OPTICAL RADAR BACKSCATTERING FROM THE MESOPAUSE REGION DURING JULY AND AUGUST 1967

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TECHNICAL REPORT NO. 765

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ABSTRACT

Optical radar studies of the atmosphere above 40 km were continued at the University of Maryland in July and August, 1967. Changes in the system components resulted in some gain in efficiency over that obtained earlier. The observed atmospheric returns from heights greater than 60 km show considerable structure and imply scattering cross sections not explained by the molecular atmosphere. Agreement with some previously published data is excellent.

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I INTRODUCTION

The purpose of this report is to present recent data obtained at College Park, Maryland on the University of Maryland optical radar system. At present, several research groups are using the Q-pulsed ruby laser to investigate the atmosphere with optical radar techniques.[1,2,3] Such a system has been under development at the University of Maryland (UM) for over three years. It has been fully described in a Ph.D. thesis by P. D. McCormick (1967)[4]. The preliminary data obtained by it has also been reported in the literature[5,6]. This system is unique in that it employees a method whereby the data is processed immediately in an on-line electronic computer. It also differs from the others cited in that it uses the same optical path for both the transmission of the laser pulse and the reception of the backscattered signal. It is presently suitable for the measurement of upper atmospheric backscattering between the altitudes of 40 and 85 km.

During the spring of 1967 several improvements were made on the system to increase its efficiency over that of the previous periods of operation. The radar was then operated on almost every clear occasion between the dates of July 16 and August 16, 1967. This resulted in much more data than was previously obtained on this system and consequently a better determination of the atmospheric backscattering function. This manuscript will discuss in order: a) the recent changes which were made in the UM equipment; b) new techniques which have been devised for operating the equipment; and c) the data obtained in the July-August run.

II EQUIPMENT

A. General

The design of the UM optical radar will be described briefly with the help of figure 1. The configuration is identical with that used by McCormick with the exception of a few component changes that will be described later. The basis of the system is a Korad K2QP ruby laser. This fires a short (20-50 nanosecond) pulse through a hole in a rotating reflective disk. The disk is tilted to the beam at a 45^{o} angle and is located at the focus of the UM 20" folded-cassegrain telescope. It spins at about 5000 rpm so that, after the laser Q-pulse is fired, the hole spins out of the optical path. The return signal is then reflected off the disk surface to a photomultiplier tube located at right angles to the initial light path. The resulting photoelectron signal is then fed through an EG and G amplifier-discriminator circuit to a buffer register. The accumulated pulse count transfers from the buffer register to the storage of a CDC 160 computer at 17 microsecond intervals. On command, the summed pulse count of a series of shots may be either printed out or stored permenantly on punched tape. The height resolution obtained is 2.56 km. The system counts for 97% of each interval.

The only major mechanical feature not accounted for above is the rotating shutter placed as shown in figure 1. Its purpose is to protect the phototube from high light levels created during the firing of the laser. This shutter is driven synchronously with the rotating mirror and its phase with respect to the mirror is adjustable. By turning the motor in its mount, it is possible to align the shutter vanes at any position with respect to the hole in the mirror. They are then held in phase by driving the synchronous motors of both the shutter and mirror withthe same audio oscillator.

Other auxiliary equipment used is the timing circuit which fires the laser at the correct time to pass through the hole in the rotating mirror. This circuit also triggers an oscilloscope when it fires the laser. The oscilloscope monitors the energy of each pulse by viewing the output of a photodiode located behind the ruby.

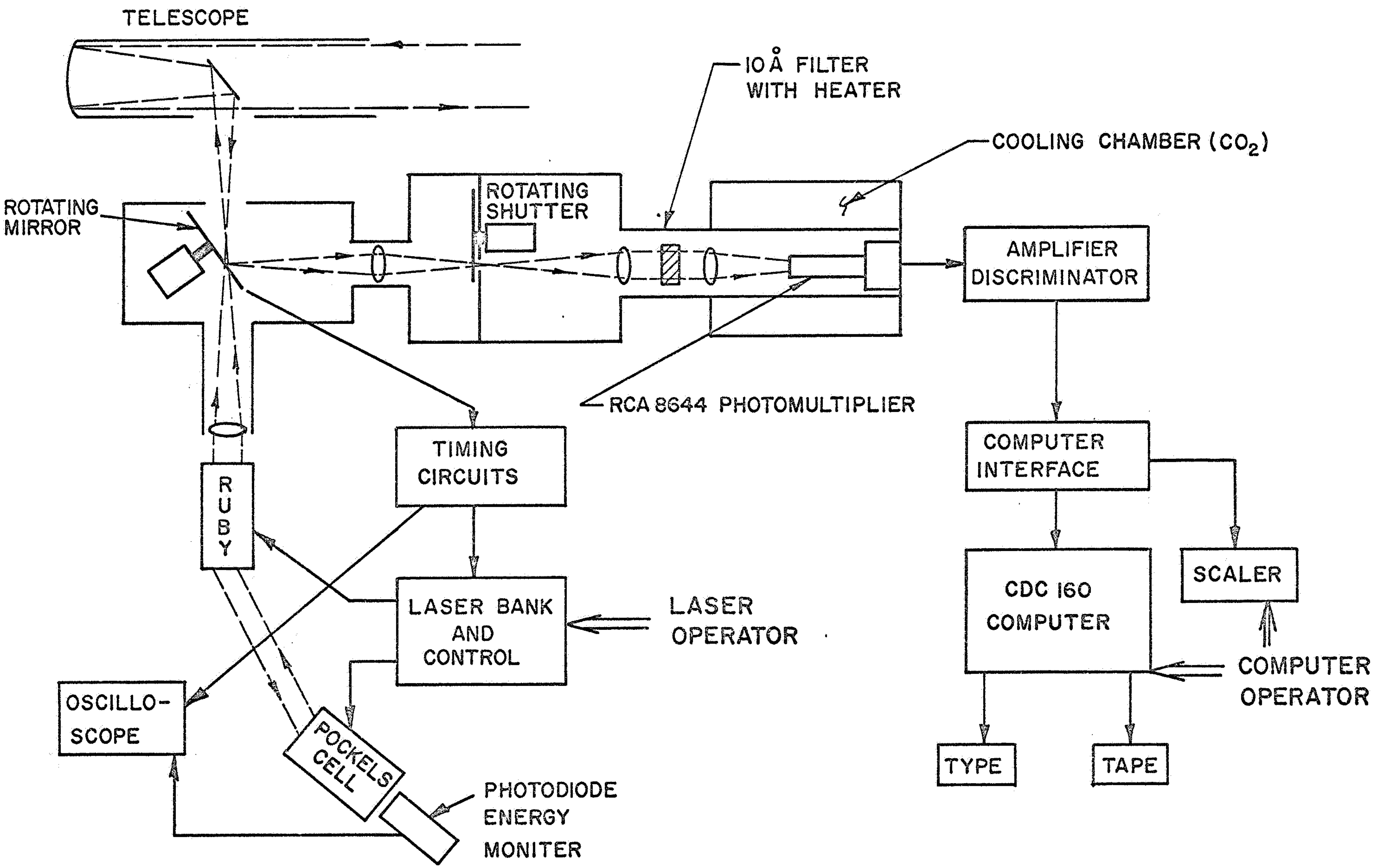

Fig. 1 OPTICAL RADAR BLOCK DIAGRAM.

B. The Photomultiplier

Due to the very low light levels which must be recorded to observe atmospheric backscattering above 60 km, it is essential that the photomultiplier used have: a) the minimum possible dark current; b) a good quantum efficiency at 6943 Å; and c) a high enough gain to permit the detection of single photoelectrons. Previous work with this system used an EMI 9558B photomultiplier. This particular tube had a more than adequate gain ($> 10^6$) and an average dark current of about 200 c/s at $0^{\circ}C$. Its quantum efficiency, however, was measured in our lab to be only about 0.6% at 6943Å. This is about a factor of five below that which should be expected for an S-20 cathode surface. Since the performance of the photomultiplier is perhaps the most stringent limitation on the capabilities of this system, it was essential that we change this component.

The dark current of an EMI 9558 is, to a great extent, set by its large physical size. Its cathode is nearly 5 cm in diameter. Since this experiment confines itself to light levels which allow the counting of individual photoelectrons, ($i_{anode} < 10^{-6}$ amps) a cathode of one millimeter in diameter would have sufficient current supplying capabilities. We thus suffer from a dark current from a much greater cathode area than we actually need. While it would be possible to lower the dark current of this tube by the use of a magnetic defocusing coil[7], or to raise its quantum efficiency by the use of internal reflections,[8] an already very crowded photomultiplier chamber made another solution more desirable.

The RCA 8644 photomultiplier has an S-20 cathode which is about 2 cm in diameter. This is an ideal size from our viewpoint because its area (and hence its potential dark current) is about 1/6 that of the 9558, while at the same time, it is not so small as to make alignment through the 10Å filter unreasonably critical. A tube of this type, which was purchased by UM, was found to have a dark current as low as nine counts per second under optimum conditions. Its quantum efficiency was measured to be about 2.6% at 6943Å. While both of these represent a significant improvement over the old tube, the current gain was only a marginal $2\text{-}5 \times 10^5$. It was thus not possible to use discriminator levels which would be as efficient as in the case of the 9558 in passing signal electrons from the photocathode. Counting tests in the laboratory indicated that we could expect to count at about 70% efficiency while keeping the dark current of the cooled tube below 50 counts per second. This would then represent a gain of about 3 times over the 9558 in total photon detection efficiency plus a factor of 4 improvement in the dark current. The 8644 was installed in the system by wiring a new voltage divider and installing a lens behind the 10Å filter. The latter alteration was to reduce the size of the light beam to less than the 2 cm diameter intercepted by the new phototube.

C. The Laser

Previous work with the UM optical radar was done using a Korad K2Q ruby laser. This device uses a Kerr Cell in order to create the giant pulse needed for radar work. During the spring the Kerr Cell was replaced with the more recently developed Pockels Cell. Whereas in the previous operation great care had to be exercised by the laser operator to monitor the output for after-pulsing and double-pulsing, the Pockels Cell removes this difficulty completely. Also, as was discovered during the run on the telescope, the Pockels Cell allows a greater output in Joules per minute. The firing rate of our operation is held to about one shot per forty five seconds by the cooling capabilities for the ruby and the time needed to process each shot. With the Pockels Cell, however, the energy of each pulse can be much higher than with the Kerr Cell, and the number of shots rejected due to double pulsing and misfires greatly reduced.

When operating with a K2Q system the energy of each pulse is limited by Raman scattering in the Kerr Cell. This is not true in the Pockels Cell configuration, and the result is a very high gain system where the energy output is extremely sensitive to the temperature of the ruby. This makes it difficult to achieve uniform pulsing unless the temperature is controlled to a very high accuracy. During a typical group of shots, our energy output would vary from 1 to 5 Joules while the temperature fluctuated only on the order of one degree. Thus, though the Pockels Cell is a very effective mode of operation, it is a dangerous system from the standpoint of ruby damage. At present we are constructing a more sophisticated temperature control device and considering the use of a shorter (lower gain) ruby to lessen the anxiety over this effect.

One other problem which should be mentioned in connection with the laser is the appearance of extreme hotspots in the near field radiation pattern.

This is bothersome in our type of configuration because it results in damage to the telescope optics. To alleviate the situation, a very highly reflective dielectric mirror is used as the diagonal of the telescope. While this proved sufficient protection when operating with the Kerr Cell, the higher power densities created with the Pockels Cell system damaged two dielectric mirrors during the month's operation. To eliminate these troublesome hotspots, we are now considering constructing a ruby laser of the oscillator-amplifier configuration using a high quality oscillator rod. It is also hoped that more durable dielectric surfaces may now be available.

III OPERATION OF THE EQUIPMENT

A. General

In order to be able to justify the following data and the subsequent conclusions, it is necessary to briefly go through the essential features of the operation of the system. This we will do by describing in chronological order the usual procedures on a clear night.

Since we operated in the summer, it was necessary to always cool with dry ice. This was usually added at the beginning of the evening when the phototube was turned on. Although it would have been more desirable to have the phototube on continuously (for dark current considerations), this was not done due to the large amounts of ice condensation from the moist summer air. This made it hazardous to leave the high voltage power on during the melting of the ice in between periods of operation. The freezing of the chamber at night by the addition of dry ice normally only took a few minutes.

The second operation which had to be performed each night was the setting of the positions of the rotating reflective mirror and the rotating shutter. The two are driven by synchronous motors from the same audio oscillator at about 85Hz. While they will run in step with each other for an indefinite period, their relative phase is quite arbitrary. They must be roughly aligned by shining a light into the telescope and observing their positions on a oscilloscope which is viewing the output of the 8644 photomultiplier. One then mechanically adjusts the relative positions of the two by twisting the motor of the shutter in its mount. This continues until a vane of the rotating shutter protects the tube while the hole in the rotating mirror is passing through the optical path. That method is then augmented by fine adjustments determined by looking at the results of several laser shots into the atmosphere.

When the ruby laser fires its pulse of light, the hole in the rotating mirror is located in the optical path from the ruby to the telescope. As the opening spins out of the path, the back of the mirror then serves as a block to close off the laser cavity from the rest of the system. This is important for the operation of the system because the ruby fluorescence lasts for over a millisecond after the pulse and would greatly contaminate the data if not eliminated. There is, however, from 270 to 340 microseconds after the shot when the hole has only partially closed, permitting the light to leak through from the ruby cavity. If the rotating shutter, whose function is to protect the phototube, begins to open during this time, then the phototube will detect a burst of light until it is cut off by the mirror. The beginning of this burst of light, as seen by the 8644 photomultiplier, marks the position of the rotating shutter with respect to the laser Q-pulse. The end of the light pulse locates the position of hole in the rotating mirror. It is thus possible to see the positions of both disks with respect to the Q-pulse simply by firing one shot and typing out the results which have been stored in the computer. You then finely adjust the positions of the disks so that the phototube is opened shortly after the laser pulse goes through the opening. Not only is it possible to adjust the positions of the disks by means of the light burst, but it has further usefulness in that every group of shots taken into the atmosphere will contain a record of the disk positions. This, as we shall see in a moment is a great help in reducing the data. One precaution, however, which must be observed, is that the disks do not expose the phototube to too great a burst of light. Even though the light level may be well within the operating limits of the tube, an increase in dark current over several milliseconds can result if the light exceeds a certain level.[4] This will be discussed further in section Vb.

After the equipment is ready to run, the telescope is pointed toward the zenith and a few shots are taken with the instrument blocked to check the noise level. If all looks well, the laser operator begins firing at about 45 second intervals. A computer operator manually checks temporary storage registers in the CDC 160 computer in between each shot to determine: a) if the shot passed through the hole in the rotating mirror correctly, b) if the digital interface loaded the shot properly into the storage of the computer, and c) if the rotating shutter was in the correct position. While the criteria are met for a large percentage of the shots, by checking for the errors at this point you may reject one shot without loading it into the computer memory and spoiling a group of 25 or 50. When the computer operator satisfies himself that all went well, he manually records the results of the first few altitude intervals and the energy of the shot as read from the oscilloscope. He then transfers that data into a permanent storage register of the CDC 160 and awaits the next shot.

B. Signal Attenuation

Since the disks do spin very fast compared to the interval time of 17 microseconds, there are a number of transition intervals when the apertures are partially open. During this time the signal is incompletely transmitted to the photomultiplier by an amount we shall call the attenuation factor. If the data is to be transformed into atmospheric scattering functions, it is important that the attenuation be well known. In order to find this coefficient, we observed the morning sky on two occasions with the same disk settings used during that night's run. Although no special precautions had been taken, it was found that the phototube begins to count signal photons at a time identical (within 17 microseconds) to the start of the fluorescence burst described earlier. This good fortune makes it a simple matter to calculate the attenuation correction. The transmission curve, which is a product of the reflective mirror and the rotating shutter, is given for any aperture by the measurements taken with the morning sun. The position of the curve, for any group of shots, is set by the first interval of fluorescence seen by the phototube.

While performing the determination of the attenuation correction, it was found that due to either a change in the reflectivity of the rotating mirror, or improper alignment of the system, the signal was slightly depressed out to interval 40 (100km). This correction curve was used in the same manner as the one for the apertures with the data normalized to interval 40. About halfway through the summer run the reflective mirror (a polished brass disk) was repolished and the system realigned. This seemed to eliminate this effect for the rest of the data taken.

C. Noise Determination

The calibration of the system noise could be most directly accomplished by the blocking of the telescope and the firing of a number of calibration shots. This, however, is not the ideal monitor because it does not account for the noise which enters the system through the telescope, nor is it a simultaneous measurement of this parameter. It is also very expensive both in terms of cost and time. For these reasons another method was initiated for this month's run.

McCormick found that while he operated the system the noise was level in time and approximately equal to that expected from the phototube dark current. Unfortunately, during our period of operation it was found that the noise level was about two or three times that predicted by the dark current shown on the scaler. This will be discussed further in Chapter V. Since it was not known immediately what was the cause (or the cure) of this extra noise, it was decided to continue operation and monitor it by printing out each set of shots to interval 100 (250km). We then could use the upper intervals, where no signal was expected, to predict the noise in the levels of interest. With this method a record of the noise is kept automatically in the form of the counts in the upper data bins. In order to check the methods accuracy about 100 blocked shots were taken early in the run and the results of the two compared. Also, the computer operator periodically recorded the dark current of the photomultiplier for later reference.

IV DATA

During the period of operation being discussed, data was obtained on the nights of July 22, 23, 25, 27, 28, 31, August 1, 2, 7, 8, 9, 14, 15, and 16. In all, approximately 1800 shots were taken; distributed such that three-fourths of the shots were in the morning hours and about three-fourths on the last seven days. Further subdivisions are about equal in weight. The average energy of the shots was about 2.0 Joules. They were fired at a rate of one every 45 seconds while operating. The conditions on these nights varied from hazy to very clear. Other nights in the month were not used due to either cloud or fog cover. Exceptions to this were the nights of July 26 and August 10 when equipment failures could not be fixed in time to allow observation.

In this report we shall confine our remarks to the total return of the 1800 shots. We thus are only considering an average for the month's operation in our subsequent remarks. Table 1 gives the total number of counts received in each interval from 17 to 100 for 1661 shots. This represents all of the shots which were taken toward the zenith when the rotating shutter had correct position and all other equipment was working properly. The number following the photoelectron count is the attenuation factor caused by the opening of the apertures. The number which is in parenthesis is the number of shots which was counted at each interval. There are fewer than 1661 shots below interval 20 due to the fact that the rotating shutter was not always set at exactly the same position. All of the upper data bins are for only 1432 shots due to a typewriter breakdown on occasion requiring the manual and incomplete recording of the storage bins in the computer.

The intervals below 17 were not recorded here, but all had the following pattern. Dark current would be recorded out to about interval 10 when the fluorescence burst discussed earlier would begin. The fluorescence level would then rise to a peak of about 70-80 counts per interval at 13 and then drop to zero about 17. In reducing the data, the first significant fluorescence interval was always used to establish the attenuation factor. Also, one interval between the fluorescence burst and the data was not counted. This latter precaution was to guard against contamination by trailing pulses related to the light burst.

TABLE I

(See Text)

Interval (1= 2.56km)	Total Count Recorded	Interval	Total Count Recorded
17	19, .48, (115)	58	9
18	109, .55, (590)	59	6
19	240, .73, (1450)	60	7
20	223, .70, (1661)	61	5
21	159, .82, (1661)	62	5
22	93, .86	63	1
23	79, .88	64	7
24	64, .90	65	1
25	51, .90	66	8
26	46, .91	67	4
27	38, .92	68	6
28	23, .94	69	6
29	22, .94	70	3
30	31, .94	71	7
31	21, .95	72	7
32	13, .95	73	3
33	9, .96	74	2
34	19, .96	75	5
35	7, .97	76	3
36	14, .97	77	3
37	7, .98	78	7
38	4, .99	79	3
39	7, .99	80	5
40	10, 1.0 (1661)	81	4
41	8, 1.0 (1432)	82	6
42	6, 1.0 (1432)	83	5
43	13, 1.0 (1432)	84	6
44	8	85	2
45	2	86	6
46	5	87	4
47	5	88	2
48	2	89	5
49	6	90	7
50	8	91	2
51	6	92	4
52	3	93	1
53	8	94	2
54	6	95	6
55	4	96	3
56	6	97	4
57	7	98	8
		99	3
		100	6

V CONCLUSIONS

A. System Efficiency

In order to know the absolute magnitude of the atmospheric backscattering functions, it is necessary to know the total optical efficiency (αQ) of the system. It was of further interest in our case because it would enable us to judge the relative merits of the new photomultiplier tube. Therefore, we considered very carefully the measurement of αQ for our summer data.

The easiest way to find the optical efficiency is by observing a star of known magnitude. Our system is fixed in the East - West axis so the only stars which will remain in the field of view long enough are those near the North Pole. With the procedure described by McCormick,[4] this observation enables one to determine the product of the optical efficiency (αQ) and the atmospheric transmission (T). Unfortunately, due to the great length of the summer day, neither meridian crossing of the pole star Polaris occurs in complete darkness between the dates of June 8 and August 20. Thus, this direct and fairly accurate determination was not available to us.

In lieu of a stellar source from which to calibrate, it was necessary to use the U.S. Standard Atmosphere Supplement[9] (USSAS) to predict the molecular density at an easily observed altitude. Using the optical radar equation in the form:

$$\alpha Q T^2 = \frac{2hN(x)x^2}{tA\lambda\sigma(\pi)n(x)} , \qquad (1)$$

where:

h	=	Plank's constant,
$N(x)$	=	the counted return from altitude x per unit energy
x	=	the altitude of the return,
t	=	the open time at altitude x (17×10^{-6} sec),
A	=	the area of the receiver (2.13×10^{3} cm^2),
$\sigma(\pi)$	=	the backscattering cross section of an air molecular (2×10^{-28} cm^2/mol/ster),
$n(x)$	=	the molecular density at height x predicted by USSAS,
λ	=	the wavelength of the light (6.94×10^{-5} cm)

we can estimate $\alpha Q T^2$ from our data.

The lowest altitudes always available to our system are those around 50km. We therefore used the sum of the altitudes from 45 to 52.5km (corresponding to intervals 19, 20, 21) for the determination of αQT^2. Referring to the expected molecular density for this season at these latitudes in the USSAS, we then can substitute into equation 1 and get

$$\alpha QT^2 = 1.14 \times 10^{-3} N(19,20,21) \qquad (2)$$

Using the total returns in these intervals recorded in table 1 we then find that

$$\alpha QT^2 = 3.9 \pm .25 \times 10^{-4} \qquad (3)$$

If T is assumed to be about .7 for this period then we find that $\alpha Q \doteq 8 \times 10^{-4}$. This compares with an optimum calculated efficiency of about 4×10^{-3} which is obtained by adding up the transmission of all the components and the quantum efficiency of the phototube. We therefore conclude that either the atmospheric transmission was lower than .7 or the components were not operating as expected.

Due to the relatively poor atmospheric conditions around Washington, D.C. during the summer months, there were times when the laser beam could be seen with the naked eye as a 20" wide red streak in the hazy sky. While we have no quantitative measurements of the transmission (T) during these times, it certainly must have been far lower than the typical value usually assumed for these experiments of $T \doteq .8$. If for instance, the average transmission was only about .4, then this would imply and average αQ of 2.4×10^{-3}; not far from our optimum expected efficiency. If most of the apparent loss in the efficiency is in the atmospheric transmission, however, we should have a correlation between our measured value of αQT^2 and the conditions of each night. Calculating αQT^2 on several representative nights, we find that although all of the hazy nights were indeed poorer than the average, not all of the clear nights registered a high value of αQT^2. The best value registered came on August 25 (a very clear night) when $\alpha QT^2 \doteq 1.3 \times 10^{-3}$. The worst values were found on July 31 and August 16 when $\alpha QT^2 < 2 \times 10^{-4}$. If we say that our best night represented an atmospheric transmission of .7, then $\alpha Q \doteq 2.7 \times 10^{-3}$.

During further tests on the receiver system later in the year, it was found that frost could have formed on the lens used to reduce the size of the beam from 5 to 2 cm. This may have caused some of the reduced efficiency of the system measured during the clear nights. To eliminate this possibility, this lens was replaced by a shorter focal length collimating lens in front of the 10Å filter. Frosting on the 8644 is prevented by drying out the chamber with desiccant prior to cooling the photomultiplier. Heating of the filter prevents frosting on the only other optical component which is near the cold box.

On November 19, 1967, the entire receiver system with the alteration described above was aligned with the telescope. By using an automatic recording device capable of about three readings per second, we were able to obtain measurements on several stars as they crossed the meridian even though they only remained in the field of view about ten seconds each. The conditions were similar to a mediocre observing night during the July - August run. The sky was slightly hazy with a few scattered cirrus clouds. The measured values of αQT for the stars used were as follows:

γ Cassiopia	-	2.1×10^{-3}
δ Cassiopia	-	1.4×10^{-3}
α Ursa Minoris	-	2.9×10^{-3}
ι Cassiopia	-	9.4×10^{-4} .

As can be seen, the values measured for the four stars differ by a factor of 3 even though the equipment and techniques used were identical. We thus conclude that the difference represent variations in the atmospheric transmission over the two hour span needed to make the measurements. Although, by eye estimate, the sky looked fairly uniform along the meridian, thin cirrus clouds could be seen outlined against the rising full moon. On a moonless night these clouds would probably go undetected with the result that the returns would vary greatly for no apparent reason.

If we chose the highest value of αQT (2.9×10^{-3}) as that when the atmospheric transmission was about .8, one can see that this is about twice our previously measured efficiency ($\alpha QT^2 = 1.3 \times 10^{-3}$). The value measured with the stellar calibration predicts an αQ of 3.7×10^{-3}, in excellent agreement with what we would expect from adding the individual components of the system (4.0×10^{-3}). This is also the predicted value of four over the efficiency measured with the 9558 photomultiplier. We thus conclude that the stellar measurements show the 8644 to indeed be a substantial improvement to the optical radar system as we had hoped. The tests also reinforce our suspicions that most of the discrepancy between αQT^2 measured during the summer and that calculated from the laboratory tests lies in the poor atmospheric transmission. The frosting of the decollimating lens and the ever present possibility of misalignment could also have been contributing factors.

It becomes obvious from our previous discussion that in order to be able to perform any absolute determinations with an optical radar system one must be able to measure the atmospheric transmission on a nightly, if not hourly, basis. As was pointed out earlier, the measurement of a stellar source, such as Polaris, will enable one to get αQT to fair accuracy. If the laser telescope system is able to track stars in different parts of the sky, one can measure αQT for a number of calibrated stars such as given by Code[10]. One then can compute T (and hence αQ) with the usual astronomical method as outlined by Hardie[11]. For most of the present atmospheric radar installations, however, including ours, the possibility of observing any star which is not near the pole and on the observer's meridian is out of the question. One can, however, derive the atmospheric transmission by observing the atmospheric backscattering from a fixed altitude with the system set at two different zenith angles. This method, which permits the direct evaluation of T^2, is outlined in the Appendix. Although small amounts of off-zenith data have been taken on this system, it was taken primarily to investigate the possibility of lowering the cut-on altitude. As will be pointed out later, the data was not (unfortunately) suitable for determing the atmospheric transmission during the summer run.

B. Noise

As was pointed out earlier, between the intervals of 50 and 100 we do not expect any detectable scattering from this number of shots. These intervals should therefore serve as an accurate example of the time-independent background noise. The average count is 5.0 for 1432 shots. This predicts 5.9 ± 2.6 counts/interval for the 1661 shots which make up the data at the lower altitudes. The returns vary from 1 to 9 counts/interval in a roughly Poisson-like manner and are fairly evenly distributed over all the shots taken.

During the data aquisition the dark current was monitored regularly. The average was about 60-80 counts per second, although times of less than 25c/s and greater than 120c/s were experienced. This is quite a bit higher than the optimum figure measured for the 8644. We believe the discrepancy is due either to the fact that the tube was not left on continuously due to icing conditions, or to the continual exposure of the tube of high light levels during the setting of the rotating shutter. Whatever the cause, this dark current would predict a noise of about 2.0 counts per 17 microsecond interval for 1661 shots. Obviously, there is a noise contribution of about 4.0 counts per interval which is not accounted for by normal dark current.

The source of the extra noise is very difficult to trace because of the number of shots which must be taken to positively detect it. It is not due to the night sky because this was measured to contribute only 2.3 counts/second, or .27 counts per interval for this number of shots. We do not feel that the noise enters through the telescope path in the form of light, since it shows up in the blocked shots as well. It is also unlikely to be of an electrical nature because of its uniformity in time. The two causes which seem to be the most likely are: a) the leakage of the fluorescence from the ruby around the block presented by the rotating mirror; and b) the temporary increase in dark current due to being hit by the fluorescence burst described earlier. Because the time scale of the effect (indicated by its slope) is about 3 milliseconds, it is thus of the correct shape for ruby fluorescence to be the main contributor. The second effect, however, cannot be ruled out completely. If we are dealing with effect b, referred to earlier as saturation of the cathode, it should be apparent in a sharply decreasing noise level directly after the fluorescence burst. A number of calibration shots were taken to determine the magnitude of the light burst which could be allowed before producing a noticeable increase in the dark current. It was found that as long as the peak light level was kept below 6×10^6 counts/sec the tube had a fairly uniform dark current. On this basis we discarded about 100 shots and feel that those remaining in Table 1 are free of any noise contribution which is not nearly uniform over 50 intervals. We could, of course, completely eliminate concern for this second noise source by protecting the photomultiplier longer. However, this would sacrifice not only several intervals of height but the information contained in the fluorescence burst. Of more immediate concern is the installation of better baffling to stop the fluorescence leakage.

We conclude that the causes of the noise are: a) the normal phototube dark current (30%); b) night sky (5%); and c) fluorescence leakage around the rotating mirror plus the possibility of the increase in dark current due to the exposure to high light levels (65%). We also conclude that the noise was well-behaved, consistent and contend that its magnitude and behavior is well known.

C. Atmospheric Backscattering Function

The net return in each interval was computed from Table 1 and multiplied by the square of the altitude to obtain the relative atmospheric backscattering. In accordance with our previous arguments, we assumed the noise had a constant level of 2.0 counts per interval due to dark current. Superimposed on the dark current was a noise level of 4.2 counts per interval which was due to light and would be affected by the attenuation factor. This adds up to a total noise slightly higher than the average stated in the previous section. The increase was meant to correct for the slight slope in the noise curve and to get a representative value for the altitudes of interest. The result for intervals 17 to 40 is shown in figure 2. The error bars indicated represent the square root of the observed count in each interval. Shown by a solid line is the relative scattering expected at these latitudes during a summer month on the basis of the USSAS.[9] A dotted line is drawn indicating three standard deviations above the background noise. A second dotted line denotes a straight-line fit of our data between 40 and 65 km.

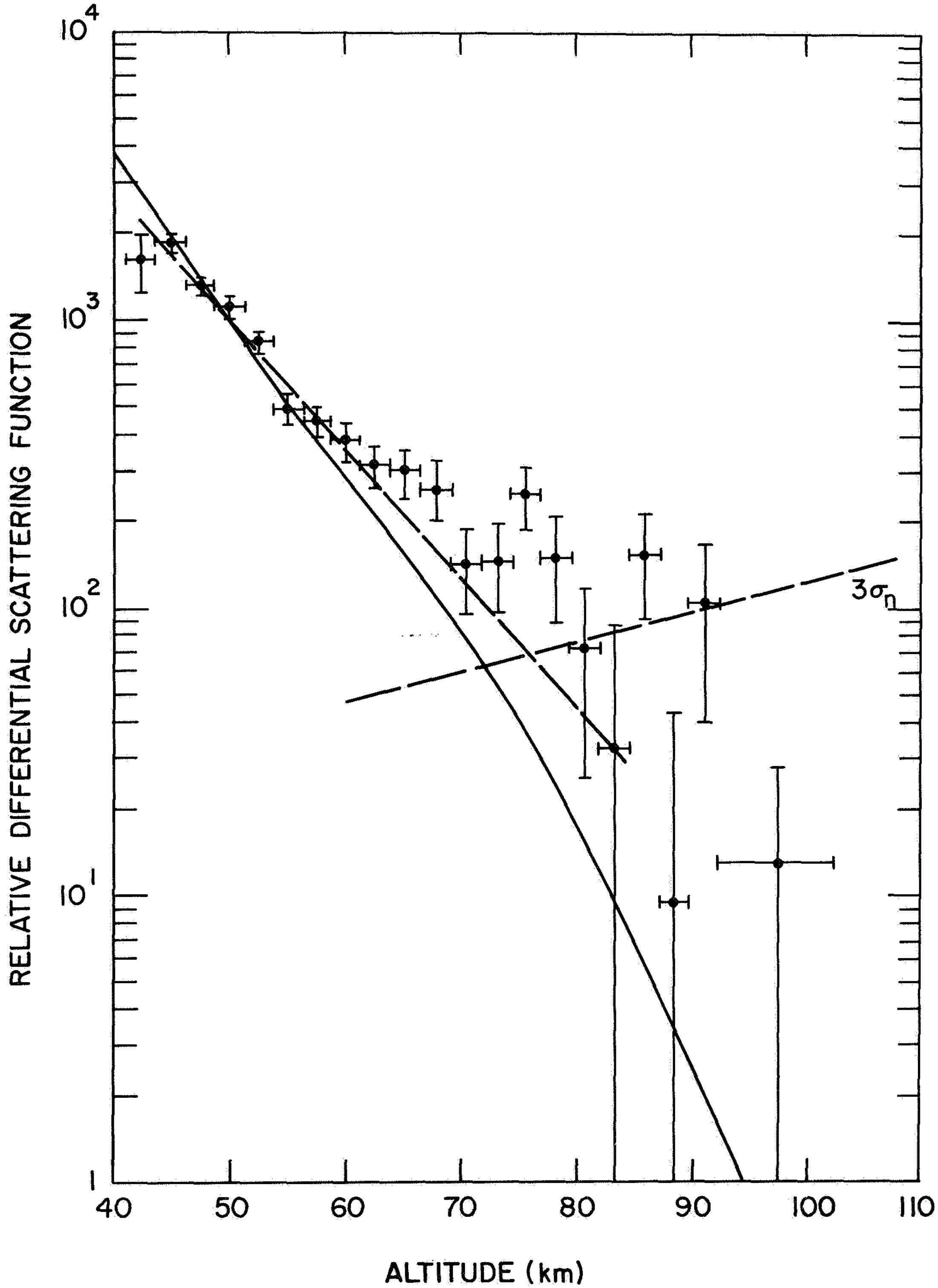

Fig. 2 DATA RECEIVED FROM JULY 16 TO AUGUST 16, 1967 (1661 SHOTS).

VI DISCUSSION

A. Atmospheric Scattering

Due to the uncertainties involved in the system efficiency, power output and other parameters, we have had no recourse but to fit the data to the expected molecular scattering at the best determined altitudes. This has already been done in figure 2. It sets the absolute magnitude of our backscatter by comparing it to the expected Rayleigh scattering. Subsequent mention of the magnitude of the measured scattering will imply the accuracy and scale set by this fitting procedure. The overall features of the scattering function shown in figure 2 can then be described by the following observations.

1. From 40-60 km the data seems to agree reasonably well with that expected from the USSAS. The scale height, however, due to either systematic error or a gradual enhancement, is about 20% greater than predicted.
2. In the 60-70 km region the scattering function levels off and indicates an enhancement over the expected molecular values. The enhancement at its maximum point near 65 km is twice the predicted molecular value implying an excess backscattering contribution of 5×10^{-13} $cm^{-1} ster^{-1}$. For Rayleigh-like scattering this implies an excess cross section of about 4×10^{-12} cm^{-1}.
3. After going through a minimum at 70 km the scattering function is consistently above the expected molecular contribution out to the last resolved point at 91 km. Statistically significant peaks are observed at 76, 86 and 91 km. The first two, which are better than 4 standard deviations above the molecular scattering, are about 6 and 40 times the expected scattering at these heights. For Rayleigh-like scattering and a scattering region is 2.5 km thick, the portions unexplained by molecular scattering are about 8×10^{-12} and $5 \times 10^{-12} cm^{-1}$.

Comparison with previously published data shows that there are at least two instances of similar occurrances with optical radar experiments. In particular, the deviation from the Rayleigh curve in the 65km region agrees very closely with that seen by Bain and Stanford[1] and is similar to that seen earlier at UM.[6] All three sets of data also show a minimum near 70km and a secondary peak between 70 and 80km. The magnitude of the second peak is identical with that seen by McCormick et al[6] but about 1.6 times higher than seen by Bain and Stanford. The altitude of the peak, however, differs from both the previous sets of data. Another more interesting difference between this and the other two publications is that we see a statistically significant enhancement above 80km. In either of the previous cases the system efficiency was such that scattering of this magnitude would have been detected. We conclude therefore, that either the atmospheric conditions were different or that the peaks represent some sort of random error.

Since a complete explanation of the measured scattering function cannot be given as yet, we will conclude simply by listing several pertinent comments.

1. The consistency of three fairly independent sets of data indicates that fairly high weight can be given to the upper atmospheric enhancements seen at 65 and 75 km. It also implies that optical radar systems in general can produce useful data from the upper mesosphere.
2. The appearance of sharp 86 and 91 km peaks in our July-August data and their absence in fall and winter data is very suggestive of a phenomenon analogous to noctilucent clouds. The backscattering, however, is at least 100 times lower than expected from such clouds.
3. The appearance of well defined peaks in the scattering function, as shown by our July - August data, makes it seem less likely than before that the upper atmospheric enhancements are due to the phenomenon of multiple scattering.[12]
4. At present the only seasonal change in the enhancements which has any statistical basis is the appearance of greater scattering above 80km during the summer months.

B. Future Improvements

Present plans call for the continuation of atmospheric research with this system for at least the next 18 months. It is hoped that selected periods may be studied to sample seasonal variations of the upper atmospheric enhancements. While the study could probably be done with the existing system, it will be many times easier if a factor of two or perhaps three could be gained in the overall performance. On the basis of the summer data and more recent tests which have been performed on the equipment, it appears that at least this amount of improvement can be had and perhaps much more.

The greatest single improvement can probably be made in the noise level. Recent tests show that with proper care of the photomultiplier we should be able to lower the dark current to no higher than 10-15 counts per second. This in itself is a factor of 4 better than the previous value. The other noise contributions, i.e. the fluorescence leakage and the saturation effects, we feel can be eliminated nearly completely with the installation of better light baffles. The net result is that an order of magnitude improvement in the noise appears possible.

The improvement of the total optical efficiency of the system is by far the most important improvement but one in which the solution is not as straight-forward as with the noise. With the lowering of the photomultiplier dark current, some gain in the counting efficiency of the tube can be had by raising the high voltage level. We have eliminated the possibility of frosting in the phototube chamber by redesigning the optics at this point. We also can take advantage of clearer atmospheric conditions by operating during the cool months of the year. In all, if we realise an average $\alpha QT > 3 \times 10^{-3}$ with the present components we would be satisfied. Further improvement beyond this point would require either a new photomultiplier selected for exceptional quantum efficiency at 6943Å, or a highly reflective replacement for the rotating mirror. The gain in each case might be as high as 30% if the proper components can be found. The end result is that we hope to realise an improvement of from 4 to 6 in the overall quantum efficiency (αQT) over that used during the July - August run.

The construction of a better cooling system for the Korad K2QP laser is being completed. With the temperature of the ruby under close control it should be possible to at least double the output of the system in Joules per minute. Further work on the laser also promises even greater gains with the possibilities of increasing the length and energy of each pulse.

One other major change which could be made is the addition of higher speed motors to drive the rotating mirror and shutter. This would allow not only a lower cut-on altitude but could better protect the photomultiplier from the fluorescence burst. It would also allow the measurement of T^2 on

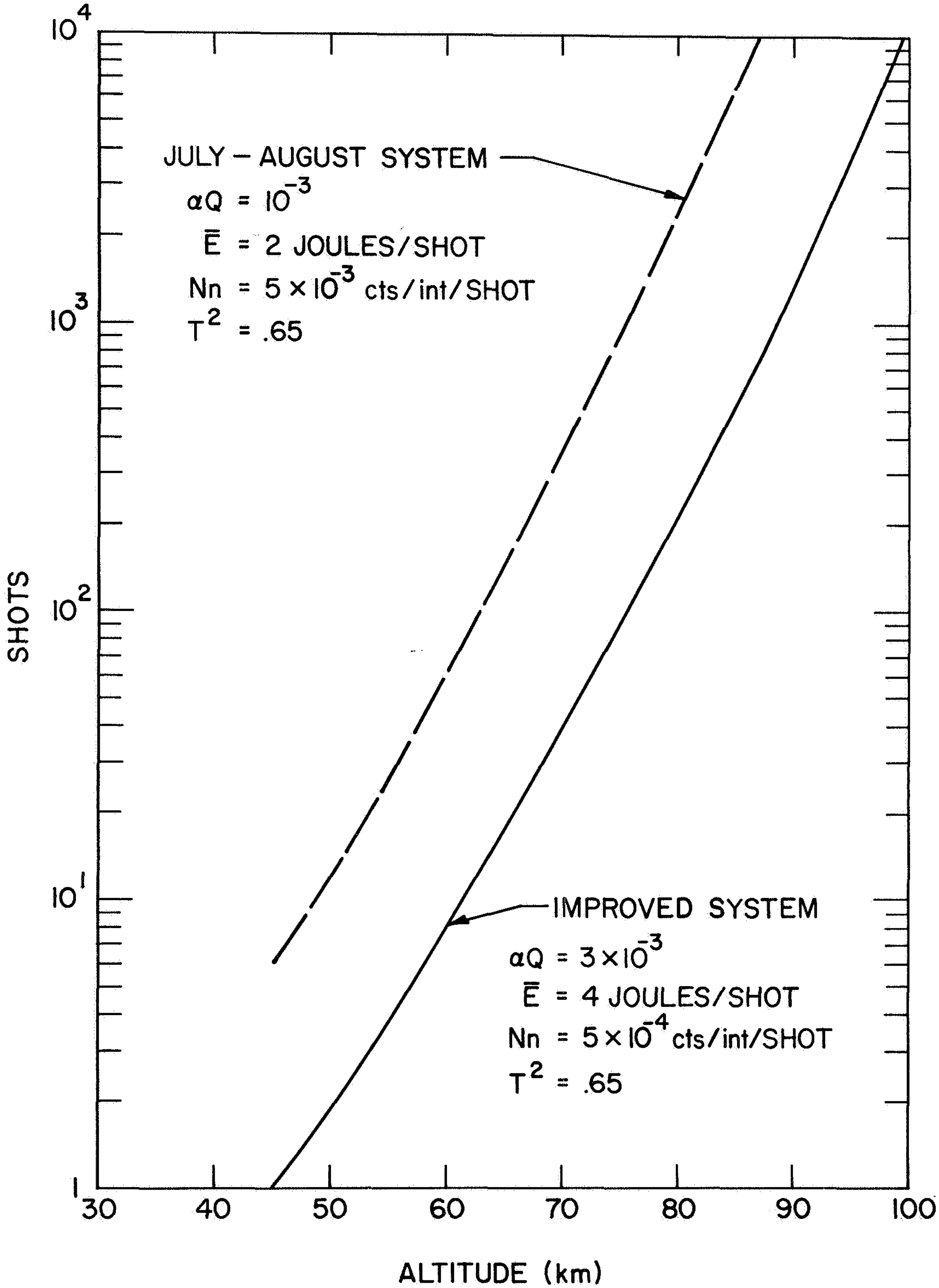

Fig. 3 NUMBER OF SHOTS NEEDED TO MEASURE MOLECULAR SCATTERING TO AN ACCURACY OF 50% WITH THE JULY-AUGUST RADAR AND THE PROPOSED SYSTEM.

each night by the method outlined in the Appendix. The gain in cut-on time by this change should be about 10km bringing the 30-35km layers into view. Any further lowering would not be practical because it would lead to the danger of saturating the photocathode and increasing the dark current in the tube (see section V-B). The change would not, however, increase the information obtained above 55km which is our main concern. The real improvement then, rest on the ability to reach altitudes which would allow us to measure the atmospheric transmission. For our purposes, however, this may not be a significant enough improvement over the stellar measurements as outlined in section V-A to justify the added bother. We thus are still only considering this as a possibility.

If the improvements mentioned above are successful, then with the present components the UM optical radar system would have a optical efficiency (αQ) of about 4×10^{-3}. The noise level should be in the order of 30 counts per second or 5×10^{-4} counts per interval per shot. The energy output is expected to be at least two 4 Joule shots per minute. If we then operate for a typical month, as indicated by the July - August run, we would have at least 2000 shots of data. This would represent a factor of 15 in net signal over the summer's data and about a factor of 5 improvement in the noise. Such data would allow the plotting of the 95km backscatter from the molecular atmosphere with an accuracy of about $\pm$ 65%. Comparable accuracy in the July - August data is only available to about 70km.

Figure 3 shows the number of shots necessary to give a 50% accurate determination of the molecular atmosphere with the July-August and the proposed radars. Such accuracy is sufficient to show any deviations from the USSAS which are of the magnitude shown in figure 2. Past experience has shown that on a good night we might expect to get about 350-400 shots with the proposed improvements. Such deviations from the molecular atmosphere in the 75km region could be studied on a nightly basis. With good weather conditions, a month long run with the proposed improvements should produce information on the time variability of the upper atmospheric enhancements.

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APPENDIX

The purpose of this section is to show how it is possible for an optical radar installation to find the atmospheric transmission without the use of stellar sources. The only prerequisites are: a) that the instrument be capable of observing both at the zenith and at a fairly large angle away from the vertical and b) that the instrument be fully sensitive at altitudes at least as low as 35km. The one assumption used is that the atmosphere is uniform in the horizontal direction over any area which can be reached from one observing site.

The method used is to observe an atmospheric layer of fixed altitude x at two different zenith distances. From the geometry shown in figure 4, it is apparent that for a nearly collimnated light source, we should expect equal total scattering functions from the two volumes of air. The difference in the light returned to the telescope from the two volumes will then be directly related to the atmospheric transmission.

The atmospheric transmission at the zenith is given by the formula

$$T(0) = \exp \left[- \int_0^x k\rho dx\right] \qquad (4)$$

where k = the average absorption per unit mass,

ρ = the density,

x = the path length through the atmosphere.

We will assume that $T(0)$ is nearly constant for any $x > 10$km.
The atmospheric transmission at zenith angle θ is then given with good accuracy by

$$T(\theta) = \exp \left[- \int_0^{\sec\theta x} k\rho dx\right], \qquad (5)$$

As long as we can neglect the earth's curvature ($\theta < 80°$). Thus, it is apparent that

$$T^2(\theta) = T^2(0)^{\sec\theta} \qquad (6)$$

Using equation 6 and equation 1, the optical radar equation for observations at angle θ and height x becomes

$$N(x,\theta) = \frac{T^2(0)^{\sec\theta}\ \alpha Q t A \lambda \sigma n(x)}{2hx^2 \sec^2\theta} \qquad (7)$$

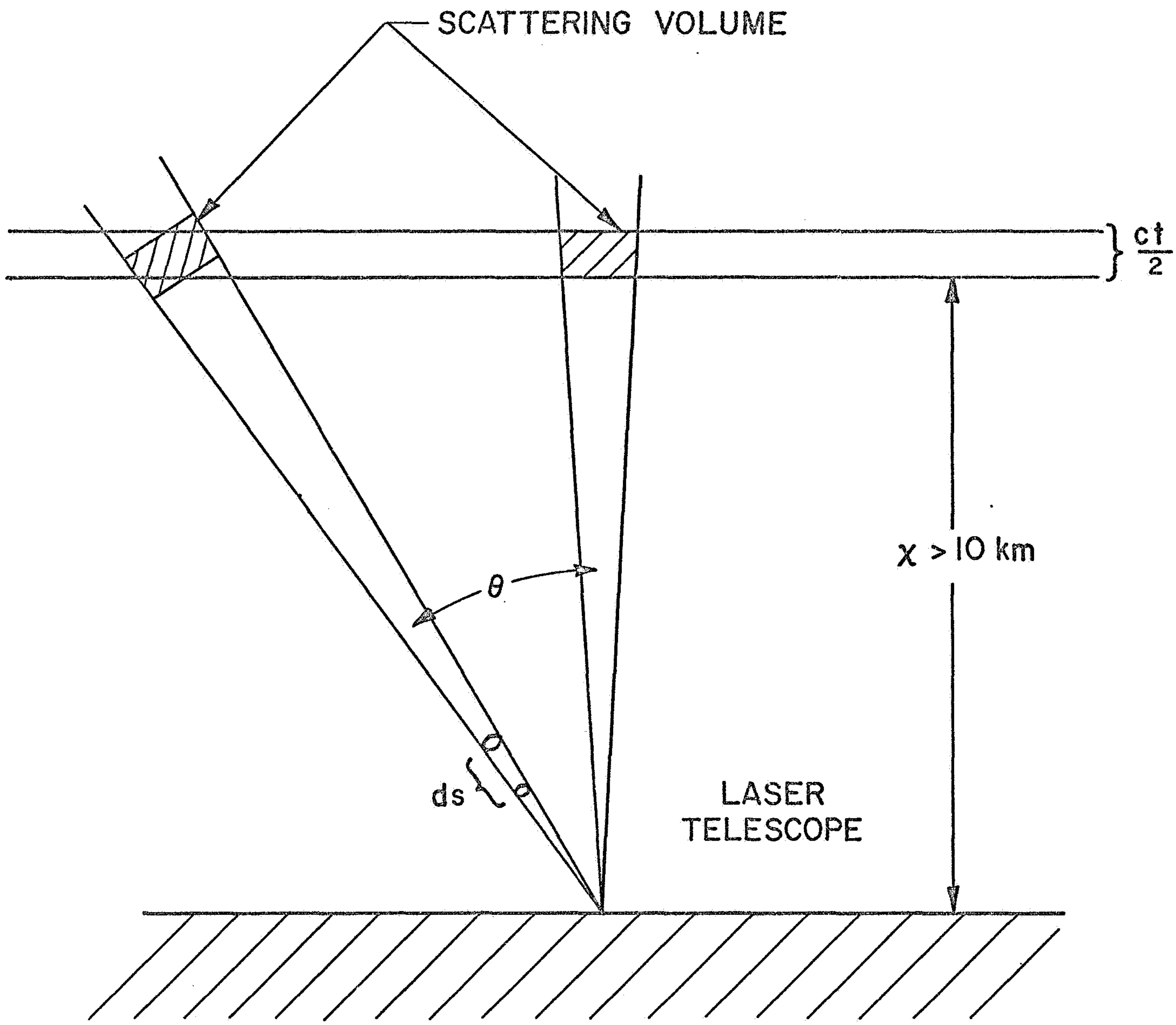

Fig. 4 OFF ZENITH GEOMETRY FOR DETERMINING $T^2(0)$.

Dividing equation 7 by equation 1, we get:

$$\frac{N(x,\theta)}{N(x,0)} = \cos^2\theta [T^2(0)]^{\sec\theta - 1} \tag{8}$$

or

$$T^2(0) = \left[\frac{N(\theta)}{N(0)} \sec^2\theta\right]^{\frac{1}{\sec\theta - 1}} \tag{9}$$

where N(0) and N(θ) are the counts per joule in each instance. Thus, you have a direct formula for $T^2(0)$ if you can obtain data at two different zenith angles.

The second requirement mentioned at the onset; that the optical radar be capable of observing below an altitude of 35 km, is an arbitrary value determined by the precision of the measurements. It is also the reason why this procedure has not been used to date on the UM optical radar. Since every shot taken at zenith angle θ is not as efficient in collecting information as those directed toward the zenith, it is necessary that a reasonable precision be attained in $T^2(0)$ with as few shots as possible. Thus, you are interested in looking at an altitude where there will be a high number of counts recorded on each shot. This will become apparent if we derive a formula for the precision of $T^2(0)$.

Using the usual method for combining uncorrelated errors, the error in $T^2(0)$ (designated by the symbol δ) will be related to the errors in N(θ) and N(0) by the formula

$$\delta T^2(0) = q\left[\frac{N(\theta)}{N(0)} \sec^2\theta\right]^q \left[\left(\frac{\delta N(0)}{N(0)}\right)^2 + \left(\frac{\delta N(\theta)}{N(\theta)}\right)^2\right]^{1/2}, \tag{10}$$

where

$$q = \frac{1}{\sec\theta - 1}$$

Dividing by $T^2(0)$, we get an expression for the fractional error (f).

$$f = \frac{\delta T^2(0)}{T^2(0)} = q\left[\left(\frac{\delta N(0)}{N(0)}\right)^2 + \left(\frac{\delta N(\theta)}{N(\theta)}\right)^2\right]^{1/2} \tag{11}$$

If we shoot j_1 joules at the zenith and j_2 joules at zenith angle θ, we will get $j_1N(0)$ and $j_2N(\theta)$ photoelectric counts respectively. The fractional error, assuming Poisson statistics, then becomes

$$f = \frac{1}{\sec\theta - 1}\left[\frac{1}{j_1 N(0)} + \frac{1}{j_2 N(\theta)}\right]^{1/2} \qquad (12)$$

We will estimate the magnitude of the fractional error by substituting for $N(\theta)$ as a function of $N(0)$ and $T^2(0)$. Using equations 8 and 12 we obtain

$$f = \frac{1}{\sec\theta - 1}\left[\frac{\sec^2\theta T^2(0)^{1 - \sec\theta}}{j_2 N(0)} + \frac{1}{j_1 N(0)}\right]^{1/2} \qquad (13)$$

Since f is a function of the angle used to obtain the off-zenith shots, there is an optimum value of θ which will minimize the error for any given transmission and predetermined number of shots. Numerical investigation of equation 13 has shown that best results can be expected if the off-zenith shots are taken at an angle of about 60°. On nights of low transmission, however, ($T < .60$) a lesser angle of about 50° is to be preferred. Table 2 is presented to illustrate the expected percentage error in $T^2(0)$ when calculated by this method. It was calculated from equation 13 by using both the U.S. Standard Atmosphere Supplements[9] and the system parameters shown below to predict return at any altitude. It was assumed that all the off-zenith shots were taken at an angle of 60°. We designate n(0) as the number

	System I	System II
Area	= 2×10^3 cm^2	= 2×10^3 cm^2
$\bar{E}$	= 2 joules	= 5 joules
αQ	= 10^{-3}	= 2×10^{-3}
T	$\doteq$ .8	$\doteq$ .8

of shots taken at the zenith and n(60) as the number of off-zenith shots. The percentage error is shown as a function of n(0) and n(60) when one uses 2.5 km layers at several representative altitudes.

As can be seen by inspection of table 2, fairly good precision can be obtained in a typical night's operation. If one can observe altitudes where the returns are as high as the pulse counting equipment can process, one whould be able to compete favorably with the determination of $T^2(0)$ from stellar sources. If, for instance, one was using the equivalent of system II, 20 shots out of every 120 directed at a zenigh angle of 60° would allow determining $T^2(0)$ to a precision of a few percent. You also

TABLE II

The Percentage Error of $T^2(0)$ as a Function of n(0) and n(60)

Layer at 20 km - System I†

n(0) \ n(60)	10	20	40	80
50	2.6	2.2	1.9	1.7
100	2.3	1.8	1.5	1.3
200	2.2	1.7	1.3	1.1
400	2.1	1.6	1.2	.9

Layer at 40 km - System I

n(0) \ n(60)	10	20	40	80
50	25	20	18	17
100	22	17	15	13
200	21	16	12	10
400	20	14	11	8

Layer at 30 km - System II

n(0) \ n(60)	10	20	40	80
50	3.8	3.2	2.8	2.6
100	3.4	2.7	2.2	2.0
200	3.2	2.4	1.9	1.6
200	3.7	2.3	1.7	1.4

†The return at this altitude is so high it may not be possible to use digital pulse counting techniques.

have the possibility of gaining even higher accuracy by using the average of several 2.5 km layers. This assumes, however, that: a) the relative output power is known to a very high accuracy; and b) the atmospheric transmission is uniform both temporally and spacially. Either criteria might limit the percentage error much more than the factors considered in table 2.

The UM system is capable at present of observing efficiently only above 50 km. A simple extrapolation of the data in Table 2 shows that no accuracy can be obtained at such an altitude with our system efficiency. As a further confirmation of this statement; when $T^2(0)$ was calculated from 35 shots at $\theta = 39°$ and 100 shots at $\theta = 0°$, we obtained the answer:

$$T^2(0) = 2.5 \pm 2.3.$$