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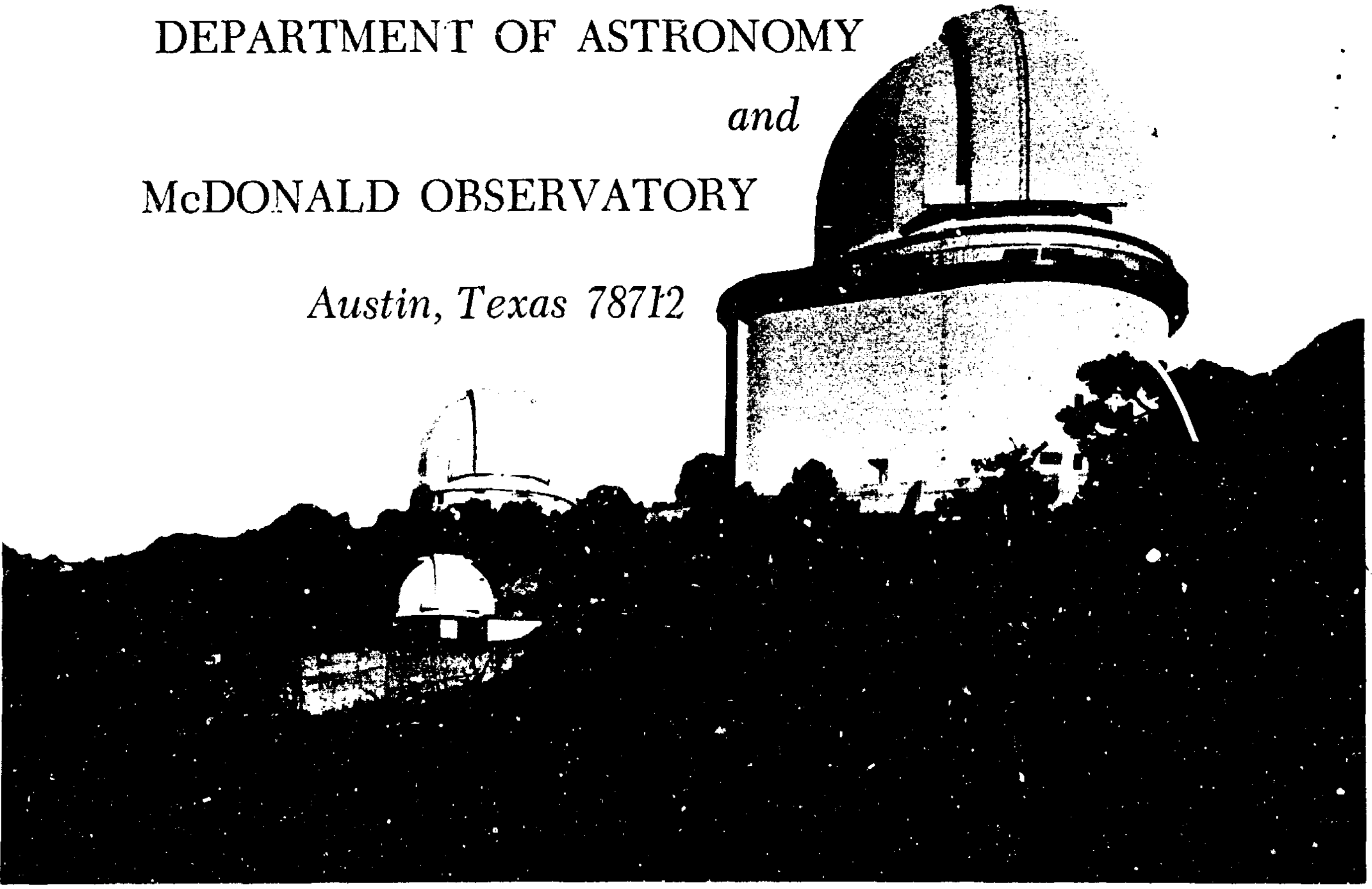

LUNAR MOTION ANALYSIS AND LASER DATA MANAGEMENT

at the

University of Texas at Austin

NASA Grant NGR 44-012-219

FINAL REPORT

covering the period

1971 July 1 - 1975 September 30

Report prepared 1976 January

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Principal Investigator

I. Introduction

The University of Texas Lunar Motion Analysis Project was funded during the interval 1971 July 1 - 1975 September 30 by the National Aeronautics and Space Administration under grant NGR 44-012-219, as a part of the NASA Lunar Laser Ranging Experiment. This final report is a summary and bibliography of all activities funded under that grant. Those activities divide naturally into two categories, which absorbed approximately equal shares of the resources made available under this grant number: data management and analysis. In the present context, data management refers to the process by which observed photon events are turned into observations and are made available to potential users. Analysis refers to theoretical or numerical studies involving real or potential application of such observations to improvement of the physical model. Over the 51 months of funded activity, each of these two categories included several distinct subdivisions, according as the needs and/or possibilities varied. Sections III and IV of this report provide a brief summary of each of these activities grouped into appropriate subcategories.

The level of effort applied towards this program varied with time, according to the resources available and the tasks underway, but was on the average 3 man years per year. The professional level personnel who participated in this effort during some part or all of the period of activity consisted of Dr. J. Derral Mulholland (Principal Investigator), Dr. Peter J. Shelus, and Dr. David W. Dunham. Research Assistants included (for varying periods) R. I. Abbot, S. Killen, G. L. Loumos, M. Powell, P. Snyder, K. L. Terrell, and P. Jordahl. Clerical assistance was provided by Diane Gregory and Nora Otto.

II. The Lunar Laser Ranging Experiment

The Lunar Laser Ranging Experiment was conceived in the laboratories of Professor R. H. Dicke, largely because of its apparent potential for providing a precise test of relativistic gravitational theory. It was quickly realized however that there was a much wider range of possibility to be obtained from highly precise measures of the instantaneous time delay from Earth to Moon and back. Indeed, a proper interpretation of the observations towards any given purpose requires a very careful consideration of elements of classical celestial mechanics, relativistic theory, astrometry, physics of the elastic Earth, laser physics, telescope design, electronics, and theory of observations. Consequently, from the very beginning of the program the project was conceived and conducted by a diverse group of scientists and engineers embodying all of the necessary disciplines. Consequently, several different institutions shared in the various responsibilities for the design and conduct of the program. From 1969 March until 1971 May, Mulholland (then at the Jet Propulsion Laboratory) was responsible for the provision of sufficiently accurate predictions to the observing crew operating at the McDonald Observatory of the University of Texas; he also participated during that period in the analysis of the early observations towards the first improvements to the lunar ephemeris. Upon his removal to the University of Texas he was given responsibility for the statistical identification of the McDonald observations and of their distribution to appropriate parties, and for a continuation of certain aspects of the analysis activity. It is in this context that the activities described below were pursued.

III. Data Analysis

a) Program Redundancy In Collaboration with Other Institutions

One of the principle recurring themes that has always underlain the conduct of the lunar laser program has been the insistence that major scientific results be corroborated if possible within the LURE Team structure before being submitted to the outside scientific world. This has been manifested for several years in an explicit demand for program redundancy, i.e. the existence of two or more institutions with overlapping analysis capability. The degree of duplication actually effected in the analysis calculations has varied with time; but totally redundant capability has been a major goal always. Consequently, the first major analysis task under this grant, occupying essentially the entire first year analysis effort was the bringing to operational status of computer programs for the numerical integration of the lunar orbit motion and for the application of lunar laser time delays for the improvement of the parameters of the physical model. The standard of comparison in these efforts were the programs then already operational at the Jet Propulsion Laboratory. This phase of the effort culminated in 1972 with the duplication at the University of Texas of the numerical lunar ephemeris LE17, which had been the last phase of Mulholland's ephemeris development studies at JPL. From the time of this event forward, collaborative activities consisted of participation in approximately parallel activities pursued in either binary or three-way combinations between UT Austin, JPL, and the Joint Institute for Laboratory Astrophysics (5,8,12,14)*. While no two of these three efforts achieved total independence, there were sufficient differences among their three ways of doing things as to provide reasonable checks on the results of any one of them in most cases.

An illustration of this latter situation is given by the computation and application of the partial derivatives of observed time delay with respect to the various physical parameters in the mathematical model, in particular those of the lunar orbit and rotation. In the case of the orbit partials, for example, the values used at the Jet Propulsion Laboratory were obtained from finite differences of numerical integrations (computed by Mulholland prior to 1971), while those used at UT and JILA were originally obtained from 2 independent and different evaluations of the Brown lunar theory. Because of various differences in approach, it was never quite possible to reach absolute agreement amongst the three in this area, but it was eventually possible to obtain sufficiently close agreement to justify

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*Numbers in parentheses refer to the bibliography, Section V.

confidence, and to proceed to a major improvement in the physical parameters describing the lunar range problem. As a first step, each of the three institutions analyzed all of the observations from the first three years of ranging operations obtained near zero declination of the Moon, with the particular end in view of improving the longitude and spin-axis distance of the McDonald Observatory(7). Efforts at UT included not only this analysis, beginning from the individual time delays, but also the computation of residuals against a specified model for use at JILA (where it has never been possible to work directly with the time delays). Among the significant results developed at UT during this study was the numerical determination and subsequent analytical derivation of the importance for a valid correction of the lunar orbit parameters that the relevent partial derivatives be computed with the inclusion of the effects of the diurnal rotation of the observing station. Failure to do this results in the biasing of the indicated longitude of the telescope, as well as a variety of smaller effects. The low declination study paved the way for a more general application of the available observations, resulting in the first (and thus far only) major publication of scientific results from the lunar laser project(17). The UT Austin contribution to this study consisted of a series of global solutions for telescope and reflector coordinates, orbital parameters, and some of the parameters governing the rotational motion of the Moon; the translation of these improved values into the generation of new lunar ephemerides; and, once again, the computation of residuals for use at JILA. During this time, of course, improvements were being made to the analysis and integration programs both here and elsewhere, and the three institutions served as mutual checks on one another to assure that improvements initiated at any one of the institutions were made properly by everyone concerned. In this enterprise, the other institutions profitted from our work, and we from theirs. In the course of the work leading up to (17), we produced nine separate numerical integrations of the lunar motion, and a large number of parameter solutions corresponding to different parameter sets and different sets of hypotheses concerning the physical model, observational weighting, etc.

In the course of 1973, and subsequently, it seemed appropriate to reduce the amount of effort directed towards parallel or redundant computations. From this time on, the three laboratories diverged their activities to a considerable extent. Later collaborative activities at UT Austin consisted of the computation of residuals for JILA as requested, and a brief comparative study of the numerical integration of equations of lunar orbit motion in different relativistic metric spaces, in support of the LURE investigation into the Nordvedt effect (34).

b) Program Improvement and Program Integrity

During FY 74, two major lines of program improvement were pursued under this grant, relating to the modelling of the lunar rotation and the computation of the lunar orbit partial derivatives.

In the case of the lunar rotation, one brute fact is paramount: there is no published theory that is adequate to discuss observations so precise as laser ranging. This has led to two developments at other institutions: numerical integration of the equations of motion at UCLA/JPL and an extension of the classic analytical theory at AFCRL. As in most confrontations between analytical and numerical procedures, each method has its advantages. The numerical approach by Williams et al was accompanied by the construction of transportable computer software which permitted the utilization of their computations at other computer facilities. In the case of the analytic development, Eckhardt produced a series of different theories corresponding to a rational sequence of values for the collection of gravitational parameters which affect the lunar rotation, but the results were provided only in the form of a collection of Fourier series with numerical coefficients corresponding to the case in question. Each individual user was left to construct his own evaluation programs, and there was no provision for explicit variation of the gravitational parameters. By making advantageous use of the Poisson series manipulation package for algebraic operations on the University of Texas computer (TRIGMAN), the material provided by Eckhardt was used to synthesize a physical libration theory containing the moment of inertia ratios and the third degree harmonics of the gravitational field as literal variables(24). At the same time, the TRIGMAN system was used to construct computer software for the evaluation of this theory for a particular lunar model at any given time. This software has been incorporated into our own analysis programs as an alternative to the numerically integrated librations (under programmer control), and has been supplied upon request to several other institutions. It is available upon request to any interested scientist.

During the course of the research discussed in the first paragraph of this section, a new analytic lunar theory became available, that by Deprit. This was the first new complete theory of the so-called "main problem" in more than half a century, and one of the explicit intentions of its author was to produce a theory sufficiently complete and sufficiently accurate for use with laser range observations. A solution to the main problem alone does not permit this, but should be sufficiently complete to be used for the computation of partial derivatives with respect to orbit parameters. In principle, such partial derivatives computed from the Deprit theory should be superior to those computed from the Brown theory. Consequently, we obtained a copy of the (as yet unpublished) new theory from Deprit and developed the computer software necessary for the inclusion of the partial derivatives into our orbit correction computations. It was and is our intention that these subprograms will be available without restriction but, as will be discussed in the next subsection of this section, there remains at this writing some uncertainty about the software, which we intend will be resolved very shortly.

The most important and by far the most time-consuming of the efforts in this subcategory concerned an investigation into the internal integrity of the numerical integration programs used both at UT and JPL. In 1972, Oesterwinter and Cohen published a discussion of the orbital motion of the nine planets and the Moon, based on a long span of transit circle observations of those objects. During the development of the NWL programs, orbit integrations were computed with the then current version of the JPL integration program, for use as a comparison standard in tests of the NWL program. The publications of the NWL results revealed a disquietingly large drift between the JPL integrations and the NWL integrations when computed from the same starting conditions. This suggested of course that there was an unknown error in one program or the other (the UT program is generically related to the one developed at JPL, and if the feature noted in the NWL study was the result of an error in the JPL program, it existed both in the JPL and UT programs at the time of the publication). Consequently we mounted a major program to determine if possible where the source of this discrepancy lay, as it was felt to be important to the overall discussion of laser range data. This study was undertaken with the full cooperation of Dr. Oesterwinter and included, until mid-1973, direct comparisons of computations made with the two programs on their respective computers. Many aspects of the two programs were compared both to each other and to hand calculations without a definitive discovery of the source of the problem. In fact, it proved to be exceedingly difficult to transform one's intentions into reality in this undertaking, whose major result, at this stage, may have been to underscore the importance of well designed hard copy output requiring that the computer tell the user what it has done and under what conditions. Nonetheless, many possible sources of such a discrepancy were investigated and given a clean bill of health. One possible source of the discrepancy that could never be satisfactorily resolved was the possibility of a program input error relating to the perturbations acting on the Moon. Certain critical information was not available on the NWL listings. Ordinarily such a problem would also be reflected in the motion of a perturbing body (planet) in question, but life was not so simple in this particular case, since the NWL program required the user to specify which objects were to be permitted to perturb each of the other objects; the practical effect of this is to raise the possibility that (for example) planet X might be perturbed by the Moon in its motion, without itself perturbing the Moon's motion. On a visit to NWL in 1973 June, Mulholland witnessed exactly such a situation arise because of a keypunch error. The direct comparison terminated shortly after(21), without a satisfactory resolution, because of the destruction of the computer in question. Still, it is not a satisfactory or satisfying state of affairs simply to assume that one's program is correct just because one has determined that there could have been an undetected error in the input data given to the other program. With the possibility of a direct comparison vanished, the only means of proceeding were to continue a careful check of the UT program coding and to seek a suitable third program against which to make comparisons. Such a program was found in the widely available Schubart-Stumpff program originated at the Astronomisches Rechen-Institut, Heidelberg. An IBM/360 version of this program was kindly supplied by Schubart, and comparison calculations were run at the INAG computation center at the Meudon Observatory. These computations, when compared with those made at Austin, indeed showed a run-off, but the drift was nearly an order of magnitude smaller than that noted by Oesterwinter and Cohen and was entirely compatible with the propagation of truncation error to be expected from the smaller word size of the IBM/360 computer. This result has been taken as presumptive proof of the internal integrity of the UT and JPL programs(26).

c) Three-Dimensional Ephemeris

A range measurement is a one dimensional observation of an activity taking place in three dimensional space. The topocentric range is not the coordinate that suffers the fastest nor the largest variations. The inevitable result of this state of affairs is that certain of the parameters of the physical model describing this motion are not adequately sensitive to laser observations, while others require a longer time interval of observation than is presently available. Among these are several of the orientation parameters of the lunar orbit. Within the LURE Team, it was thought to be very desirable to find some means of a direct tie between the orbit of the Moon, the FK4 star system, and some radio star frame. The tie between the lunar orbit and radio sources was undertaken at the Jet Propulsion Laboratory, where appropriate observations could be taken. As early as 1970, Mulholland had undertaken to use a combination of lunar laser observations and meridian circle observations as a means of tying to the FK4, but it was decided that the meridian observations were unsatisfactory for this purpose, and the more immediate needs of the LURE program took priority over further activities in this direction at that time. Beginning in FY 1973, it was undertaken at UT Austin to pursue the tie with the optical star system by means of a combination of laser range and stellar occultation observations. This seemed particularly appropriate since the Austin Department was and is an important center for the high precision observation of such events. Since the goal of this activity was to obtain a new lunar ephemeris based on observations in three coordinates approximately orthogonal, this activity has been customarily referred to as the "three-dimensional ephemeris" (the phrase three dimensional refers thus to the observations and not the ephemeris, which is three dimensional but is not unique in that respect). The complete reduction of occultation observations is a very complicated affair due to the irregularities of the lunar limb, and the computations require complex computer software. Since this computer software already existed at the Nautical Almanac Office of the United State Naval Observatory, and since one of our staff members was quite familiar with this software, it was imagined that a great deal of time and effort could be saved in pursuing the three-dimensional ephemeris as a collaborative project between this department and USNO. The principle was embraced enthusiastically by both parties, with the ephemeris to be supplied by UT Austin, the occultation residuals and partial derivatives to be computed at USNO, the laser residuals and partial derivatives at Austin, and the determination of corrections to the orbit parameters also computed at UT Austin. Unfortunately, a combination of the hazards and difficulties of trying to communicate between different computer systems by means of magnetic tape, incomplete or inaccurate communications between the two groups, and personnel problems did not permit this goal to be realized as efficiently as imagined. In retrospect, one suspects that it would have been more efficient and cost-effective to reproduce the entire occultation residual program system at Austin, with appropriate consultation from USNO. This activity represented the major analysis effort under the subject grant during FY 1974 and one of the two major efforts during FY 1975.

During 1975, the system was broght into what was thought to be a production operational configuration and was applied to the analysis of McDonald laser observations over the interval 1969-1974 (about 1400 observations) and approximately double that number of photoelectric stellar occultation observations from all over the world covering the interval 1955-1973. The results obtained were both interesting and disappointing. There were several reasons why they were interesting. a) It was clear that the occultation data corroborated some of the indications relative to the motions of the reference frame obtained from laser ranging; b) the value obtained for the correction to the obliquity of the ecliptic appears to corroborate the absence of an erroneous rate of that parameter, as discussed by Laubscher;* c) it is evident that this combination of observations will permit the determination of the three-dimensional offset between the center of the Watts datum and the center of mass of the Moon. (The Watts datum is the reference frame to which the profiles of the lunar limb "the marginal zone of the Moon" are related; preliminary values for this offset have been obtained, but more definitive values are expected as soon as the problem discussed below is resolved).

As has already been implied, the three dimensional ephemeris study has not yet been brought to a successful conclusion. A twenty year ephemeris (covering one complete cycle of the lunar node circulation) has been established as a baseline from which to make further corrections based on the two sets of observations. Observational residuals have been computed with respect to this ephemeris for both sets of observations, and the partial derivatives of these observations with respect to the physical parameters have been completed also, and they have been used to produce differential corrections to the parameters. It was at this stage, essentially the final step in the entire program, that an unexpected difficulty was encountered. Attempts to cycle the computations through multiple iterations failed to produce convergence of the solutions, particularly for the orbit orientation parameters and the mean motion. What made this so particularly surprising was that these aspects of the software system had been working quite successfully at an earlier epoch. The immediate suspicion, because of this, was that recent additions to the programming system had inadvertently destroyed some earlier part of the program. Alternative possiblities are related to the evaluation of the Deprit partial derivatives and/or the use of these derivatives in applying the indicated corrections to the starting conditions of the numerical integration. Despite very intense activity during the last two months of the lifetime of the subject grant, this question remains unresolved. Nonetheless, sufficient information was obtained during this period to indicate the probably most fruitful directions in which to seek the problem. Despite the termination of this grant, it is our

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*This question is of great importance in galactic dynamics and observational astrophysics.

intention to complete the three-dimensional ephemeris study.

d) Miscellaneous Independent Studies

In addition to the major efforts described in the preceeding paragraphs of this section, there were some occasions for isolated independent studies that might be referred to as "targets of opportunity". Three of these will be mentioned briefly.

From the point of view of the participants, the most interesting of these was the multi-episodic activities concerning the initial acquisition and subsequent determination of the final location of the Lunakhod II vehicle on the surface of the Moon. This object carried a laser reflector array provided to the Soviet space agency Intercosmos by the French space agency CNES. Perhaps by coincidence (but perhaps not), the Lunakhod II vehicle was deposited on the lunar surface during the course of an international colloquium on the lunar motion and surface coordinate systems (Houston, 1973 January). Two members of the French lunar ranging team attended this meeting, and at its close accompanied Mulholland to Austin, where the Intercosmos information was used to prepare a set of acquisition predictions and a search strategy. This latter was felt to be necessary because, unlike acquisition at McDonald Observatory of the Apollo retroreflectors, it was not known in what coordinate system the nominal position was given, and the landing site was in one of those many regions where the American and Soviet selenographers differ by a considerable amount. From there the trio proceeded to the Observatory to join Dr. Eric Silverberg in the initial acquisition attempts. The search was successful the second night (9,18).

Silverberg's observing crew (operating under NASA Grant NGR 44-012-165) attempted to repeat the observations on each of several succeding months, but such observations would have had more technical and psychological value than scientific, because of the fact that the vehicle was operating as an unmanned rover and thus changing its position between observing sessions. Unfortunately, it was very difficult to observe, even after coming to a final stop, and a Soviet implication of dust covering led to the abandonment of further observations at McDonald. Many months later, Mulholland learned that the Soviets themselves had succeeded in locating the reflector on several successive months. On the basis of this information, predictions for McDonald were computed once again and these permitted the final acquisition of Lunakhod II in 1973 November. It has been a standard part of the observing sequence ever since; LURE 1 compatible coordinates for the reflector were computed at Austin early in 1974 based on the McDonald observations from the preceeding few months(27).

Early in 1974 also, it became apparent that there began to be sufficient observations satisfying the conditions necessary to determine the apparent variations in Earth rotation at McDonald. A very brief and cursory study was devoted to calculating apparent values of UT0 and the variation in latitude from these data. Although the results were somewhat contaminated by the lack (at that time) of sufficient accuracy in the lunar libration model, it was possible to show that the results were roughly compatible with values recently determined from VLBI measures(23).

Finally, at the request of the project monitor, and in support of the geophysics group at UT Galveston, a covariance study was undertaken to determine the degree of internal precision that could be expected in the determination of coordinates from a mobile ranging station. This study assumed the existence of a network of three or four fixed stations that provided determinations of universal time and the location of the pole. An attempt was made to allow for a realistic weather model and the results were computed as a function of geographic position, being displayed in the form of contour maps. Generally speaking the results of these computations were very encouraging for the proposed use of mobile ranging stations for monitoring internal movements of the Earth's crust(31).

IV. Data Management

a) Data Identification

At the inception of the subject grant, no machinery existed anywhere for the systematic identification, reduction and distribution of the observations then being taken at the McDonald Observatory. Since no serious analysis effort could be mounted under such circumstances, the most important priority in the early stages of our activity was focussed in this direction.

The first step, of course, was the identification of real observation events. To appreciate this, it is necessary to realize that lunar ranging is based on single photon counting and detection. Since the targets are on the surface of the Moon, one is faced with the circumstance that the telescope is always pointed in the direction either of a bright object or a bright sky. Consequently, lunar ranging nearly always involves signal to noise ratio less than unity and, especially in the early days, often <u>much</u> less than unity. In order to verify that an observation has in fact taken place, it is necessary to have relatively good predictions, both the existence and knowledge of a short pulse length from the laser, and a statistical analysis of the results of a series of laser firings. The technique adopted for the gross filter, which is applied directly to the mass of raw photon events recorded at the Observatory, was based on a partition of the residual domain into corridors which were submitted to an analysis based on the expectation of a Poisson distribution (6,16). This seemed like a reasonable hypothesis, and subsequent experience has in general born the validity of that hypothesis out. Since this process has been described in detail in the literature, we will not discuss it further here. By the end of FY 1971, the computer software for this process had been designed, coded, and certified as an operational program, and it had been used to process all of the photon detections recorded at the Observatory during 1969. We had also begun a regular schedule of monthly processing of the observation tapes as they arrived from the Observatory, a service that continued virtually without incident throughout the remainder of the grant period. Identification processing of the backlog of observed photon events from 1970 and 1971 was completed before the end of FY 1972.

Data identification activities pursued under this grant were not restricted to the LURE Team activities. We had made the offer early of providing investigatory filtering for other groups attempting to bring lunar ranging facilities to operational status, agreeing to respect any confidentiality in the observations in the same manner as in our agreement with the LURE Team. For us, this represented an insignificant diversion of effort, while it was potentially of extremely high value to the other observing groups. This offer was in fact accepted by the AFCRL lunar facility at Tucson (for whom we processed one set of data), and by the Smithsonian group (for whom we processed three blocks of data during 1972) (11). Filtering of the photon events from experimental observation runs at the University of Hawaii LURE station at Mt. Haleakala began in 1975.

As the observing program proceeded, it became clear that the use of individual photons in data analysis would not long be feasible. In addition, it was recognized that a suitable means of data compression would also serve to reduce the level of stochastic noise. During 1972, we turned our attention to this problem and developed the necessary machinery for computing "normal points" from the individual photon events. A normal point produced by this means consists of a pseudo-observation representing, in a least squares sense, some "best" single approximation to a series of photon events over a limited time span, customarily not more than 15 minutes. Such a point will represent anywhere from three to 50 or more photon events; if the process is done properly the random errors of observation incorporated into the normal point will be reduced by a factor of $\sqrt{n}$ with respect to the random noise on the individual photon events. Since 1973, when the software system received its final configuration, these normal points have been computed as a matter of course, as the next step after the gross filtering of the Observatory raw data tape (16).

With the existence of the normal points, with their reduced noise level, it became possible in 1973 to introduce a second level of filtering, more refined than the first. First, perhaps it is useful to discuss why such a second filter might be necessary. It concerns not a failure of the gross filter, but rather the existence of cases in which marginal coincidences have been permitted to pass the gross filter or cases in which the underlying assumptions of the gross filter have not been satisfied, usually because of equipment failures in the operational aparatus. The first case is, of course, quite clear. The gross filter operates on the assumption of Poisson statistics, and there is always the possibility of a perfectly random coincidence of 2, 3 or 4 photons in the residual domain, which will give the appearance of an observation, although usually a very weak one. The other possibility is somewhat more difficult. Suppose for example that, for brief periods of time, the time delay timing system counts an extra (spurious) cycle from the basic frequency generator. Any photon even that are detected while this is happening will be mis-timed by precisely the basic cycle time of the system (at McDonald this basic cycle time is 50 nanoseconds). If this condition persists throughout an entire run, it is perfectly conceivable that one will have a real observation in the sense of photons reflected from the lunar surface, but they will be spurious observations from the point of view of precise time delays; they cannot be used in data analysis. There is no way that such an event can be detected as spurious by the gross filter, which has no absolute reference and no memory. The second filter is constructed by imposing dynamical consistency on the normal points covering some finite time span, usually one lunation. It requires the application of the analysis programs discussed in the previous section. The process that was adopted is as follows: once each month after the raw data tape from McDonald has gone through the gross filter and the resulting output compressed into normal points, those normal points are fed into the data analysis programs, which are used to perform a differential correction of telescope and reflector coordinates and orbital parameters. It must be understood that the corrections thus obtained are of no scientific value whatsoever. The operation is performed for the single reason of forcing a dynamically consistent model to fit as closely as possible this particular group of observations, so that the normal points can be measured in terms of this consistency. When this operation is performed, many of the erroneous observations resulting from hardware failures at the Observatory are very easily identified and eliminated.

By 1974, hardware improvements at the Observatory had made it possible to begin considering how to use pulse shape information to reduce the uncertainty estimates on the measured time delay. The basic filtering programs assume that the laser produces a pulse that is both symmetric and without structure. Thus, in terms of the timing resolution, the pulse is very broad, and it is not possible to determine with any certainty from what part of the original pulse the photon returns came. With improved monitoring of the outgoing pulse, however, it was evident that there frequently was structure to the pulse raising the possibility that a deconvolution process might permit one to determine the position of the photon returns or rather the probable position of the photon returns relative to the average outgoing pulse. This could lead to sharply higher accuracy in the entire process. The studies begun during FY 1975 will be implemented (under another grant) during FY 1976.

b) Observatory Interfaces

In line with the general LURE predisposition towards a fail-safe philosophy, it was decided that the capability of producing prediction computations for the McDonald Observatory should exist also at Austin. This seemed particularly worthwhile, since major portions of the computer software required for the predictive capability were useable also for the construction of analysis programs. Consequently, the JPL prediction program was transported to Austin in 1971 and converted to the local computer system. The wisdom of this move was demonstrated several times in the case of Observatory emergencies or, as in the case of Lunakhod II, unexpected situations requiring short turnaround.

The section on the construction of the second filter discussed above implied that, from time to time, there have been hardware problems at the Observatory affecting the quality of observations. This indeed has been the case, and the example given was one of them. We have always tried to maintain the closest relations possible with Silverberg and his observing crew, and the fine filtering process gave us the opportunity to close a feedback loop which has worked to improve the quality of observations available. Information provided to Silverberg, resulting from the fine filtering process, has permitted him and his crew to isolate and correct equipment problems hitherto unknown.

Based on the experience acquired in the course of this grant, the principal investigator believes strongly that the McDonald facility could have been used with much more effectiveness, producing many more observations, during the first two years of operation had there been a closed loop such as we have described here: observation, followed very quickly by filtering, and the results of that filtering fed back to the observers so that they might make use of whatever information and interpretation could be obtained from the filtering process. This is not intended as a criticism of the early conduct of the experiment, because everyone had more than enough to do, and it was difficult to know what would be viewed as the ultimate priorities with the advantage of 20/20 hindsight. Nonetheless, now that the systems exist with which this cycle can be established, it is extremely important that the feedback exist at as early a stage as possible for new observing stations. Consequently, discussions were begun in 1974 to establish data formatting and transmission ground rules with the Haleakala station, with the intention that the first data tape received from their operations could be subjected to the gross filter process with virtually no delay. When that station began firing in 1975, the feedback loop was still in an incomplete and experimental configuration, but it did exist and it did operate successfully and without significant delay. During filter processing of the earliest Haleakala tapes, the first suspected lunar returns using the lunastat as both transmitter and receiver were discovered (JD≃2442470.9). Although residuals were two orders of magnitude larger than expected (probably due to timing or detector problems), the cluster of residuals closely mimicked the short ranges tests between Haleakala and Mauna Kea. These observations were of no value for analysis purposes but were indicative that photons had been transmitted to the Moon and later received back at the Earth. They had been unrecognized at the Observatory due to a computer system failure just subsequent to the observing run.

c) Data Distribution

Of course, the data filtering activity was not intended solely for our own benefit, but rather as a LURE facility, whose products were to be available almost immediately to any LURE Team member for purposes of data analysis. Thus, throughout the life of the grant, the monthly processing cycle which began with the gross filtering of a raw data tape, was not concluded until a summary of that month's observations had been distributed to every LURE Team member and machine-readable copies either of the normal points or of their residuals with respect to a well-defined model transmitted to those Team members who had requested them.

Even before the adoption of the federal freedom of information act, it was standard NASA policy that such projects as the lunar laser ranging experiment adopt a policy for placing the observational data into the public domain on some approved time schedule. Such a data release policy was adopted by the LURE Team, and responsibility for its implementation was delegated to Mulholland as a natural extension of the data identification responsibilities(2). The first public deposition of lunar laser data was transmitted from the University of Texas to the National Space Science Data Center late in 1971. A second deposit in 1972 January brought the actual public release of data onto the adopted schedule of semi-annual data releases, where it has remained ever since. We believe that there are few NASA programs in which a public data release protocol has been satisfied so promptly and so rigorously.

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