. Dickey, J.G. Williams, X.X. Newhall
Jet propulsion Laboratory
California Institute of Technology
4800 Oak Grove Drive
Pasadena, California 91 109

Telephone (818) 354 4321
TWX 910 588 3294 / 910 588 3269

ABSTRACT

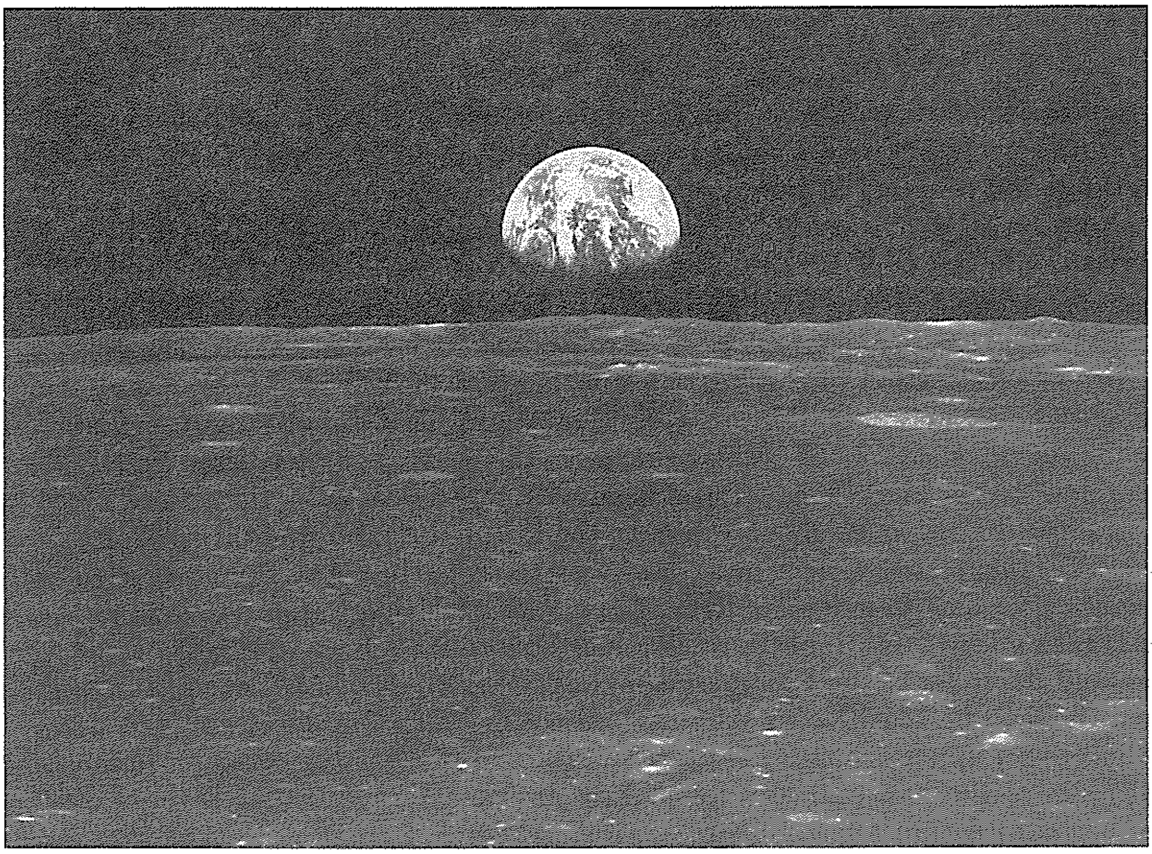
The past decade and a half has been a period of achievement for Lunar Laser Ranging (LLR), having made the transition from an Apollo experiment to a program of scientific impact. Areas influenced by this technique include geodynamics, geodesy, astronomy, lunar science, and gravitational physics. Scientific results are reviewed here and are grouped by areas of impact : geophysical parameters, ephemerides, references frames, and coordinate systems and their unification. Lunar science, gravity, and relativity have been advanced by this program. Future challenges are addressed. With the reality of multi-station LLR (three sites, four systems), the future is indeed promising.

July 21 of this year marked the fifteenth anniversary of the first manned lunar landing by the Apollo 11 Mission. On the fifth day of that historic mission the lunar module Eagle touched down on the lunar surface and Man first stepped onto the Moon. The visitors stayed for less than a day, but their journey marked a new era for mankind. Included on this mission and the later Apollo flights 14 and 15 were laser reflectors that permit precise measurement of the Earth-Moon separation. In Lunar Laser Ranging (LLR), individual photons are detected. When all losses are considered, out of the $\sim 10^{19}$ photons transmitted per shot, the receiver detects only one photon every 10 or 20 shots. The three Apollo reflectors plus the French-built reflector on Lunakhod 2 create a favorable geometry for studying the rotations of the Moon and permit separation of geodynamic effects from lunar motion.

The main block of lunar range data is from McDonald Observatory (August 1969 to May 1982); the ranging system was of 10 cm accuracy during the latter half of this period. There are also less accurate data from Orroral Valley, Australia (October 1978 to October 1980), the CERGA site at Grasse, France (April 1982 to March 1984), and a few days of range data from Haleakala Observatory on Maui (in 1977). There was a hiatus in the McDonald data from May 1982 until July 1983 due to the development of a new ranging system (MLRS), which is expected to be considerably more accurate. The new system is still being optimized, and useful data were obtained last spring. April also brought an abrupt improvement in the French data to about 10 cm precision for the best ranges, as judged from our fits. The Haleakala site has also returned part of its effort to lunar ranging, after a number of years devoted to satellite ranging, and has now obtained verified lunar ranges with an improved system. These acquisitions marked a historic event for LLR; for the first time in its fifteen-year history, data were acquired at three sites with four systems (McDonald 2.7 m, MLRS, CERGA 1.5 m, and Haleakala). Multiple-station ranging is now a reality. The gap in Orroral data is due to the time required for system upgrade, and ranging will resume shortly, with improved accuracy. Research activities are also underway at the Goddard 48-inch optical facility under Carroll Alley of the University of Maryland. The future has the potential for higher accuracy and possible additional stations, such as Wettzell.

LLR has contributed much in its history. The results can be grouped and reviewed by areas of impact: geophysical parameters, ephemerides, reference frames, and coordinate systems and their unification. Lunar science, gravity and relativity have also been advanced by this technique. Reviews have addressed some of these topics: Bender *et al.* (1973) mark the transition of the LLR program from a mission experiment to a program of scientific exploration; Williams (1977) outlines the scientific accomplishments; Mulholland (1980) reviews the progress made during the first decade of LLR; and Alley (1983) discusses LLR results as a test of gravity theories.

Of importance to the geodynamics community has been the series of measurements permitting long-term studies of variations in the Earth's rotation, as well as determination of many parameters of the Earth-Moon system. The coordinates of the observatories are determined in the geocentric frame. LLR provides an accurate value of



Earth Rise on the Moon

the principal term GM_{Earth} in the Earth's gravity field. The LLR-determined value of the secular acceleration of the Moon (-25.3 ± 1.2 arcsec/century^2, Dickey *et al.*, 1984*a*), is now significantly better than values based on conventional astrometry or inferred from artificial satellite detection of the tidal gravity field. This acceleration in longitude, which corresponds to a linear increase of 3.7 ± 0.2 cm/yr in the mean distance of the Moon, has implications for ocean tides, the decrease in spin rate of the Earth, and the evolution of the lunar orbit. LLR has contributed to determination of Universal Time (UT1) and polar motion; the long-term stability and temporal resolution of a day or less are assets of LLR data. Recent tabulations of Earth rotation from LLR data are given by Langley *et al.* (1981*a*), Calame (1982), and Dickey *et al.* (1983; 1984*b*). Earth rotation intercomparisons between LLR and other techniques (e.g. Robinson *et al.*, 1983; Dickey *et al.*, 1984*c*) are one of the principal goals of the MERIT Campaign, an effort organized by a joint working group of the International Astronomical Union and the International Union of Geodesy and Geophysics to Measure Earth Rotation and to Intercompare Techniques.

For studying the processes which underlie variations in the Earth's rotation, the long span of available LLR data is valuable. LLR has produced new information about the exchange of angular momentum between the solid Earth and atmosphere (Eubanks *et al.*, 1984 and 1985), and was instrumental in the discovery of the near

50-day oscillation in the length of day (Feissel and Gambis, 1980; Langley *et al.*, 1981*b*) and its correlation with a similar oscillation in the atmosphere. This discovery has stimulated research in the atmospheric community (Anderson and Rosen, 1983). An analysis (Yoder *et al.*, 1983) of LAGEOS satellite range data (University of Texas) with the LLR UT1 determination revealed significant nodal residual signatures, apparently arising from variations in the zonal gravitational harmonic coefficient J_2. The implied decrease of J_2 is consistent with historical observations of the nontidal acceleration of the Earth's rotation and models of postglacial viscous rebound. The determination of $\dot{J}_2$ is significant, as it constitutes the first unambiguous demonstration of a secular change in the Earth's gravity field. Tidally driven periodic terms in UT1 have been studied by Yoder *et al.* (1981*a* and *b*), who determined the response of the Earth at the fortnightly and monthly periods. Morgan *et al.* (1982) used LLR estimates of variation of latitude to derive spectra of polar motion for a shorter span of data than is possible using classical optical observations; such spectra are important for studying non-stationary mechanisms for excitation and damping of the Chandler wobble. The analysis of LLR observations has shown them to be sensitive to the nutation coefficients. Dickey *et al.* (1984*a*) reported improved upper limits for the free nutation of the Earth's core and found the amplitudes of the half-year and fortnightly nutation terms to match those of the Wahr series to within a few milliarcseconds. However, a small deviation of the annual term similar to that reported from VLBI observations (Gwinn *et al.*, 1984) appears to be present. A longer data span is needed to have a definitive separation between the precession of the Earth's equator and the 18.6-year terms.

LLR has revolutionized the lunar ephemeris, being three orders of magnitude more accurate than the classical optical data. Both JPL and MIT have produced numerically integrated lunar orbits and librations and have made solutions which include lunar and planetary data (Newhall *et al.*, 1983; King, private communication, 1984). Here, we have the best of two worlds, combining the sensitivity of the Viking ranges to Mars with the lunar ranges. The lunar and planetary ephemerides based on range data are set in a nearly inertial celestial coordinate system. LLR is sensitive to the mutual orientation of the planes of the Earth's equator, the lunar orbit, and the ecliptic; hence it locates the intersection of ecliptic and equator (the dynamical equinox) and determines the obliquity. The dynamical equinox has been used as the zero point of the right ascension system in several JPL ephemerides and has been proposed as the celestial origin for the space techniques (Williams *et al.*, 1984). Preliminary ties have been made between the quasar VLBI frame and the ephemeris frame by performing VLBI experiments between Mars- and Venus-orbiting spacecraft and quasars at small angular separation (Newhall *et al.*, 1985). The satellite systems can be linked to the dynamical equinox and the inertial frame by using colocation data with LLR and VLBI instruments; the LLR instruments which are operating or under development either have LAGEOS capability or are located near instruments which do.

Lunar laser ranging has made possible a several-order-of-magnitude improvement in measurement of the forced and free variations in the Moon's rotation—the lunar physical librations. These measurements have had two important results: the detection of apparent large free librations (Calame, 1977; Cappallo *et al.*, 1982) and the detection of rotational dissipation within the Moon (Yoder *et al.*, 1978; Yoder, 1981; Ferrari *et al.*, 1980; Cappallo *et al.*, 1981). Taken together, these results place constraints on the internal structure of the Moon, particularly the size of a lunar core (Stevenson and Yoder, 1981; Yoder, 1981). In addition, LLR determines lunar gravitational harmonics, the lunar Love number k, and the fractional differences of the lunar moments of inertia. The reflector coordinates are obtained and serve as cartographic control points.

Verification of the principle of equivalence for massive bodies was achieved by seeking the Nordtvedt (1968) effect in the lunar orbit (Shapiro *et al.*, 1976; Williams *et al.*, 1976). This contribution to fundamental physics gave the first test of the nonlinear and dynamical structure of General Relativity's post-Newtonian field components (Nordtvedt, 1983).

The future is promising with the reality of multi-station LLR. Both components of polar motion will be measured; UT1 will be better determined with more continuous coverage in time. Studies by Stolz and Larden (1977) predict accuracies of 1–2 cm for polar motion and 0.02–0.04 msec for UT1 using four stations (Orroral, CERGA, Haleakala, and McDonald) operating at 3 cm accuracy; better results are expected if the goal of 1 cm range accuracy can be achieved. Baselines and corresponding plate motions can be studied using multi-station LLR results. A covariance study (Dickey *et al.*, 1984*a*) indicates that the accuracy of the nutation amplitudes and the precession constant improves substantially as the data span increases. Simulations (based on a three-station network—McDonald, Haleakala, and Orroral—with an *a priori* uncertainty of 0.5 nsec) predict an accuracy of 0.06 arcsec/century for the precession constant by the end of 1988, surpassing the standard error of 0.15 arcsec/century quoted by Fricke (1977; 1981) from analyses of optical results. The error in the 18.6-year nutation terms will be reduced to 2 milliarcseconds by the end of 1988, a level that should be useful for limiting the Earth's interior structure. Another goal is to combine LAGEOS tidal results with those from LLR (see Williams *et al.*, 1978). Artificial satellites are sensitive to many tidal terms because of their proximity to Earth. A joining of both data types can advance our understanding of the tidal processes.

In lunar science, further progress awaits only the acquisition of more accurate observations and the redundancy useful in separating signatures in the data due to (terrestrial) polar motion from those due to errors in our models of the lunar orbit and rotation. In the area of lunar interior structure, there may be range signatures having amplitudes of a few centimeters which can distinguish between solid-body and core-mantle dissipation. This discrimination requires range data having uncertainties of at most 5 cm. Another clue, advanced by Yoder (1981), to the existence of a liquid core would be the presence of irregularities or changes in the free physical librations due to turbulence at the core-mantle interface. Again, precise data are needed to detect such small effects, but a success would be scientifically valuable.

In gravitational physics, results can be improved by a factor of four by the availability of more accurate observations. Estimates of PPN (Parametrized Post-Newtonian) quantities can be made using a combination of LLR data and planetary observations.

The past decade and a half has been productive and exciting for LLR; the technique made the transition from an Apollo experiment (LURE) to a program of scientific impact. Areas influenced are geodynamics, geodesy, astronomy, lunar science, and gravitational physics. A "giant leap" is underway with the advent of high accuracy multi-station LLR. The science of this period has been done with ranges of 10 cm or more uncertainty, heavily dominated by a single station. New insight and knowledge will be gained with 1 to 3 cm ranges from several sites. Indeed, the best is yet to come!

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EFFECTS OF INSTRUMENTAL ERRORS ON GEOPHYSICAL RESULTS

P.L. Bender, M.A. Vinvent
Joint Institute for Laboratory Astrophysics
National Bureau of Standards and University of Colorado
Boulder, Colorado 80309, USA

Telephone (303) 492 6952
TWX 910 940 3441

ABSTRACT

A quality assurance program for satellite laser ranging data is a necessary part of trying to assess the effects of systematic instrumental errors on studies of tectonic motions and other geophysical quantities. The present informal program includes accuracy self-checks of individual stations, initial colocations of new systems, some field colocations, and analysis of residuals with respect to global orbits. Intercomparisons with results from other techniques are an essential final check, but the value of the results for each technique is enchanced if reliable confidence intervals can be obtained for each technique by itself.

As part of efforts to evaluate the level of instrumental systematic errors in data being used for tectonic studies, we have started to analyze colocation data in terms of residuals from 5 to 30 day orbits fitted elsewhere to global observations. The first case looked at was the MOB 6/ MOB 7 colocation at Goddard in October, 1982. For eight of the best passes, the rms difference of the smoothed instrumental errors for the two stations was 7.9 cm. This rms difference can be reduced to 3.4 cm by adjusting the horizontal position of MOB 6 by 13 cm, but it seems more likely that the 7.9 cm rms difference was due to the performance of MOB 6. Other colocations for wich residuals from orbits fitted to global observations are available will be analyzed also.

ATMOSPHERIC REFRACTION AND TARGET SPECKLE EFFECTS ON THE ACCURACY OF LASER RANGING SYSTEMS

C.S. Gardner
Department of Electrical and Computer Engineering
University of Illinois
Urbana, IL 61801

Telephone (217) 333 3090
TWX 910 245 2434

J.B. Abshire
NASA / Goddard Space Flight Center
Greenbelt, Maryland 20771

Telephone (301) 344 7000
TWX 710 828 9716

ABSTRACT

Atmospheric refraction and target speckle can affect significatly the accuracy of satellite laser ranging systems. The performance of the atmospheric correction formulas for both single and two color ranging systems is reviewed and the effects of target speckle on timing accuracy are discussed.

Atmospheric Effects

Pulsed laser ranging systems estimate the distance to retroreflector equipped satellites by measuring the roundtrip propagation time. The accuracy of satellite laser ranging systems is limited in part by atmospheric refraction and turbulence. Small random fluctuations in pressure and temperature due to turbulence along the propagation path will cause the path length to fluctuate. The rms path length fluctuations caused by turbulence are related to the turbulence spatial power spectrum and the refractive index structure parameter $C_n{}^2$, which varies with altitude and time of day. The mean-square path deviation calculated using the von Karmon spectrum is given by[1]

$$\langle \Delta L^2 \rangle = 3.12\ C_{no}^2\ L_o^{5/3} h_{Tur} / \cos E \qquad (1)$$

where

ΔL = path length deviation

C_{no}^2 = structure parameter value at the ranging site

L_o = outer scale of turbulence

h_{Tur} = atmospheric scale height for turbulence

E = satellite elevation angle.

For satellite ranging, L_o and h_{Tur} are on the order of 100 m and 3 km respectively. Under these conditions, the rms path deviations can be up to a few centimeters when the satellite is at low elevation angles (≈ 10°), and the turbulence is very strong $\left(C_{no}^2 \approx 10^{-13}\ m^{-2/3}\right)$. Under most conditions C_{no}^2 will be much weaker $\left(< 10^{-15}\ m^{-2/3}\right)$ so that the rms deviations will be a few millimeters or less. Two color ranging systems can partially correct for the random path fluctuations so that in most cases turbulence effects are negligible[1].

Atmospheric refraction increases the optical path length to an orbiting satellite by 2 1/2 m when the satellite is near zenith and by more than 13 m when the satellite is at 10° elevation. Numerous formulas have been developed which can partially correct range measurements for the effects of atmospheric refraction. However, only the correction formulas derived by Saastamoinen[2], Marini and Murray[3] and Gardner[4] provide centimeter level accuracies at the lower elevation angles (10 - 20°).

Marini and Murray's[3] formula is particularly convenient for correcting satellite ranging data because it only requires measurements of atmospheric pressure, temperature and relative humidity taken at the laser site during the satellite pass. However, their formula was derived by assuming that atmospheric refraction is spherically symmetric. Because this assumption holds only approximately in the troposphere, horizontal refractivity gradients can introduce centimeter level errors into the Marini and Murray formula at low elevation angles. A correction formula that compensates for horizontal gradients was derived by Gardner[4]. The accuracies of both the Marini and Murray and Gardner formulas were evaluated by comparing them with data obtained by ray tracing through refractivity profiles calculated from radiosonde measurements of pressure, temperature and humidity. The results indicate that these correction formulas provide accuracies which vary from a few millimeters when the satellite is near zenith to a few centimeters at 10° elevation.

The range correction for atmospheric refraction can be written in the form

$$AC = SC + GC \quad . \tag{2}$$

The spherical correction term SC corresponds to a spherically symmetric atmosphere, while the gradient correction term GC includes the effects of horizontal refractivity gradients. The correction terms can be expressed as functions of meteorological parameters by evaluating the integral of the group refractivity along the propagation path. The resultant spherical and gradient correction formulas are given by[2-4]

$$SC = \frac{f(\lambda)}{F(\theta,H)} \frac{A + B}{\sin E + \dfrac{B/(A + B)}{\sin E + .01}} \tag{3}$$

$$GC = \frac{C}{\sin E \ \tan E} \underline{n} \cdot \nabla (P_s T_s K_s) + \frac{D(1 + 1/2 \cos^4 E)}{\sin^3 E \ \tan E} \underline{n} \cdot \nabla \left(\frac{P_s T_s^2 K_s^2}{2 - K_s} \right) \tag{4}$$

where

$$f(\lambda) = 0.9650 + 0.0164/\lambda^2 + 0.000228/\lambda^4 \tag{5}$$

$$F(\theta,H) = 1 + 0.0026 \cos 2\theta - 0.00031H \tag{6}$$

$$K_s = 1.163 + 0.00968 \cos 2\theta - 0.00104 T_s + 0.00001435 P_s \quad (7)$$

$$A = 0.002357 P_s + 0.000141 e_s \quad (8)$$

$$B = (1.084 \times 10^{-8})\, P_s T_s K_s + (4.734 \times 10^{-8}) \cdot (P_s^2/T_s)\, 2/(3 - 1/K_s) \quad (9)$$

$$C = 80.343 f(\lambda) \frac{R^2}{(Mg)^2} 10^{-6} = 6.915 \times 10^{-2} f(\lambda) \quad , \quad (10)$$

$$D = 80.343 f(\lambda) \frac{2}{r_o} \frac{R^3}{(Mg)^3} 10^{-6} = 6.362 \times 10^{-7} f(\lambda) \quad , \quad (11)$$

and

e_s = water vapor pressure at ranging site (mb)

P_s = surface pressure at ranging site (mb)

T_s = surface temperature at ranging site (K)

θ = colatitude of ranging site

H = altitude of ranging site above sea level (km)

M = 28.966 = molecular weight of dry air

$R = 8314.36$ J $(K)^{-1}$ (kg-mole)$^{-1}$ = universal gas constant

$g = 9.784$ m/sec^2 = acceleration of gravity

r_o = 6378 km = nominal earth radius

$\underline{n} = \sin \alpha \underline{x} + \cos \alpha \underline{y}$,

α = satellite azimuth angle (α = 0 = North), and

$\underline{x}$ and $\underline{y}$ are the east and north unit vectors.

Both SC and GC are given in meters when the listed values for A, B, C and D are used and the gradients are in units of m^{-1}.

The accuracy of the spherical correction formula has been extensively checked by Marini and Murray[3] by ray tracing through atmospheric refractivity profiles which were calculated from radiosonde data. The radiosonde data, which consist of pressure, temperature and humidity measurements taken at various altitudes during the balloon's ascent, were used to construct spherically symmetric refractivity profiles above the balloon's release point. The ray trace corrections and formula showed very good agreement even at low elevation angles. Table I summarizes Marini and Murray's results for comparisons with 634 different ray traces through refractivity profiles generated from radiosonde observations taken near Dulles Airport, VA during 1967. The formula for SC is nearly an unbiased estimator of the spherically symmetric ray trace correction, RT_1.

The standard deviation of the difference between SC and RT_1 arises from two factors: modeling errors in the formula for SC and errors in the measured values of atmospheric pressure, temperature and humidity which are used to calculate SC. The dominant error source is pressure. A 1 mb pressure error introduces approximately 14 mm error in SC at 10° elevation. The effects of measurement errors can be estimated by taking the partial derivatives of SC with respect to the meteorological parameters.

TABLE I

Range error calculated by Marini and Murray[3] for a ruby laser (λ = 694 nm). RT_1 is the ray trace correction for spherically symmetric profiles.

Elevation angle	RT_1 Mean (m)	RT_1 - SC Mean (cm)	RT_1 - SC Standard deviation (cm)
80°	2.47	0.07	0.04
40°	3.69	-0.1	0.07
20°	6.91	-0.05	0.12
15°	9.08	0.05	0.19
10°	13.32	-0.08	0.49

parameters. Since the measurements of pressure, temperature and relative humidity (Rh) are statistically independent, the total rms error in SC is given by

$$\sigma_{SC} = \left[\left(\frac{\partial SC}{\partial P}\sigma_P\right)^2 + \left(\frac{\partial SC}{\partial T}\sigma_T\right)^2 + \left(\frac{\partial SC}{\partial RH}\sigma_{Rh}\right)^2\right]^{1/2} \qquad (12)$$

where

$$\frac{\partial SC}{\partial P} \simeq \frac{f(\lambda)}{F(\theta,H)} \frac{2.357 \times 10^{-3}}{\sin E} \text{ (m/mb)} \qquad (13)$$

$$\frac{\partial SC}{\partial T} \simeq \frac{f(\lambda)\ 1.084 \times 10^{-8}\ P_s K_s}{\sin^3 E} \text{ (m/°K)} \qquad (14)$$

$$\frac{\partial SC}{\partial Rh} \simeq \frac{f(\lambda)}{F(\theta,H)} \frac{8.615 \times 10^6}{\sin E} \exp\left[\frac{17.27(T_s - 273.15)}{237.15 + (T_s - 273.15)}\right] (m/\%) \quad (15)$$

and σ_P, σ_T and σ_{Rh} denote respectively the rms errors in pressure, temperature and relative humidity. The derivatives are plotted versus elevation angle in Fig. 1. Typical measurement errors are 0.5 - 1 mb for pressure, 0.7 - 1.5 °K for temperature and 5 - 10% for relative humidity. Consequently, above 10° elevation angle, pressure errors are the dominant source of error in SC.

The gradient correction is a function of the horizontal pressure and temperature gradients and is significant only at the lower elevation angles. GC is a sinusoidal function of azimuth with a peak-to-peak value of 4 - 6 cm at 10° elevation and 1 - 1.5 cm at 20° elevation. Because surface pressure is relatively uniform, under normal conditions horizontal refractivity gradients will be predominantly a function of the temperature gradients. At a 20° elevation angle, the sea level gradient correction is approximately 1 cm peak-to-peak for a horizontal temperature gradient of 1°C/100 km. The gradient correction is more difficult to calculate than SC because the formula requires measurements of the horizontal pressure and temperature gradients at the ranging site. The horizontal gradients can be determined only by measuring pressure and temperature at three or more points surrounding the ranging site. The measurements are used to calculate the parameters of an appropriate model for the horizontal variations of P_s and T_s.

The accuracy of the GC formula was also evaluated by comparing it with ray trace corrections[5]. The results for 10° elevation are illustrated in Fig. 2. RT_3 is the correction obtained by ray tracing through a 3-D refractivity profile calculated from data obtained by radiosondes released almost simultaneously from eight locations near Leonardtown, MD during January and February 1970. RT_1 is the ray trace correction for the equivalent spherically symmetric refractivity profile. The gradient effects ($RT_3 - RT_1$) vary sinusoidally with azimuth and are predicted reasonably well by GC. The comparisons at 10°, 20°, 40° and 80° elevation are summarized in Table II. The amplitudes of the gradient correction predicted by the GC formula are within a few percent of the ray trace values ($RT_3 - RT_1$). However, the phase differs by 11°. The average ray trace correction peaks at 0° azimuth while GC peaks at 11° azimuth. Refractivity gradients have their greatest influence at the higher altitudes, where the laser beam trajectory is relatively far down range from the laser site. The correction formula attempts to predict the effects of these high altitude gradients from surface measurements of pressure and temperature. Terrain features such as mountains, large bodies of water, and ground cover probably have a greater influence on the weather near the ground than at the higher altitudes. Consequently, local geography could introduce amplitude and phase biases into the gradient correction formula.

The major error source in the gradient correction formula appears to be errors in the measured values of pressure and temperature, which are used to calculate GC, and terrain features, which distort the temperature and pressure fields near the ranging site. Both of these problems can be minimized by using many weather stations to obtain the

TABLE II

Gradient correction and ray trace comparison;
Model: $-A \cos(\alpha - \phi)$

Elevation Angle	$\overline{RT_3 - RT_1}$		$\overline{GC}$		$\overline{(RT_3 - RT_1) - GC}$	
E	A	ϕ	A	ϕ	A	ϕ
10°	2.4 cm	0°	2.2 cm	11°	0.49 cm	-66°
20°	6.5 cm	0°	6.3 mm	11°	1.2 mm	-73°
40°	1.5 mm	0°	1.5 mm	11°	0.29 mm	-75°
80°	0.15 mm	5°	0.14 mm	11°	0.041 mm	-78°

required meteorological data and distributing them over a large area. This approach has the added advantage of also improving the accuracy of spherical correction. However, there have been studies indicating the presence of relatively large temperature variations occurring over short spatial scales (≈ 10 km) which may significantly distort the calculated value of GC[6,7]. As a consequence, care must be exercised in computing the required pressure and temperature gradients. This problem becomes even more difficult in mountainous terrain where the surrounding weather stations may be at widely differing altitudes.

Two-Color Laser Ranging

Two-color laser ranging provides a very attractive alternative for determining the atmospheric correction. The difference in path length at two laser frequencies is a measure of the refractive conditions existing over the propagation path at the instant the measurements are taken and can be used to estimate the atmospheric correction[8]. Let L_1 and L_2 denote the optical path lengths measured at wavelengths λ_1 and λ_2 respectively. Let n_{g1} and n_{g2} denote the group refractive indices of air at the ranging site for wavelengths λ_1 and λ_2 respectively. Then the atmospheric correction at wavelength λ_1 is approximately

$$AC = \gamma(L_2 - L_1) \qquad (16)$$

where

$$\gamma = (n_{g1} - 1)/(n_{g2} - n_{g1}) \quad . \qquad (17)$$

Equation (16) is accurate at optical frequencies. However, at radio and millimeter wavelengths the water vapor content of air can introduce substantial errors into Eq. (17). If we ignore the small water vapor effects at optical frequencies, γ can be written as

$$\gamma = f(\lambda_1)/[f(\lambda_2) - f(\lambda_1)] \tag{18}$$

Because γ is on the order of ten for all wavelength pairs of the fundamental, doubled and tripled YAG laser frequencies, it is necessary to determine the differential path length ($L_2 - L_1$) with an accuracy which is approximately ten times greater than the desired accuracy for the atmospheric correction.

The accuracy requirements on the differential path length measurement can be eased considerably if the results of numerous measurements are averaged. Since the atmospheric correction and differential path length are functions of the satellite azimuth and elevation angles, the satellite position must be taken into account when measurements are averaged. For typical refractivity profiles, the atmospheric correction given by Eqs. (2), (3) and (4) can be modeled approximately as

$$AC = \frac{\beta_1}{\sin E} + \frac{\beta_2}{\sin^3 E} + \frac{\beta_3 \cos\gamma}{\sin E \tan E} + \frac{\beta_4 \sin\gamma}{\sin E \tan E} \tag{19}$$

The model coefficients $\beta_1 - \beta_4$ can be expressed in terms of meteorological parameters using Eqs. (3) and (4). Alternatively, they can be calculated by using Eqs. (16) to compute AC from measurements of L_1 and L_2 taken during the satellite pass and using a regression analysis to fit the data to a curve of the form given by Eq. (19). A more accurate value of AC could then be obtained by evaluating the regression curve.

The performance of the regression model given by Eq. (19) has been evaluated using the parameters of Starlette Satellite passes over the Goddard Space Flight Center in Greenbelt, MD[9]. The rms error of the regression model can be written as

$$\sigma_{AC} = \frac{\gamma\sigma_{\Delta L}}{N^{1/2}} F \tag{20}$$

where $\sigma_{\Delta L}$ is the rms differential path length error at zenith, N is the number of two-color measurements made during the satellite pass and F is a dimensionless error factor which depends on azimuth and elevation angle and on the satellite pass. σ_{AC} is proportional to $N^{-1/2}$. This dependence is typical of the error reduction obtained when independent measurements are averaged. If N is large and F is small, the regression error σ_{AC} will be much smaller than the single measurement error $\gamma\sigma_{\Delta L}$.

The azimuth and elevation angle of the Starlette Satellite is plotted versus time in Fig. 3 for a typical low elevation angle pass over Greenbelt, MD. The satellite rises in the NE, reaches a maximum elevation angle of 24° and then sets in the SE. Figure 4 is a plot of the error factor F versus time for this pass. Measurements were assumed to be taken only when the satellite was above 15° elevation. At low elevation angles the laser pulses will be attenuated more than at zenith because of the increased atmospheric extinction. This effect was taken into account in calculating the data plotted in Fig. 4 by assuming that the differential path length error was proportional to $1/(\sin E)^{\nu}$. ν was chosen so that the path length error at 20° was 1, 2, 5 and 10 times larger than the error at zenith.

The error factor is largest at the beginning and end of the pass where the satellite is at the lower elevation angles. The reason for this behavior is evident from Eq. (19). The effects of errors in the regression coefficients become more pronounced as the elevation angle decreases, particularly for errors in β_2, β_3 and β_4. Also, the error factor increases when the path length error is more severe at the lower elevation angles. However, the error factor is usually less than 10 so that if N is large, the regression model will provide a much more accurate estimate of AC than a single two-color measurement. The high elevation angle Starlette Satellite passes provide similar results[9]. Therefore, it is not unreasonable to expect a factor of 10 or more improvement in the accuracy of AC by using the regression model.

Ranging Accuracy and Laser Speckle

Mode locking and Q-switching techniques are now used routinely to generate laser pulses of a few picoseconds in duration. These short pulses can provide higher accuracies in laser ranging and altimetry. However, when the range spread of the target is larger than the transmitted pulse length, speckle can cause random small scale fluctuations within the reflected pulse which distort its shape. This effect is called time-resolved speckle and can introduce errors in laser ranging measurements.[10]

Estimation of the arrival times of laser pulses was first studied by Bar-David[11] who derived the Maximum Likelihood (ML) estimator for pulses contaminated by shot noise

$$\hat{\tau}_{SHOT} = \arg\max_{\tau} \sum_{i=1}^{n} k_i \ \ell n \ \overline{k}_i(\tau) \tag{21}$$

where

k_i = received photocount in the i^{th} time bin and

$\overline{k}_i$ = expected photocount.

The ML estimator is implemented by correlating the received pulse shape (k_i) with the logarithm of the expected pulse shape ($\overline{k}_i$). The ML estimate τ_{SHOT} is the time (τ) at which the correlation is maximum. If the expected received pulse shape is Gaussian with an RMS length of σ_R and the speckle is fully developed, the variance of the ML estimator is

$$c^2 \ \mathrm{Var}(\hat{\tau}_{SHOT}) = \left(\frac{1}{\langle M \rangle} + \frac{1}{K_s}\right) \sigma_R^2 \tag{22}$$

where

$\langle M \rangle$ = expected received photocount/pulse

K_s = speckle signal-to-noise ratio.

K_s is related to the target geometry and the laser cross-section and has a minimum value of 1. In general, K_s is small (~ 1) whenever the target is small. The RMS ranging error using the ML estimator is plotted versus photocount ($\langle M \rangle$) in Fig. 5 for the case of an infinitely large flat diffuse target. Results are plotted for laser incidence angles of 5, 10 and 20°. Initially, in the shot noise dominated regime, the ranging error decreases ($\sim \langle M \rangle^{-1/2}$) as the photocount increases. But the error then reaches a limiting value in the speckle noise dominated regime. Similar results would be expected for partially developed speckle of the type generated by reflections from retro-reflector arrays used in satellite ranging. Most laser ranging receivers use constant fraction discriminator (CFD) timers. The timing error for the CFD is larger than the error for the ML estimator. As a consequence, speckle establishes a fundamental limit in ranging accuracy and its effects should be considered when using short pulse lasers.

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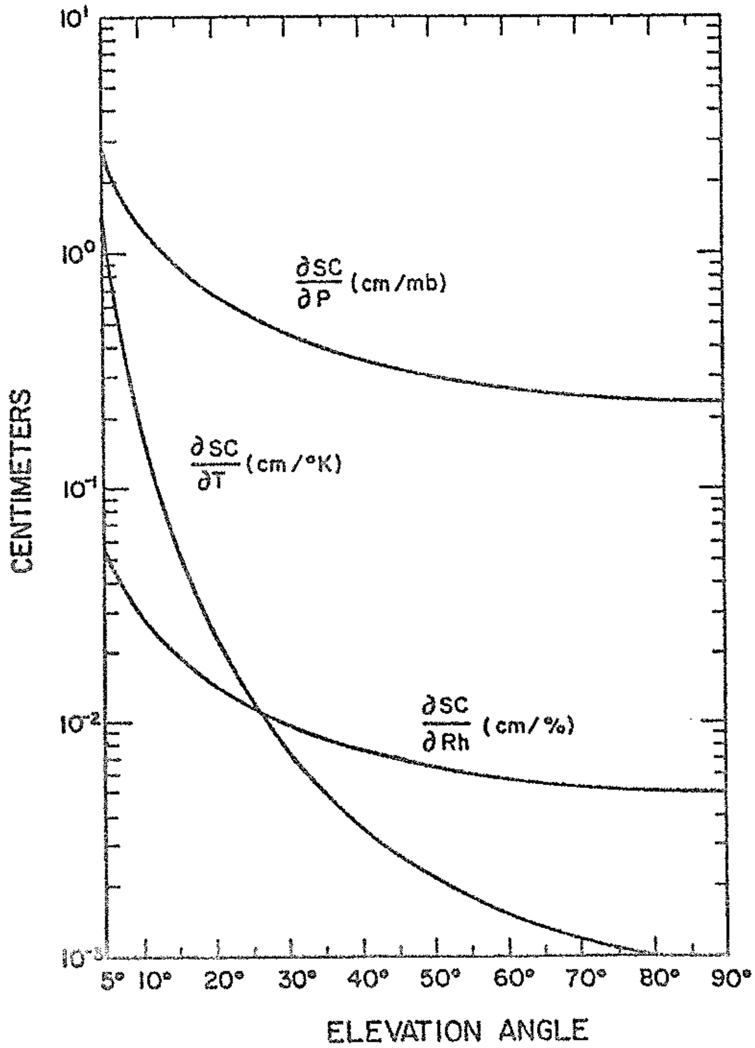

Figure 1. Variation of the spherical correction formula (Equation (3)) with respect to pressure, temperature and relative humidity.

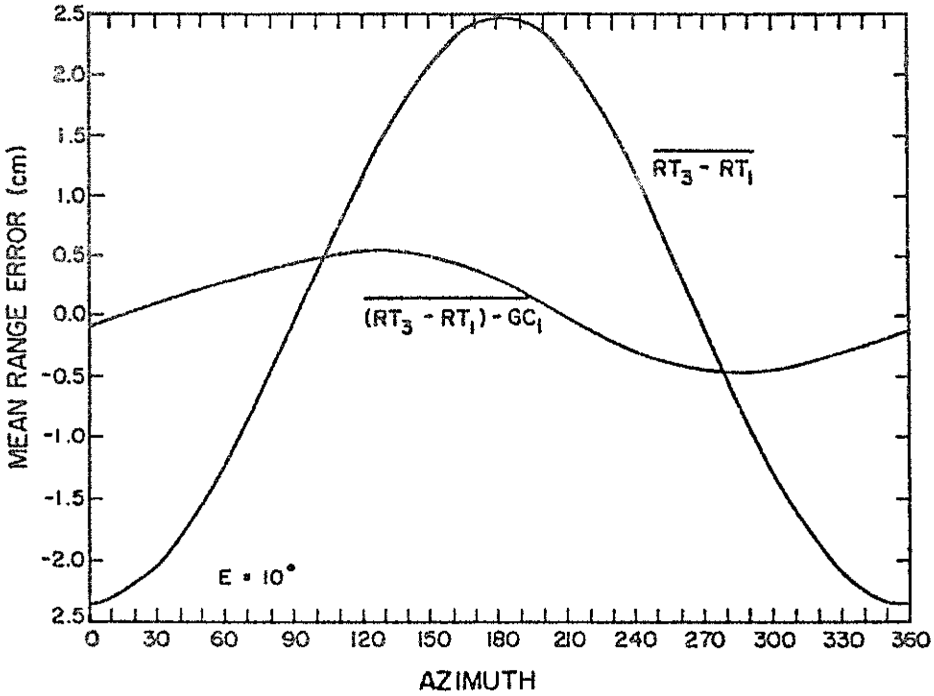

Figure 2. Mean of the uncorrected (RT_3 – RT_1) and corrected (RT_3 – RT_1 – GC_1) gradient error versus azimuth. The elevation angle is 10°.

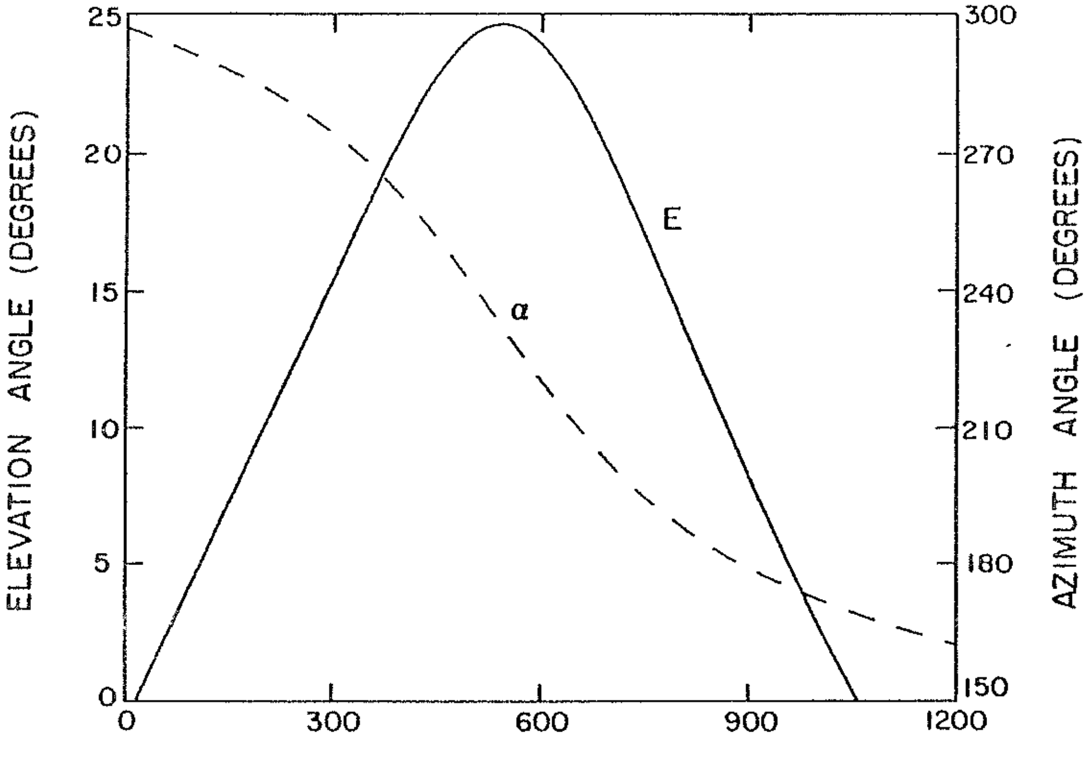

Figure 3. Azimuth and elevation angle of the Starlette Satellite as seen from the Goddard Space Flight Center in Greenbelt, MD on July 5, 1979. Zero seconds into the pass is 03:47 GMT.

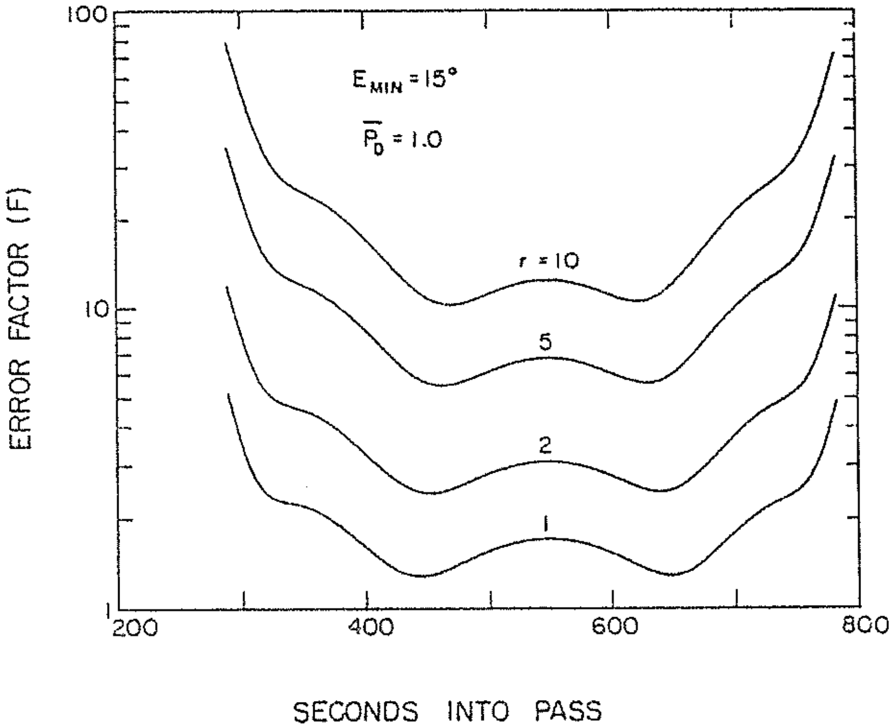

Figure 4. Error factor for the atmospheric correction model of Eq. (19) and the low elevation angle Starlette pass plotted in Figure 1. The detection probability is one and the minimum elevation angle is 15°. r is the ratio of the differential pathlength error at 20° elevation to the error at zenith.

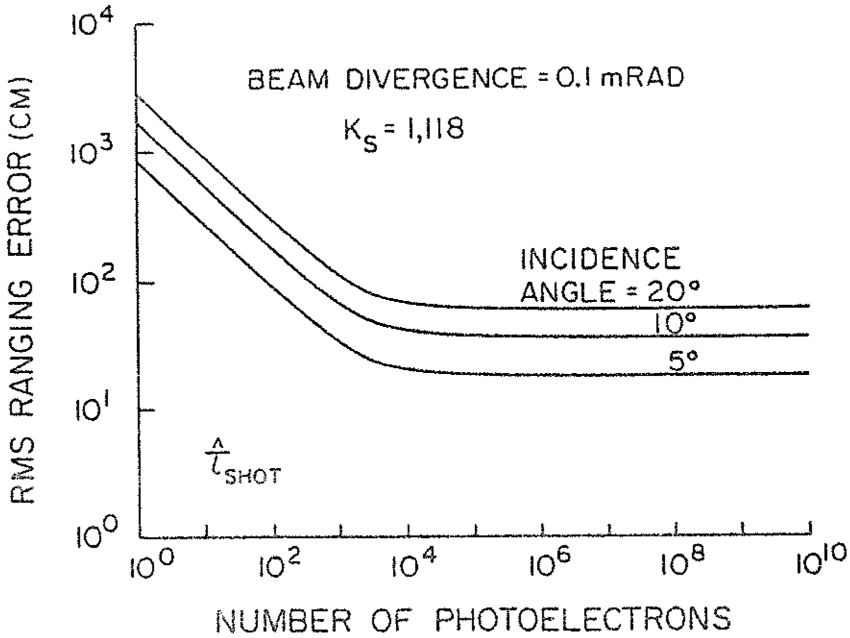

Figure 5. RMS ranging error using $\hat{\tau}_{SHOT}$ for non-normal incidence on an infinite flat diffuse target. (Target distance = 500 km, Transmitted pulse length = 0.5 cm, Receiver area = 100 cm^2, λ = 1 μm)

SOME MODELLING REQUIREMENTS FOR PRECISE LAGEOS ORBIT ANALYSIS

P.J. Dunn, EG. G. Wasc
6801 Kenilworth Avenue,
Riverdale, Maryland 20737

Telephone (301) 779 2800
Telex 590613

D. Christodoulidis, E.D. Smith,
Geodynamics Branch
NASA / Goddard Space Flight Center,
Greenbelt, Maryland 20771

Telephone (301) 344 7000
TWX 710 828 9716

ABSTRACT

The potential accuracy of LAGEOS observations from the worldwide laser network can only be realized if relatively subtle effects in the station and satellite force model are considered. In this report, the effects on station position predicted by recent models for the Earth and ocean tides are described. The perturbations on the LAGEOS orbit due to tidal effects must also be modelled as well as along-track variations which have been ascribed to the effect of charged particle drag.

SOME MODELLING REQUIREMENTS FOR PRECISE LAGEOS ORBIT ANALYSIS

In order to use the capability of LAGEOS observations to monitor crustal deformation and tectonic plate motion at the centimeter level, tidal influences on the tracking stations must be modelled to a similar level of precision. The tidal model adopted for the MERIT Project (USNO, 1983) includes the solid earth response due to Wahr (1981). Wahr considers an elliptical, rotating, elastic and oceanless earth, and this model yields station motion which differs from the decimeter variation predicted by Love's simpler spherically symmetric model at the K_1 tidal frequency. The differential effect amounts to about one centimeter in the radial direction and is a maximum at 45^{o} latitude. A thorough mathematical treatment is given in the MERIT Standards document (op. cit.) which also alerts the user of laser observations to the need for a consistent treatment of a zero frequency station displacement which may be included in nominal station coordinates.

The ocean tidal model currently adopted for LAGEOS analysis is that due to Schwiderski (1980). Goad (1980) has developed a technique using integrated Green's functions which defines tidal loading height displacement amplitude and phase values for important laser sites. The vertical displacement can amount to several centimeters at coastal locations and should be included in a precise station position analysis.

The ocean tidal model is however more critical in its long period effect on the orbital behaviour of LAGEOS. Eanes et al. (1981) have shown that effective modelling of the ocean tides can improve our determination of the inclination and node of the orbit at the meter level. The period of these effects ranges from 14 days (M2) to 1050 days (K1) and influence the definition of the inertial reference system as well as the resolution of earth rotation rate. The much larger effects on the orbit due to the solid earth tides (see, for example, Smith and Dunn, 1980) can be accommodated with more certainty that the ocean tidal perturbations, which will require refinement from analyses of LAGEOS and other laser satellite observations.

A very long period effect has also been observed in the nodal evolution of the LAGEOS orbit by Yoder et al. (1983). It has been ascribed to the viscous rebound of the solid Earth from the decrease in load due to the last glaciation, and appears as an apparent secular decrease of the second zonal harmonic. This subtle perturbation is unlikely to warrant inclusion in most geodynamic studies.

A much larger secular variation has been observed in the along-track component of the orbit (Smith, 1983). Rubincam (1982) concluded that charged particle drag could account for the effect, but Anselmo et al. (1983) have suggested that the Earth's albedo could also contribute significant periodic terms. An empirical model for the along-track variation must be used to accommodate the effect in orbital analyses based on continuous orbits of more than a few days. Data reduced in shorter arc lengths allow the perturbation to be absorbed into an estimate of the orbital semi-major axis, and the size of the orbit must be continuously monitored to provide a measure of the variation.

E M P T Y   P A G E

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ESTABLISHING GROUND TIES WITH MTLRS PERFORMANCE AND RESULTS

E. Vermaat
Delft University of Technology
Observatory for Satellite Geodesy
P.O. Box 581
NL - 7300 AN APELDOORN The Netherlands

Telephone 057 69 341
Telex 36442

ABSTRACT

The method employed to position the Modular Transportable Laser Ranging System (MTLRS) with respect to ground markers has been optimized to produce ground ties with optimal precision and reliability.

This paper describes the practical application of this method and summarizes numerical results obtained during the testing phase of MTLRS1 at the Kootwijk Observatory in the period April-July 1984

1. Introduction

Laser ranging to satellites utilising mobile ranging equipment requires the realisation of a geometric connection between an operationally well defined reference point S in the ranging system and an equally well defined reference point P for the site (figure 1).

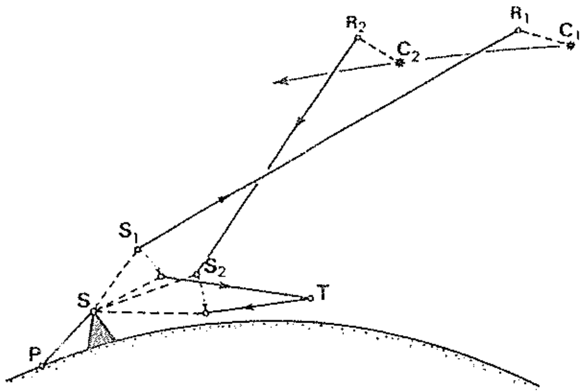


figure 1. Earth-fixed geometry of laser ranging to satellite C and to calibration target T. The observed ranges are referred to the instrumental center S. Coordinate solutions must be referred to marker P in case of mobile satellite laser ranging.

Once this connection has been established, the latter point serves as the terminal point of the baseline which can be solved for in the data reduction of the observed satellite ranges. If this geometric tie is not available or erroneous it will be impossible to relate baseline solutions from different site occupations, since a proper common reference for the baseline terminal points does not exist. Therefore a scrupulous approach to the determination of this geometric connection is a necessity.

For the Modular Transportable Laser Ranging System (MTLRS) a special positioning device has been constructed which can be attached to the front end of the telescope tube and with which markers in the immediate vicinity of the telescope mount can be observed in 3 dimensions. The method of data reduction employed to obtain the ground tie, has been designed to minimise the influence of undetected errors in the observations i.e. to maximise the reliability of this determination.

In the period of April-July 1984 MTLRS1* has been stationed at the Kootwijk Observatory for final testing and performance validation. Also the positioning method has been tested in this period and the results clearly indicate the excellent precision and

* The first one of two identical systems to be constructed

reliability of the obtained ground tie, in spite of the remarkable simplicity of the observational technique. Essential to the approach is the use of a number of markers more or less symmetrically arranged around the telescope mount.

2. The Technique

2.1 The positioning device

The positioning device (figure 2) comprises a standard He-Ne laser together with a simple 3 meter spring-rule, housed in a framework which can be firmly attached to the front end of the telescope tube. The He-Ne laserbeam points downward and passes through a prism which allows for small corrections to the direction of the beam. The tape of the spring-rule, once pulled out (figure 3) will be immediately adjacent to the laserbeam and thus directions and slant range can be observed simultaneously.

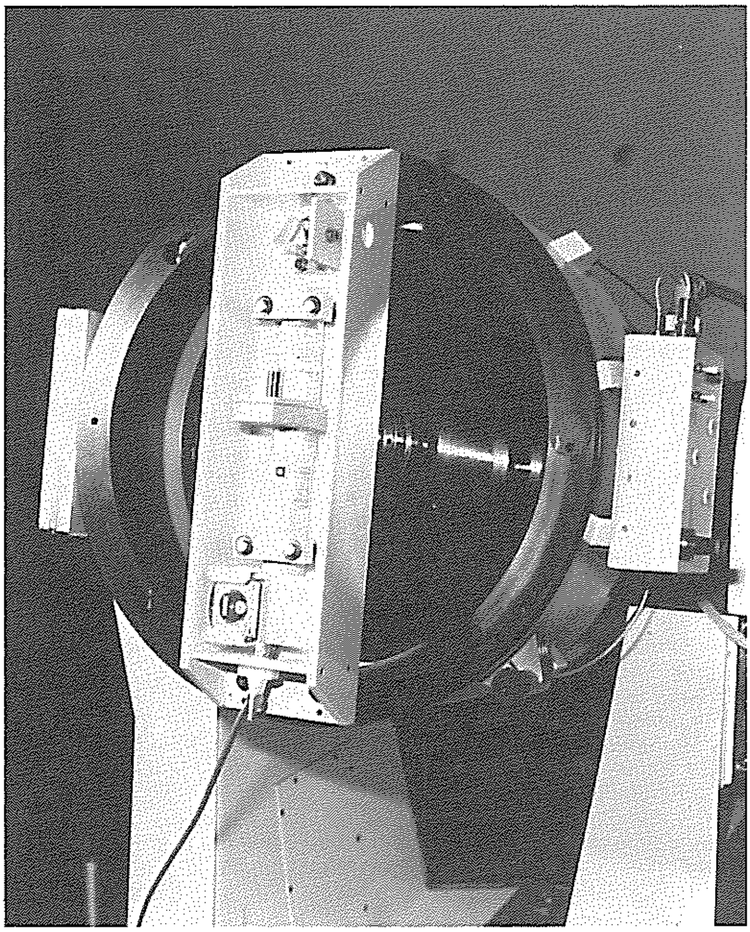


Figure 2 The positioning device attached to the front end of the telescope of MTLRS. The device is made up of a He-Ne laser for pointing at the marker and of a spring rule for ranging to the marker.

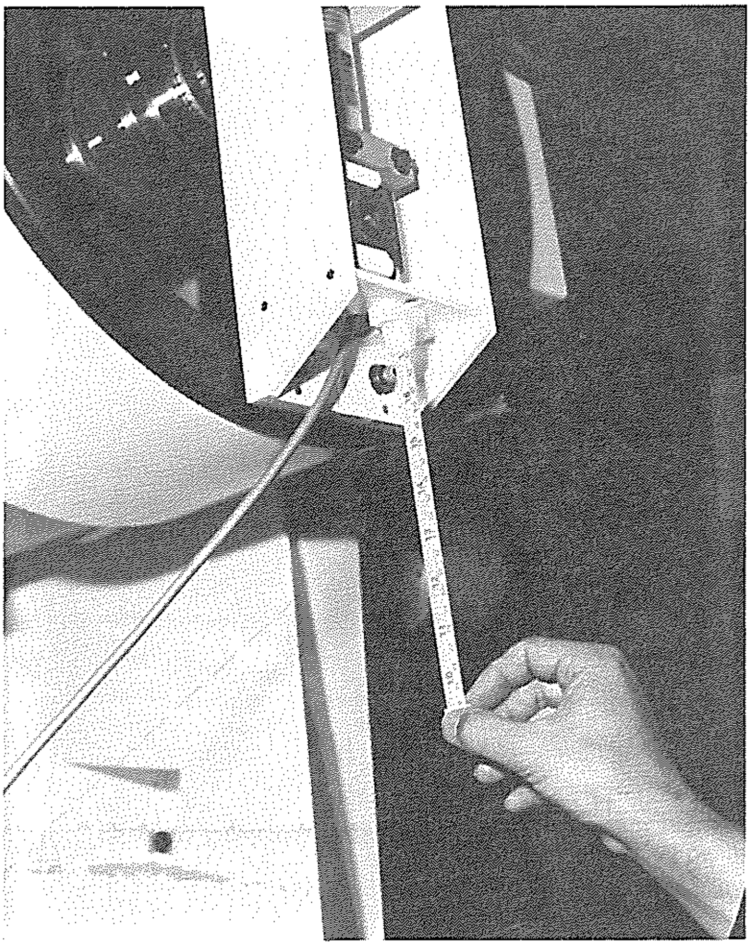


Figure 3 Close-up of the spring rule device.

During installation of MTLRS at a site, the mutual orthogonality of the telescope axis, the azimuth- and elevation axis will be checked and the index error of the elevation circle will be eliminated utilising standard techniques, involving stars and other remote targets. Subsequently, after attaching the positioning device to the front end of the telescope tube the He-Ne laserbeam will be adjusted to be orthogonal to the telescope axis and parallel to the azimuth axis, employing a simple auto-collimation technique illustrated in figure 4. Salad oil turned out to be a liquid that excellently reflects the laser beam. After this calibration procedure accurate directions can be obtained by simply pointing the He-Ne laserbeam at markers utilising the mount positioning system. The slant ranges can be obtained by pulling out the tape and reading the tape at a mark in the positioning device.

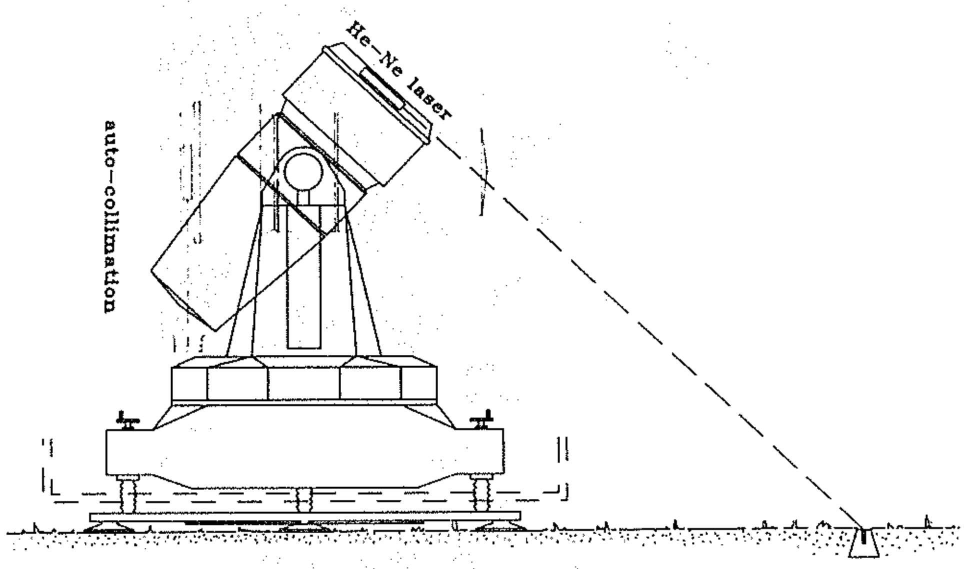


figure 4. Observing a marker utilising the positioning device. Prior to the observations the laser beam is properly adjusted, employing a simple technique of auto-collimation.

2.2 The markers

The markers must be designed to allow for precise pointing with the He-Ne laser beam and for observing the slant range with the spring rule. An engraved circle of about 9 mm diameter turned out to be optimal for centering the oval shaped reflection of the laser beam at a distance of 2 to 3 meters. A central pinhole in the circle defines the actual point of reference and facilitates the taking of the slant range.

The bronze marker must have a slightly curved topsurface to enable precise 3-dimensional surveying. These markers must be carefully installed at the site, firmly attached to the subsurface soil and properly isolated from surface soil or site pad. (figure 5). Installation in vertical constructions like a stable wall or the side of a pier is also possible. The topsurface of the marker should then preferably be tilted to have a similar angle of incidence of the laserbeam as for ground based markers (figure 6).

Especially if more than one marker is available at a site, a clearly readable letter or other character must be engraved in each marker for reliable identification.

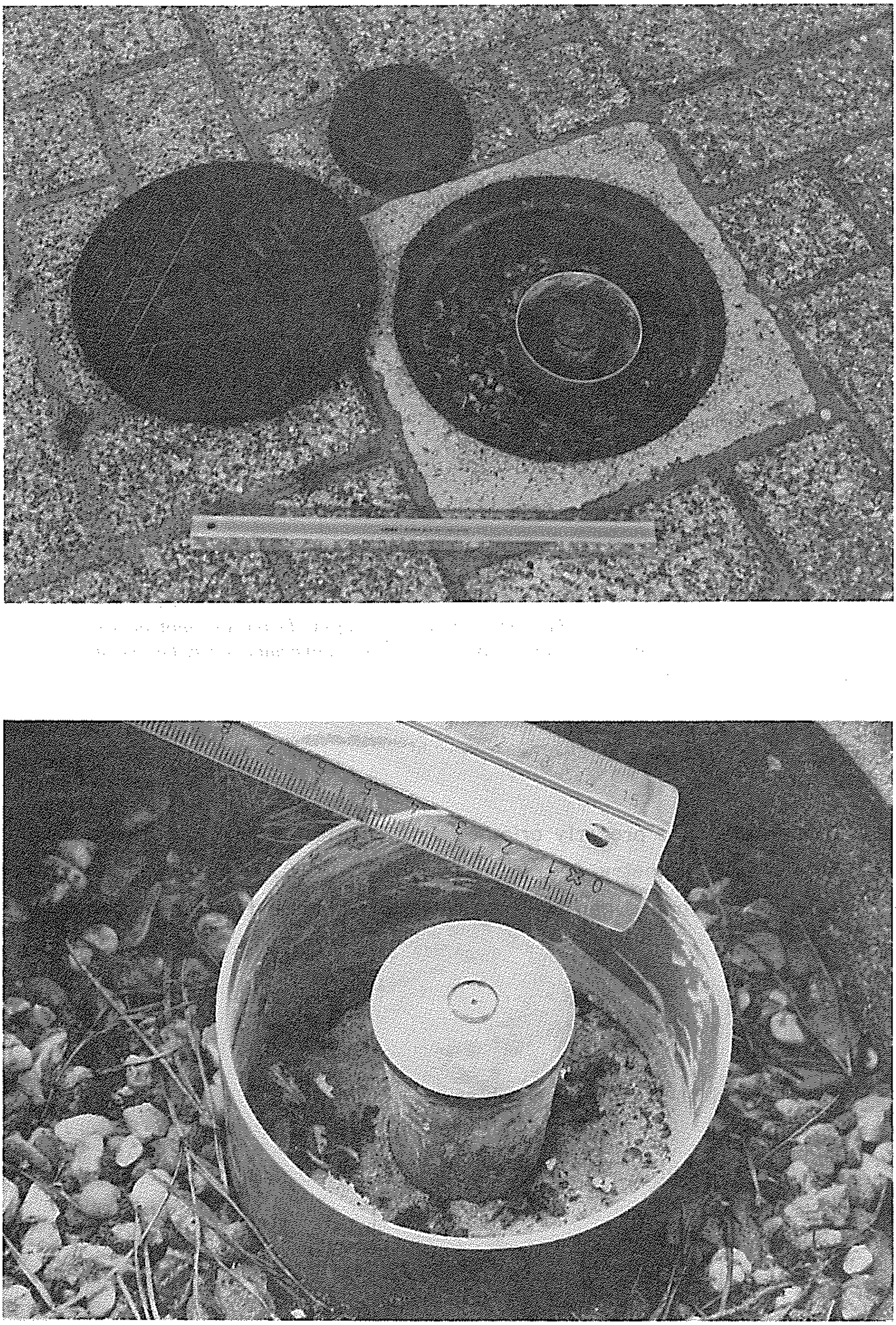


Figure 5 The markers must be properly isolated from the surfac soil or side pad.

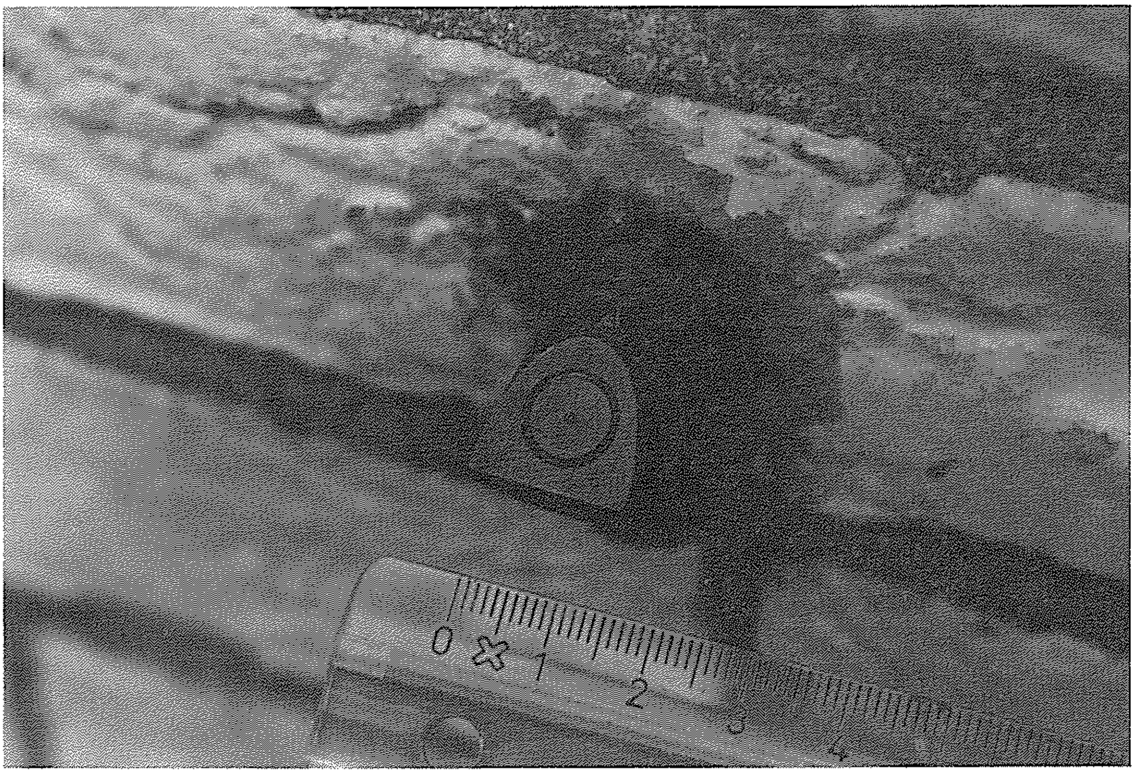


Figure 6 A marker attached to a vertical wall. An engraved circle of 9 mm diameter facilitates pointing the laser beam. The pinhole materializes the actual reference point.

2.3 The redundant approach

If the telescope mount is properly oriented in azimuth, the required ground tie can be deduced from simple geometry. If the vector $\mathbf{SP_i}$ in figure 7 is expressed in components on the reference system defined by the telescope mount and scaled by the spring rule (the S-system) as:

$$\mathbf{SP_i} = (X_i^{s_1}, X_i^{s_2}, X_i^{s_3}) \tag{2.1}$$

this vector can be related to the observables as:

$$\left.\begin{aligned} E_i &= \frac{1}{2}\pi - \operatorname{atan}\left(\frac{\lambda_o^{s} a}{R_i}\right) - \operatorname{atan}\frac{C\,S}{C\,P_i} \\ A_i &= \operatorname{atan}\left[\frac{X_i^{s_2}}{X_i^{s_1}}\right] \\ R_i &= (S\,P_i^2 - (\lambda_o^{s} a)^2)^{\frac{1}{2}} \end{aligned}\right\} \tag{2.2}$$

where $CS = X_i^{s3}$

$$CP_i = ((X_i^{s1})^2 + (X_i^{s2})^2)^{\frac{1}{2}}$$

$$SP_i = ((X_i^{s1})^2 + (X_i^{s2})^2 + (X_i^{s3})^2)^{\frac{1}{2}}$$

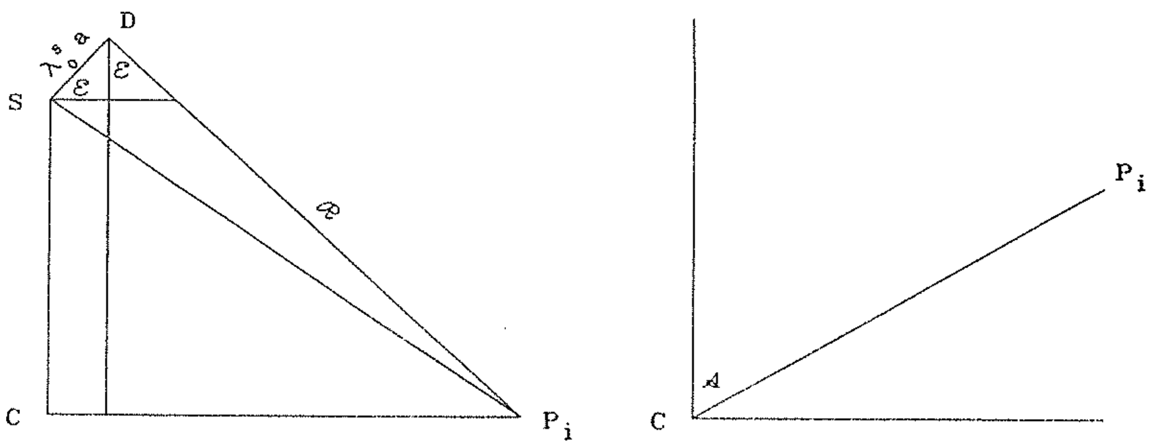


figure 7. The geometry of observing elevation, azimuth and range to a marker P_i. The observations determine the vector SP_i in the instrumental reference system S.

in which the distance $\lambda_0^s a$ is a calibrated instrumental constant. If only one marker is observed, these observations would be sufficient to uniquely define the ground tie vector. However, there would be no way of checking the occurrence of errors in pointing, reading or recording. Realizing the vital importance of a proper ground tie for relating baselines obtained from different site occupations, it would be extremely hazardous to suffice with observations to only one marker. Moreover, in view of the relative low cost of installing several markers at a site and the ease of observing them, it must at least be considered careless not to adopt a redundant approach to the ground tie problem.

The method employed for MTLRS not only requires redundancy, but also seeks optimal reliability in the ground tie vector. (Vermaat and Van Gelder, 1983) studies the effect of number and distribution of markers on the precision and reliability of this determination. This study reveals that a minimum of four or five markers, more or less symmetrically arranged about the site center is an optimum. It is required that from a previous, precise survey, relative positions of the markers are available in a cartesian and right-handed, but otherwise arbitrary coordinate system (0-system).

The software installed in MTLRS then solves for a seven parameter similarity transformation between the instrumentally defined S-system in which the observations are taken and the O-system in which the marker coordinates are given (figure 8):

$$X_i^s = \lambda_o^s (R_o^s)(X_i^o - X_s^o) \tag{2.3}$$

where X_i^s is the observed position vector of marker i in the S-system

X_i^o is the vector of given coordinates of marker i in the O-system

λ_o^s is the ratio of scale factors of O- and S-system

(R_o^s) is the 3-dimensional rotation from O- to S-system i.e.

$$(R_o^s) = R_1(\gamma)\, R_2(\beta)\, R_3(\alpha)$$

X_s^o is the position vector of point S in the O-system.

In the satellite range data reduction a baseline will be solved for, terminating at point S, the center of the S-system. This baseline must be corrected for the eccentricity vector X_o^s to obtain the baseline terminating in point O. (figure 8). This vector can be obtained from the transformation parameters solved for:

$$X_o^s = \lambda_o^s (R_o^s)(-X_s^o) \tag{2.4}$$

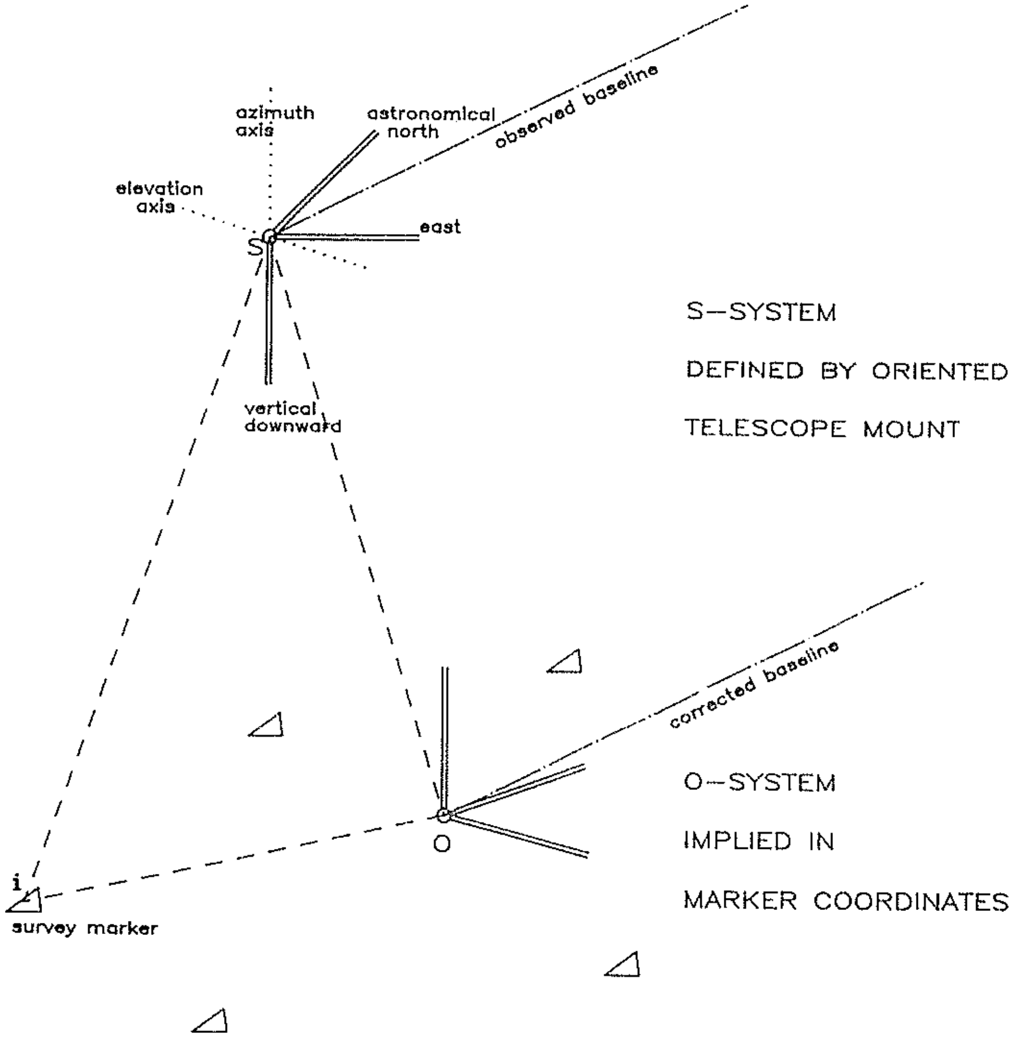
It is recommendable to maintain the length scale as implied in the marker coordinates in the O-system, instead of the scale of the S-system being determined by a bending and temperature dependent spring rule, thus:

$$X_o^{s'} = (R_o^s)(-X_s^o) \tag{2.5}$$

This correction can be best applied in a global reference system, requiring astronomical latitude (Φ) and longitude Λ, so the baseline correction can be obtained from:

$$X_o^g = R_3(-\Lambda)\, R_2(90^o + \Phi)(R_o^s)(-X_s^o) \tag{2.6}$$

MTLRS



TRANSFORMATION:

$$X_i^s = \lambda_o^s \,(R_o^s)(X_i^o - X_s^o)$$

figure 8. The similarity transformation between S-system and O-system.

3. Numerical results

During the test-period for MTLRS1 at Kootwijk, various ground tie determinations were performed employing the method outlined above. At the observatory two different sites are available for MTLRS. The so-called astronomical platform (figure 9) can accommodate MTLRS in a semi-stationary position when actual satellite observations are to be performed. The second site is at the parking lot where five positioning markers are arranged just as suggested for international site pads where MTLRS is to be expected (figure 10). This site is primarily meant for testing purposes. Both sites have been occupied in the testing period and the numerical results obtained with the positioning device are presented in tables 1 and 2.

The upper part of each table displays the seven estimated similarity transformation parameters, their formal precision (σ) as well as their worst-case reliability (∇) i.e. the upper bound influence of marginally detectable errors in any of the observations. The lower part of each table contains the residuals of the observations together with their test-variates i.e. the squared normalised residuals. These test variates are used for testing against a critical value of 10.80 resulting from an adopted significance level of 0.1% and a power of the test of 80%. An asterisk indicates rejected observations.

3.1 The site at the astronomical platform

Table 1a presents the results of the first positioning attempt at this site. Obviously this solution cannot be accepted since the test rejects all but one of the observations. Inspecting the magnitude of the normalised residuals it becomes apparent that the range to marker A is suspected most, because the magnitude of its test variate is about ten times higher than any other one. Due to correlation between the residuals most observations will be rejected in case of one large error. After re-measurement it became clear that in the range to marker A, a 30 cm error had occurred. A "9" had been replaced by a "6" probably because the range at the spring-rule had been read in an upside-down position. The new results after re-measurement are presented in table 1b. The residuals and the test-variates are very small and the observations obviously fit the adjustment very well. The precision of the translation parameters is about half a mm and their reliability about 2 mm. The latter means that a marginally detectable error in any one of the observations (in this case producing a test variate value of about 10.8) can only have a maximum influence on these parameters of about 2 mm. These very satisfactory results are a consequence of the utilisation of five markers, about symmetrically arranged around the ranging system, and are in agreement with the expectations arrived at in the figure 9.

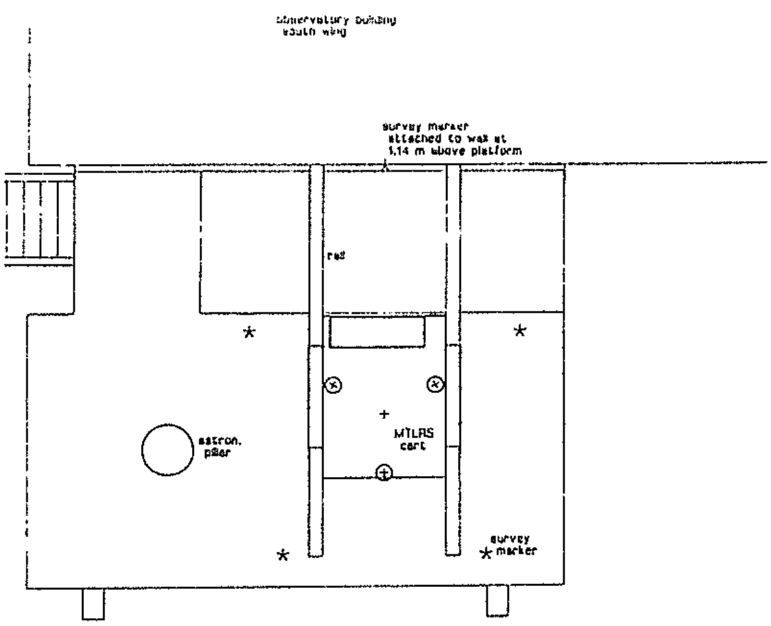
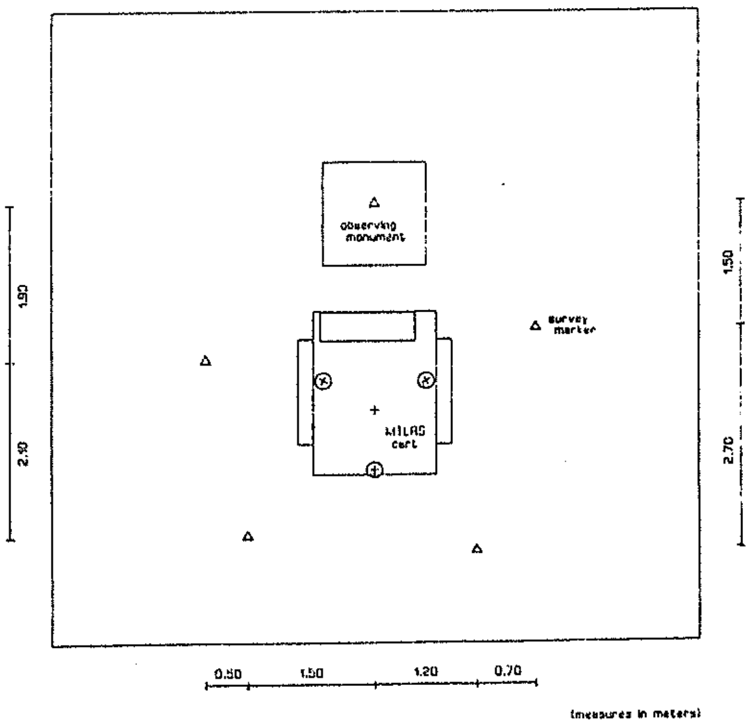


figure 10.



Footprint of MTLRS.
Figure 9 depicts the accomodation for MTLRS at the Kootwijk observatory.
Figure 10 displays the optimal configuration of five markers as suggested for international site pads.

	param.	σ	∇	
X_s^{o1} m	-.0080	.6	2.0	mm
X_s^{o2} m	.0520	.5	1.7	mm
X_s^{o3} m	.0288	.4	1.4	mm
α_o^s degr	90.3592	27.5	86.6	arcsec
β_o^s degr	.4204	50.5	228.0	arcsec
γ_o^s degr	180.0217	65.0	175.9	arcsec
λ_o^s	.9713	.4	1.0	1E-3

observation		res. degr/m	test
marker "A"	elevation	.1710	303.74 *
	azimuth	.0073	.40
	range	.1966	14795.50 *
marker "B"	elevation	-.1148	101.55 *
	azimuth	.2595	571.20 *
	range	-.0698	1552.46 *
marker "C"	elevation	-.2300	463.73 *
	azimuth	-.1629	215.43 *
	range	-.0526	940.01 *
marker "D"	elevation	-.2419	512.02 *
	azimuth	-.1565	200.69 *
	range	-.0529	951.37 *
marker "E"	elevation	-.1170	105.88 *
	azimuth	-.2731	641.05 *
	range	-.0701	1563.03 *

table 1a

	param.	σ	∇	
X_s^{o1} m	-.0078	.6	1.9	mm
X_s^{o2} m	.0323	.5	1.7	mm
X^{o3} m	.0203	.4	1.4	mm
α_o^s degr	90.3589	27.4	86.2	arcsec
β_o^s degr	-.0012	50.3	225.8	arcsec
γ_o^s degr	180.0210	64.7	176.0	arcsec
λ_o^s	1.0006	.4	1.0	1E-3

observation		res. degr/m	test
marker "A"	elevation	-.0080	.66
	azimuth	.0067	.33
	range	.0011	.49
marker "B"	elevation	.0058	.26
	azimuth	-.0041	.14
	range	-.0005	.08
marker "C"	elevation	.0030	.08
	azimuth	.0058	.28
	range	.0006	.11
marker "D"	elevation	-.0103	.92
	azimuth	-.0008	.01
	range	-.0003	.03
marker "E"	elevation	.0068	.36
	azimuth	-.0076	.50
	range	-.0013	.52

table 1b

table 1. Positioning results at the site at the astronomical platform.

design study (Vermaat and Van Gelder, 1983). The size of the translation parameters is only a few cm due to the fact that the origin of the 0-system has been chosen at the site center at an elevation of 1.3 m above the pad, thus very close to the expected location of the instrumental center S. This results in an only marginal influence of the rotation parameters on the baseline correction derived from formula (2.6).

3.2 The site at the parking lot

The results of the first positioning attempt at this site are presented in table 2a, which indicates the rejection of one observation: the elevation of marker E. Closer inspection reveals that some other observations have rather large test-variate values as well (e.g. the elevation to marker A and D). This rather puzzling situation could not be improved after re-measurement. The next step was to leave out any one suspected marker from the solution (e.g. marker E, D or A) but not any of these attempts gave acceptable results. Ultimately it could only be concluded that a rather complicated distortion had occurred at this site, after the survey and prior to the occupation by MTLRS, affecting the position of the majority of the markers. Thus these markers were re-surveyed and the coordinate differences obtained are presented in table 3. These figures fully support the assumption of a complicated distortion of a magnitude of 0.5 to 6.0 mm. Subsequently the positioning procedure was repeated utilising the new marker coordinates and table 2b presents the results, which are very acceptable. As could be expected, the precision and reliability is very similar to the results obtained at the astronomical platform.

It must be clear that a problem of disturbed markers never may occur in practical situations. Especially in a situation without evidence that only one particular marker has been disturbed, the reference point of the site has been irrecoverably lost and no accurate relation to baseline solutions obtained from previous site occupations will be possible. The site at the parking lot is only intended for testing purposes and for training crews in manoeuvring, packing and unpacking of the system. Although some care has been taken to isolate the markers from the pavement (figure 5) it is obvious that this has not been very successful, mainly due to the type of pavement, the instability of the subsurface soil and the sometimes heavy traffic to be expected at this location.

Sites meant for satellite observations have to be selected with extreme care and special attention has to be paid to the installation of the markers.

		param.	σ	∇	
X_s^{o1}	m	.0053	.7	1.9	mm
X_s^{o2}	m	.0863	.6	1.8	mm
X_s^{o3}	m	.0656	.5	1.5	mm
α_o^s	degr	90.3343	26.9	82.0	arcsec
β_o^s	degr	-.0760	61.5	234.8	arcsec
γ_o^s	degr	180.0109	66.9	198.2	arcsec
λ_o^s		1.0003	.4	.9	1E-3

observation		res. degr/m	test
marker "A"	elevation	.0326	9.44
	azimuth	.0202	2.82
	range	.0017	1.03
marker "B"	elevation	-.0087	.63
	azimuth	-.0113	1.05
	range	.0009	.27
marker "C"	elevation	-.0169	2.78
	azimuth	.0087	.68
	range	-.0029	2.95
marker "D"	elevation	.0346	9.56
	azimuth	-.0018	.02
	range	-.0004	.05
marker "E"	elevation	-.0407	13.28 *
	azimuth	-.0157	1.95
	range	.0005	.10

table 2a

		param.	σ	∇	
X_s^{o1}	m	.0066	.7	1.9	mm
X_s^{o2}	m	.0890	.6	1.8	mm
X_s^{o3}	m	.0631	.5	1.5	mm
α_o^s	degr	90.3486	26.9	82.0	arcsec
β_o^s	degr	-.0064	61.5	234.6	arcsec
γ_o^s	degr	180.0065	66.9	198.2	arcsec
λ_o^s		1.0005	.4	.9	1E-3

observation		res. degr/m	test
marker "A"	elevation	.0101	.91
	azimuth	-.0005	.00
	range	.0014	.70
marker "B"	elevation	-.0142	1.65
	azimuth	.0125	1.29
	range	-.0012	.52
marker "C"	elevation	.0096	.89
	azimuth	-.0171	2.64
	range	-.0002	.02
marker "D"	elevation	-.0066	.35
	azimuth	.0164	2.02
	range	-.0002	.01
marker "E"	elevation	.0007	.00
	azimuth	-.0114	1.02
	range	.0000	.00

table 2b

table 2. Positioning results at the site at the parking lot.

	ΔX	ΔY	ΔZ
marker "A"	0.5	-1.0	-6.0 mm
"B"	0.5	-0.9	-2.0
"C"	4.6	-0.5	-1.0
"D"	2.8	1.4	-2.0
"E"	1.8	0.1	-1.0

table 3. Coordinate differences at the site at the parking lot due to local deformation.

4. Concluding remarks

From tests at two different sites, it can be concluded that the method designed for MTLRS of determining the ground tie vector, not only easily discovers observational errors, but also detects relatively small local disturbances in the immediate site area.
In addition it has become evident that the precision of the estimated parameters is very satisfactory, especially the translation can be obtained to sub-millimeter precision, in spite of the rather simple surveying technique employed.
The necessary requirement for accurate ground tie vector determination is the availability of a sufficient number of markers in an optimal configuration. These markers must be accurately surveyed prior to site occupation.
Another feature of the method employed for MTLRS, which already has proven its value, is the fact that the data analysis is performed on-site, immediately after obtaining the observations. Thus the operators are able to identify problems of observational errors or local site deformations immediately, and take measures accordingly.

Reference

Vermaat, E. and B.H.W. van Gelder, 1983. "On the eccentricity of MTLRS". Delft University of Technology. Reports of the Department of Geodesy, Mathematical and Physical Geodesy, No. 83.4.

Acknowledgement

The software utilised, could be scrupulously tested with laboratory measurements made by Leendert van Dijk and Ayse Açikel. They also surveyed the markers at Kootwijk assisted by Danny van Loon who, subsequently supervised the positioning procedures with MTLRS. Joop Bodde manufactured and installed the markers and last but not least an unknown truck-driver disturbed the site at the parking lot.

LASER SYSTEM CHARACTERIZATION

M.R. Pearlman
Smithsonian Astrophysical Observatory
60 Garden St.
Cambridge, MA 02138

Telephone (617) 495 7481
Telex 92148

ABSTRACT

A model is provided to standardize the evaluation of laser ranging system perfomance in terms of ranging accuracy. The model deals with the magnitude and temporal nature of the known data error sources and aggregates them in terms of Ranging Machine Errors, Epoch (Timing) Errors, and Modelling (Environmental) Errors. The model is provided to characterize and verify system performance for engineering operations and data analysis requirements. It is anticipated that this model will be dynamic, evolving with our understanding and needs. An application of the model to the Arequipa station is included as an example.

LASER SYSTEM CHARACTERIZATION

1. REQUIREMENT AND METHODOLOGY

The Laser System Characterization is intended to provide a "Standard Error Model" to: 1) verify system performance; 2) verify system upgrading; 3) compare systems, and 4) establish and adopt constants and models for intercomparisons and data analysis. The model is not a substitute for collocation tests which evaluate the total aggregated error budget of the systems under study, but rather is designed to support collocation and other system performance tests by providing the basis upon which different systems utilizing different philosophies and techniques may compare error budgets. In addition, total model specification is considered essential for accurate preprocessing and optimal weighting of network observations in any least squares adjustment process.

The model characterizes each system, including local site dependent variables, under normal operating conditions of a given epoch. That is, the model parameters are tabulated for each system and site as a function of time, being updated on a regular basis or whenever maintenance or modification effecting the measurement occurs. The model also provides a format to characterize system performance under malfunctioning conditions, but its application to such a situation would have to be considered on a case by case basis. It may be more practical to disregard certain data than try to characterize data under conditions of equipment malfunctions or operator error.

In organizing this model, we placed requirements that it should:

1. Focus on the systematic error sources.
2. Specify the statistical means of characterizing each component (1 sigma, peak-to-peak, etc.)
3. Specify relevant time period or periods for each component.
4. Define a means of measuring and specifying each error component.
5. Specify a means of aggregating the error components.
6. Be practicable.

This model does not include the averaging effect derived through orbital geometry. Such averaging depends upon the method of analyses, the station configuration, and the geophysical parameters being sought. This model is intended to provide the analyst with the input required to test error sensitivity in his own application of data.

For convenience, we have divided the error components into three categories corresponding to the nature of the errors.

1. Ranging machine errors are those associated with the laser hardware and its calibration.

2. Epoch or timing errors are those associated with the station clock, or time and frequency transfer.

3. Modelling or environmental errors are those associated with data compensation for effects outside the ranging and timing system.

In order to provide a firm basis for evaluation of total system performance, this specification aggregates hardware related effects independently from environmental effects. This has the advantage of allowing the user to focus on his area of immediate interest. It is common practice in laser ranging for the observing station to provide estimates for ranging machine and timing errors but not for modelling and environmental errors. In addition, traditional parametric data describing the atmosphere is usually supplied by the station without precision estimates. Since corrections for all three types of errors are applied or furnished for all range observations, and an accurate a-priori estimate of the precision of this corrected range is needed, it is necessary to state all corrections with precision estimates.

The "Standard Model" should evolve and improve with our knowledge of the error sources. In particular, it is assumed that the models and techniques used to characterize the environmental effects will be replaced by new models as they are developed and accepted. It is also anticipated that archived data will be periodically reanalyzed as major improvements are introduced.

2. CLASSIFICATION OF ERROR SOURCES

The model components are divided into categories:

1. Ranging Machine Errors

   a. Wavefront distortion (Spatial Errors)
   b. Uncorrected System Drift (Temporal Errors)
   c. Uncorrected Variation in system delay with Signal Strength
   d. Errors in target range or calibration path length
   e. Error in calibration due to uncertainties in meteorological conditions along the calibration path
   f. Variation in system calibration with background noise level
   g. Mount eccentricities

2. Epoch (Timing) Errors

   a. Portable Clock Set
   b. Broadcast Monitoring

3. Modelling (Environmental) Errors

   a. Atmospheric Propagation (Model)
   b. Atmospheric Propagation (Meteorological Measurements)
   c. Spacecraft Center-of-Mass
   d. Ground Survey of Laser Position
   e. Data Aggregation

The user must be aware of the nature of each of the error sources, otherwise, he runs the risk of confusing an error source with a geophysical observable. This means that the operators of each laser ranging system must provide a determination of each error source (size and time constant) on a routine basis and make the full characterization schedule available to the users.

A comprehensive system evaluation must be made at least every six months and before and after each major modification to the hardware data flow path.

3. CHARACTERIZATION OF ERRORS

Each error source for each participating laser system must be characterized by its size and temporal nature. For simplicity, we use a one sigma representation for those components that appear random (such as wavefront) and one-half peak-to-peak for those effects that appear to have well defined trends (such as uncorrected variation with signal strength). This gives strong incentive to make analytic a posteriori corrections where possible.

Each error component has a characteristic signature in the pattern of residuals from a perfect orbit. In this model, the temporal nature of the error sources are quantified by time constants (decorrelation time) after which the pattern of residuals would change appreciably; it is assumed that the influence of error sources average out over 4-6 time constants. A specific component of error may decorrelate in steps owing to the various contributing activities.

In this model we characterize the error sources by their influence over specific integration periods which span the range of geophysical interest and operational constraints. In particular, we have chosen periods of a pass, a day (several passes), a month, a year, and several years (indefinite or trends). Many of the error sources, especially those in the environmental category, are much better understood over short periods and hence semi-annual, annual and decade fluctuations still need to be defined or improved.

4. RANGING MACHINE ERRORS

The known ranging machine errors are summarized in Figure 1.

4.1 Spatial Variations

Spatial variations in time of arrival (or wavefront distortion) are the result of mode structure in the laser. Patterns in the far field tend to change appreciably over periods of a few hours or less, and hence the effect which can give a strong residual signature (depending upon mode pattern and satellite path within the laser beam) can vary from pass to pass. The effect tends to vary with pulse width and laser configuration.

Spatial variations are measured by mapping the wavefront with a fixed ground-based retroreflector. The effect would be characterized by the r.m.s. variation over the wavefront. Sufficient data must be taken to assure that range noise is negligible and there must be enough redundancy in the data taking sequence to verify the pattern (and avoid temporal effects).

4.2 Temporal Variations

Temporal variations refer to uncompensated system drift (change in internal delay) during ranging operations. These would be due to changes in temperature, cycling of fans and compressors, changes in line voltage, etc. The potential for a problem is exacerbated by increased time intervals between calibrations; systems that are calibrated on a pulse by pulse basis avoid the problem, whereas those that rely on pre-and-post pass calibrations must be very carefully monitored.

Temporal variations are evaluated on an r.m.s. basis by monitoring and analyzing pre-minus-post calibration differences over an extended period of time (at least one month). The pre-minus-post calibration is not unambiguously separable from meteorological fluctuations along the calibration path, (see below) but the method is simple and will give an upper bound to the effect.

Temporal variations can also be monitored by ranging to a close ground target (to minimize propagation effects) over a period of several hours.

SOURCE	DEPENDENCE	MEASUREMENTS	RELEVANT TIME PERIOD	COMMENTS
SPATIAL VARIATIONS (WAVEFRONT DISTORTION)	PROPORTIONAL TO PULSE WIDTH	MAP WAVEFRONT WITH CORNER CUBE	PASS OR SEVERAL HOURS	SYSTEMATIC RESIDUAL SIGNATURE (PASS); MAY AVERAGE OUT OVER SEVERAL PASSES
TEMPORAL VARIATION (UNCORRECTED SYSTEM DRIFT)	SYSTEM STABILITY INTERVAL BETWEEN CALIBRATIONS	STABILITY TEST RUN PRE-POST CALIBRATIONS	PASS (BETWEEN CALIBRATIONS)	REAPPEARING SYSTEMATIC TREND: TENDS TO AVERAGE OUT WITH TIME
SIGNAL STRENGTH VARIATION (UNCORRECTED VARIATION IN SYSTEM DELAY WITH SIGNAL STRENGTH)	PMT, PULSE AMPLITUDE AND WIDTH	CALIBRATE OVER FULL DYNAMIC RANGE	INDEFINITE (LONG TERM)	RANGE ERROR CORRELATED WITH SIGNAL STRENGTH (RANGE)
ERROR IN CALIBRATION TARGET DISTANCE (EXCLUSIVE OF METEOROLOGICAL EFFECTS)	SURVEY MEASUREMENT	SURVEY	INDEFINITE (LONG TERM)	FIXED BIAS
ERROR IN CALIBRATION MEASUREMENT	METEOROLOGY	P.T.%R.H.	DAY, ANNUAL	BIAS WITH DIURNAL CYCLE AND SLOWER VARIATIONS
VARIATION WITH BACKGROUND LEVEL	PMT	CALIBRATE OVER RANGE OF ANTICIPATED CONDITIONS	DIURNAL	DIURNAL VARIATION
MOUNT ECCENTRICITY	TRACKING ANGLES	STELLAR CALIBRATION, SURVEY	INDEFINITE	SYSTEMATIC RESIDUAL SIGNATURE OVER A PASS; VARIATION IN INFLUENCE WITH SATELLITE ORBITAL GEOMETRY

FIGURE 1
SATELLITE LASER RANGING SYSTEMS
RANGING MACHINE ERROR SOURCES

4.3 Signal Strength Variations

Variations in system delay with signal strength arise because performance of devices within the system including PMTs are amplitude and/or pulse-width dependent. Those systems that are calibrated and intended to operate at the single photoelectron level only would have very minimum degradation due to this effect. This, of course, presumes that there is proper discrimination against occasional multiple photon returns (with different system propagation times) which would degrade range accuracy.

The variations with signal strength, which are measured by detailed target calibrations over the full dynamic range of the system, tend to have a systematic trend which may lend itself to a posteriori analytic correction. Since this error source is dependent upon signal strength and hence range, it can give systematic residual patterns. As such, the effect is long term. As an incentive to consider analytic corrections, this model uses a one-half peak-to-peak representation (over the pertinent dynamic range) to characterize this effect.

4.4 Calibration Target Distance

4.4.1 Measurement Techniques (Exclusive of Meteorological Correction)

Error in calibration target distance includes both ground targets and internal calibration paths. This is essentially how well a path can be measured by ground survey or tape measure. Each station must provide an estimate of target range accuracy which is based on the measurement technique. This error is a fixed long term bias.

In addition, as mentioned in 6.3 below, each station may have significant diurnal and annual signatures in the distance between the laser and the ground target. Ideally, target distance should be measured at several times during the day as well as a number of times during different seasons to determine: (1) if such a variation exists; (2) if it is significant and reproducible, and, (3) if a useable model can be developed.

4.4.2 Meteorological Correction to Calibration

In those systems that use ground targets for calibration, corrections must be made for horizontal propagation delay. The technique for computing this correction should be standardized to the group refractivity (Ng) derived from the Barrel and Sears formula adopted by the IAG in 1963.

$$Ng = N - \lambda \frac{dN}{d\lambda} = 80.343 \quad f(\lambda) \frac{P}{T} - 11.3 \frac{e}{T}$$

where:

$$f(\lambda) = 0.9650 + \frac{0.0164}{\lambda^2} + \frac{0.000228}{\lambda^4}$$

which has been normalized to 1 for λ = 6943Å (ruby laser wavelength)

and where:

λ = wavelength in microns

P = total air pressure (mb)

e = partial pressure of water vapor (mb)

T = temperature (degrees Kelvin)

The refractive correction must be based on measurements of P, T, and e (or %R.H.) at both ends of the calibration path or in the very least, an extrapolation based on the slope of the calibration path. No curvature corrections need be applied if the line is shorter than 10 km.

The total effect of the atmosphere is about 270 parts in 10^6 at sea level. The major uncertainties in making this correction are temperature and pressure variations along the path. This effect probably includes short period terms which average out over time spans of a day plus longer term biases which may include seasonal and even annual effects. Fluctuations of several degrees, which are not uncommon over a 1 km path can lead to an error in the refraction correction of as much as 1% (3mm). The size of the annual component is not clear, but it may be significant.

Instrument and procedural errors in the reading of pressure and temperature also add uncertainties to the refraction correction. A reading error of 1 mb in pressure or 0.5 C in temperature will introduce a bias error of .1% in the refraction correction (or about .3 mm for a 1 km calibration path).

The value of the error (r.m.s.) in the meteorological correction must be determined by each station based on local measurements, topography, and instrument calibration.

4.5 Mount Eccentricities

Laser range measurements must be referred to an "invariant" (fixed) reference point (usually termed the "intersection of the axes") on the laser mount. This point must be specified along with the associated path offset. In reality, however, these "invariant" points may not be fixed in space and the resulting "mount eccentricities" can produce pass-dependent systematic range errors. The pertinent eccentricities must be measured and/or modelled with appropriate range error characteristics. The influence of this effect is of particular importance with large instruments and with X-Y mounts. Since mount eccentricities produce reproducible, systematic components, the unmodelled (uncompensated) effects should be estimated on a half peak to peak basis.

4.6 Variation with Background Noise Level

There is some speculation that system delay may be a function of background noise level. However, to date there has been no verification of this effect.

5. TIMING ERRORS

The standard epoch reference used for laser ranging is UTC (BIH) or its close proximity UTC (USNO). The accuracy to which epoch is maintained is station dependent and must be furnished by each operating station. In practice, all station clocks are checked periodically with a portable clock and monitored at least once per day using LORAN, GPS, TV Reception, VLF or some other broadcast source. On a single pass basis with Lageos, a 1 microsec epoch error will introduce an error in station position of about 4 mm.

5.1 Portable Clock Check

Portable clock checks are typically of .1-1.0 microsec quality depending upon the portable clock, the length of the clock trip, and the station clock. An error in the portable clock set introduces a fixed bias component (long term) until a subsequent clock trip takes place.

5.2 Time Broadcast Monitoring

Epoch and/or frequency broadcasts are monitored at least daily by most operating stations. Those that receive TV line signals, or ground wave LORAN should be able to monitor epoch to 1 microsec; GPS reception should be considerably better. The daily values are independent determinations of station clock offset and hence the time constant for this component of epoch error is one day. For those using skywave LORAN or VLF, daily fluctuations of several microseconds due to propagation effects are common. In this case, averaging over several days is required to smooth out the data. The time constant in this case is 3-5 days. Routine monitoring of VLF propagation by the U.S. Coast Guard indicates that long term (even annual) variations measured during periods of stable propagation during the day are typically 1 microsecond or less.

It should be pointed out that historically long term timing errors have been notorious at the field stations. For the most part however, these have been the result of hardware and/or operational difficulties which should be documented as malfunctions.

6. MODELLING ERRORS

A summary of the modelling errors appears in Figure 2, with notation whether they are determined (measured) on a site by site basis or estimated from general models in use.

CORRECTION	METHOD	ESTIMATED ACCURACY	TIME PERIOD	NATURE
ATMOSPHERIC PROPAGATION (MODEL)	MARINI AND MURRAY MODEL	0.5 CM (AT 45 ALT)	DAY; PROBABLY ANNUAL	BIAS (P.T.%R.H.): VARIES WITH AZIMUTH AND ALTITUDE
ATMOSPHERIC PROPAGATION (MEASUREMENT)	MEASUREMENT OF P, T, H	DETERMINED	LONG TERM	OFFSET INCREASES WITH RANGE
S/C CENTER OF MASS (MODELS)	GSFC MODELS ARNOLD MODELS	2 MM	INDEFINITE (LONG TERM)	FIXED BIAS
GROUND SURVEY OF LASER POSITION (MEASUREMENT)	SURVEY MEASUREMENT	DETERMINED	INDEFINITE; PROBABLY ANNUAL	STATION POSITION ERROR
DATA AGGREGATION	AVERAGING 1-3 MINUTE DATA SEGMENTS	DETERMINED	PASS	DEPENDS ON DATA YIELD AND DISTRIBUTION

FIGURE 2
SATELLITE LASER RANGING SYSTEMS
MODELLING ERROR SOURCES

6.1 Atmospheric Propagation Model

6.1.1 Model

The recommended model for columnar refraction between ground station and satellite is the model by Marini and Murray (1973) based on the Barrel and Sears model for atmospheric refractivity and a standard exponential atmosphere. (The use of this model should be standardized and changed only with the organized consensus of the community.) Although this model does not include the effects of horizontal gradients in atmospheric density and temperature, it is believed to be accurate to within 1-2 centimeters of ray tracing results performed on radiosonde data (Marini and Murray, 1973, Gardner 1976).

It must be recognized, however, that this model does not include the effects of horizontal gradients in atmospheric density. At low elevation angles, the laser beam may be passing through pressure fields that vary by a few millibars at ground level. This alone could introduce uncertainties as large as 1 cm or more. Even with no surface pressure changes with position, horizontal gradients in temperature can influence the model error for slant ranges by making the scale height depend on position. Gardner (1976) and Dunn et. al. (1982), have studied this effect and find typical errors of 1.5 and 2 cm (r.m.s.) respectively at 20 degrees elevation if no correction for horizontal gradient is made.

Since observations are taken over all accessible elevation angles (usually above 20 degrees), and since the effects of horizontal gradients fall off rapidly with elevation angle, the average effect is about 0.5 cm. In lieu of more definitive data at the moment, we have characterized the refraction error as 0.5 cm at 45 degrees elevation. Since atmospheric conditions typically change on both diurnal and longer time scales, we anticipate that the size of this error source would decrease slowly with observing time. In addition, there is probably an uncorrected annual variation, but as yet this is unquantified.

6.1.2 Meteorological Measurement Error

The most significant term in the Marini and Murray model is proportional to pressure (p) and inversely proportional to elevation angle (E):

$$\delta\Delta R(m) = \frac{0.0024}{\sin E}\ \delta p(mb)$$

The dependance on temperature change (δT) of this model can be expressed as:

$$\delta\Delta R(m) = \frac{1\times10^{-5}}{\sin^3 E}\ \delta T(^\circ C)$$

A measurement error of 1 mb in pressure and 1 C in temperature, which are common in todays field operations, will introduce errors of about 7 mm and 0.3 mm respectively at 20 degrees altitude. However, it is quite feasible with available instrumentation to measure barometric pressure at field stations to 0.3 mb. To the extent that errors in pressure and temperature readings are due to instrument calibration or reading procedure, the influence of these components would be long term range biases which increase with zenith angle and hence range. These errors should be estimated on a site by site basis by comparison with calibrated instrumentation.

6.2 Spacecraft Center of Mass

The range correction to spacecraft center-of-mass for Lageos has been calculated analytically (Fitzmaurice et. al. 1978; Arnold 1978) and measured in the laboratory prior to launch (Fitzmaurice et. al. 1978). The analytical models show a dependence of range correction on pulse width and pulse detection scheme. For those situations in common the differences between the analyses by Fitzmaurice et. al. and Arnold is less than 1 mm. Our estimate for the error in range correction to Lageos is taken from the experimental measurement uncertainty which was about 2 mm (Fitzmaurice et. al. 1978). This value, of course, assumes that the correction made is appropriate for the laser pulse width and detection scheme. Otherwise, an error as large as 1 cm is possible. This error would be a long term fixed range bias.

6.3 Ground Survey of Laser Position

Lasers that reoccupy a site can not be placed in exactly the same position each time. As such the system reference point must be surveyed to the local geodetic reference marker. The error in this measurement will constitute a fixed offset in station position for the period of one site occupation. These estimates of measurement accuracy must be furnished by each laser ranging group for each occupation by a mobile laser system. In the case of fixed laser systems, the local survey errors are important from the standpoint of interconnecting datum, however, they do not effect direct measurement of station position or crustal motion. It should also be recognized that many ground sites have significant annual signatures due to changes in ground water. At some point, this issue must be systematically addressed.

6.4 Data Aggregation

No specification is recommended at this stage as there is at yet no agreed "best" method. Several methods based on 1-3 minutes of ranging data are being used to produce normal points with errors less than 1 mm are currently under intensive study. Once these are concluded we expect standardization to occur.

7. AGGREGATION OF ERRORS

Since the nature and representation of the separate error sources is quite varied a rigorous aggregation of the error sources would be quite difficult. However, a simplified approach to data aggregation is to assume that the individual components of error are uncorrelated and that an r.s.s.

of all pertinent error sources is sufficient to give an overall estimate of total ranging error. For this, we would form separate estimates of range error for each integration (averaging) time of (1) a pass, (2) a day, (3) a month, and (4) an indefinite period (long term).

As pointed out earlier, once the annual components are better understood, they should be tabulated separately. An example of how the data could be presented and aggregated is shown in Figure 3. An example using the SAO laser in Arequipa is shown in Figure 4.

8. AN EXAMPLE: THE AREQUIPA LASER

The "Standard Error" Model for the Arequipa Laser appears in figure 4.

8.1 Environmental Errors

8.1.1 Atmospheric Propagation Model

We use the Marini and Murray Model for the atmospheric propagation correction to satellite ranges. We estimate the refraction error to be 0.5 cm (see above). With our ground based meteorological instruments we read barometric pressure with a mercury column to an estimated accuracy of ± 1 mbar based on a comparison among instruments. Temperature is measured to ± 1 degree Celsius with a mercury thermometer and relative humidity to $\pm 10\%$ with a sling psychrometer.

8.1.2 Spacecraft Center-of-Mass

SAO uses the Arnold Models for its spacecraft center-of-mass corrections. The correction used for Lageos on the Arequipa data is 24.3 cm. This is appropriate for a 3 nsec pulse and a centroid (center of gravity) detector. The estimated error is 2 mm (r.m.s.).

8.1.3 Ground Survey of Laser Position

Since the Arequipa laser is a fixed system, no error for ground survey of laser position is included.

8.1.4 Data Aggregation

We do no aggregation on the quick-look or final data.

8.1.5 Summary of Environmental Errors

The aggregated environmental contribution is estimated at 1.6 cm over the short term (a day or less) and 1.2 cm for longer periods.

RANGING ERRORS (CM)

	PASS	DAY	MONTH	INDEF.
MODELLING ENVIRONMENTAL ERRORS				
ATMOSPHERIC PROPAGATION (MODEL)				
ATMOSPHERIC PROPAGATION (METEOROLOGICAL MEASUREMENTS				
SPACECRAFT CENTER OF MASS				
GROUND SURVEY OF LASER POSITION				
DATA AGGREGATION				
R.S.S.				
RANGING MACHINE ERRORS				
SPATIAL VARIATION				
TEMPORAL VARIATION				
SIGNAL STRENGTH VARIATION				
CALIBRATION PATH (SURVEY)				
CALIBRATION PATH (METEOROLOGICAL CONDITIONS)				
MOUNT ECCENTRICITIES				
R.S.S.				

RANGING ERRORS (CM)
TIMING ERRORS (MICROSEC)

PORTABLE CLOCK SET				
BROADCAST MONITORING				
R.S.S.				

FIGURE 3
ESTIMATED RANGING ERRORS FOR SATELLITE LASER RANGING SYSTEM

RANGING ERRORS (CM)

	PASS	DAY	MONTH	INDEF.
MODELLING (ENVIRONMENTAL ERRORS)				
ATMOSPHERIC PROPAGATION (MODEL)	0.5	0.5	0.5	0.5
ATMOSPHERIC PROPAGATION (METEOROLOGICAL MEASUREMENTS	0.5	0.5	0.5	0.5
SPACECRAFT CENTER OF MASS	0.2	0.2	0.2	0.2
GROUND SURVEY OF LASER POSITION	-	-	-	-
DATA AGGREGATION	-	-	-	-
R.S.S.	0.7	0.7	0.7	0.7

RANGING MACHINE ERRORS

SPATIAL VARIATION	3.0	2.0	1.0	1.0
TEMPORAL VARIATION	2.0	1.0	1.0	1.0
SIGNAL STRENGTH VARIATION	3.0	3.0	3.0	3.0
CALIBRATION PATH (SURVEY)	1.0	1.0	1.0	1.0
CALIBRATION PATH (METEOROLOGICAL CONDITIONS)	0.4	0.4	0.4	0.4
MOUNT ECCENTRICITIES	0.1	0.1	0.1	0.1
R.S.S.	4.8	4.0	3.5	3.5

RANGING ERRORS (CM)
TIMING ERRORS (MICROSEC)

PORTABLE CLOCK SET	1.0	1.0	1.0	1.0
BROADCAST MONITORING	4.0	4.0	1.0	1.0
R.S.S.	4.2	4.2	1.4	1.4

FIGURE 4
ESTIMATED MEASUREMENT ERRORS FOR THE AREQUIPA SATELLITE LASER RANGING SYSTEM

8.2 Ranging Machine Errors

8.2.1 Spatial Variations

Spatial variations are measured in Arequipa by ranging on a ground-based corner cube at a distance of about 1 km. Range measurements are made in sets of 50-100 laser shots at return signal strengths in the range of 5-20 photoelectrons. Measurement sets are taken over a matrix with 20 arcsec spacings over the 2 arcmin wide laser output beam. The sets are taken in random order around the matrix with scheduled returns to the central "reference" position to check for temporal drift. The mean values of the sets are used to map the wavefront contours and to calculate the r.m.s. wavefront variation.

The r.m.s. spatial variation in Arequipa is typically in the range of 2-3 cm. Experience has shown that the wavefront pattern changes appreciably over a period of a day. We use a value of 2 cm for the daily average to accommodate the fact that the acquired Lageos pass in a given day may come within a few hours of each other. Examination of wavefront data over extended periods of time indicates that over the long term, the effect averages to zero for this ranging system. However, since the resolution of the Arequipa system is about 1 cm, we use this value (1 cm) for our long term estimate of error.

8.2.2 Temporal Variations

An upper bound for the temporal variations have been estimated from the historical pre- and post-calibrations (which are taken on the billboard target before and after each pass). In pre- and post-calibrations at least 50 laser measurements are taken to the ground target in the return signal strength range of 5-25 photoelectrons. Mean values for each are calculated; the pre-post difference for each pass is used to bound the system drift over the pass time duration. These differences, which have typical r.m.s. values of 2 cm, show no systematic trend over a period of several months, indicating that temporal variations (if they are at all significant) average out very quickly. Once again, due to the limitation in system resolution, we estimate the long term error component for temporal variations at 1.0 cm.

8.2.3 Signal Strength Variations

In Arequipa, the system delay variation with signal strength is measured routinely with extended calibrations on the billboard target. Measurements are taken over the range of 1 to 100 photoelectrons by adjusting neutral density filters in the photoreceiver. Sufficient data are taken to ensure that at least a hundred returns are received at the single photoelectron level and at least 25-50 returns are received in each half decade interval over the return energy range (the actual set size is made sufficiently large to reduce the statistical errors (1 sigma) to about 1 cm). The data are aggregated in corresponding signal strengths sets to examine system performance. Typical variations over the full dynamic range are 3 cm or less (half peak-to-peak). As a rule, system calibration value increases with signal strength, but point by point fluctuations make it difficult to model and correct.

8.2.4 Calibration Target Distance

The target distance in Arequipa is about 1 km along a nearly horizontal path. The target distance is measured with a laser geodimeter (Hewlett Packard Model 3808A) which has an accuracy of about 1 cm. The distance is measured repeatedly over the period of a day to average out statistical errors. Propagation corrections are made using the Barrel and Sears formula. At the moment we measure temperature and pressure only at the ranging site. We anticipate fluctuations of a few degrees (Celsius) along the path giving an uncertainty of about 1% or 3 mm. It is not clear how much of this is short term and how much is seasonal. At the moment we assume that this is a long period effect. We use a Mercury column to measure pressure and a standard mercury thermometer to measure temperature. In addition, a reading error of 1 mb and 1.0^{o}C which could add another mm in long term bias error.

8.2.5 Mount Eccentricities

The eccentricity of the mount in Arequipa has not been measured but on the basis of the compact design of the Azimuth-Altitude Mount and the separated laser and photoreceiver we estimate the eccentricity at 1 mm or less.

8.2.6 Summary of the Ranging Machine Errors

The aggregated ranging machine errors amount to about 5 cm on a single pass basis, and about 3.5 cm over the long term.

8.3 Timing Errors

The timing system at the Arequipa station uses redundant clocks (with Cesium and Rubidium Standards), VLF, Omega and portable clock checks. The accuracy of portable clock sets as determined from closure is typically 1 microsecond (r.m.s.) or better. The portable clock readings indicate that station time continuity over the short term (single pass) as maintained by VLF phase reading to be better than $\pm$4.0 microseconds. Based on our experience and that of the U.S. Coast Guard in monitoring VLF, it appears that data smoothing reduces this error considerably over a few days.

The long term bias is assumed to be 1 microsecond which is typical of U.S. Coast Guard measurements.

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Contributors and Reviewers

Peter Bender/UColorado
John Bosworth/GSFC
Robert Coates/GSFC
Steve Cohen/GSFC
Dave Edge/Bendix
Charles Finley/NASA
Tom Fischetti/NASA
Ben Greene/NATMAP Australia
Wayne Hughes/GSFC
Tom Johnson/GSFC
Henry Linder/GSFC/DIS
Lou Macknik/UHawaii Hollas
James Maddox/SAO
Peter Morgan/NATMAP Australia
Hays Penfield/SAO
Randy Ricklefs/UTex/TLRS-1 MLRS
Robert Schutz/UTexas
David Smith/GSFC
Chris Stephanides/GSFC
Byron Tapley/UTexas
David Townley/NASA
John Thorp/SAO
Peter Wilson/IFAG Germany