GRGS-CERGA

SIXTH INTERNATIONAL WORKSHOP

ON LASER RANGING INSTRUMENTATION

ANTIBES JUAN-LES-PINS

6^{e} COLLOQUE INTERNATIONAL
SUR L'INSTRUMENTATION
DE LA TELEMETRIE LASER

EDITED BY / EDITE PAR :

- JEAN GAIGNEBET
- FRANCOISE BAUMONT

WE WISH HEREBY TO EXPRESS OUR THANKS TO /
NOUS TENONS A REMERCIER ICI :

- MINISTERE DES AFFAIRES ETRANGERES
- ASSOCIATION INTERNATIONALE DE GEODESIE
- UNION GEODESIQUE ET GEOPHYSIQUE INTERNATIONALE
- INSTITUT NATIONAL DES SCIENCES DE L'UNIVERS
- CENTRE NATIONAL D'ETUDES SPATIALES
- AEROSPATIALE
- BRASSARD MICHELET INDUSTRIES
- QUANTEL
- SOCIETE D'ETUDES ET DE CONSTRUCTION D'INSTRUMENTS ASTRONOMIQUES

An international technical meeting is one of the effective ways to propel the World's science forward.I believe that this exchange and discussion not only be beneficial to the academic researches carried out by every country's laser engineers, but also can promote the existing friendship between people, and further the mutual understanding and cooperation among the scintists of all countries.

Friends and colleagues from distant part of the World ! It is Apollo's rover that has brought you here from all different directions, from the States, from China, from Eastern Countries, from all Europe. The Rendez-Vous is not Olympia, but a city where we can have dialogue with Apollo for about 300 days in the year. A marvellous city, where flowers blossom in all four seasons. Every cloud has a silvery nimbused : take this one and don't forget to go back home with the last jasmine or a lot of carnations.

At last, I am impressed by the High quality of the program booklet : this guarantee that we may look forward to a highly inspiring and successful meeting.

Thank you for all that you have done so far !

I wish you all success in this workshop, and a pleasant stay on the French Riviera.

PREFACE

Le Sixième Colloque International sur l'Instrumentation en Télémétrie s'est déroulé du 22 au 26 Septembre 1986 à Antibes Juan-Les-Pins (France).

Comme lors des précédents colloques, un nombre important de présentations ont eu lieu. Les progrès accomplis depuis la dernière réunion (Herstmonceux) sont spectaculaires et extrêmement prometteurs. L'exactitude des stations a continué à s'améliorer grâce aux avancées technologiques et à une meilleure maîtrise des problèmes liés à la calibration. La mobilité et la fiabilité opérationelle de quelques stations ouvrent la voie à des systèmes complètements automatisés. De nouveaux concepts (2 couleurs, haute cadence de répétition, logiciels de pretraitement, photodiodes en régime Geiger,...) ouvrent le champ à un nouveau progrès des performances (stations millimétriques) et à la possibilité de concevoir des équipements embarqués.

Ce tableau impressionnant des progrès réalisés et à venir, ne doit pas masquer quelques problèmes qui me semblent apparaître :

Le développement de systèmes de positionnement "Tout Temps" comme le système GPS Navstar (D.O.D), du V.L.B.I va conccurencer sérieusement la télémétrie laser dans ses applications traditionelles (Géodésie, Geodynamique) et l'application de notre technique à des domaines et objectifs moins aditionnels (relativité, altimétrie spatiale laser sur les continents et les glaces, synchronisation horaire de très haute exactitude...) me semble nécessaire pour continuer à exister à moyen ou long terme. La part de plus en plus grande prise par les sessions non techniques (organisation de campagnes) au cours des derniers colloques me semble également dangereuse. Les discussions et les contacts personnels entre techniciens deviennent difficiles, donc rares, tant le programme est chargé. Par ailleurs les organisateurs de campagnes ont déjà à leur disposition un nombre annuel important de réunions spécialisées. Je pense que le temps dédié à l'instrumentation laser tous les deux ou trois ans doit être sauvegardé. Enfin la représentation de plus en plus fréquente de groupes par un seul exposé de "manager" exclu les rapports techniques détaillés qui me semblent le sang de ce type de colloque.

Ces remarques pour personnelles quelles soient et n'entraînant que ma responsabilité me semblent néanmoins refléter la sensibilité d'un nombre non négligeable de participants. Elles peuvent servir à ouvrir une réflexion générale, je serais heureux de connaître la réaction de notre Communauté.

Avant de terminer en souhaitant bonne chance au Nouveau Comité Scientifique d'Organisation, je tiens à remercier tous ceux qui ont aidé à faire de ce colloque une réussite. C'est à dire :

- Les participants sans lesquels nous n'existerions pas,
- les responsables de session dont la tâche ne s'arrête pas à la fin du colloque, puisqu'ils ont collecté les exposés pour les minutes,
- le Comité Local d'Organisation et en particulier Madame F. Baumont sans qui le colloque eut été assez "pagaille",
- le Comité Scientifique d'organisation :

  C.O. Alley, son dynamisme inlassable a apporté beaucoup aux derniers colloques et à la télémétrie laser en général,

  B.A. Greene dont les idées nouvelles et non conformistes ont dynamisées la discipline,

  K. Hamal, pilier infatiguable de la physique du laser et hôte à plusieurs reprises de comités d'organisation
- enfin, Madame M. Perrin pour la préparation du tirage des minutes.

Merci à tous et que vive la télémétrie laser.

J. GAIGNEBET
Membre du Comité Scientifique et Responsable du Comité Local d'Organisation du VI I.W.L.R.I.

PREFACE

The Sixth International Workshop On Laser Ranging Instrumentation was held in Antibes Juan-Les-Pins (France) 22-26 September, 1986. A large number of presentations was given as in the previous workshops. The improvements accomplished since the last meeting (Herstmonceux) are spectacular and very promising. The accuracy of the station is still increasing thanks to the technological progress and to a better knowledge of the problems related to calibration.Completely automated systems are foreseen driven by the need for the mobility and operational efficiency of some stations.

We have to be aware of some approaching problems despite the impressive progress of our technique. Development of all weather and accurate positioning networks such as GPS/NAVSTAR (D.O.D.) or the VLBI will present competition to some traditional of laser ranging (Goedesy and Geodynamics). I feel that our technique has to aim towards less conservative goals (relativity, spaceborne altimetry to the ground and ice caps, time synchronization,..) to be able to grow in the medium and long term. I feel a dangerous trend in the increase of the time devoted to the technical sessions. The difficulties in holding adequate discussions and in managing personnal contact among those participants interested in improving the experimental techniques of laser ranging have increased as the schedule has become really crowded. Campaign organizers have at their disposal a number of specialized meetings every years for that purpose. I do not think they need to take a substantial part of the time intended for laser ranging instrumentation during the only meeting every two or three years devoted to this topic. Last of all we see more and more managers representing their group with a single presentation. This tendency eliminates detailled technical reports wich are the life blood of such workshop. These personnal remarks are on my own responsability but I feel that they reflect the sensitivity of a non negligible part of the attendees. They may be a starting point for a general discussion and I would be happy to know the reaction of the community.

Prior to ending with my best wishes to the New Scientific Organizing Committee, I want to thank everyone who helped to make a success of this Workshop, that is to say :

- Participants,
- session chairmen and cochairmen for their task during and after the workshop,
- local organizing committee and particularly Mrs. F. Baumont whose work prevented the transformation of the workshop into a happy jumble,
- scientific organizing committee :
- C.O. Alley whose permanent dynamism was a great support for the organization of the session and laser ranging in general,
- B.A. Greene whose bright new ideas and 'non conformism' have boosted the discipline,
- K. Hamal tireless pillar of the laser physics and host of many organizing committees
- at last but not the least, Mrs. M. Perrin for the preparation of the proceedings.

Thanks to everyone and hurrah for laser ranging.

J. GAIGNEBET
Member of the Scientific Organizing Committee
and Chairman of the Local Organizing Committee
of the 6th I.W.L.R.I.

The 6th International Workshop Laser Ranging Instrumentation meeting at Antibes Juan-Les-Pins, France,

RECONGNISING the unique value and complementary nature of joint lunar/artificial satellite tracking stations for the determination of earth orientation parameters and recognising that new facilities of this kind are under development, strongly recommends that due attention be given to ensuring the continuation of these measurements and their exploitation to the fullest extent.

The 6th International Workshop on Laser Ranging Instrumentation meeting at Antibes Juan-Les-Pins, France,

NOTING that since October 1983 the Royal Greenwich Observatory's laser ranging group has been one of the major contributors to international collaborative programmes related to the dynamics of earth satellites and the surface and body of the earth and

RECOGNISING that the quality and quantity of these observations are comparable with the best achieved elsewhere,

VIEWS with concern the uncertain future of the group and

REQUESTS that all feasible steps be taken to ensure its continued activity in a suitable environment.

The 6th International Workshop on Laser Ranging Instrumentation meeting at Antibes Juan-Les-Pins, France,

RECOGNISING that most institutions creating normal points are conforming now to the Herstmonceux recommendations and recognising the normal point comparison experiment initiated by NASA,

STRONGLY recommends that all institutes performing normal point calculations should create normal points for the October 1983 Lageos test data set and send the results to NASA for detailed intercomparisons which may lead to further refinements and definitions.

The 6th International Workshop on Laser Ranging Instrumentation, meeting at Antibes Juan-Les-Pins, France,

RECOGNIZING the important scientific results being obtained with the LAGEOS spacecraft, and recognizing the remarkable improvements in ground-based laser ranging technology that have occured in the last decade since the launch of LAGEOS,

strongly endorses

(1) the plans to develop and launch a second LAGEOS (LAGEOS II) in support in geodetic, geodynamics, and technology objectives and urges its launch at the earliest possible opportunity.

In addition,

recognizing the unique value of precise laser ranging to satellites in increasing our knowledge and understanding of fundamental forces of nature , including the "gravito-magnetic force" predicted by Einstein's theory of gravity,

urges strongly

(2) that a third LAGEOS satellite (LAGEOS III) be constructed and launched into an appropriate orbit allowing the detection and measurement of the gravito-magnetic orbit precession produced by the rotating Earth, as well as increasing our ability to monitor Universal Time.

The 6th International Workshop on Laser Ranging Instrumentation meeting at Antibes Juan-Les-Pins, France,

RECOGNISING the significant contributions that Laser Ranging systems are making to geodesy, geophysics, geodynamics and other disciplines hereby GRATEFULLY ACKNOWLEDGES the dedicated efforts of the crews operating these systems for the benefit of the scientific community.

The VIth International Workshop on Laser Ranging Instrumentation

recognizing the many contributions of the Centre d'Etudes et Recherche en Geodynamique et Astronomie to the success of the Workshop through its sponsorship and local supporting organization,

and further recognizing the exceptionally effective and untiring efforts of the Chairman of the Local Organizing Commitee for the Workshop, Jean Gaignebet and its Scientific Secretary, Francoise Baumont,

Wishes to express its deep appreciation to the members of CERGA and especially to Dr. Gaignebet and Dr. Baumont for selecting such as attractive location and for providing excellent support.

PAPERS PRESENTED BUT NOT PUBLISHED

SCIENTIFIC RESULTS AND FUTURE GOALS OF LASER RANGING INVITED PAPERS

- X.X. Newhall et al.
  Lunar Laser Ranging Results Review
- D.E. Smith
  Tidal Dissipation With Lageos
- C. Yoder
  Implication Of Tidal Dissipation On G'
- B.D. Tapley et al.
  Lageos Results Review

LASERS

- R. Dewhurst et al.
  A Passively Mode Locked Nd:YAG Laser Using A Half Symetry Unstable Resonator With Continuous Output Coupling
- B.A. Greene
  Laser Design For Fifth Generation SLR System

OPTICS, TRACKING AND MOUNTS

- K. Hamal
  Transmit Receive Switch

HIGH AVERAGE POWER LASERS AND NEW LASER SPACE BORNE SYSTEMS AND NEW SATELLITES

- D.M. Smith
  Topex, Poseidon And ERS-1 Satellite For Laser Tracking
- I. Ciufolini et al.
  The Status Of Lageos 2 ; Informal Discussion Prospects For A Lageos 3.

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NEW RELATIVISTIC MEASUREMENTS WITH LASER RANGED SATELLITES

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ABSTRACT

The accuracy of laser ranging associated with the use of a LAGEOS like satellite (inclination supplementary to the existing LAGEOS) allows the measurement of the gravitomagnetic field of the earth.

The proposal of a satellite for this determination is developped here.

NEW RELATIVISTIC MEASUREMENTS WITH LASER RANGED SATELLITES

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The importance of measuring the gravitomagnetic field is comparable to the importance of measuring gravitational waves.

In electrodynamics the wave equation describing electromagnetic waves in vacuum is, in the Lorentz gauge:

$$\Box A^{\alpha} = 0 \tag{1}$$

where $\Box = \eta^{\alpha\beta} \frac{\partial^2}{\partial x^{\alpha} \partial x^{\beta}}$ and A^{α} is the 4-vector potential.

Similarly in General Relativity [(1), (2), (3)] in the weak field limit, the wave equation describing gravitational waves in vacuum is:

$$\Box h_{\alpha\beta} = 0 \tag{2}$$

where $\Box = g^{\alpha\beta} \frac{\partial^2}{\partial x^{\alpha} \partial x^{\beta}}$ is the D'Alambertian operator in curved spacetime and in the weak field limit: $h_{\alpha\beta} \cong g_{\alpha\beta} - \eta_{\alpha\beta}$ ($g_{\alpha\beta}$ is the spacetime metric tensor and $\eta_{\alpha\beta}$ is the Minkowski metric tensor).

A similar analogy is valid for the gravitomagnetic field.

In electrodynamics the equation of motion of a particle with mass m and charge q subjected to an electric field $\vec{E}$ and a magnetic field $\vec{B}$ is the Lorentz equation:

$$m \frac{d^2 \vec{x}}{dt^2} = q(\vec{E} + \vec{v} \times \vec{B}) \tag{3}$$

The torque acting on a test magnet with magnetic dipole moment $\vec{\mu}$ is $\vec{\tau} = \vec{\mu} \times \vec{B}$ and the force on the magnetic dipole is $\vec{F} = (\vec{\mu} \cdot \vec{\nabla})\vec{B}$ where $\vec{B} = \vec{\nabla} \times \vec{A}$ and for a source with magnetic moment $\vec{m}$: $\vec{B} = \frac{3\vec{n}(\vec{n} \cdot \vec{m}) - \vec{m}}{|\vec{x}|^3}$ and $\vec{A} = \frac{\vec{m} \times \vec{x}}{|\vec{x}|^3}$.

Similarly in General Relativity [(4), (5)] the equation of motion of a test particle in the field of a central body with mass M and angular momentum $\vec{J}$, can be written in the weak field and slow motion

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limit:

$$m\frac{d^2\vec{x}}{dt^2} = m(\vec{g} + \frac{d\vec{x}}{dt}\times\vec{H}) \tag{4}$$

where $\vec{g} \cong -\frac{M}{r^2}\hat{r}$ is the standard, radial Newtonian acceleration, $\vec{H}$ is the gravitomagnetic field given in this limit by $\vec{H} \cong \vec{\nabla}\times\vec{\beta} \cong 2\left[\frac{\vec{J}-3(\vec{J}\cdot\hat{r})\hat{r}}{r^3}\right]$ and $\vec{\beta}$ is the gravitomagnetic or Lense-Thirring potential $\vec{\beta} = (\beta^r, \beta^\theta, \beta^\phi) = \left[0, 0, -\frac{2J}{r^3}\right]$, in geometrized units: $G \equiv c \equiv 1$. Furthermore in General Relativity [4], [5] the torque acting on a gyroscope with spin angular momentum $\vec{s}$ is in the weak field and slow motion approximation:

$$\vec{\tau} = \frac{d\vec{s}}{dt} = \frac{1}{2}\vec{s}\times\vec{H} \tag{5}$$

and therefore the gyroscope precesses with respect to an asymptotic inertial frame, defined by the distant stars, with angular velocity:

$$\vec{\Omega} = -\frac{1}{2}\vec{H} = \frac{-\vec{J}-3(\vec{J}\cdot\hat{r})\hat{r}}{r^3} \tag{6}$$

This phenomenon is the "dragging of gyroscopes" or "dragging of inertial frames" of which the gyroscopes define the axes. The force exerted on the gyroscope by the gravitomagnetic field $\vec{H}$ is

$$\vec{F} = (\frac{1}{2}\vec{s}\cdot\vec{\nabla})\vec{H} \tag{7}$$

Finally, due to the second term in the force (4), the orbital plane (and the orbital angular momentum) of a test particle - which can be thought as an enormous gyroscope - is dragged in the sense of rotation of the central body. This dragging of the whole orbital plane is described by the formula for the rate of change of the longitude of the node discovered by Lense and Thirring in 1918 [6], [7]:

$$\Omega^{\text{Lense-Thirring}} = \frac{2J}{a^3(1-e^2)^{3/2}} \tag{8}$$

where a is the satellite semimajor axis, e the eccentricity and J the angular momentum of the central body.

Many experiments have been proposed to measure the gravitomagnetic field: Everitt - 1974 and Lipa, Fairbank and Everitt - 1974; Van Patten and Everitt - 1976; Braginski, Caves and Thorne - 1977; Scully - 1979; Braginski and Polnarev - 1980; Braginski, Polnarev and Thorne - 1984. In particular the experiment of Lipa, Fairbank and Everitt [8] will try to measure the gravitomagnetic precession (6) of a gyroscope orbiting the Earth.

We propose here a different experiment based on the Lense-Thirring effect (8).
The idea [9], [10], [11], [12] is to measure the gravitomagnetic nodal precession (8) due to the angular momentum of the Earth on laser ranged satellites like LAGEOS [13], [14]. The Lense-Thirring precession (8) is for LAGEOS $\Omega^{\text{Lense-Thirring}} \cong 31$ milliarcsec/year. The total nodal precession is [14] for LAGEOS $\Omega^{total} \cong 126°$ and can be measured [15] with laser ranging with an accuracy of 1 or 2 milliarcsec/year. Therefore, if all the classical perturbations on LAGEOS were known, it would be possible to measure Ω^{LT} with a few percent accuracy. The deviations of the Earth gravity field from

spherical symmetry - quadrupole and higher mass moments of the Earth - are responsible for the most part of the total nodal precession [16]. Even though the Earth's multiple mass moments are very well known [17], [18], they are unfortunately not known at the level of accuracy to measure the Lense-Thirring precession. The uncertainty in the even zonal harmonic coefficients J_{2n} relative to J_2 is [17], [18] of the order of $\frac{\delta J_{2n}}{J_2} \cong 10^{-6}$, which uncertainty corresponds for J_2 to an uncertainty in the nodal precession of ± 450 milliarcsec/year, much larger than the Lense-Thirring precession (8).

The idea [9], [10], [11], [12] is to launch a tandem laser ranged satellite "LAGEOS-X" with the same orbital parameters of LAGEOS apart from a supplementary inclination i.e. $I_{\text{LAGEOS-X}} \cong 70°$ ($I_{\text{LAGEOS}} \cong 110°$). In such a way the classical precession will be equal and opposite for the two satellites; in fact this classical precession is proportional to the cosine of the inclination I and is a function of even trigonometric functions of I [16]. On the contrary, the Lense-Thirring precession will be the same in both magnitude and sign, thus allowing [9], [10], [11], [12] the extraction of the general relativistic drag.

In other words, the two tandem satellites define a "gyroscope".

The bisector of the angle between the nodal lines of the two satellites is not affected by the Earth's multipole mass moments but only by the Lense-Thirring drag and by other small calculable classical precessions [12]. Since the precession of the nodal lines of the two satellites, due to the Earth's multiple moments, is equal and opposite, the precession of the bisector between the two nodal lines is zero, apart for other small classical precessions [12].

We studied [12] several non-gravitational nodal perturbations.

The result [12] is that the error in the calculated value of the secular nodal precession or the value of the secular nodal precession itself is for each perturbation less than 1% of the Lense-Thirring drag, we list some of the dominant perturbations.

Direct solar radiation pressure:

The rate of change of the nodal longitude Ω, due to an external force $\vec{f}$, can be written [16]:

$$\frac{d\Omega}{dt} = \frac{1}{na\sin I}(1-e^2)^{-1/2} f W \frac{r}{a}\sin(v+\omega) \tag{9}$$

where n is the mean motion, a the semimajor axis, I the inclination, e the eccentricity, r the radial coordinate, ω the argument of the pericenter, v the mean anomaly, f is the magnitude of the external force per unit satellite mass and W is the direction cosine of the force $\vec{f}$ along the normal to the orbital plane, which can be written [19], [20], [21]:

$$W = \sin I \cos^2\frac{\varepsilon}{2}\sin(\lambda_\odot - \Omega) - \sin I \sin^2\frac{\varepsilon}{2}\sin(\lambda_\odot + \Omega) - \cos I \sin\varepsilon \sin\lambda_\odot \tag{10}$$

where ε is the obliquity of the ecliptic and $\lambda_\odot$ is the ecliptic longitude of the Sun.

The acceleration $f_\odot$ due to direct solar radiation pressure on a spherical satellite like LAGEOS, can be written [20], [21]:

$$f_\odot = s\frac{A}{m}P\left[\frac{a_\odot}{r_\odot}\right]^2 \tag{11}$$

where s is a number between 0 and 2, depending on the reflection properties of the satellite surface, $\frac{A}{m}$ is the satellite cross-sectional area to mass ratio and $P \equiv \frac{\phi}{c} = \frac{\text{solar constant}}{\text{speed of light}} \cong 4.65\times 10^{-5}\ \text{dyn}\times cm^{-2}$

is the solar radiation pressure at the Earth when the geocentric distance $r_\odot$ is equal to its mean distance $a_\odot$.

Integrating equations (9) and (10) with the proper initial conditions [15], we found [12] that over one orbital period $P = 3.758h$:

$$\dot{\Omega}^{\text{Direct radiation pressure}}\Big|_P \cong 10^{-1}\dot{\Omega}^{\text{Lense-Thirring}}\Big|_P \tag{12}$$

Since [15] the uncertainty in the value of $f_\odot$ is for LAGEOS less than 1%, the error in the calculated nodal precession due to direct solar radiation pressure is over one orbital period P:

$$\text{Error}\left[\dot{\Omega}^{\text{Diret radiation pressure}}\Big|_P\right] \lesssim 10^{-3}\dot{\Omega}^{\text{Lense-Thirring}}\Big|_P \tag{13}$$

Earth's albedo:

On the basis of works of Lautmann [22], [23] and Bender [24], [25] and due to the periodicity in the sign of W, we found that the secular nodal precession due to the Earth's albedo is over one year:

$$\dot{\Omega}^{\text{Albedo}}\Big|_{1y} \lesssim 10^{-1}\dot{\Omega}^{\text{Lense-Thirring}}\Big|_{1y} \tag{14}$$

Assuming a 10% error in the model [22], [23] we have:

$$\text{Error}\left[\dot{\Omega}^{\text{Albedo}}\Big|_{1y}\right] \lesssim 10^{-2}\dot{\Omega}^{\text{Lense-Thirring}}\Big|_{1y} \tag{15}$$

Satellite eclipses by the Earth:

Because of the change of sign of W, when the Sun is in opposite regions with respect to the satellite orbital plane, we have that the secular nodal precession due to satellite's eclipses is small over one year [12]:

$$\dot{\Omega}^{\text{Eclipses}}\Big|_{1y} \lesssim 10^{-1}\dot{\Omega}^{\text{Lense-Thirring}}\Big|_{1y} \tag{16}$$

Assuming [15], [26] an uncertainty of 10^{-2} radians in the determination of the boundary of the shadow's region and an uncertainty [15] in $f_\odot$ of less than 1%, we have that the error in the calculated secular nodal precession due to satellite's eclipses by the Earth, is over one year:

$$\text{Error}\left[\dot{\Omega}^{Eclipses}\Big|_{1y}\right] \lesssim 10^{-3}\dot{\Omega}^{\text{Lense-Thirring}}\Big|_{1y} \tag{17}$$

Neutral and charged particles drag:

The neutral particle drag force on a satellite can be written [16], [27]:

$$F = \frac{C_D}{2} A \rho v^2 \tag{18}$$

where C_D = drag coefficient, ρ is the density of the atmosphere and v is the velocity of the satellite relative to the atmosphere.

Even with the extreme hypothesis that the atmosphere is corotating with the Earth at the LAGEOS altitude - 12,270 km - and with the hypothesis that the total drag on LAGEOS - neutral plus charged particles - is [26], [27] of the order of 2.3×10^{-10} cm/sec^2 ($\cong$ 6 times the neutral drag (18)), we find [12], [25] that the secular nodal precession due to atmospheric drag is:

$$\dot{\Omega}^{\text{Total drag}} \lesssim 10^{-2}\dot{\Omega}^{\text{Lense-Thirring}} \qquad (19)$$

Anisotropic thermal radiation:

Due to the finite heat conductivity of the body, there is an anisotropic distribution of temperature on the satellite [26] and therefore an anisotropic flux of radiation causing its acceleration. Over one period P, the corresponding secular nodal precession is [7]:

$$\dot{\Omega}^{\Delta T_*}|_P \lesssim 1.3\times10^{-3}\dot{\Omega}^{\text{Lense-Thirring}}|_P \qquad (20)$$

Satellite albedo:

Due to the anisotropic temperature distribution on LAGEOS, there is an anisotropic flux of reflected radiant energy from the satellite. The corresponding secular nodal precession is [12]:

$$\dot{\Omega}^{\text{Albedo}}|_P \lesssim 6.6\times10^{-4}\dot{\Omega}^{\text{Lense-Thirring}}|_P \qquad (21)$$

Poynting-Robertson effect:

Because of the relative velocity between LAGEOS and the Sun there are [28], [29] small corrections, of the orber of $\vec{v}$, to the formula (11); over one period P, we have [12]:

$$\dot{\Omega}^{\text{Poynting-Robertson}}|_P \lesssim 7.2\times10^{-7}\dot{\Omega}^{\text{Lense-Thirring}}|_P \qquad (22)$$

Infrared radiation:

The Earth's infrared radiation contribution to the nodal precession was studied by Sehnal-81 [30]. From his work we find that:

$$\dot{\Omega}^{\text{Infrared-radiation}}|_{\text{1 day}} \cong \dot{\Omega}^{\text{Lense-Thirring}}|_{\text{1 day}} \qquad (23)$$

and assuming an error of less than 10% in the model we have:

$$\text{Error}\left[\dot{\Omega}^{\text{Infrared radiation}}|_{\text{1 day}}\right] \lesssim 10^{-1}\dot{\Omega}^{\text{Lense-Thirring}}|_{\text{1 day}} \qquad (24)$$

However, the infrared radiation is mainly described by zonal terms of zero and second degree, that is the flux of infrared radiation has [30] a latitudinal dependence:

$$\sigma = A_o + A_2 P_2(\sin\phi) \qquad (25)$$

therefore, for the particular configuration LAGEOS plus LAGEOS X, we have:

$$\dot{\Omega}^{\text{Infrared radiation}}_{\text{LAGEOS}} \cong -\dot{\Omega}^{\text{Infrared radiation}}_{LAGEOS\ X} \qquad (26)$$

and consequently a null contribution from the Earth's infrared radiation to the uncertainty in the measurement of the Lense-Thirring drag.

Solar wind:

With a calculation similar to the atmospheric drag, for the neutral and charged solar wind [31] drag, we have [12]:

$$\dot{\Omega}^{\text{Solar wind}}|_P \lesssim 2.1\times10^{-3}\dot{\Omega}^{\text{Lense-Thirring}}|_P \qquad (27)$$

Drag from interplanetary dust:

With a similar calculation, we have [12]:

$$\dot{\Omega}^{\text{Cosmic dust}}\big|_P \lesssim 1.8\times10^{-3}\dot{\Omega}^{\text{Lense-Thirring}}\big|_P \tag{28}$$

Earth's magnetic field:

Assuming [27] a LAGEOS total surface charge $q_L \cong 3.3\times10^{-11}$ C, we have:

$$\dot{\Omega}^{B\oplus}\big|_P \lesssim 1.6\times10^{-4}\dot{\Omega}^{\text{Lense-Thirring}}\big|_P \tag{29}$$

In conclusion, formulae (13), (15), (17), (19), (20), (21), (22), (26), (27), (28), (29) show that each non-gravitational perturbation contributes to the secular rate of nodal precession of LAGEOS less than 1% of the Lense-Thirring drag, or can be calculated to an accuracy better than 1% of the Lense-Thirring precession.

Concerning the earth's tides, due to the periodicity of the Earth's tides, the measurement of the total nodal precession should be taken over a period of a few years, over such a period of time the corresponding uncertainty should be of a few milliarcsec [15], [32]. We must also consider the accuracy of our knowledge of the orbital parameters. For the special configuration LAGEOS plus LAGEOS X with supplementary inclinations, the error in the measurement of Ω^{LT} due to errors in the determination of the inclination, including polar motion determination errors, should be [15], [32] of a few milliarcsec when averaged over a period of a few years. Finally we observe that to have less than 3% individual contribution to the experimental uncertainty - with the hypothesis of improvements in the uncertainties $\frac{\delta J_{2n}}{J_2}$ to 3×10^{-7} - the differences between the orbital parameters of two satellites should be: $a_\varepsilon=(a_x-a_I)\lesssim \pm16$ km, $I_\varepsilon=(I_x-I_I)\lesssim \pm0.13°$, and $e_\varepsilon=(e_x-e_I)\lesssim \pm0.04$.

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COMPARISON OF LAGEOS SATELLITE LASER RANGING NORMAL POINTS

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ABSTRACT

The high repetition rates of currently deployed satellite laser ranging instruments allow the data to be compressed into normal points which will contain the essential characteristics of the original data. The generation of normal points is desirable in that it reduces both the computer storage space and time necessary for the analyses of these data to obtain the final end product of geophysical parameters. Several groups have been generating the LAser GEOdynamics Satellite (LAGEOS) normal points, and the resulting points can be evaluated by subjecting them, and the full rate data from which they come, to a common geodetic test. For this evaluation the raw full rate laser measurements were comprised of an edited set of LAGEOS observations taken by 20 laser stations, located worldwide, and collected in October 1983. The noise level of the 206,000 range measurement residuals varied between 1 and 20 cm, and when compressed yielded approximately 5800 two-minute normal points. The geodetic test consisted of a data reduction, using the GEODYN computer program, to obtain a simultaneous estimate of the orbit parameters and station positions. In particular, the laser site heights were compared among the four data sets used in each reduction. The over-all fit of the normal point residuals to the finally adjusted satellite and station parameters was 8 cm, with individual stations fitting between 5 and 20 cm. The expected standard error in the estimated station heights varied between 1 and 3 cm, and in every case the difference in the estimated heights from each normal point data set fell within this expected range. The conclusion is that starting with the same set of LAGEOS edited data, the algorithms used by the various groups are adequate in producing normal points which are in agreement with each other.

Normal Point Generation

At the Fifth International Workshop on Laser Ranging Instrumentation at Herstmonceux, England in September 1984 a procedure for generating normal points from full-rate laser ranges was adopted. The steps in the procedure are listed in Table 1, which also indicates at which stage a choice of technique is necessary for its implementation. Even when a particular step is so rigorously defined that no choice is required, alternative algorithms are possible which can improve data concentration or computational efficiency.

The choices of technique at each stage are listed in Table 2, which shows, for example, in step 6 the possibility of starting a bin interval at the first point in the pass instead of at an even UTC time. This alternative allows more information to be concentrated in the first normal point in the pass, but could reduce the total number of points in each pass by one. The median epoch time within the bin interval is simpler to compute than the arithmetic mean suggested in the Herstmonceux standard and is therefore presented as an alternative in step 7.

Normal Point Test Date

Each of the groups represented by the co-authors of this paper applied their normal point generation technique to a test data set comprising of edited LAGEOS observations collected by the global laser ranging network during the month of October 1983. The quantity of data from each station in the reference set is shown in the second column of Table 3. When the first point acquired within each second was chosen to reduce the normal point computation time, the number of ranges in the third column were obtained. The fourth column of Table 3 gives the number of normal points obtained with the regular UTC bin intervals recommended at Herstmonceux, and the reduced number of observations given by starting the bin interval at the first point in the pass is shown in the last column.

The data set generated by the Bendix group (BEN HER) adheres most closely to the Herstmonceux standard, although the University of Texas normal points were adopted as the base in the tests described here. They differ from the strict convention by the occasional estimate of a linear trend within each two-minute bin interval (choice 7(c) in Table 2). The normal point generation at GSFC (GOD MED) was based on one second samples (choice 1(c) in Table 2) and the choice 7(b) of the median epoch time tag. Another reasonable option (GOD FIRST) employed choice 6(b) for the bin interval. A final coarse data set was generated by simply taking the actual range at the times of the GOD FIRST normal points with no bin correction at all (2 MIN.DATA).

Normal Point Testing Procedure

Each normal point data set was subjected to a common geodetic test, which corresponds to the standard dynamic technique used by the Goddard Space Flight Center's Geodynamics Branch for laser data analysis. To assess the quality of the observations from each station, the 30-day data arc was reduced adjusting six orbital elements, an along-track orbit acceleration parameter, a solar radiation coefficient and all components of station position except for three. The latitude and longitude of the Greenbelt station and the latitude of the Hawaii laser were fixed at arbitrary values to stabilize the reference system for the adjustment of earth orientation parameters every 5 days. The characteristics of each of the test data sets were essentially the same and are given in Table 4.

To monitor the differences between the test data sets, all parameters of the orbit, force model and earth orientation were fixed at the same reasonable values and all components of each station were estimated. The differences in millimeters for the height components of each station are tabulated in Table 5. The formal standard deviation for data at the 10cm. noise level (20cm. for station 7181) is also given in Table 5. A key to the station numbers used throughout this analysis is presented in Table 6.

Test Results

Examination of Table 5 shows that necessary choices in normal point generation make insignificant differences to the results of a properly designed geodetic experiment. Some differences are detectible in the results from sparse, noisy data such as provided by stations 7181 and 7833. Possible choices of procedure such as sampling the original observations each second, taking the median epoch time and starting the bin interval at the first point in the pass, give acceptable differences in results, which are always within the expected uncertainties. Simply sampling the data every two minutes gave a data set which occasionally yielded results outside the allowable formal error. It should finally be pointed out that editing procedures, which are likely to cause the greatest differences in alternative normal point generation procedures, were not examined in the tests described here.

TABLE 1. NORMAL POINT GENERAL PROCEDURE

** 1. GENERATE RESIDUALS

** 2. COARSE EDIT

** 3. COMPUTE TREND FUNCTION

** 4. FINE EDIT

5. GO TO 3

* 6. CHOOSE BIN INTERVAL

* 7. COMPUTE MEAN RESIDUAL AND MEAN EPOCH WITHIN BIN

** 8. LOCATE CLOSEST RANGE TO MEAN EPOCH

9. APPLY RESIDUAL BIN CORRECTION

10. COMPUTE STATISTICS

11. REPORT STATISTICS

12. FOLLOW STANDARD FORMAT

13. QUICK LOOK CARRY OVER CHECK

14. REPORT SCREENED FULL-RATE DATA

**A CHOICE OF TECHNIQUE IS NECESSARY

* A CHOICE OF TECHNIQUE IS POSSIBLE

TABLE 2. CHOICES OF TECHNIQUE

**1. GENERATE RESIDUALS

a. FIT or FIX 'PREDICTION'
b. If FIX go to 2
c. Sample data
d. Fit ORBIT over arc
e. Fit FORCE MODEL over some interval
f. Fit EARTH ORIENTATION over some interval
g. Fit STATIONS over arc
h. Fit RB/TB over pass

**2. COARSE EDIT

a. Sample data
b. Choose RMS multiplier per arc
c. Choose RMS Multiplier per pass

**3. COMPUTE RESIDUAL TREND FUNCTION

a. Fit ORBIT over pass
b. Fit POLYNOMIAL over pass
c. Fit RB/TB over pass

**4. FINE EDIT

a. Choose RMS multiplier per pass

*6. CHOOSE BIN INTERVAL

a. Count from zero hours UTC
b. Count from first point in pass

*7. COMPUTE MEAN RESIDUAL AND MEAN EPOCH

a. Pick arithmetic MEAN TIME
b. Pick MID TIME (MEDIAN)
c. Fit residual TB/RB as well as MEAN

**8. LOCATE CLOSEST RANGE

a. Equidistant TIMES from MEAN (eg: 2 points)
b. Even number of points for MEDIAN

TABLE 3. 8310 TEST DATA QUANTITY

STATION	TOTAL OBS	SAMPLED ONE SEC.	NORMAL ZERO UTC	NORMAL FIRST POINT
7062	3,800	2,600	108	101
7086	1,800	1,400	66	61
7090	7,200	3,000	40	39
7105	91,500	36,800	507	492
7109	52,900	24,800	343	335
7110	71,600	32,000	521	508
7112	5,500	5,500	220	211
7121	4,500	4,500	175	176
7122	21,400	21,400	313	299
7181	100	100	43	40
7210	13,800	13,800	390	371
7220	51,900	19,800	504	489
7831	16	16	7	6
7833	229	229	79	77
7834	15,000	9,900	252	240
7838	5,100	4,100	204	186
7839	6,400	5,800	271	256
7840	1,600	1,500	241	231
7907	12,300	12,300	1122	1085
7939	6,400	6,400	437	430
TOTAL	373,300	206,100	5843	5633

TABLE 4. 8310 TEST DATA QUALITY

STATION	NORMAL POINTS	BEST NOISE NORMAL PT.	FINAL 30 DAY FIT	BEST NOISE SINGLE SHOT
7062	108	1 cm.	6 cm.	8 cm.
7086	66	2	7	7
7090	40	1	2	2
7105	507	1	7	2
7109	343	1	6	2
7110	521	1	7	4
7112	220	3	9	12
7121	175	2	9	10
7122	313	1	7	7
7181	43	16	22	16
7210	390	1	5	4
7220	504	1	8	7
7831	7	21	21	23
7833	79	10	14	15
7834	252	1	7	7
7838	204	2	11	8
7839	271	1	8	4
7840	241	1	7	4
7907	1122	3	10	13
7939	437	3	13	12
TOTAL			9 cm.	

TABLE 5. DIFFERENCES OF HEIGHT ESTIMATES FROM THOSE USING TEST DATA SET

STATION	FORMAL SIGMA	BEN HER	GOD MED	GOD FIRST	2 MIN. DATA	FORMAL SIGMA
7062	14 mm.	0 mm.	0 mm.	-3 mm.	- 6 mm.	14 mm.
7086	21	- 1	-1	-1	.23	21
7090	26	- 1	1	4	6	26
7105	7	- 1	0	-3	1	7
7109	10	0	2	1	- 1	10
7110	7	0	-1	0	1	7
7112	10	1	-1	8	- 8	10
7121	11	0	-1	-9	-11	11
7122	9	- 1	-1	-2	- 7	9
7181	42	-37	-2	21	54	42
7210	8	1	0	4	6	8
7220	7	0	2	7	10	7
7831	∞	-	-	-	-	∞
7833	30	5	7	4	27	30
7834	8	0	-1	1	-10	8
7838	11	- 2	-1	9	13	11
7839	9	0	0	3	1	9
7840	8	0	0	1	3	8
7907	5	1	0	-2	- 5	5

HER: STRICT HERSTMONCEUX
MED: MEDIAN EPOCH IN BIN
FIRST: BIN STARTS AT FIRST POINT

TABLE 6. KEY TO STATION NUMBERS

STATION	NO.	OCC.	NAME	LOCATION
7062	12	05	TLRS-2	OTAY MOUNTAIN
7086	24	03	MLRS	MACDONALD OBS.
7090	05	01	MOBLAS-5	YARRAGADEE
7105	07	02	MOBLAS-7	GREENBELT
7109	08	02	MOBLAS-8	QUINCY
7110	04	02	MOBLAS-4	MONUMENT PEAK
7112	02	01	MOBLAS-2	PLATTEVILLE
7121	01	01	MOBLAS-1	HUAHINE
7122	06	01	MOBLAS-6	MAZATLAN
7181	39	01	GRDLAS	POTSDAM
7210	23	01	HOLLAS	HALEAKALA
7220	11	01	TLRS-1	MONUMENT PEAK
7831	46	01	HELLAS	EGYPT
7833	32	01	KOOLAS	KOOTWIJK
7834	30	01	WETLAS	WETTZELL
7838	36	01	SHOLAS	SIMOSATO
7839	34	01	AUSLAS	GRAZ
7840	35	01	RGOLAS	RGO
7907	40	01	SAO201	AREQUIPA
7939	41	01	SAO102	MATERA

SUB-CM MULTIPHOTOELECTRON SATELLITE LASER RANGING

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ABSTRACT

A satellite laser ranging receiver configuration has been developed and tested to generate sub-cm precision in laser ranging to earth-bound satellites. Multiphotoelectron data taken within the dynamic range of the receiver has shown a standard deviation of 5 mm on ground targets and 7-9 mm on Lageos satellite data residuals. The systematic error from this receive package is measured to be less than 3 mm and is a significant improvement over the previous configuration.

1. INTRODUCTION

The projected requirements of the NASA Crustal dynamics program for the 1990s include sub-cm observational accuracy in laser ranging to Lageos. This would be particularly relevant since Lageos-II is projected for deployment in the not so distant future and accuracy enhancement would significantly impact the high volume data period. The precision of Mobile Laser ranging systems (MOBLAS) of the NASA Goddard Laser Tracking Network(GLTN) has been receiver limited above 1cm. To meet the program requirements of increased accuracy and precision, Bendix designed a receiver system based on a Microchannel plate photomultiplier tube (MCP-PMT) and a Tennelec constant fraction discriminator. Prototype testing of this advanced receiver package in the laboratory yielded RMS around 3.5mm over a dynamic range ~15, and during the field tests in November of 1984 the system produced calibration rms of 4.5mm and satellite data RMS of 9-10mm. Further improvements were made to the system which was installed for field operation in April of 1986. This paper describes briefly the device characteristics and performance features of the receiver package in the laboratory, and also sub-cm satellite data results from approximately 1 year operation from Moblas-7.

2.0 DEVICE CHARACTERISTICS

The desirable device features for precision opto-electronic detection of low photoelectron are high gain, low electron transit time (and jitter), and low pulse spread. Conventional photomultipliers have a fairly large electron transit time and have an impulse response time of several nanoseconds, and, hence, are not suitable for low photoelectron optical detection with sub-cm precision. The use of a proximity focussed microchannel plate in the pmt instead of conventional electron photomultipliers generates all of the above desirable features. Besides, it has low transit time, large dynamic range, and is well suited for precision laser ranging.

GLTN requirements for satellite ranging include daytime tracking. Although a 10 angstrom spectral filter is used for daytime tracking, the 30 inch telescope still produces a large mean background. The lifetime of the DC biased (normally-ON) device would be considerably reduced if used for daylight tracking due to increased charge accumulation at the anode from high continuous background noise. However, electronic gating of the device would alleviate this problem. We have performed qualitative and quantitative evaluation to examine spatial and temporal ON-voltage uniformity of the tube under gated conditions to determine problems in the mm domain.

Our receiver package consisted of ITT F4129f 3-stage MCP-PMT, Tennelec TC 454 constant fraction discriminator, a gating module with output of -600 volts, and a delay unit for delayed proportional gating of the discriminator. In laboratory measurements, the system produces 3-4mm rms data over a dynamic range ~15 and hence covers 5-60 photoelectrons. This design also accomplishes electron isolation of ~500. The gate is adjustable from 100ns-10us and the time walk is ~1mm within this interval. The discriminator response also is adjusted to have variation of no more than 2mm.

3.0 MOBLAS 7 DATA AND DATA PROCESSING

Targets currently used by MOBLAS 7 are the satellites LAGEOS, Starlett, and Ajisai, corner cubes mounted as ground targets at ranges from 75 to 3500 meters, and an internal calibration target.

Raw ranging data from the station contain the round trip time of flight of the laser pulse, the epoch time at which the pulse is transmitted, meteorological data consisting of pressure, temperature, and humidity, and system measurements of transmit and receive energy.

Data processing takes place on two levels, operational data processing and engineering analysis processing. For operational data processing, the rigidly controlled and heavily benchmarked DSG Laser Processor is used to prepare satellite data for release to the scientific community and to provide basic information on data quality. During operational data processing, time of flight measurements are converted to ranges and corrected for system delays, atmospheric refraction, and satellite center of mass. The epoch times of the range measurements are corrected to the times the laser pulses are at the satellite. For MOBLAS 7, a single system delay is applied throughout each pass. A 15 degree polynomial is fit to the ranges in each pass for an analysis of data quality.

Engineering analysis processing utilizes several specialized routines to provide information beyond the scope of the DSG Laser Processor on tracking system characteristics. For the data presented here, a 20 degree polynomial was fit to the time of flight measurements of each pass without corrections. The least squares fitting procedure includes editing of data beyond 3 sigma (standard deviation) from the polynomial and refitting of the remaining data. Editing and refitting cycles are repeated until no improvement in the standard deviation is obtained, or a maximum of 10 iterations is reached. The residuals are then used in several types of analysis plots including those displayed in the text.

4.0 RESULTS

The plots which follow demonstrate the sub-centimeter precision of the MOBLAS-7 ranging system. Fig.1 displays the RMS value of every LAGEOS pass(day and night) and associated combined pre-post pass calibration tracked by MOBLAS-7 during the month of November, 1986. All rms values were taken from the DSG Laser Processor. Of the 30 LAGEOS passes tracked, only two passes have RMS values greater than or equal to 1.00 centimeter(cm). The mean RMS of all 30 passes is 0.866cm, and the mean RMS of the combined calibrations is 0.595cm. A corner cube mounted on a water tower at a range of 3482.547 meters from MOBLAS-7 was the operational calibration target during this time frame. Targets located at distances of 200 meters show data RMS of ~5mm. The larger RMS in calibration on the operational target is a consequence of the target distance,the meteorological variations and the dynamics of the target.Results from four individual passes are illustrated in Fig.2-4 where satellite residuals are displayed using 20 degree polynomial least squares fitting and editing (as described above).These passes include:

DATE	TIME (GMT)	OBSERVATIONS	RMS (CM)
June 18, 1986	01:18	7537	0.79
Nov. 17, 1986	07:19	8546	0.80
Nov. 22, 1986	07:30	8995	0.88
Nov. 25, 1986	06:57	10233	0.89

Satellite range residuals vs. time(minutes) into the pass are shown in Fig.2(a),3 and 4. Two of these plots have polynomial fit errors as can be seen in Fig.2(a) and 3(b) while fig.3(a) and Fig.4 show no such problems.

Two types of Receive Energy Dependence plots illustrate the response of the system over a wide range of receive energies. In Fig.2(a), a scatter plot of satellite residuals vs. relative receive energy is provided. The anomalous accumulation of long residuals just above the value of 1200 is due to a hardware/software limitation(bit error) which reduces the values above 1999 by 1000 units. These very high energy returns represent data around 80-100 photoelectrons and are present only in high elevation passes under very good tracking conditions. Typically, this constitutes less than 5% of the data within a pass and have little impact on overall data quality. Fig.2(c),3(c-d)& 4 display the mean and rms of all residuals within 20 standard deviations of the polynomial with a bin resolution of 20 units of relative receive energy.The slight increase in the variation of the mean and larger RMS values at the higher receive energies are due, in part, to the small number of data occurring within each receive energy interval.

5.0 SUMMARY

We have shown for the first time the possibility of obtaining consistent ranging precision of sub-cm on Lageos .The proven dynamic range in this design is particularly relevant considering the transmitted power level and the telescope aperture. The Goddard Laser Tracking Network is presently undergoing the necessary hardware upgrade to meet sub-cm satellite laser ranging goal of NASA Crustal Dynamics program.

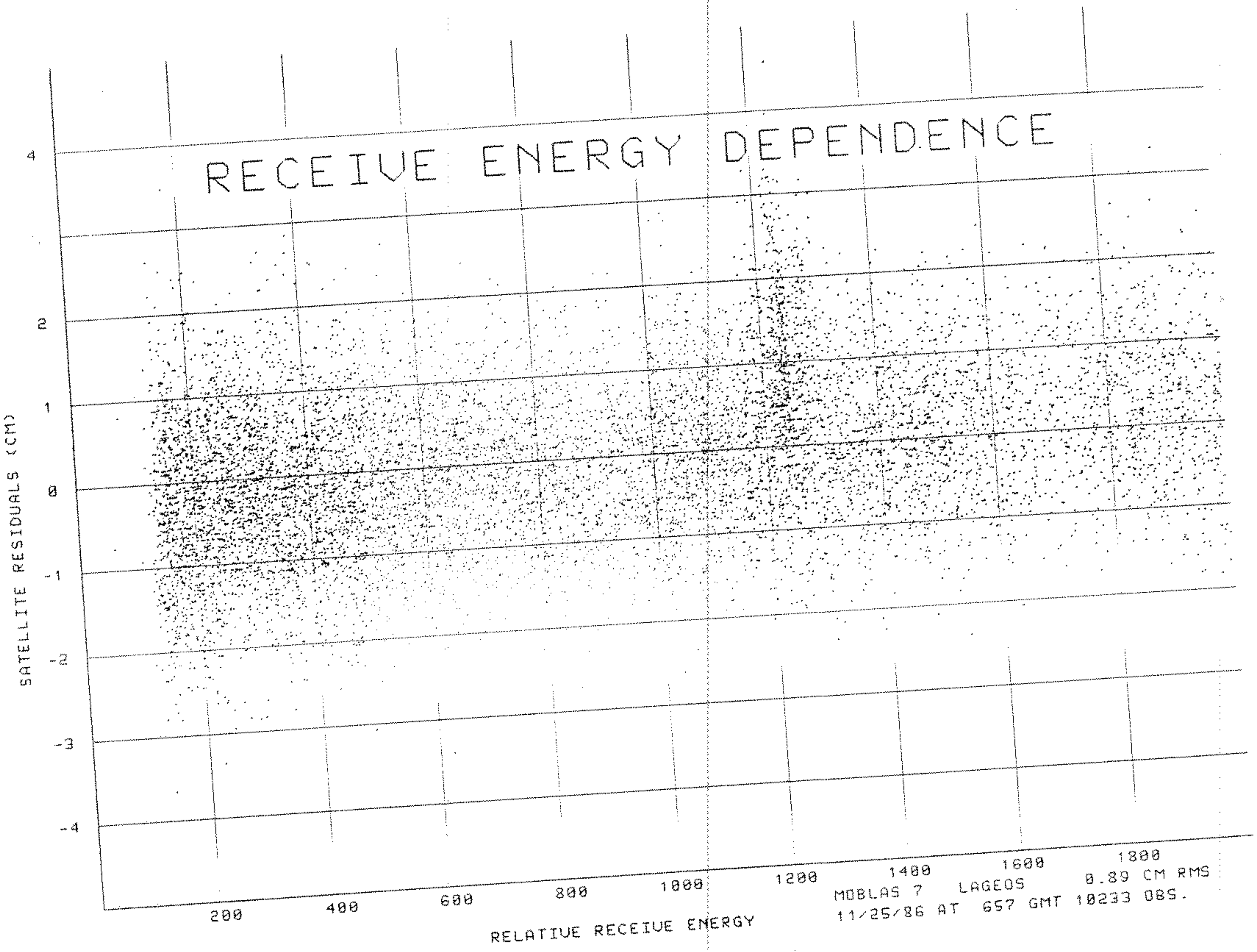

RECEIVE ENERGY DEPENDENCE
SATELLITE RESIDUALS (CM)
4
2
1
0
-1
-2
-3
-4
200
400
600
800
1000
1200
1400
1600
1800
RELATIVE RECEIVE ENERGY
MOBLAS 7 LAGEOS 0.89 CM RMS
11/25/86 AT 657 GMT 10233 OBS.

FIG. 2(B)

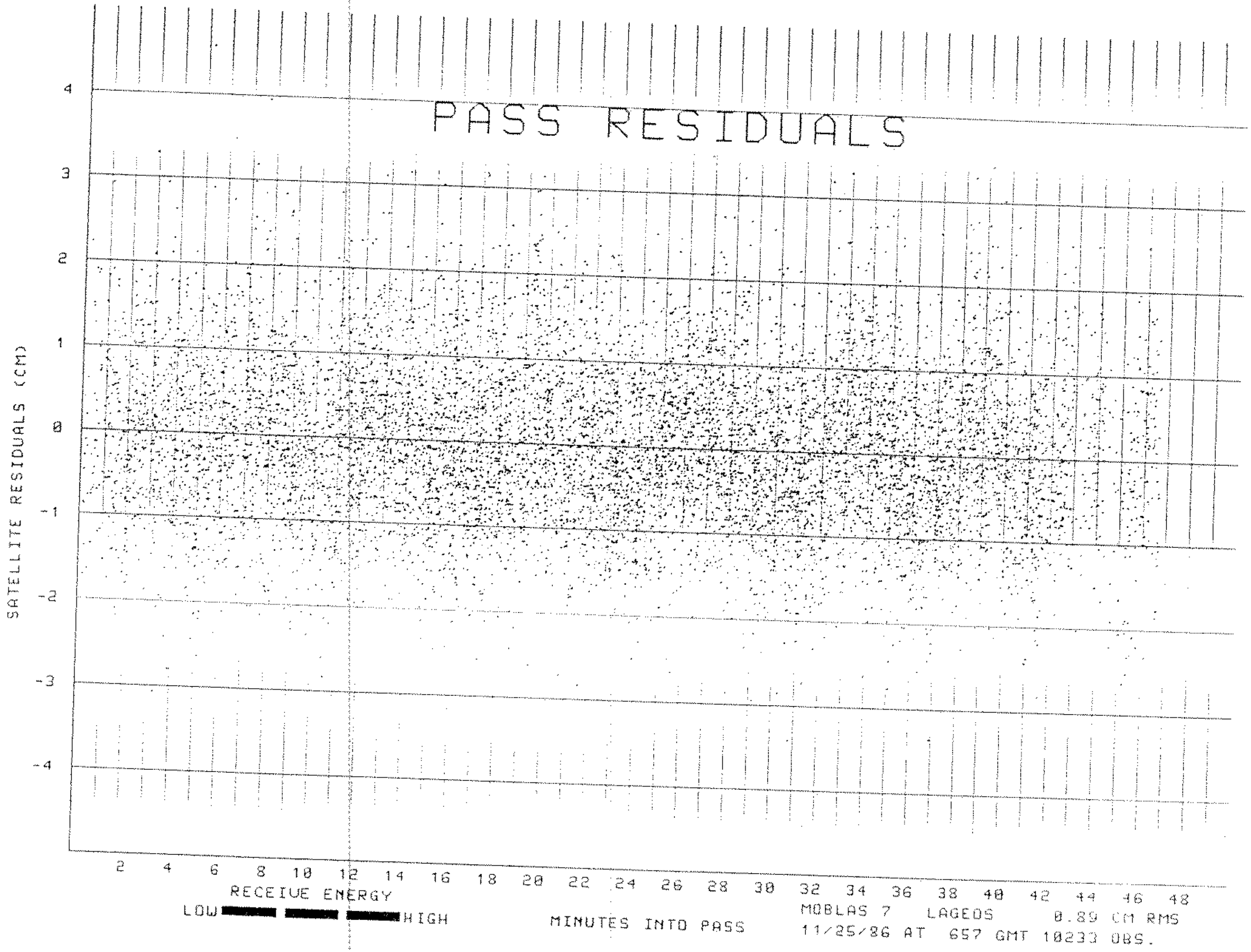

PASS RESIDUALS
SATELLITE RESIDUALS (CM)
4
3
2
1
0
-1
-2
-3
-4
2 4 6 8 10 12 14 16 18 20 22 24 26 28 30 32 34 36 38 40 42 44 46 48
RECEIVE ENERGY
LOW HIGH
MINUTES INTO PASS
MOBLAS 7 LAGEOS 0.89 CM RMS
11/25/86 AT 657 GMT 10233 OBS.

FIG. 2(A)

LAGEOS & CALIBRATION RMS

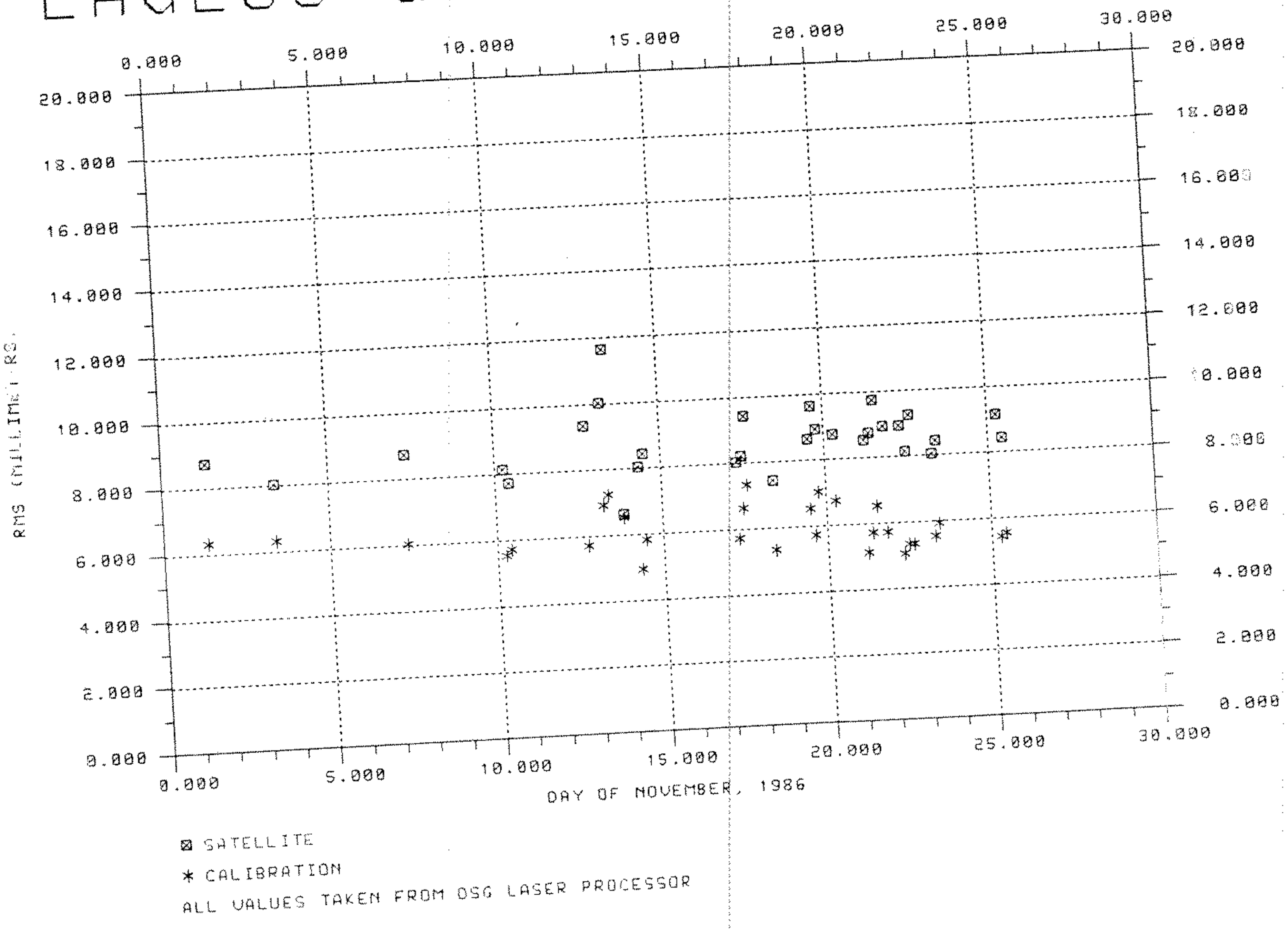


FIG. 1

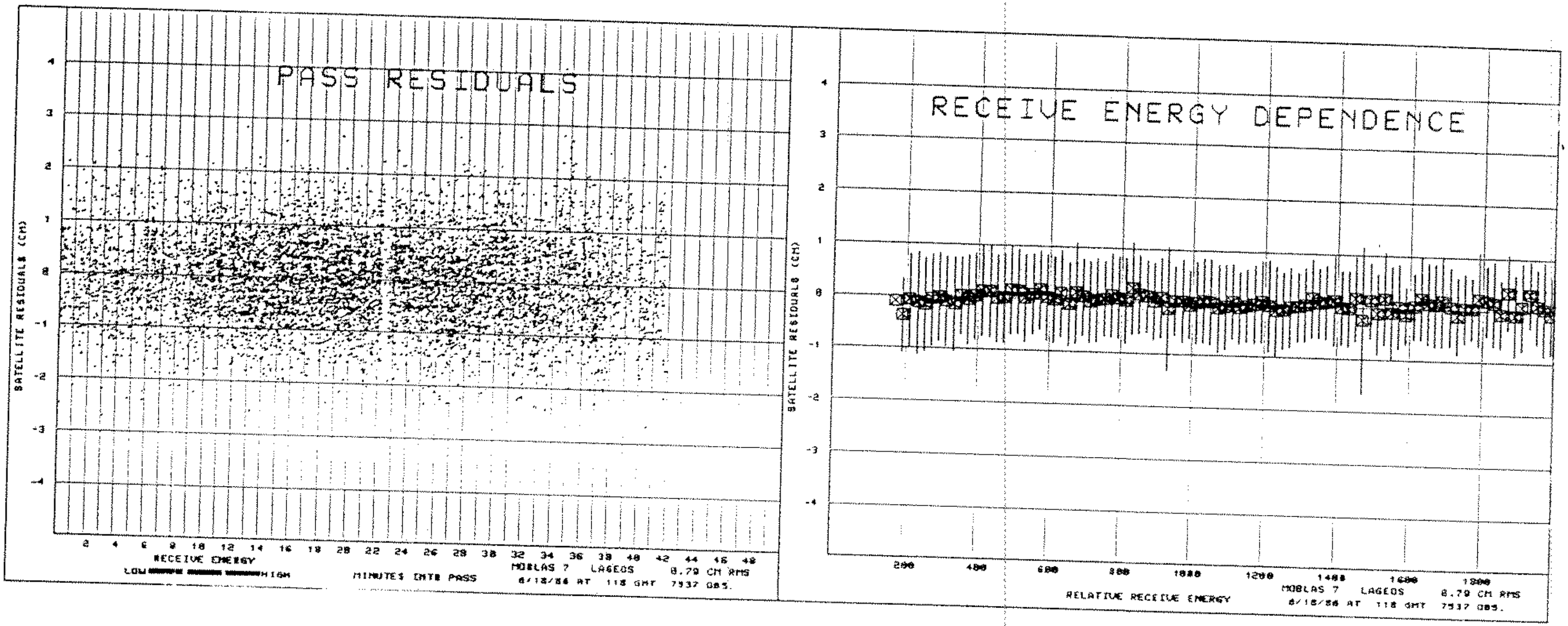

PASS RESIDUALS
SATELLITE RESIDUALS (CM)
4
3
2
1
0
-1
-2
-3
-4
2 4 6 8 10 12 14 16 18 20 22 24 26 28 30 32 34 36 38 40 42 44 46 48
RECEIVE ENERGY
LOW HIGH
MINUTES INTO PASS
MOBLAS 7 LAGEOS 0.79 CM RMS
8/18/86 AT 118 GMT 7537 OBS.
RECEIVE ENERGY DEPENDENCE
SATELLITE RESIDUALS (CM)
200 400 600 800 1000 1200 1400 1600 1800
RELATIVE RECEIVE ENERGY
MOBLAS 7 LAGEOS 0.79 CM RMS
8/18/86 AT 118 GMT 7537 OBS.

FIG. 4

FIG. 3(A)

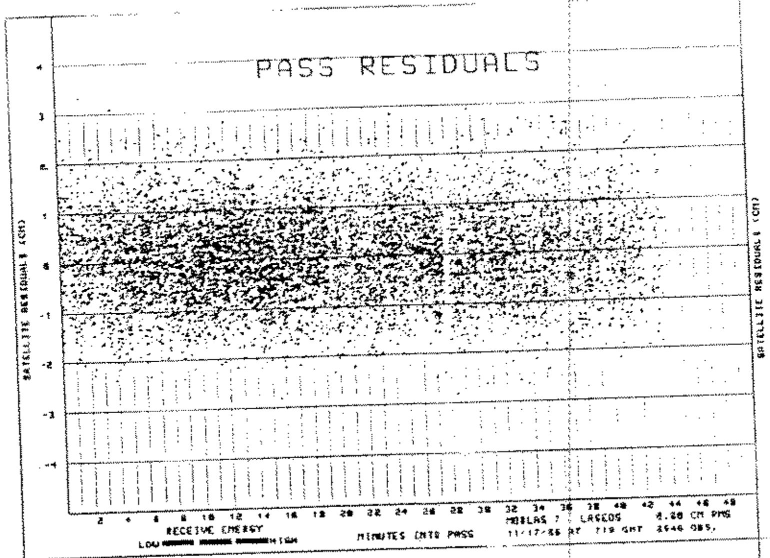
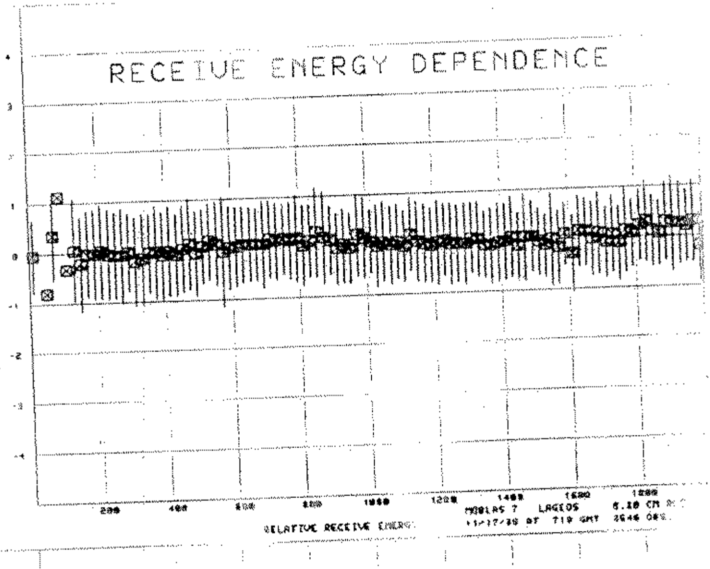


FIG. 3(C)



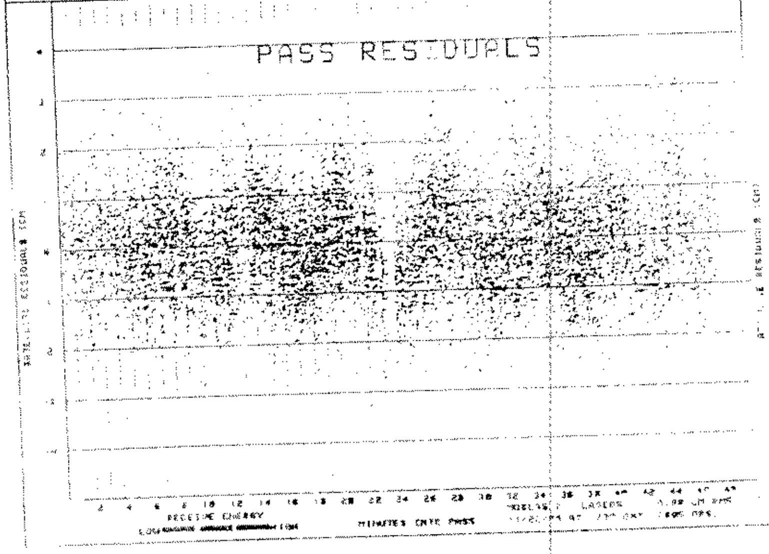


FIG. 3(B)

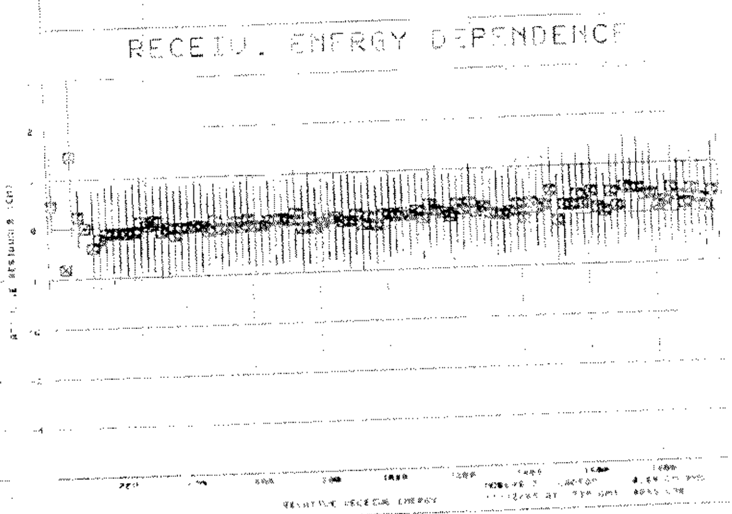


FIG. 3(D)

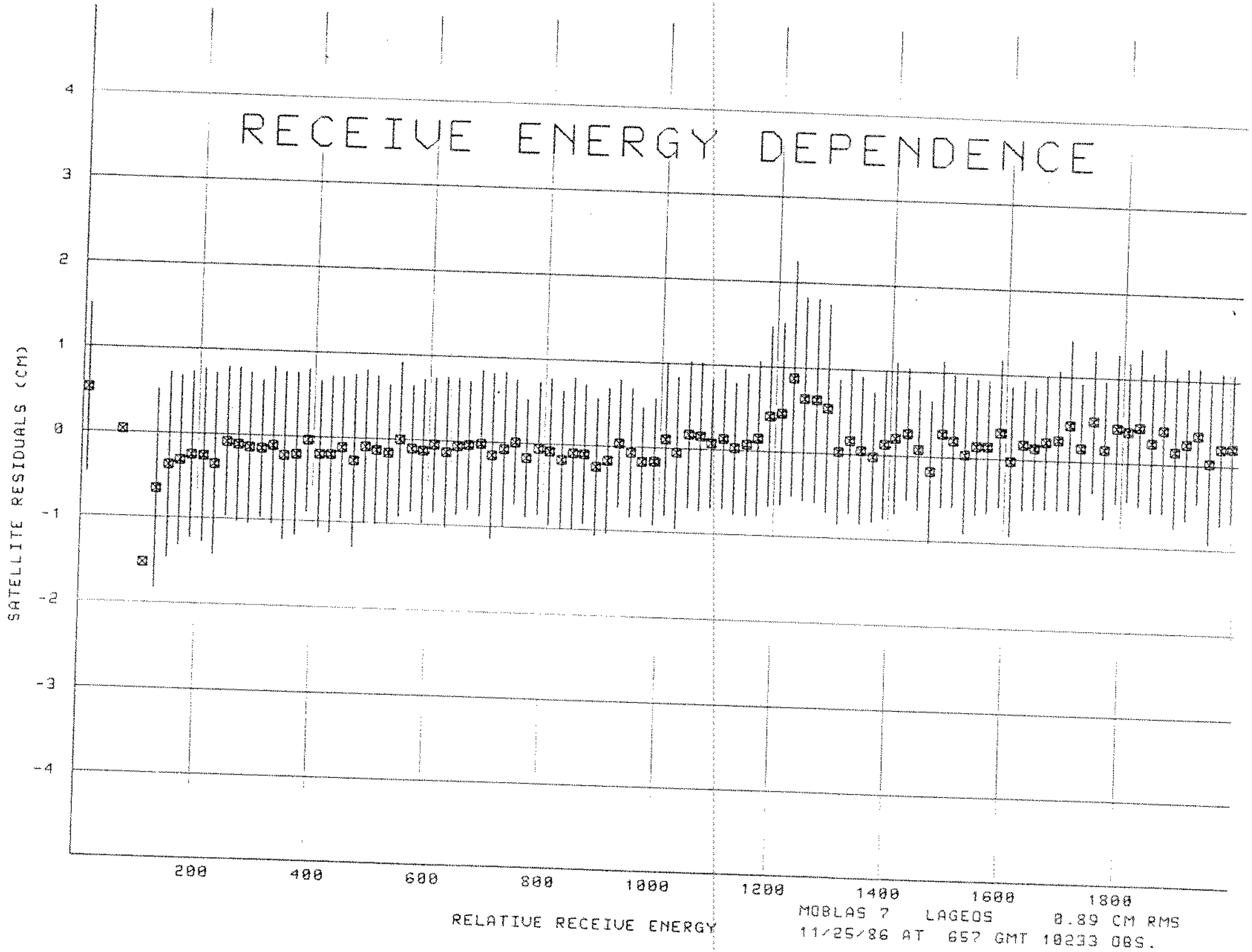

RECEIVE ENERGY DEPENDENCE
SATELLITE RESIDUALS (CM)
4
3
2
1
0
-1
-2
-3
-4
200
400
600
800
1000
1200
1400
1600
1800
RELATIVE RECEIVE ENERGY
MOBLAS 7 LAGEOS 0.89 CM RMS
11/25/86 AT 657 GMT 10233 OBS.

FIG. 2(c)