AD 741875

CONTRACT NO.AF - AFOSR - 616 - 67

UNIVERSITY OF THE WEST INDIES

DEPARTMENT OF PHYSICS

REPORT NO. 43

Final Report for the period April 1964 - June 1971

# A STUDY OF THE FEASIBILITY OF MEASURING ATMOSPHERIC DENSITIES BY USING A LASER SEARCHLIGHT TECHNIQUE.

Department of Physics,
University of the West Indies,
Mona, Kingston 7,
JAMAICA.

Unclassified

Security Classification

71

## DOCUMENT CONTROL DATA - R&D

*(Security classification of title, body of abstract and indexing annotation must be entered when the overall report is classified)*

| | |
|---|---|
| 1. ORIGINATING ACTIVITY (*Corporate author*)<br>University of the West Indies<br>Mona, Kingston 7, Jamaica | 2a. REPORT SECURITY CLASSIFICATION<br>Unclassified<br>2b. GROUP |

3. REPORT TITLE

A STUDY OF THE FEASIBILITY OF MEASURING ATMOSPHERIC DENSITIES BY USING A LASER-SEARCHLIGHT TECHNIQUE

4. DESCRIPTIVE NOTES (*Type of report and inclusive dates*)

Scientific Final. 1 April 1964 - 30 June 1971

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| 6. REPORT DATE | 7a. TOTAL NO. OF PAGES | 7b. NO. OF REFS |
|---|---|---|
| February 1972 | 71 | 24 |

| | |
|---|---|
| 8a. CONTRACT OR GRANT NO.<br>AF AFOSR-616-67<br>b. PROJECT, TASK, WORK UNIT NOS.<br>6682-07-01<br>c. DOD ELEMENT<br>65402154<br>d. DOD SUBELEMENT<br>676682 | 9a. ORIGINATOR'S REPORT NUMBER(S)<br><br>9b. OTHER REPORT NO(S) (*Any other numbers that may be assigned this report*)<br>AFCRL-72-0167 |

10. DISTRIBUTION STATEMENT

A - Approved for public release; distribution unlimited.

| | |
|---|---|
| 11. SUPPLEMENTARY NOTES<br>TECH, OTHER | 12. SPONSORING MILITARY ACTIVITY<br>Air Force Cambridge Research Laboratories (LY)<br>L. G. Hanscom Field<br>Bedford, Massachusetts 01730 |

13. ABSTRACT This report summarizes the work done during the period between April 1964 and June 1971 in developing and testing a laser radar technique to obtain backscattered signals from the atmosphere at altitudes up to 100 km. A vertically directed pulsed ruby laser signal with a 10 joule, 10 microsecond pulse provided the transmitted energy and an array of 30" diameter spherical mirrors provided a mirror area of 15 square meters to collect the backscattered energy. Photon counting techniques were utilized for high altitude returns and many returns are integrated to provide high sensitivity and to reduce the variance of the signals.

KEYWORDS: Laser searchlight, High altitude density, Atmospheric tides

DD FORM 1 NOV 65 1473

Unclassified

**FINAL REPORT**

for the period

1 APRIL 1964 - 30 JUNE 1971

CONTENTS

## 1. INTRODUCTION

This report is the final one on the work done under Grants AF-AFOSR 616-64, 65, 66, 67 between April 1964 and June 1971. The greater part of the report is devoted to discussion of the performance and reliability of the systems developed during this period, and to measurements made during the final year. The earlier work, which was essentially developmental, is discussed in Section 2, which contains an outline of the history and main objectives of the project. Full descriptions of this have been given in earlier reports. An assessment of the final systems, and their capabilities is given in Section 3, together with tables of operating periods and the status and values of the results obtained.

Appendices are given which list the personnel involved in the work, reports submitted and publications made. Als[illegible]ed as an appendix, is the content of a paper containing results obtained with the Mark II system, which has recently been accepted for publication. All other data, obtained during the grant period, which has so far been analysed, has either appeared as an earlier publication or as a report.

## 2. HISTORY AND OBJECTIVES OF GRANT

In 1963 a research proposal was put to the Offices of Aerospace Research through A.F.C.R.L. The proposal was to develop a new method of studying the atmospheric properties by adapting the modulated searchlight beam technique devised and extensively developed by Dr.Elterman of AFCRL. It was original in that it replaced the conventional searchlight source by a pulsed ruby laser. By the use of narrow passband filters on the receiver a very considerable improvement in range and accuracy was predicted and it was hoped to extend the range, from which measurements of significant value could be obtained, up to 100 Km. The project started in April 1964, when AFCRL made a one year's grant to test the feasibility of measuring atmospheric density and temperature, over height ranges up to 100 Km. using a laser radar technique.

Funds were provided to purchase a laser and appropriate photomultipliers. The electric pulses produced by each individual effective photon were displayed on an oscilloscope tube. The thermal noise pulses emitted at random from the photomultiplier were reduced by cooling the photocathode by blowing a jet of cold air on the front. The display of photons returned against range for each shot was photographed and then analysed. The collecting mirror (21" diameter) and the fast oscilloscope and camera were supplied by the Physics Department of the University of the West Indies.

Considerable delay was experienced in the delivery of a laser which met the specifications laid down. In addition a variety of problems were experienced during the contract period.

Firstly it became clear that fluorescent emission by the ruby after the main pulse was appreciable and back scatter of this light by the relatively dense lower atmosphere obscured the light scattered from the main pulse by the less dense upper atmosphere. In order to remove this effect a shutter was installed which closed immediately after the end of the main pulse and so eliminated the effects of fluorescence.

Secondly, it was discovered that after a sequence of about 15 shots, the signal received from the upper atmosphere suffered a rapid decrease. This was studied and found to be due to the temperature drift of the ruby which changed the wavelength of the ruby emission so that the wavelength emitted moved into a water vapour absorption band. This effect was removed by improved temperature stabilisation.

Thirdly, when adequate signal data were collected from the uppermost range of the equipment, 60-90 km., it was discovered that the signal did not fall as rapidly with height as the decrease of the density of the atmosphere would predict. After a long study it was eventually established that the effect of the very large signals incident upon the photomultiplier from the main pulse scattered from the dense lower atmosphere was to cause a long-term effect on the photomultiplier, in fact to increase the rate of noise pulses for a period of milliseconds. This effect was removed by shielding the photomultiplier from any returned signal from the lower atmosphere by means of a very fast shutter. This arrangement was complicated by the need for the precise synchronisation which was required with the fluorescent shutter and the laser firing.

One further problem remained, which was not solved during the contract period. The signal strength returned and measured was an appreciable factor below that which would be calculated from the known parameters of the system and the density of the atmosphere. It was suspected that a part of this loss of signal might be due to losses in the lower atmosphere either by dust, or by cloud and water vapour.

By the end of the contract period, March 1966, adequate data were accumulated establishing the feasibility of the method for comparative density measurements up to 70 km. with a statistical accuracy of about 10%. The equipment also made the first detailed studies of the 20-25 km. aerosol layer and discovered for the first time the pronounced stratification which occurs in this layer. It was also shown that it was possible to observe the layer by day as well as by night. As a consequence of the success of the system, a proposal was put forward for an extension of the grant to make further measurements, with a view to establishing more reliably the capabilities of the technique. At the same time improvements were to be made to the system to enable the data retrieval to be more easily performed. A study was also to be made for a new instrument based on the knowledge gained with the existing system.

The observations which it was hoped could be made with the existing system included:

(i) the variation of temperature in the 30-50 km. region both from night to night and from season to season;

(ii) the variation of the aerosol content in the 15-30 km. region from night to night and from season to season;

(iii) a study of the possible existence of other dust layers;

(iv) a study of the usefulness of polarisation measurements of the scattering.

In 1966 the scope of the contract was extended through a proposal to construct the new instrument mentioned above. This, known as the Mark II system, was to be several orders of magnitude larger than the original instrument and would be able to make accurate comparative measurements of atmospheric density up to a height of 100 km. It incorporated a new ruby laser of increased power and a collecting mirror of vastly increased area, made up of a mosaic of 36 individual 30" diameter mirrors arranged with a common focus 80' above the ground. At this point receiving photomultipliers and pre-amplifiers were to be rigidly mounted on a steel lattice mast.

A Mark III system was to be designed which was both portable and steerable, but nevertheless had the range and capability of the original (now known as the Mark I) system. By observations of the returned signals from the same heights in a vertical and in an oblique direction, measurements of the atmospheric transmission coefficient, T, could be made. This work would enable one possible source of the apparent signal loss mentioned above to be assessed.

A prolonged series of observations using the new Mark II system was proposed. When the system was completed then it was expected that the same magnitude of signal would be received from 90 km. as was received by the Mark I system at 70 km. In addition to the routine measurements,it was considered essential to assess the reliability of the new system, to compare its performance with that of other methods of examining this region of the atmosphere, and to comment on the possibility of scattering, from other than atmospheric molecules, being a relevant factor in the laser radar method of study of the atmosphere above 30 km.

Construction of the system closely followed the design study but major delays were experienced in supply of equipment. Firstly, the laser manufacturers could not meet the specifications to which they had agreed. After almost a year of delay the laser was accepted as being the best possible at the then state of the art. It gave approximately 11 joules in a 10 microseconds pulse. Secondly, the mirror suppliers had not realised that they could not obtain a grinding tool of the required size (30" diameter) of such a long radius of curvature (160 ft.). Again a delay of about one year was experienced in the delivery of the first mirror. The final array, when assembled, did in fact exceed the predicted precision and a circle of least confusion of 1 cm. diameter at the focus was easily attained. A further source of improved performance was also studied. The front surface of the photomultiplier was fitted with a glass prism in which the signal light from the mirror was trapped by a series of multiple total internal reflections. By this means, a considerable increase in quantum efficiency of the photomultiplier was achieved. Because of the large dynamic range of the signal the signal light was split and fed to 2 photomultipliers: the more sensitive one for the highest altitude region, and one for the intermediate height range. A third photomultiplier was used with a separate mirror to cover the low heights.

The counting system was constructed but took longer than was expected. Its operation was only satisfactory when various adjustments were kept at absolutely critical levels. As a counting system it was a success, performing according to its design criteria, but maintenance proved more and more difficult with time. Eventually, as is discussed in Section 3(a) it became necessary to design a new counting system.

The Mark III system was designed and constructed with its counting system but was not fully operational until 1968. A study of T has been carried out; this stablished the fact that Jamaica is a good site for laser radar studies. It also establishes that the apparent loss of signal mentioned earlier could not be explained by poor atmospheric transmission.

In 1968 and 1969 further extensions to the grant were made in order to enable the Mark III system to be completed and tested in operation. A further grant was made in 1970 for the purchase of operational spares. During this period considerable delays and difficulties occurred caused by a variety of conditions. These ranged from internal damage to the ruby laser rod, to electronic damage caused by lightning striking the lattice mast. Although test measurements were made in 1968 and 1969 a full operational programme did not start until 1970. Fuller descriptions of these and the equipment performance are given in Section 3(a). Development of the Mark III system also continued and a description of this is given in Section 3(b). Preliminary measurements were made from 1968 onwards and a full observational programme was established in 1971.

## 3. ASSESSMENT OF PROJECT

(a) Mark II System (Reports No.20 and No.27)

(i) Outline of work done in 1970-71

The operation of the system in 1970-71 has been principally in terms of an investigation of the behaviour of the mesosphere. The concentration of effort on this particular area was made for the following reasons:

(1) Variations in atmospheric density in the mesosphere appear to be greater than at any lower altitude and of considerable interest, as the region lies just above the maximum height reached by a standard meteorological sounding rocket.

(2) The system of three photomultipliers to cover different height ranges proved somewhat less satisfactory than had been expected. The result of this was that comparatively much more accurate results could be made within the range covered by a single photomultiplier, than could be made over the complete range covered by all three. Since the accuracy at the lower end of any photomultiplier range was virtually the same it was clearly desirable to concentrate ones effcrt into the range where least was known by other techniques.

(3) As was mentioned in the previous section, the original

counter designed for the Mark II system proved unreliable and the last useful measurements were made with it in April 1970. While a new unit was being designed and constructed it was necessary to borrow the counter from the Mark III system. This had only ten recording channels which again meant only a limited height range could be covered.

Despite these limitations the period 1970-71 can be regarded as a successful one. Data of considerable meteorological value has been gathered and the system has been given a very thorough proving. Various failures have occurred, some of a serious nature, and these will be discussed in the secitons on performance and reliability. Main operational periods have been limited to approximately one week around each new moon, because of background noise considerations at full moon, and have also been dependent on the weather. Approximately 30 nights' observations have been made, with an average of 9 hours continuous operation on each. Periods between the new moon have been used for maintenance and repair of minor damage which has often occurred during the operational periods. Construction was also continued on the new counting system which was put into service (in a partially complete state) in June 1971.

In addition to the above semi-routine observations which were primarily concerned with a study of variations of atmospheric density two sets of observations were made on specific occasions to look for effects produced by cometary dust. These were in May 1970 and February 1971 when an influx of dust from comets Bennet and Encke respectively, were expected. The Mark II system has also been used to commence observations on the Raman scattered signal from atmospheric nitrogen. It has been found possible to observe such signals scattered from heights up to 40 km. Studies are still proceeding to see if the method is capable of competing with meteorological balloon soundings. All the above are concerned with the actual use of the system as an observing instrument. In order to improve the system, an experimental study has been made of two aspects of photomultipliers. The first was a study of the apparent variation of quantum efficiency with angle of incident light, a study which was started several years ago and the results of which were used in the design of the system, but which was never completed. The second has been an examination of the changes in noise count following an intense incident pulse of light. The latter study now shows considerable promise in explaining the slight discrepancies that exist between the expected and observed signals from heights above 90 km.

(ii) Performance

The principal objective of the construction of the Mark II system was to provide a unit that was capable of giving values of atmospheric density (and hence temperature and pressure) up to 100 km., comparable with those obtainable by rockets. This implies an accuracy of measurement that decreases with increasing altitude but having a value of the order of 10% at 100 km. (It is difficult to give an exact figure here as the agreement between the different rocket techniques is subject to some uncertainty - Faucher & Morrissy, 1971). The original design was made with a figure of this order in mind.

The ultimate performance of the instrument depends on

(i) the laser output power;

(ii) the receiver mirror area and photomultiplier sensitivity;

(iii) background noise;

(iv) firing rate.

In addition, other factors such as receiver linearity, dynamic range, overload characteristics and ability to operate for many hours continuously without maintenance must also be considered. With so many variables the design of an instrument to give a certain performance is necessarily uncertain, and the attainment of objective is best judged in terms of final performance rather than each single item. As the latter has, itself, varied somewhat during the operational life of the instrument and is strongly dependent upon uncontrollable factors such as weather conditions, it is not simple even to state what the performance is.

A detailed description of the instrument has been given by Kent and Wright (1971), and Figure 1 shows the atmospheric profile reproduced in that reference. This is a mean atmospheric profile obtained for a total of 1600 shots on 718 April, 1971. At the time this profile was taken, 1600 shots represented a complete night's observation. Since then much higher firing rates have been achieved, and maintained, and 1600 shots may be made in four hours. In addition, the signal received on that particular occasion was, because of optical losses in the system and poor atmospheric transmission, about

50% of that attainable in October 1971. The profile thus represents the accuracy now attainable under good atmospheric conditions with about 2 hours continuous operation.

Figure 1. shows the statistical accuracy attainable at any height by means of error bars. This, of course, is not the same as the true accuracy of measurement of atmospheric density, since the latter depends also on the reliability of interpretation of the data. There are two main problems with this. One is concerned with the freedom of contamination of the scattered signal by either spurious noise or by scattering from aerosols. The second is concerned with the accuracy of normalisation of the profile since it is not possible to know the system parameters with sufficient accuracy for this purpose. From observations made during 1970-71 it is possible to say with some degree of confidence that contamination of the signal by scattering from atmospheric dust is not a major effect. The only occasion on which a definite effect has been observed was in May 1970 when a temporary 20% enhancement of signal from 70 km. occurred, believed to be due to influx of dust from Comet Bennett. On no other occasion has such an enhancement been seen although a special observational programme was carried out in February 1971 when an influx of dust from Comet Encke was expected. One can therefore say that it seems unlikely that dust in the atmosphere at great altitudes will normally produce an enhanced signal of greater than a few percent of that due to scattering from atmospheric molecules. To improve on this figure is extremely difficult. At heights of above 70 km. it has been found that the scattered signal

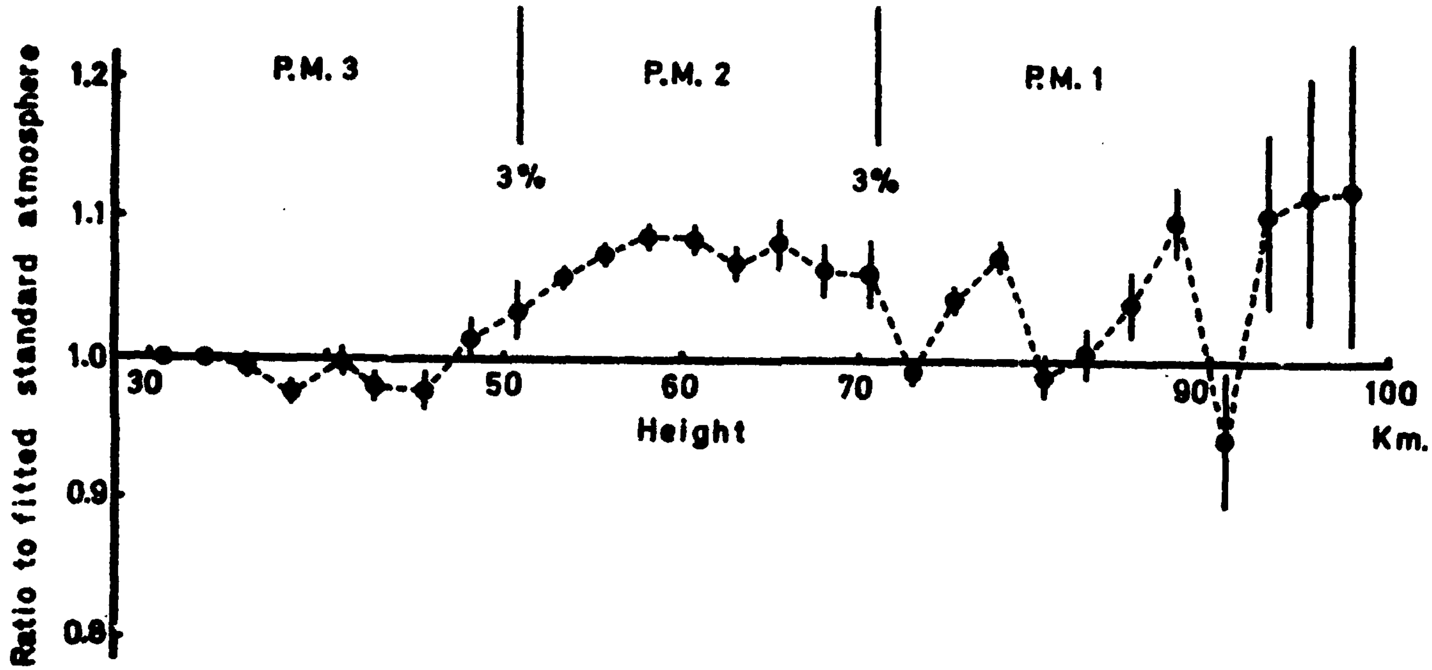


Fig. 1 - Scattering profile observed over Kingston, Jamaica, on 7-8 April, 1970, expressed as a ratio to the standard atmosphere for 15°N fitted at a height of 30 km.(Error bars give the statistical accuracy of points for each photomultiplier, while figures under the dividing lines give the fitting accuracy between photomultipliers.).

fluctuates with time. These fluctuations, which may be as large as 50% at 100 km., are believed to be due mainly to atmospheric tides and they obscure small enchancements. Only an average over a large period of time is thus meaningful and even this may be biased, since all measurements are made at night. The only completely satisfactory way of checking the reliability of the data is by a simultaneous rocket flight from a nearby location and this facility has not been available. The long period average does agree with the standard atmosphere for 15°N to within a few percent for all altitudes below 90 km. Above 90 km. a slight enhancement of signal is observed, amounting to nearly 20% at 100 km. It is possible that this is an atmospheric effect as atmospheric density at that height is not too accurately determined and is certainly subject to large diurnal variations. Perhaps more likely is that this is an instrumental effect that has not yet been eliminated. Although a receiver shutter is used to cover the photomultiplier system at the instant the laser is fired this commences opening at about the time when scattered signal is being received from a height of 30 km. This signal is still very strong and it is possible that it could produce a small temporary increase in noise. This particular problem is still unsolved but there is the likelihood that an answer will be agailable in the near future when the work on photomultiplier behaviour is completed.

The second problem listed above is that of normalisation of the profile. This is normally done on the assumption that the signal returned from between 30 to 40 km. is uncontaminated by aerosol scatter. Normalisation at these altitudes may then be carried out by reference to either a standard atmosphere or to balloon soundings. More accurate normalisation was attempted by a comparison with flights of high altitude meteorological balloons made by the Jamaican Meteorological Service. Unfortunately this comparison failed due to a particularly poor batch of balloons supplied at the time of the experiment. With the Mark II system there is the disadvantage that the normalisation has to be transformed from one photomultiplier to another. When the system was designed it was anticipated that the sensitivity ratio of the photo-multiplier would not change appreciably over a short interval of time. This has proved to be incorrect and it is necessary to determine the sensitivity ratio by periodically alternating the switching heights between photomultipliers. The accuracy with which this sensitivity ratio can be determined is shown in Figure 1. It can be seen that it limits the overall accuracy of measurements on PM-1 to about 5% for this particular profile. In order to improve the system the new counter has been designed to allow parallel counting so that a permanent overlap between photomultipliers may be achieved and the possible fitting error reduced. This has so far only been tested for photomultipliers 1 and 2 but it is found to be a considerable improvement over the former arrange-ment. A final area which may give some uncertainty of the atmospheric profiles measured is the possibility of a change of composition with height, such as the influence of disassociation of the oxygen molecule with height. This effect is believed to be very small, particularly below 100 km.

A summary of the discussion above may be made as follows.

(1) Relative density measurements within the range of a single photomultiplier may be made (at night, at new moon) with an accuracy comparable to that of rocket techniques, provided 2 hours continuous operation is possible.

(2) Accuracy of normalisation is rather less than was hoped for owing to the difficulties of determining accurately the relative photomultiplier sensitivity. This problem may, to a large extent, be limited by use of a suitably designed counter.

(3) There is still some doubt as to the absolute reliability of the signals received from above 90 km.

(4) No evidence of scattering from atmospheric dust at great altitudes has been obtained except during the observations made at the time of influx of dust from Comet Bennett.

(5) A completely reliable assessment of the system performance cannot be given without accompanying rocket flights and even then will be subject to the uncertainties inherent in rocket techniques.

In conclusion it may be pointed out that original results on variations in atmospheric density above 70 km. have been obtained and that these were not hitherto available from rocket measurements (Appendix III).

(iii) Reliability

The following is a fairly detailed account of the major faults that have occurred with the system:

(1) Transmitting system

(a) Laser Head

The cavity and laser head supplied by Spacerays for the experiment has performed reliably during the course of the last few years and has not required modification in any way. However the original ruby rod had to be replaced in October 1970. The old rod showed signs of deterioration during the course of a night's run and the lasing threshold increased to about 3.0 kv. Minor problems have been encountered with the metal clamps for the ruby as the chromium coatings have been slowly disintegrating and in some cases being burnt on to the ruby rod. This has given rise to some surface damage on the rod but it does not appear to have any effect on the performance.

Periodic changes of flash lamp have been required, the average lifetime being of the order of 50,000 shots per lamp at voltages up to 2.8 kv. Difficulties have been encountered due to the spread of triggering voltages of the lamps, especially after they have been in use for some time. The slow drop off in performance of the lamps is not always immediately evident and on occasions a poor flashlamp has been in the laser for quite some time.

The quartz end-flat has suffered severe pitting due to dust being burnt onto its surface and has had to be resurfaced. Similar problems have been encountered with the Q-switch prism, although not to the same degree. However the prism has had to be replaced due to chips coming off the corners of the original.

No damage is apparent in the cavity itself but it requires careful cleaning every ten thousand firings.

(b) Power supply and control unit

This section of the laser equipment has proved to be the most unreliable.

The main rectifier stack in the charging unit failed completely on one occasion, causing a large storage capacitor to go short circuit and several other components to become faulty.

Triggering difficulties such as multiple triggering have occurred and are due mainly to the spark gap arrangement which requires frequent maintenance. These trigger pulses have also produced serious problems of noise pickup with the new high speed counter system. This has necessitated screening all the cables from the charging banks to the laser head. The high voltages involved in the trigger pulse have caused breakdown to occur in the plugs and sockets on the discharge leads, giving rise to frequent explosions. The type of connections used in the main capacitor banks have caused periodic trouble since they are not mechanically rigid enough to withstand the continual shock produced during discharge and this has led to several short circuit discharges in these units.

The control circuitry in the main unit has never functioned completely adequately due to thermal effects. The heat dissipated in the main rectifier stack, which is located in this unit, affects the semiconductor components on the control cards to such an extent that at times it is not possible to trigger the flashlamps. The automatic firing and timing units have not worked successfully for any length of time. Some of these problems have been overcome by the addition of a large fan in the top of the rack but this is not completely successful. Due to insufficient documentation and incorrect circuit diagrams the repair and maintenance of these circuits has been more arduous than necessary.

(c) The cooling system

The cooling system for the ruby rod and the flashlamps has proved to be fairly reliable except for one major breakdown earlier this year when a leak developed on the heat exchanger which controls the water temperature around the ruby rod. The system has now been overhauled and operates within its specifications.

(d) Associated electronics

The Q-spoiler pickup pulse, fluorescent shutter, and photomultiplier shutter pulses and the synchronisation unit have all functioned successfully although problems have arisen due to the gradual drift of these pulses during the course of a run. This is mainly due to the variation in drive to these motors during the time for which the laser is charging but this has been partially overcome by redesigning the drive amplifiers.

Serious damage was done to the pickup amplifier in July 1971 when the tower was struck by lightning, but this has now been rectified. In general the transmitting section has been capable of providing all that has been demanded of it but periodic breakdowns have caused serious delays in certain cases. As a routine, the laser head and power supply are given a complete check every month to ensure that it is capable of being used when wanted.

(2) Receiver system

(a) Mirror installation and optical arrangement

At present only 24 of the complement of 36 mirrors envisaged have been erected and aligned, although 6 more are now in Jamaica and await erection. The fundamental design and layout of the system has not been altered from that previously described (Report No.20). Difficulties have been encountered in keeping the mirrors completely clean due to condensation which accumulates on them during the course of a run, thus causing a slight deterioration in the measured signal. The same problem has occurred on the diagonal up the tower but it has been found possible to put a heating coil on the back surface of the mirror and this appears to keep it condensation free.

Temperature cycling effects in the photomultiplier housing have given rise to deterioration in the narrow band filter in front of the photomultiplier tube. The housing is continually flushed with dry nitrogen to avoid condensation occurring on the photomultiplier prism when it is cooled by the Peltier unit. It is not certain, however, if this completely eliminates condensation from the prism face or if the canada balsam which cements the prism to the photomultiplier tube undergoes refractive index changes. As mentioned in Section 3(a)(ii) so far unexplained variations in photomultiplier sensitivity over periods of the order of an hour give rise to difficulties in interpretation of data.

(b) Electronics associated with the detection and counting of photons

The E.M.I. 9558 photomultipliers used as detectors have been extremely reliable, apart from the variations in the relative sensitivities of the tubes. Some of this may be due to slight instabilities in the photomultiplier preamplifiers which tend to be sensitive to large signal inputs. This occurs when the photomultiplier is overloaded due to large scattered returns from the lower atmosphere.

This effect has been partially overcome by the rotating shutter in front of the photomultiplier, but since the shutter takes several hundred microseconds to open completely, a certain percentage of the overload signal still reaches the photomultiplier. Further addition of a blanking unit, which only allows the EHT on the dynode chain for a given period of time has led to a reduction in this overload problem.

The original counting system (Report NO13) was designed to work using a magnetic core in which to store the information obtained from different heights sequentially. However this system has had to be abandoned in April 1970 due to major instabilities in the read and write gates associated with feeding information to and obtaining information from the core store. These instabilities gave rise to the production of spurious signals leading to erroneous counts.

The new high speed counting system has a frequency capability in excess of 75 MHz and has parallel counters. This is in contrast to the old system which had one counter which was used for all height ranges. With parallel counters it is possible to measure the signal simultaneously on different photomultipliers. A considerable increase in flexibility of channel width and start height has also been incorporated.

(iv) Measurements

Table I shows the principal operating periods with the Mark II system. These began in July 1968 as part of equipment development and testing, but no observations of scientific value were made before March, 1970. The list is continued through to October 1971 to include all measurements made before the date of this report. Some discussions have been made in Section 3(a) of the objective of these observations and this will not be repeated here.

The final column of Table 1 lists the status and value of the data obtained. It can be seen that all data obtained after October 1970 is still in course of analysis. A preliminary study has however been made of this and there is little doubt that it is of considerable scientific value. The observations made in March-April 1970 (Appendix III) have shown the existence of atmospheric tidal oscillations at heights between 70 and 100 km and it has been possible to make a comparison of the observed properties with those expected theoretically. The more recent data supports this earlier work and it is hoped that when the analysis is complete that it will be possible to comment on the seasonal changes in the region. The observations at expected times of cometary dust (May 1970 and February 1971) have already been commented upon (Section 3(a)(ii) and the Raman scattering measurements are still preliminary.

Two points are worth noting from the table which relate to the performance of the system. The first is that operation has been achieved for several days in succession (this is normally limited by weather rather than technical problems); the second is that the number of firings possible in a single night has risen from a few hundred or even less in 1968 to over 3000 in 1971.

TABLE I

Principal operating periods with the Mark II Laser Radar System

| Date | Time | No of Firings | Objective | Value and status of data obtained |
|---|---|---|---|---|
| 15. 7.68 | 2205-2340 | 100 | Equipment test and development and preliminary atmospheric investigation | Data analysed. Fulfilled required function for equipment testing but of little meteorological interest. |
| 18. 7.68 | 2130-2310 | 100 | | |
| 10. 9.68 | 1945-2025 | 30 | | |
| 15.11.68 | 0050-0130 | 30 | | |
| 24.12.68 | 2314-2400 | 100 | | |
| 25.12.68 | 0000-0115 | 140 | | |
| 23. 2.69 | 0030-0115 | 100 | | |
| 25. 3.69 | 0010-0230 | 300 | | |
| 21-22. 4.69 | 2215-0005 | 170 | | |
| 22. 4.69 | 0450-0504 | 25 | | |
| 26. 4.69 | 0330-0420 | 150 | | |
| 27. 4.69 | 0315-0420 | 100 | | |
| 8. 5.69 | 1940-2030 | 150 | | |
| 12. 5.69 | 2005-2040 | 100 | | |
| 15-16. 5.69 | 1950-0405 | 800 | All night atmospheric study | Accuracy limited, maybe useful in conjunction with other data |

**TABLE I continued:**

| Date | Time | No.of Firings | Objective | Value and status of data obtained |
|---|---|---|---|---|
| 13. 2.70 | 0005-0130 | 200 | System test | |
| 28.2 - 1 . 3.70 | 2020-0010 | 800 | To study mesospheric density variations | First set of data of real meteorological value. Data analysed and in course of publication |
| 4 - 5 - 3.70 | 2000-0545 | 1800 | | |
| 5- 6 . 3.70 | 1930-0530 | 1800 | | |
| 6- 7 . 3.70 | 2035-0500 | 1200 | | |
| 7- 8 . 3.70 | 1915-0535 | 1600 | | |
| 5- 6 . 4.70 | 1925-0505 | 1400 | | |
| 6- 7 . 4.70 | 1915-0500 | 1800 | | |
| 7- 8 . 4.70 | 1910-0445 | 1600 | | |
| 4 . 5.70 | 2020-2240 | 250 | To study the feasibility of dust from Comet Bennett entering the earth's atmosphere | A positive result obtained, data analysed and published |
| 7. 5.70 | 0200-0430 | 160 | | |
| 7- 8 . 5.70 | 2130-0100 | 260 | | |
| 8 . 5.70 | 2030-2240 | 280 | | |
| 9- 10. 5.70 | 2350-0150 | 280 | | |
| 10. 5.70 | 2140-2330 | 280 | | |
| 11. 5.70 | 2110-2330 | 120 | | |

TABLE I continued:

| Date | Time | No.of Firings | Objective | Value and status of data obtained |
|---|---|---|---|---|
| 2- 3 . 7.70 | 2120-0500 | 500 | To study mesosphere density variations | Datu too limited to be of significant use |
| 5- 6 . 7.70 | 1952-0312 | 450 | | |
| 4 . 8.70 | 1943-2040 | 200 | | |
| 6 . 8.70 | 2150-2225 | 150 | | |
| 7 . 8.70 | 1930-2015 | 200 | | |
| 30.9 - 1 .10.70 | 2120-0230 | 1200 | To investigate photomultiplier overload effects | Data somewhat inconclusive |
| 2- 3 .10.70 | 1910-0510 | 2000 | To study mesospheric density variations | Data still in course of analysis |
| 29- 30.10.70 | 2034-0227 | 1000 | | |
| 30- 31.10.70 | 1850-0430 | 1800 | | |
| 1- 2 .11.70 | 1905-0510 | 1800 | | |
| 2- 3 .11.70 | 1822-0315 | 1000 | | |
| 27- 28.11.70 | 1840-0530 | 1800 | | |
| 30.11- 1 .12.70 | 1830-0520 | 2000 | | |
| 2- 3 .12.70 | 1837-0336 | 1000 | | |
| 20- 21. 2.71 | 1955-0510 | 1400 | To study possibility of dust entering the earth's atmosphere from Comet Enke | A negative result on dust but data of meteorological value. Still in course of analysis. |
| 21- 22. 2.71 | 2135-0510 | 1200 | | |
| 23- 24. 2.71 | 1910-0515 | 1400 | | |

**TABLE I continued:**

| Date | Time | No.of Firings | Objective | Value and status of data obtained |
|---|---|---|---|---|
| 26-27. 6.71 | 2020-0440 | 2000 | To study meso-spheric density variations | Data still in course of analysis |
| 12. 7.71 | 2300-2320 | 100 | To study Raman scattering from nitrogen | Useful data obtained |
| 21. 7.71 | 2015-2115 | 400 | ) | |
| 23-24. 7.71 | 1943-0432 | 1600 | )To study )mesospheric )density )variations | Useful data obtained |
| 24-25. 7.71 | 2030-0430 | 2000 | ) | |
| 26-27. 7.71 | 1958-0435 | 2000 | ) | |
| 27-28. 7.71 | 2034-0445 | 1800 | ) | |
| 25-26. 8.71 | 2130-2817 | 1200 | ) | |
| 1 . 9.71 | 2230-2330 | 200 | )To study Raman )scattering from )nitrogen | Useful data |
| 6-7 . 9.71 | 2330-0010 | 400 | ) | |
| 10-11 .9.71 | 1930-0307 | 2200 | )To study meso- )spheric density )variations | Data still in course of analysis |
| 11-12 .9.71 | 1941-0315 | 2000 | ) | |
| 24-25.10.71 | 1934-0457 | 3000 | ) | |
| 26-27.10.71 | 1840-2900 | 3400 | ) | |

## 3.(b) Mark III System

### (i) Introduction

As explained in Section 2, the Mark III system was designed to make measurements of the atmospheric transmission coefficient T, and also to study the 20 km. aerosol layer. It was designed as a portable, steerable unit and has been described in detail in Report No.31. The design and operation of the associated electronic counting and display unit has been described in Report No.15. The following sections give an assessment of its performance and reliability together with a list of observational periods.

### (ii) Performance

In terms of the ability of the equipment to measure the transmission coefficient, the Mark III system has been completely successful. The capabilities of the system are more than adequate for the purpose of obtaining a T value up to 18 km within 10 minutes (Ottway et al, 1970). The full potential for making swept measurements over a range of zenith angles to observe horizontal gradients and the variation of T with altitude, has not yet been exploited.

The system has also been well suited to the investigation of the 20 km aerosol layer and some useful data has been collected. The recent addition of a receiver shutter with new synchronising circuitry, an adjustable mount for a frequency doubling crystal, a rotating filter holder and another bank of ten receiver channels has further increased the versatility of the system. The design and installation of a proper frequency limited pulse amplitude discriminator and a second photomultiplier would further increase its sensitivity and usefulness.

(iii) Reliability

The overall reliability of the system has been very good, except for the laser head and its power supply. These are commercial units manufactured by Spacerays Inc. Early in the life of the system the power supply charging unit had to be rebuilt, and the lifetime of the reflection coating on the glass cavity was rarely better than five hundred shots. As this 101-6 model became obsolete in 1969, in order to be able to continue experiments a new all metal cavity was designed and built. This was a complete success, firing a high output and retaining its aluminium coating for 5000 shots before recoating.

Early in 1971 however, Spacerays Inc. kindly provided one of their new twin flash tube 101-6 cavities, which was installed. This required twice the trigger voltage, which unfortunately necessitated thorough screening of the H.T. cables between the power supply and the laser head. This was to prevent high frequency pickup from interfering with the operation of the electronic counting unit.

The only other cause for concern has been the tendency of the narrow band interference filter in the receiver to shift off frequency. This is possibly due to insufficient protection against moisture by the manufacturer.

Use has been made of balloon meteorological measurements made at the same time as the Mark III observations for accurate normalization of the results.

(iv) Measurements

TABLE II

List of Atmospheric Profiles from Mark III Laser Radar

1968

| Date | Time | Height Range | No. of Shots | |
|---|---|---|---|---|
| 23. 4.68 | 2130-2300 | 8 to 30 | 30V.;20 ob. | T = 0.77 ± 0.02 |
| 24-25.4.68 | 2245-0015 | 8 to 26 | 40V.;30 ob. | T = 0.85 ± 0.02 |
| 2 . 5.68 | 2150-2400 | 8 to 26 | 40V.; 40 ob. | T = 0.84 ± 0.02 |
| 24. 7.68 | 2245-2400 | 10 to 26 | 20V.; 20 ob. | T = 0.86 ± 0.02 |
| 7-8.8.68 | 2300-0010 | 6 to 36 | 54 total | Can just be normalised<br>Shows possibly volcanic dust |
| 12-13.8.68 | 2315-0055 | 6 to 24 | 40V.; 40 ob. | T = 0.78 ± 0.02. Ditto. |

1969

| | | | | |
|---|---|---|---|---|
| 22-23.6.69 | 2400-0040 | 14 to 30 | 40V.; 40 ob. | T = 0.87 ± 0.02 |
| 9. 7.69 | 0330-0445 | 14 to 32 | 40V.; 40 ob. | T = 0.75 ± 0.02 |
| 9. 7.69 | 0445-0500 | 24 to 44 | 20 | Can just provide normalisation |
| 9.10. 69 | 2330-0030 | 14 to 32 | 20V.; 20 ob. | T = 0.73 ± 0.02 |
| 9-10.7.69 | 2330-2400 | 24 to 44 | 40 | Can just provide normalisation |
| 22. 7.69 | 0200-0325 | 14 to 32 | 50V.; 40 ob. | T = 0.75 ± 0.02 |
| 22. 7.69 | 0200-0230 | 24 to 44 | 60 | Can just provide normalisation |
| 22. 7.69 | 0330-0340 | 30 to 60 | 20 | |
| | ALL runs before 26.12.69 Used NO SHUTTERS | | | |
| 26.12.69 | 2030-2100 | 10 to 30 | 30 | Use fluorescence shutter |

1970

| | | | | |
|---|---|---|---|---|
| 6-7.4.70 | 2016-0051 | 24 to 44 | 450 | Scrapped due to contamination above 30 km. |

**TABLE II continued:** **1971**

| Date | Time | Height Range | No. of Shots | Comments |
|---|---|---|---|---|
| 26. 1.71 | 0045-0220 | 12 to 32 | 200 | |
| | 0310-0405 | " | 200 | |
| | 0445-0545 | " | 200 | |
| | 0558-0632 | " | 200 | |
| 8-9.2.71 | 1930-2035 | 12 to 32 | 100 | |
| | 2306-0055 | " | 80 | |
| 9 . 2.71 | 0236-0256 | 12 to 32 | 50 | $\lambda$= 347.15 nm. |
| | 0114-0333 | " | 80 | |
| 13. 2.71 | 1855-1902 | 12 to 32 | 40 | |
| 22. 2.71 | 0150-0207 | 20 to 40 | 100 | Using p/m 3,Mk.II system |
| | 0215-0246 | 28 to 68 | 100 | Ditto |
| 23. 2.71 | 0253-0315 | 28 to 68 | 100 | Ditto |
| 24. 2.71 | 0325-0350 | 32 to 72 | 100 | Ditto |
| | 0504-0524 | " | 100 | Ditto |
| 10. 3.71 | 0120-0247 | 22 to 42 | 400 | |
| | 0312-0348 | 12 to 32 | 100 | |
| | 1938-1949 | " | 100 | |
| 17. 3.71 | 1921-2113 | 22 to 42 | 400 | |
| | 2115-2151 | 12 to 22 | 200 | |
| 17-18.3.71 | 0040-0334 | 22 to 42 | 326 | |
| 25. 3.71 | 1953-2034 | 12 to 32 | 200 | |
| | 2059-2432 | 22 to 42 | 400 | |
| 2 . 4.71 | 0300-0343 | 12 to 32 | 200 | |
| | 0345-0453 | 22 to 42 | 400 | |
| | 0457-0530 | 12 to 32 | 200 | |
| 15-16.4.71 | 2350-0129 | 12 to 32 | 200 | |
| | 0143-0340 | 20 to 40 | 300 | |
| | 0350-0410 | 11 to 22 | 100 | $\theta = 60^{o}$N.W. |
| | 0412-0442 | 12 to 32 | 200 | |
| 29. 6.71 | 0011-0108 | 12 to 32 | 200 | First run using Rx shutter and new laser cavity |
| | 0155-0301 | 22 to 42 | 243 | |

TABLE II continued:

| Date | Time | Height Range | No. of Shots | Comments |
|---|---|---|---|---|
| 12. 7.71 | 2258-2330 | 14 to 34 | 87 | Preamplifier destroyed |
| 14-15.7.71 | 2349-0120 | 14 to 34 | 200 | |
| | 0145-0405 | 22 to 42 | 400 | |
| 16. 7.71 | 0123-0201 | 12 to 32 | 200 | |
| | 0205-0325 | 20 to 40 | 400 | |
| 19. 7.71 | 0225-0315 | 12 to 32 | 200 | |
| | 0316-0429 | 22 to 42 | 400 | |
| 21. 7.71 | 2310-2330 | 12 to 32 | 100 | Signal ÷ 20 due to haze and cloud |
| | 2330-2335 | 8 to 28 | 10 | |
| 23-24.7.71 | 2323-0223 | 24 to 44 | 400 | Using p/m 3 Mk.II system |
| | 0232-0322 | 16 to 36 | 250 | |
| | 0324-0440 | 24 to 44 | 350 | |
| 24-25.7.71 | 2100-2230 | 22 to 42 | 400 | |
| | 2236-2315 | 16 to 36 | 200 | |
| | 2315-0130 | 22 to 42 | 400 | |
| | 0135-0225 | 16 to 36 | 300 | |
| | 0230-0340 | 22 to 42 | 400 | |
| | 0400-0435 | 16 to 36 | 200 | |
| 26-27.7.71 | 2000-2055 | 16 to 36 | 200 | |
| | 2100-2230 | 24 to 44 | 400 | |
| | 2245-2330 | 16 to 36 | 199 | |
| | 2330-0120 | 24 to 44 | 400 | |
| | 0140-0233 | 14 to 34 | 300 | |
| | 0233-0415 | 20 to 40 | 400 | |
| | 0420-0440 | 16 to 36 | 100 | |
| 27-28.7.71 | 2030-2240 | 16 to 36 | 250 | |
| | 2240-2325 | " | 250 | |
| | 2325-2400 | " | 200 | |
| | 0002-0107 | 20 to 40 | 400 | |
| | 0109-0142 | 16 to 36 | 200 | |
| | 0310-0335 | 28 to 48 | 200 | |
| | 0335-0339 | 16 to 36 | 200 | |
| | 0335-0359 | 16 to 36 | 200 | |
| | 0405-0455 | 16 to 36 | 200 | |

TABLE II continued:

| Date | Time | Height Range | No. of Shots | Comments |
|---|---|---|---|---|
| 11-12.8.71 | 2235-2322 | 16 to 36 | 200 | p/m calibration off |
| | 2325-0033 | 20 to 40 | 400 | |
| | 0118-0256 | 14 to 34 | 300 | |
| 12-13.8.71 | 2329-2414 | 16 to 36 | 200 | |
| | 2417-0134 | 20 to 40 | 400 | |
| | 0145-0215 | 12 to 32 | 200 | |
| 14. 8.71 | 0058-0135 | 16 to 36 | 200 | |
| | 0138-0240 | 20 to 40 | 400 | |
| 15. 8.71 | 0120-0210 | 16 to 36 | 200 | |
| | 0211-0330 | 20 to 40 | 400 | |
| 19. 8.71 | 0237-0324 | 16 to 36 | 200 | |
| | 0328-0437 | 20 to 40 | 400 | |
| 25-26. 8.71 | 2238-2345 | 16 to 36 | 329 | Using p/m 3 Mk.II system |
| | 0115-0335 | 16 to 36 | 400 | |
| | 0340-0423 | 20 to 40 | 200 | |
| 6 . 9.71 | 2215-2410 | 16 to 36 | 400 | Using p/m 3 Mk II system |
| 7 . 9.71 | 0215-0235 | 16 to 36 | 90 | p/m calibration off |
| 8 . 9.71 | 0129-0148 | 22 to 42 | 100 | Ditto |
| 8 . 9.71 | 0129-0148 | 22 to 42 | 100 | Ditto |
| 10-11.9.71 | 2100-2240 | 16 to 36 | 212 | Using p/m 3 Mk.II system |
| | 2247-2350 | 20 to 40 | 400 | |
| | 2400-0054 | 16 to 36 | 300 | |
| | 0058-0149 | 24 to 44 | 300 | |
| | 0155-0238 | 16 to 36 | 300 | |
| | 0240-0310 | 20 to 40 | 200 | |
| 11-12.9.71 | 2356-0117 | 18 to 38 | 414 | |
| 9-10.10.71 | 2347-0101 | 20 to 40 | 400 | p/m calibration now O.K. |
| | 2347-0101 | 20 to 28 | 400 | Using 0.8 km gates in parallel |
| | 0127-0204 | 16 to 36 | 200 | |
| | 0212-0235 | " | 100 | |
| | 02[illegible]2-0235 | 16 to 56 | 100 | Using 4 km. gates in parallel |
| | 0321-0355 | 12 to 32 | 200 | Check with 2 km gates in parallel |

## 4. CONCLUSION

Two instruments have been constructed, one to study the whole atmosphere up to a height of 100 km, the other to measure atmospheric transmission and to study the 20 km aerosol layer. The main objectives of both can be said to have been achieved and work of scientific value has and still is being done on these instruments. The work with both systems now gives the information necessary to design a model system for use elsewhere capable of giving results comparable to those obtained from the use of rockets.

## 5. CONTINUING WORK

### (a) Photomultiplier studies

Studies of the increased noise effects due to overload effects on the photomultipliers is continuing. This should enable the high altitude measurements to be corrected for this effect.

### (b) Raman scattering studies

By using different filters it is possible to obtain height profiles of the concentration of various atmospheric constituents. Present observations are being made on nitrogen and these appear successful; an extension to study water vapour is being considered.

### (c) Resonant scattering

A dye laser tuned to the potassium line has been constructed. It is hoped to measure the density of potassium atoms in the atmosphere. Similar experiments may be carried out on Sodium.

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Ottway, M.T., Wright, R.W. and Kent, G.S. J.Atmos.Terr.Phys. 33 1337, 1971

# APPENDIX I

## Personnel engaged on Project

### Scientific

Dr. B.R.Clemesha

Mr. F. Felix

Mr. M. Garvey

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Mr. R. Chapman

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## APPENDIX II - BIBLIOGRAPHY

### (a) REPORTS SUBMITTED

| Grant Period Covered | Title |
|---|---|
| April 1 - June 30, 1964 | Progress Report No.1 |
| July 1 - September 30, 1964 | Progress Report No.2 |
| Oct. 1 - December 31, 1964 | Progress Report No.3 |
| April 1,1964 - March 31,1965 | Scientific Report No.2 |
| April 1 - June 30, 1965 | Progress Report No. 5 |
| July 1 - September 30,1965 | Progress Report No.6 |
| Oct. 1 - December 31, 1965 | Progress Report No.7 |
| Jan. 1 - March 31, 1966 | Progress Report No.8 |
| May 1 - July 31, 1966 | Progress Report No.9 |
| Aug. 1 - October 31, 1966 | Progress Report No.10 |
| Nov. 1,1966-January 31,1967 | Progress Report No.11 (Final Report for period May 1,1966- Jan.31, 1967) |
| Feb.1 - April 30,1967 | Progress Report No.12 |
| May 1 - July 31, 1967 | Progress Report No.13 |
| Aug. 1 - October 31, 1967 | Progress Report No.14 |
| Nov. 1,1967 - Jan. 31,1968 | Progress Report No.15 |
| Feb. 1 - July 31, 1968 | Scientific Report No.20 (Semi-annual Report) |
| Aug. 1, 1968- Feb.1,1969 | Scientific Report No.22 |
| Feb.1 - June 30, 1969 | Scientific Report No.27 (Final Report for period Feb.1,1967 - June 30,1969) |
| July 1 - Dec.31, 1969 | Scientific Report No.31 |
| Jan.1,1970 - June 30,1971 | Scientific Report No.43 (Final Report for period April 1,1964 - June 30,1971) |

APPENDIX II continued:

(b) PUBLICATIONS

1. "Laser probing the lower Atmosphere"
   by B.R.Clemesha, G.S.Kent and R.W.Wright
   Nature 209, 184-185, 1966

2. "Optical radar evidence for atmospheric dust layers around 85 km.altitude"
   by B.R.Clemesha, G.S.Kent and R.W.Wright
   Nature 214 261-262, 1967

3. "A laser radar for atmospheric studies"
   by B.R.Clemesha, G.S.Kent and R.W.Wright
   J.Appl.Meteor. 6, 386-395, 1967

4. "High altitude atmospheric scattering of light from a laser beam"
   by G.S.Kent, B.R.Clemesha and R.W.Wright
   J.Atmos.Terr.Phys. 29, 169-181,1967

5. "Investigation of the strato-spheric aerosol by infra-red and lidar techniques"
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7. "Laser radar observations of dust from Comet Bennett"
   by G.S.Kent, W.Keenliside and M.C.W.Sandford
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8. "A second generation laser radar"
   by G.S.Kent, P.Sandland and R.W.Wright
   J.Appl.Meteor. 10,443-452, 1971

9. "Measurement in Jamaica of the optical transmission coefficient of the atmos-phere for the wavelength 694.3 mm"
   by M.T.Ottway, R.W.Wright and G.S.Kent
   J.Atmos.Terr.Phys. 33,1337-1343,1971

10. "Laser radar observations of atmospheric tides in the 70-100 km.height region"
    by G.S.Kent, W.Keenliside, M.C.W.Sandford and R.W.Wright
    Accepted by:
    J.Atmos.Terr.Phys. for publication.

# APPENDIX III

## Laser Radar Observations of atmospheric tides in the 70-100 km. height region

by

G.S. Kent

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and

R.W. Wright

## ABSTRACT

Laser radar observations are described that have been made on the optical scattering cross-section of the mesosphere and lower thermosphere. Variations in scattering cross-section are seen which are attributed to atmospheric density fluctuations produced by tides. Values are obtained for the apparent period, vertical wavelength and amplitude of these variations, and it is shown that these are consistent with the theoretical predictions for the $\Theta_1^{\omega,1}$ and $\Theta_3^{\omega,1}$ modes of the solar diurnal thermal tide.

## 1. Introduction

Several laser-radar establishments have reported observations of scattering from atmospheric molecules at heights up to 100 kilometres (Silverberg and Poultney, 1967; Sandford, 1968; Kent and Wright, 1970). These authors have been principally concerned with discussing how well their experimental results fit the theoretical predictions based on the standard atmosphere. Sandford claims to have detected the expected seasonal changes in scattering cross-section but hitherto, no measurements of short-term variations have been possible. The Mark II Laser-radar system at Kingston, Jamaica (Latitude 18°N, Longitude 77°W) with a much greater sensitivity has made it possible to observe changes within a single night.

This paper describes the results of eight nights intensive observations made in March and April,1970 using this system. The variations in scattering cross-section observed at any height are attributed to changes in atmospheric density and they have been compared to those expected from the presence of atmospheric tidal oscillations.

## 2. Equipment and Observations

The laser radar system used for the observations is described by Kent and Wright (1971) and a summary of its principal parameters is given in Table I. The system was designed to be used over the height-range 30 - 100 km. It was not possible to use a single receiver system over the whole of this height-range owing to the very large dynamic range in the received signal. Instead, three separate receiver channels of different sensitivities were used, covering approximately the height-ranges 30 - 50 km, 50-70 km., and 70 - 100 km.

Each channel was switched in turn into the digital counter, a calibration of the relative sensitivities of the channel being done by periodically varying the switching heights. Unfortunately, it was found that, although in principle this method of calibration was sound, its accuracy was limited by changes in receiver sensitivity. Accordingly, in the results presented here it has not been possible to relate accurately the signal intensities observed from great altitudes to those observed from low altitudes and all measurements are presented as ratios over the height range observed on receiver channel number one.

The useful height-range covered by receiver channel number one was 72.5 - 102 km. in 12 range-gated intervals, each of length 2.0 km. and separated by 0.5 km. From a single firing of the laser, approximately 25 photons were detected in the height-range 72.5 - 74.5 km. falling to an average of 0.1 photons per shot in the height-range 100 - 102 km. The background noise, due mainly to light from the night-sky, was approximately equal to the signal in the highest gate interval. It was determined by measuring the total signal plus noise received from above 120 kilometres, where the signal may be assumed to be negligible. After allowing for corrections due to the finite receiver counting rate, and an inverse square law in distance to the centre of the scattering volume, the received signal should be proportional to the scattering cross-section of the volume being studied. On the assumption that no particulate matter is present, this will in turn be proportional to the atmospheric density there (Kent and Wright, 1970). Comparison of an average scattering profile, obtained over several thousand firings of the laser, with the density variation given in the U.S.Standard Atmosphere Supplement for 15°N (1966) showed agreement to within a few per cent over the height range 30 to 90 kilometres. Above 90 kilometres a slight increase in observed signal relative to that expected was found. The effect is believed to be due to spurious noise but this has not yet been definitely established. Its presence does not seriously affect the validity of observations above 90 kilometres provided they are expressed as ratios to each other rather than to the standard atmosphere.

The normal firing rate of the laser was approximately 7 per minute. Because of time taken in recording observations and making periodic calibration of the equipment a much lower average rate of about 200 firings per hour was usual over a long period. The number of hours of complete darkness in Jamaica at the equinoxes

## TABLE I

### The University of the West Indies

### Mark II Laser-Radar System

| | | |
|---|---|---|
| Laser | Wavelength | 694.3 nm |
| | Transmitted energy per pulse | 7 J |
| | Normal firing rate | 7 $min^{-1}$ |
| Receiver | Mirror area | 15 $m^2$ (Channels 1 & 2) |
| | | 0.11 $m^2$ (Channel 3) |
| | Photomultipliers | Three EMI 9558A's arranged to give overall sensitivity ratios of approx: 200 : 15 : 1 |
| | Filters | 2.0 nm bandwidth |
| Counting and Recording | Digital, 64 consecutive, range-gated intervals of width 2 km., separated by 0.5 km. deadtime. | |

is between ten and eleven, consequently on a night on which no serious interruption occurred, a maximum number of about 2000 firings was possible. In practice poor meteorological conditions and occasional equipmental failures reduced this number somewhat. The actual periods of observation and the numbers of firings made for the observations reported here are shown in Table II. The periods shown here were chosen to correspond to new moon as at other times scattered moonlight seriously increased the background sky noise.

TABLE II

Observation Periods

| Date | Time | No.of Laser Firings |
|---|---|---|
| 28 Feb.- 1 Mar. 1970 | 2025 - 0015 | 800 |
| 4 - 5 Mar. 1370 | 2008 - 0540 | 1800 |
| 5 - 6 Mar. 1970 | 1945 - 0530 | 1800 |
| 6 - 7 Mar. 1970 | 2100 - 0430 | 1200 |
| 7 - 8 Mar. 1970 | 1940 - 0530 | 1800 |
| 5 - 6 April 1970 | 1930 - 0510 | 1400 |
| 6 - 7 April 1970 | 1938 - 0455 | 1800 |
| 7 - 8 April 1970 | 1927 - 0440 | 1600 |

3. Analysis and Results

For analysis, each night's observations were divided into groups of 200 consecutive laser firings. It was found that this was the maximum number required to give a significant result and that any larger size of group would have given an insufficient number of independent samples on any particular night. A mean photon count was calculated for each group for each of the twelve useful height-ranges within it. The statistical accuracy of this count, which is proportional to the scattering cross-section, varied from about 1.5% for the height-range 72.5 - 74.5 to about 35% for the height-range 100 - 102 km.

Since it was not possible to obtain absolute scattering cross-sections it was necessary to compare the observed cross-sections, which were expressed as ratios, to mean values calculated from themselves. The procedure adopted for this was as follows:

(a) A mean scattering profile for the whole night was calculated. This was expressed as the ratio of the scattering cross-section in each height-range to that for the lowest height-range of 72.5-74.5 km.

(b) For each 200 firing group within the night similar scattering cross-section ratios were calculated. These were then compared to the mean ratios for the whole night at the same heights and percentage deviations from the mean ratios calculated.

(c) The two operations just described will show any variations in atmospheric scattering cross-section that occur within a single night but they will not be in a very satisfactory form since each nieght-range is expressed as a ratio to a single other height-range, namely that for 72.5 - 74.5 km. Variations which occur within this particular range, whether atmospheric or statistical, will affect all the ratios calculated. In order to avoid this, the data for each 200 firing group was normalized so that the ratios were expressed, not to the scattering cross-section for the 72.5 - 74.5 km height-range, but to a mean level calculated for the whole height-range from 72.5 - 74.5 km. This mean level was found by weighting the percentage deviation for each individual height-range by the statistical accuracy of the data in that height-range and taking an average over all heights (for that 200 firing group).

The operation of this analysis is shown in Fig.1. Fig.1(a) is a table of the scattering cross-section ratios for the whole night of 7-8 April 1970, and for one single 200 firing group on this night. In each case the ratios are taken to the height-range 72.5 - 74.5 km. The final row of the table shows the % deviations of the scattering ratios for the 200 shot group from those for the whole night and in Fig. 1(b) these values are shown plotted as a function of height; by definition, the deviation for the height-range 72.5 - 74.5 km. is zero. The error bars in Fig.1(b) are based on the statistical accuracy of the points which in turn related to the total photon count in each height-range. Fig. 1(c) shows the % deviations after normalization to the mean level chosen so that the total weighted mean deviation is zero, the

| Height Range(Km) | | 72.5-74.5 | 75-77 | 77.5-79.5 | 80-82 | 82.5-84.5 | 85-87 | 87.5-89.5 | 90-92 | 92.5-94.5 | 95-97 | 97.5-99.5 | 100-102 |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Scattering ratio to 72·5-74.5 Km ht. range | Whole Night | 1.00 | .686 | .450 | .260 | .160 | .101 | .062 | .032 | .022 | .013 | .008 | .007 |
| | 0340-0440 | 1.00 | .696 | .458 | .287 | .188 | .105 | .058 | .021 | .021 | .017 | .015 | .004 |
| % deviation during 0340-0440 | | 0 | 1.4 | 1.9 | 10.2 | 15 | 4 | -7 | -33 | -4 | 33 | 90 | -43 |

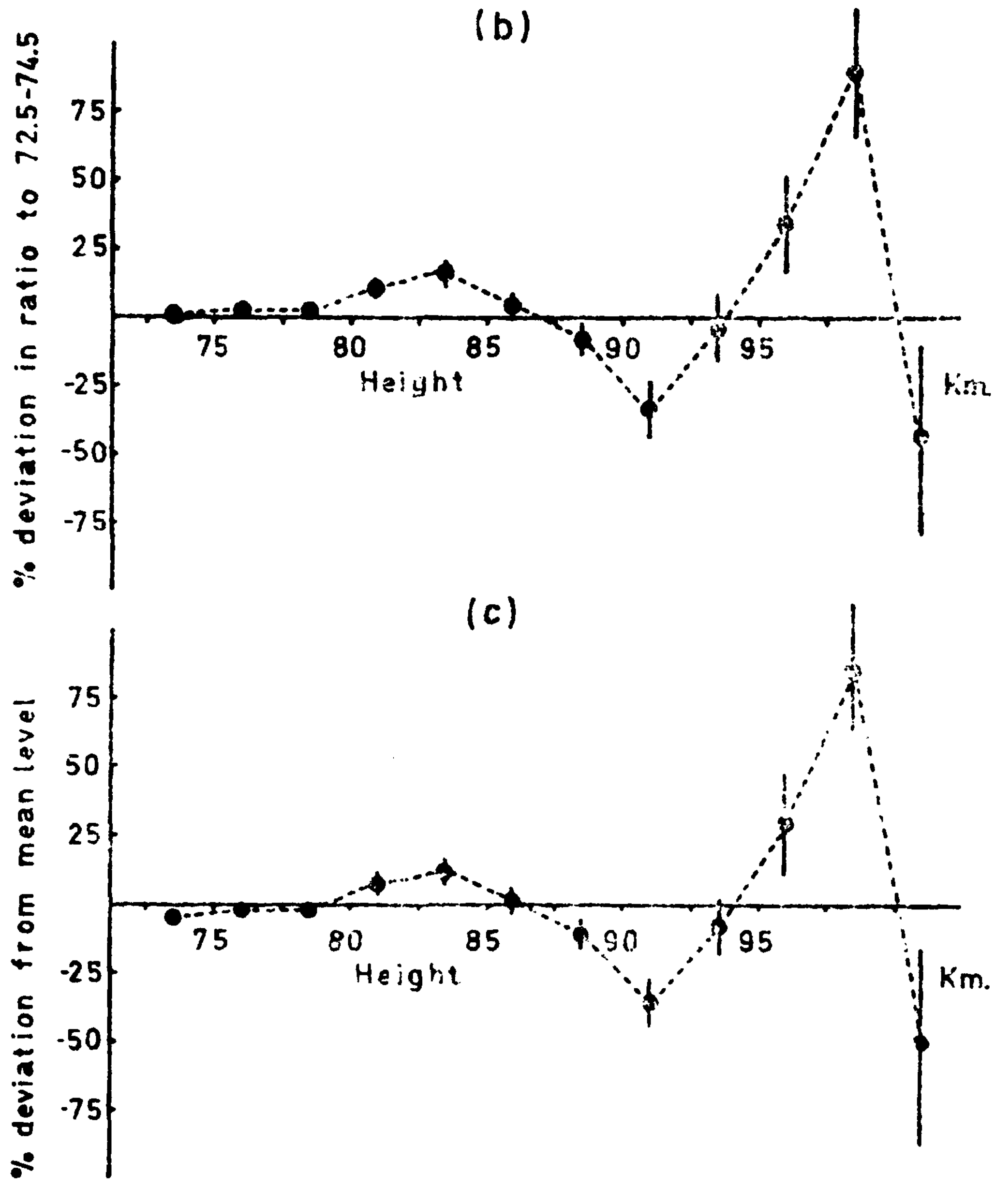


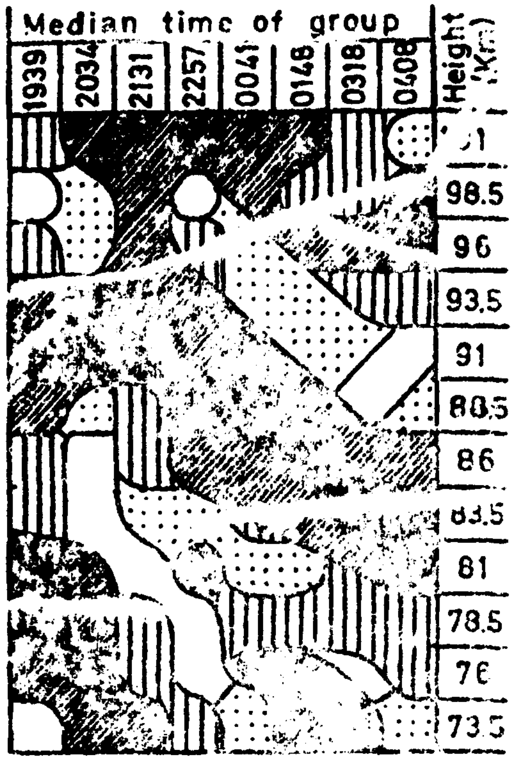

Fig 1. Method of analysis.
(a) Scattering ratios on 7-8 April, 1970.
(b) % deviations in the ratios for the 0340-0440 period.
(c) % deviations adjusted to mean level.

weighting factors being proportional to the reciprocal of the error bars shown in Fig. 1(b). It can be seen that the effect of normalization can be considerable at the lowest altitudes but that above 80 km. it does not have a great effect.

Fig. 1 shows a periodic variation in scattering ratio with altitude. This was a feature of almost all the observations taken and in addition it was found that the scattering profile descended during the night. This is illustrated in Fig. 2(a) which shows the variation of the scattering cross-section for the night of 7-8 April, 1970. The final column in Fig. 2(a)(i) shows the standard statistical error calculated on the basis of total photon count received in any height range and allowing for background noise effects. All figures are expressed as percentage deviations from the mean and it is clear that the values observed are often not much greater than the statistical error. Nevertheless, there is a definite periodic variation in space and time with a gradual descent of the profile throughout the night. This is shown in Fig. 2(a)(ii) where the same data is presented in contour form, the contour levels being in units of the standard error at each height. Similar descending profiles were obtained on all nights on which observations were made. The apparent period in time was always fairly close to 12 hours while the vertical wavelength varied between 10 and 20 kilometres.

Fig. 2(b) shows the average variation in the scattering cross-section over the whole period of observation. The observations have been averaged over two-hour intervals, approximately twelve sets of observations being made in each interval. The absolute values of the average deviations are rather less than those observed on any individual night; this is to be expected as the statistical fluctuations will be much less and also any true variation which is not correlated from one night to another will tend to cancel. In spite of this, an average behaviour is very apparent. The mean profile has an apparent period of twelve to sixteen hours, a vertical wavelength of about fifteen kilometres and a descent rate of about 1.1 km. per hour.

| Height (Km) | Median time of group: 1939 | 2034 | 2131 | 2257 | 0041 | 0148 | 0318 | 0408 | Standard Error |
|---|---|---|---|---|---|---|---|---|---|
| 101 | -13 | 20 | 30 | 57 | 0 | 27 | -33 | -58 | 34 |
| 98·5 | -48 | -25 | 23 | -53 | 12 | -8 | -23 | 86 | 24 |
| 96 | -14 | -26 | 12 | -10 | -18 | 10 | 12 | 30 | 18 |
| 93·5 | 6 | 13 | 18 | 3 | -20 | 20 | 0 | -7 | 13 |
| 91 | 12 | 17 | 21 | 3 | 9 | -13 | -15 | -36 | 9 |
| 88·5 | 1 | -9 | -5 | 25 | 9 | 0 | -14 | -11 | 7 |
| 86 | -2 | -15 | -4 | 4 | 4 | 5 | 4 | 2 | 5 |
| 83·5 | 0 | -8 | -6 | -7 | 0 | 1 | 14 | 12 | 4 |
| 81 | 3 | 1 | -8 | 5 | -4 | -3 | 0 | 8 | 3 |
| 78·5 | 5·7 | 1·7 | -1·1 | -3·1 | -0·3 | -2·0 | 0 | -1·4 | 2·5 |
| 76 | 0·2 | 5·3 | -1·2 | -5·3 | 3·2 | 3·0 | -4·2 | -1·6 | 2·0 |
| 73·5 | -2·4 | 1·0 | 0·2 | -0·8 | -2·2 | 1·6 | 4·6 | -3·2 | 1·7 |




(b)

(i)

(ii)

| Height (Km) | Time period: 1900–2100 | 2100–2300 | 2300–0100 | 0100–0300 | 0300–0500 | Standard Error (σ) |
|---|---|---|---|---|---|---|
| 101 | -11 | -4 | -16 | 21 | -9 | 10 |
| 98.5 | -13 | -4 | -1 | 6 | 10 | 7 |
| 96 | -6 | -5 | 4 | 1 | 3 | 5 |
| 93·5 | 8 | 4 | -9 | 0 | 3 | 4 |
| 91 | 8 | 1 | 2 | -4 | -6 | 3 |
| 88·5 | -3·7 | 2·9 | 0·9 | -0·1 | 1·5 | 2·0 |
| 86 | -4·7 | -2·5 | 0·7 | 5·1 | -2·0 | 1·5 |
| 83·5 | -2·2 | -2·3 | 1·1 | -0·2 | 3·5 | 1·1 |
| 81 | 2·6 | -0·8 | 1·0 | 0·3 | -0·2 | 0·9 |
| 78·5 | 1·7 | 0·7 | 0 | -2·1 | 0 | 0·7 |
| 76 | 0·5 | 1·2 | -0·3 | -0·2 | -1·1 | 0·6 |
| 73·5 | 0 | 0·3 | 0·2 | -0·6 | 0 | 0·5 |

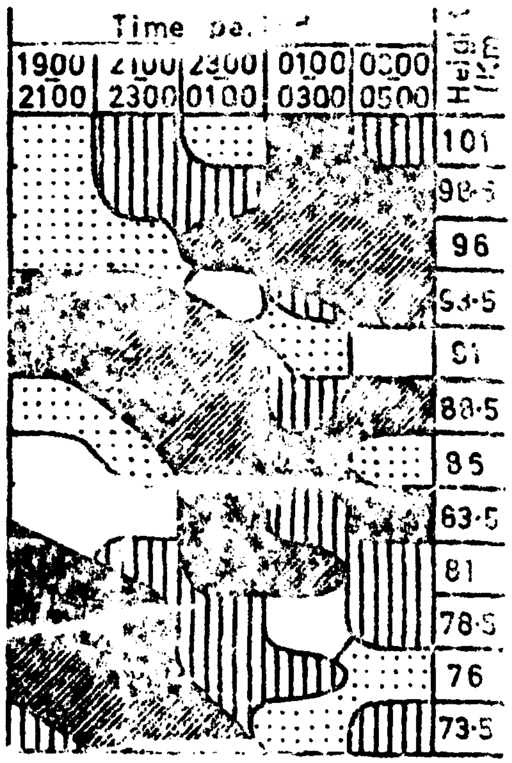





**Fig 2.** Variation of scattering cross-section with height and time of night. (Values are given as % deviations) (a) on 7-8 April, 1970. (b) mean for 8 nights.
(i) % deviations. (ii) contour plot of data in (i) in units of the standard error

## 4. Interpretation of Results

### 4.1 Theoretical Background

The data obtained is very similar in behaviour to measurements made in the same altitude range by the radio-meteor method (Spizzichino, 1969; Muller, 1966) and the chemical trail method (Rosenberg and Edwards, 1964; Murphy et al, 1966). These two techniques give information about the atmospheric winds in the mesosphere and lower thermosphere and the results have been interpreted in terms of prevailing winds, tides and gravity waves. Corresponding fluctuations in atmospheric density will occur and, on the assumption that there is no appreciable scattering from particulate matter, (Kent and Wright, 1970) the variations in scattering cross-section observed here may be interpreted directly as variations in atmospheric density.

In view of the high relative statistical error, there is probably little point in analysing the data for short-term fluctuations due to gravity waves. These will be expected to have periods from about 2 hours upwards. While on any particular occasion they may well be expected to be present, they will be difficult to detect with any certainty. Since they will have random phase and period, they will tend to average to zero when the mean behaviour over several nights is studied. It may be necessary to remember however that their effect will be to increase the apparent mean deviation observed on a single night.

An average taken over several nights will, on the other hand, be expected to show tidal effects, provided the phase of these is relatively constant. Tidal theory (Chapman and Lindzen, 1970) shows that the tidal oscillation will be made up of various modes with different periods and latitudinal and vertical structure. Table 3 shows those modes likely to be of most importance in the region of the atmosphere between 70 and 100 kilometres altitude. Of the semi-diurnal modes, the $\Theta_2^{2\omega,2}$ mode, which has an extremely long wavelength, is expected to be dominant, although at the upper end of the height range the $\Theta_4^{2\omega,2}$ and $\Theta_6^{2\omega,2}$ modes will become progressively more important . In contrast to the bahaviour of the semi-diurnal tide, none of the diurnal modes dominates the others and their relative importance depends very much on tropospheric temperature structure. All the modes have a phase which descends with time and it may be noted that the wavelength of the diurnal modes is considerably less than that of the semi-diurnal modes. Radio meteor observations (Spizzichino, 1969), have confirmed some of the theoretical predictions. Evidence has been obtained for the existence of the $\Theta_2^{2\omega,2}$ mode. Evidence has also been obtained for a diurnal oscillation with a vertical wavelength of 20-30 kilometres. This is compatible with the $\Theta_1^{\omega,1}$ mode; however the phase and period of this oscillation appears to be very irregular and to change considerably even between successive days.

TABLE 3

Tidal modes likely to be of importance in the Mesosphere and lower Thermosphere (Equinoctial Conditions)

(Designation as in Chapman and Lindzen,1970)

| Type | Description | Period | Vertical Wavelength |
|---|---|---|---|
| Migrating solar Semidiurnal | $\Theta_2^{2\omega,2}$ | 12 hours | > 150 km. |
| " | $\Theta_4^{2\omega,2}$ | 12 hours | 40 - 60 km. |
| " | $\Theta_6^{2\omega,2}$ | 12 hours | 25 - 35 km. |
| Migrating solar Diurnal | $\Theta_1^{\omega,1}$ | 24 hours | 23 - 30 km. |
| " | $\Theta_3^{\omega,1}$ | 24 hours | 9 - 12 km. |
| " | $\Theta_5^{\omega,1}$ | 24 hours | 6 - 7 km. |

4.2 Comparison with results

(a) The time variation

In order to study the time variation of the apparent density, time autocorrelation functions have been calculated of the variation in scattering cross-section on each night. An average correlation function has been derived from these which has then been corrected for the effects of statistical noise. The effect of statistical noise on the correlation function is two-fold. It reduces its amplitude by a factor that depends on the relative variance of the wanted signal and the noise, and it also displaces the whole curve negatively by an amount that depends on the relative variances and the number of sample points.

The corrected average correlation function for the whole period of operation (except for 28 February - 1 March and 6-7 March which had the two shortest times of observation) is shown in Fig.3. Because of the limited period of observation possible in a single night the function does not extend beyond a nine-hour time displacement. The general shape of the function is very clear and it is quite close to a section of a semi-wave with a period of about fourteen hours.

It might be considered, from the period just quoted, that this result constitutes strong evidence for a semi-diurnal tidal oscillation and the expected correlation function for a semi-diurnal oscillation is shown on the figure. Unfortunately the limited sampling period makes such a simple interpretation misleading. The effect of a ten hour sampling period, together with the method of relating the

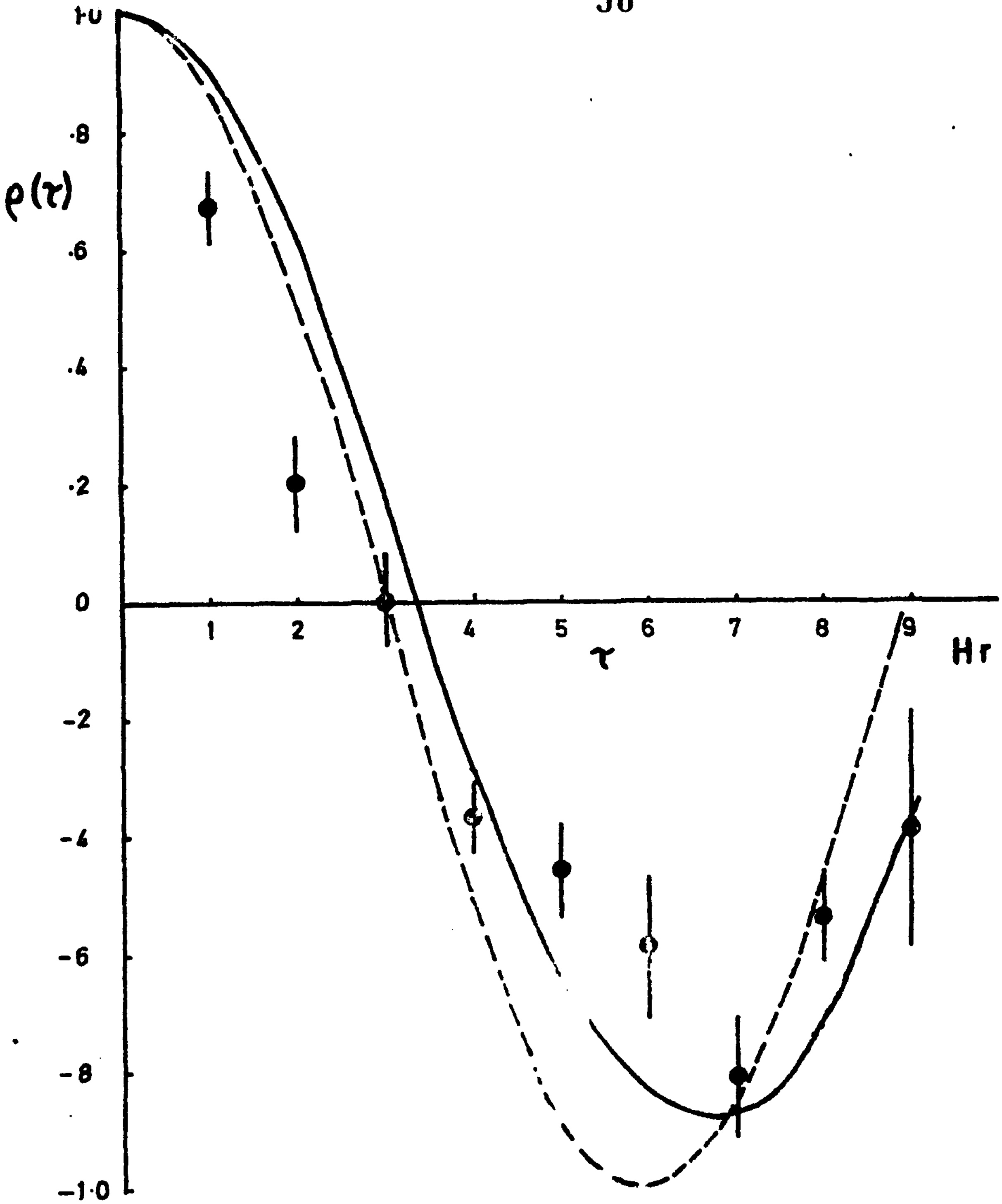



Fig 3. Time autocorrelation function
Experimental values (average for 6 days)
--- Semi diurnal tide
— Diurnal tide

scattering cross-section to a nightly mean value, causes any oscillation with a period longer than ten hours to have an apparent period that is not much greater than this figure. The effect of the sampling period on the apparent correlation function of a diurnal oscillation is also shown in Fig.3. It can be seen that it is very similar to that for the semi-diurnal oscillation, the main difference being a shift in the minimum from 6 to 7 hours. The experimental points agree better with the diurnal correlation function but the difference between the two curves is not far outside the probable limit of experimental error and it is not possible to make a definite distinction on the basis of this data alone.

The effect of the finite sampling length on oscillations whose periods are appreciably shorter than ten hours, such as would be produced by gravity waves, is small and such oscillations, if present, may be expected to modify the experimental correlation function. Some, or all, of the difference between the absolute value of experimental points and the theoretical curves may be attributed to these. The average absolute value of the difference is about 0.1, while the root mean square value of the theoretical functions is 0.5. These figures indicate that the effects of short period oscillations were not much more that 25% of those due to the long period oscillations associated with atmospheric tides.

(b) <u>The height variation</u>

As we have seen in the previous section, the mean variation with altitude of the scattering cross-section is periodic with a wavelength of about fifteen kilometres. Unlike the time variation, which consistently shows the same period, the height variation is not constant but has a wavelength which may be anywhere in the range ten to twenty kilometres although it appears constant on a given night. This difference in time and space behaviour may reflect a true difference or it may be only apparent. The effect of finite sampling period on the apparent time variation is severe but the comparable effect of finite sampling height range on wavelengths shorter than about 25 kilometres will be very small and true variations will still be present even after normalization. The effect of finite sampling height range on long wavelengths such as would be produced by the $\Theta_2^{2\omega,2}$ mode will be severe and this will be discussed in more detail below.

Mean height correlation functions have been calculated for the variation of the scattering index for each night (Because of the large variation of amplitude with height, each point has been normalized by the values given in Fig.2(a) for the standard error before calculation of the correlation function). All of these are oscillatory and that for 7-8 April 1970 is shown in Fig.4(a) where it has been corrected for statistical noise. Since considerable variation in wavelength is observed it has not been thought useful to average these functions. Instead, Fig.4(b) shows a histogram of the positions of maxima in the correlation functions. This has been chosen on the criterion that a maximum must lie at least 0.25 above its adjacent minima to be considered significant. The figure indicates which are first maxima (closest to the origin) and which are not. Also shown

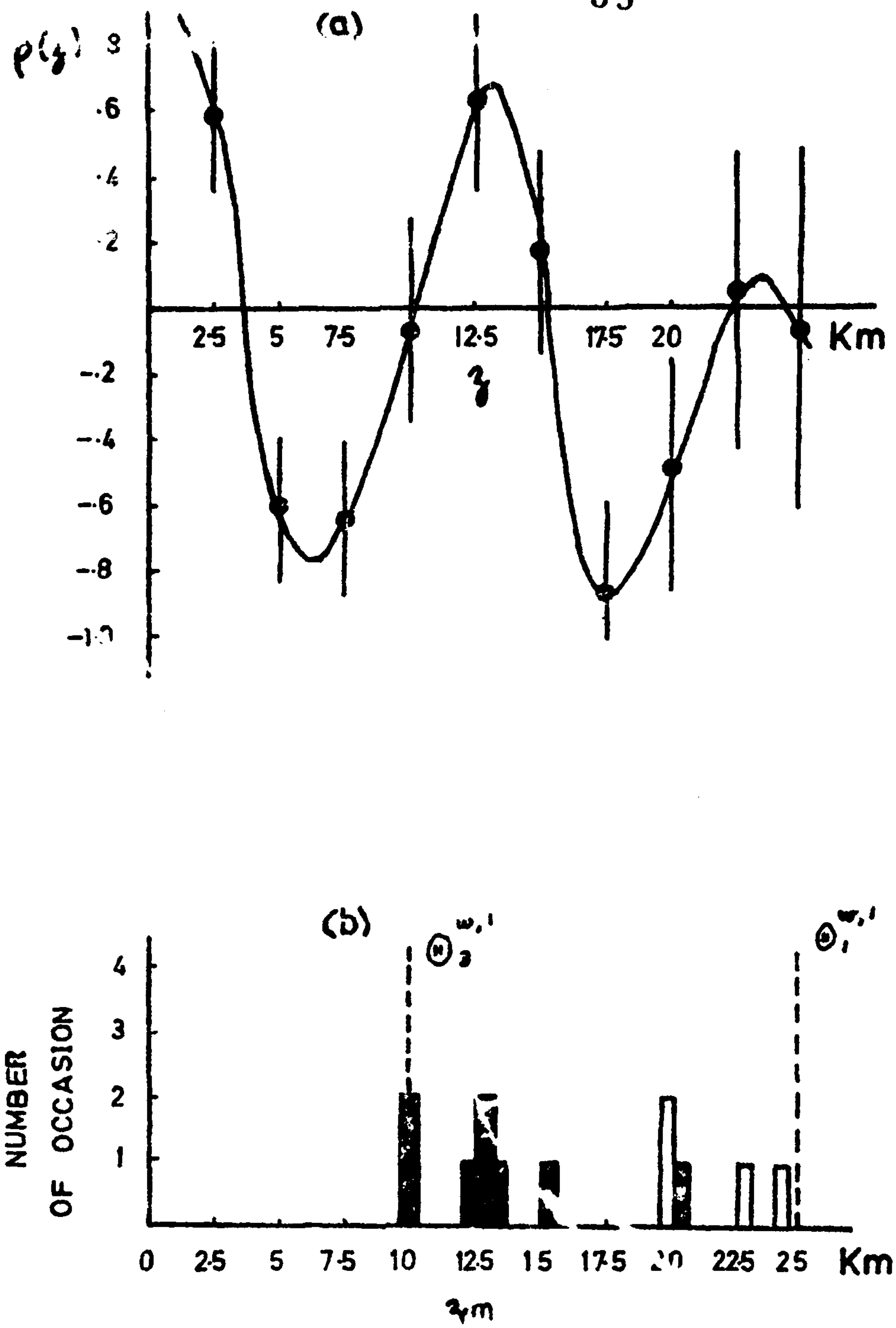



Fig. 4

(a) H·ight autocorrelation function for the night of ?-8 april 1970.

(b) Hist·gram showing positions of correlation maxima for all nights.

█ first maxima (closest origin)

▯ other maxima

┆ wavelengths of the main diurnal tidal modes in the figure, are the wavelengths of the tidal modes that fall within the range shown. None of these is semi-diurnal and it is difficult to see how any of the expected semi-diurnal modes can contribute appreciably to the short wavelength behaviour. The wavelengths of the diurnal modes do not correspond exactly either, although the theoretical values for the first two modes bracket the experimental points, suggesting that the observed behaviour consists of a superposition of these two modes. Such a model would account well for the large variation seen in the wavelength from one day to another since, as was pointed out earlier, the relative importance of these modes depends critically on the temperature structure much lower in the atmosphere.

(c) The amplitude

Two related problems, not so far discussed, are whether the observed variations in scattering cross-section have amplitudes which agree with the theoretical tidal predictions and to account for the apparent absence of the $\theta_2^{2\omega,2}$ mode. As mentioned earlier, the effect of the finite altitude sampling range will be severe in this case and needs to be calculated in detail. Fig.5(a) shows the r.m.s. deviation in scattering cross-section plotted as a function of altitude. This is derived from the 8-day average shown in Fig.2(b) and has been corrected for statistical noise. Also shown in the figure are the theoretical predictions for the semi-diurnal and diurnal tides. These have been calculated by Lindzen (1969) for a latitude of 20°N, at equinox. The figures have than been subjected to the same normalization and sampling procedure as the experimental points. The dip at 80 km. in the semi-diurnal curve is due to the normalization process, while the fluctuations in the diurnal curve are due mainly to the effect of the finite sampling time on the short wavelength modes. The positions of maxima and minima in this curve will depend critically on the relative phase and amplitude of the different modes and the general trend only of the curve should be considered as definitive. The general trend and magnitude of the experimental points are in general accord with the theoretical predictions. There is no exact agreement and, given the limits of experimental error, it could not be expected.

The principal feature of the experimental results has been the short wavelength behaviour and it is of importance to see whether the semi-diurnal $\theta_2^{2\omega,2}$ mode is present at all. This is expected to dominate the semi-diurnal tide and its main characteristic is an almost constant phase over the height range from 70 - 100 km. The density fluctuation is expected to have its maximum negative excursion at 2100, to be zero at midnight and to have its maximum positive excursion at 0300. The effect of normalization to a mean night profile will be to invert the apparent variation at 70 km., to cause it to disappear at about 80 km. and to reduce its value at greater altitudes, the correct phase however, being preserved. In order to see if the experimental values exhibited any variation of this kind, the values given in Fig. 2(b) have been reduced using the formula below:

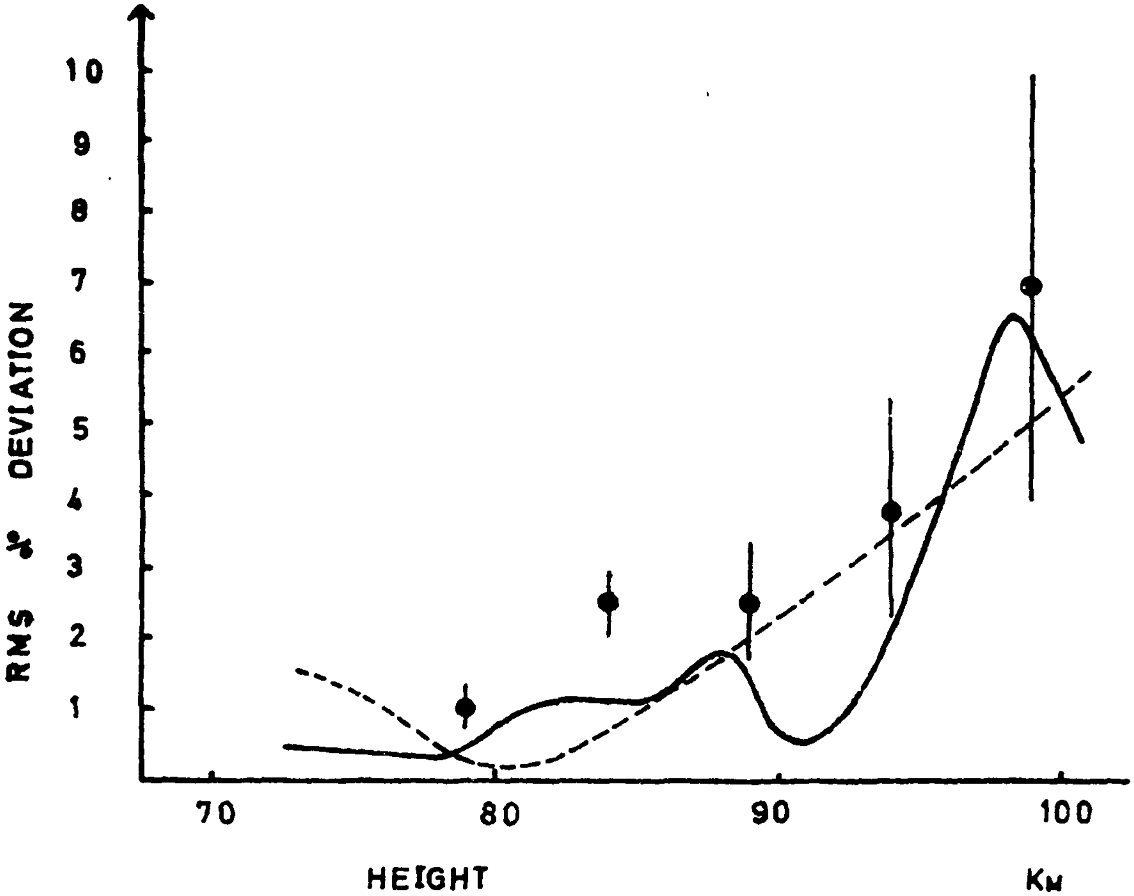



Fig. 5

R.M.S. apparent density fluctuations as a function of altitude.

Experimental points

--- Semi-diurnal tide

— Diurnal tide

$$\left(\frac{\Delta\rho}{\rho}\right)_s = \left(\frac{\Delta\rho}{\rho}\right)_{2000} + \left(\frac{\Delta\rho}{\rho}\right)_{2200} - \left(\frac{\Delta\rho}{\rho}\right)_{0200} - \left(\frac{\Delta\rho}{\rho}\right)_{0400}$$

where

$\left(\frac{\Delta\rho}{\rho}\right)_{2000}$ is the apparent relative density fluctuation at 2000

$\left(\frac{\Delta\rho}{\rho}\right)_{2200}$ is the apparent relative density fluctuation at 2200

$\left(\frac{\Delta\rho}{\rho}\right)_{0200}$ is the apparent relative density fluctuation at 0200

$\left(\frac{\Delta\rho}{\rho}\right)_{0400}$ is the apparent relative density fluctuation at 0400

and $\left(\frac{\Delta\rho}{\rho}\right)_s$ is a derived index which is a measure of the semi-diurnal tide.

$\left(\frac{\Delta\rho}{\rho}\right)_s$ has been plotted as a function of altitude in Fig. 6. Also in the figure is the theoretical value of $\left(\frac{\Delta\rho}{\rho}\right)_s$ for the semi-diurnal tide. The effect of normalization on the latter can be seen in the change of sign of $\left(\frac{\Delta\rho}{\rho}\right)_s$ at 80 km.

The experimental points show the strong short wavelength behaviour which masks quite effectively any steady trend. The mean level of the oscillation, whose amplitude is growing approximately exponentially with altitude, is however, considerably closer to zero than it is to the predicted semi-diurnal tide. In spite of the size of the statistical error, as shown by the error bars, it is fairly clear that for this period of observation the magnitude of the

$Q_2^{2\omega,2}$ mode could not have been as large as that predicted theoretically. A value perhaps as large as 50% of that predicted could have been present and masked by the short wavelength effects.

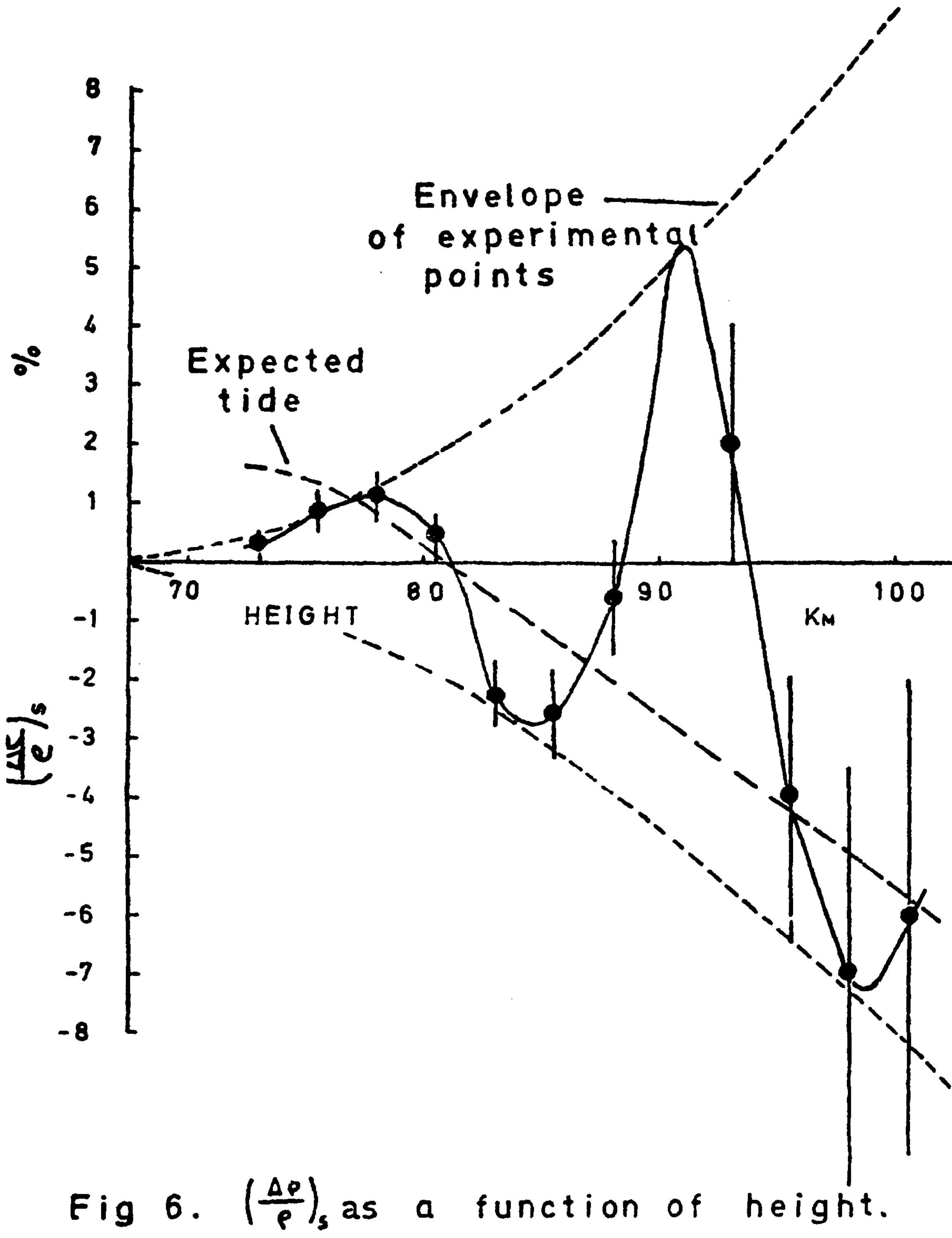



Fig 6. $\left(\frac{\Delta\rho}{\rho}\right)_s$ as a function of height.

● experimental values

– – theoretical semi-diurnal tide.

5. More recent data

A quantity of data has been obtained since that already discussed here which has so far only been partially analysed. This extends from October 1970 - February 1971 and the behaviour of the scattering cross-section appears similar to that of the March-April 1970 data, although the regularity is somewhat less apparent and short-term changes may be relatively more important. Fig.7 shows examples of the time and space correlation functions calculated for 1-2 November 1970. Although the statistical error is large the main trends are still apparent. The time correlation function has a minimum in the vicinity of 6 hours and the space correlation function has a maximum at about 12 kilometres. It thus appears, that in this respect at least, the behaviour of the March-April data may be taken as fairly typical for the atmosphere over Jamaica.

## 6. Conclusions and Future Work

A limited study of the optical scattering cross-section of the mesosphere has shown the presence of periodic variations in both space and time. The amplitude and period of these are consistent with those expected on the basis of tidal variations in the atmospheric density. The vertical structure size corresponds to a mixture of the $\Theta_1^{\omega,1}$ and $\Theta_3^{\omega,1}$ diurnal tidal modes. No evidence has been obtained for the $\Theta_2^{2\omega,2}$ (or any other) semi-diurnal mode although a rather smaller amplitude than that predicted might have gone undetected.

The results given in this paper are for eight days of observation only, and also show large statistical fluctuations making a detailed interpretation impossible. Further, as yet only partially analyzed, observations have been made and a preliminary study of these supports those already fully analysed. Unfortunately, at the time that all the observations were taken, the optical system of the laser radar was operating at 50% of its possible sensitivity owing to a defective interference filter. For future observations this will no longer be the case and it is also hoped shortly to gain a further 40% increase in sensitivity by adding to the existing receiving mirror area. These changes will considerably reduce the statistical error in the observations and make it possible to both reliably compare the behaviour on successive nights and study short period changes of only a few hours. A further improvement to be introduced soon is a new counting system which will enable an accurate determination of relative scattering cross-section to be made between the very high altitudes of interest and much lower altitudes where density fluctuations will be negligible. This

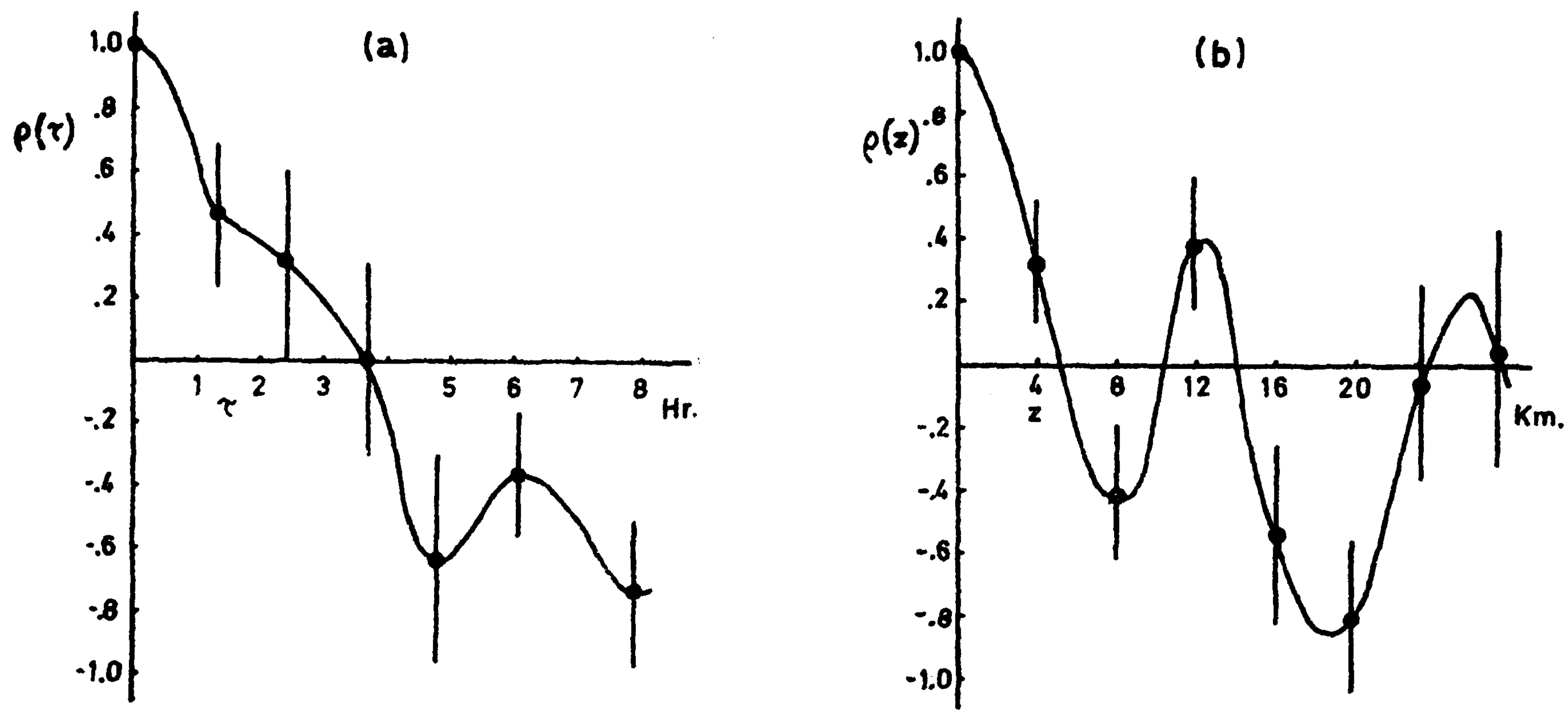



Fig 7 Auto-correlation functions of the apparent density fluctuations observed on 1–2 November, 1970.
(a) Time (b) Height

will render unnecessary the somewhat tortuous method of analysis, adopted in this paper, and enable the long wavelength tidal modes, such as the $\Theta_2^{2\omega,2}$ mode, to be studied with much greater ease.

## 7. Acknowledgements

We would like to acknowledge the valuable assistance of Mr.R.A.Chapman in the maintenance and running of the laser radar system, and of Mr.M.T.Ottway for the loan of the electronic counting system on which the data shown in Fig.7 was obtained. We would also like to express our gratitude to Dr.R.S.Lindzen for the calculation of the figures on which the graphs shown in Figs. 5 and 6 were based.

The research described here was sponsored by the Air Force Cambridge Research Laboratories, Office of Aerospace Research, United States Air Force under grant A.F.O.S.R. Grant No. 616-67.

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