(NASA-CR-136234) PROJECT APOLLO GUIDANCE
AND NAVIGATION PROGRAM Monthly Technical
Progress Report, 11 Aug. - 13 Sep. 1961
(Massachusetts Inst. of Tech.) 55 p

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MASSACHUSETTS INSTITUTE OF TECHNOLOGY

APOLLO
GUIDANCE AND NAVIGATION

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and

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REPORT E-1067

(Title Unclassified)

MONTHLY TECHNICAL PROGRESS REPORT
PROJECT APOLLO GUIDANCE AND NAVIGATION PROGRAM

Period August 11, 1961
to
September 13, 1961

INSTRUMENTATION LABORATORY

CAMBRIDGE 39, MASSACHUSETTS

ACKNOWLEDGMENT

This report was prepared under the auspices of DSR Project 55-191, sponsored by the National Aeronautics Space Administration under Contract NAS-9-153.

The publication of this report does not constitute approval by NASA of the findings or conclusions contained herein. It is published for the exchange and stimulation of ideas.

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MONTHLY PROGRESS REPORT FORMAT

The generation of the monthly progress report will be combined with two other functions. These functions will be carried out at a monthly meeting of all M. I. T. Instrumentation Laboratory staff personnel engaged in the Apollo effort. This meeting has the following objectives:

1. Technical presentations by Laboratory members to NASA representatives and to the Apollo staff will be a means of communication.
2. The NASA representatives will be partially fulfilling their responsibility of monitoring the activities of the contract.
3. The publication of the minutes of this meeting will result in a written monthly progress report.

It is anticipated that the customary agenda for the monthly meetings, and thus the progress report, will consist of a number of status reports and one or more presentations in depth on selected subjects. The first several meetings, however, will consist only of presentations in depth. This type of agenda will persist until most activities have been thus considered.

It is intended that the staff members will not participate substantically in the conversion of the meeting minutes into the written report. It is felt that the advantage of engineering time and effort saved will outweigh the penalty of an imperfect written presentation. Polished technical reports will be published

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separately, however, as the status of the various efforts warrent.

The topics of the 13 September 1961, meeting are shown in the table of contents. It is anticipated that the 4 October meeting will consist of the following:

Introduction - M. Trageser
Organization - R. Woodbury
Space Sextant Visibility Problems - R. Magee
Space Sextant Geometry - J. Dahlen
Gear Train Analysis - R. Magee
Vacuum Environmental Approach - W. Toth
Midcourse Guidance Theory - R. Battin
Inertial Measurement Unit - D. Hoag
Gyro - E. J. Hall
Computer - E. C. Hall and R. Alonso

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The next phase of the problem is entering the satellite orbit around the moon. During this interval, both systems are in use: the inertial guidance system gets its initial orientation and position as determined by the space sextant and then controls the retrothrust to put the space craft into its satellite orbit.

The lunar landing is still another phase of the problem. In addition to the inertial guidance system, more data are required to control the final approach for a gentle landing on the moon. Present preference is for the use of the range finder, for optical range and drift determinations. It is too early to state whether this is preferable to radar "doppler" signals. A lot depends on the scattering of dust, rocks and debris around the moon surface resulting from the rocket blast that allows the space craft to hover above the moon.

The first discussion relates to the definition of horizon as will be explained by Dr. Peterson. He will exlain why you do not actually see the marine horizon but see instead some depth of atmosphere. The next discussion will relate to the problem of visibility and identification of landmarks because of cloud cover, atmospheric effects, and the like.

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INTRODUCTION

M. B. Trageser

The guidance problem has a number of phases. A Saturn rocket will probably be used to launch the vehicle on its flight to the moon and will place the space craft in parking orbit. Monitoring of the booster guidance system is the first phase of the problem. Some check-out of the mid-course guidance equipment may be required before the final thrust out of parking orbit into the translunar flight. During the last stage of powered flight, the inertial guidance system controls the error of injection into the orbit to the moon. If any error were not corrected, a large miss of the moon would result.

There is a mid-course guidance system by which the astronaut uses a space sextant, as yet, an undefined number of times. This optical system uses several methods to determine fix:

1. The angle between some star and the horizon.
2. The angle between some star and some landmark.
3. A measurement between some star and a preselected spot on the moon.

Any one of these by itself gives one of three necessary measurements to accurately fix the position of the space craft.

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DEFINITION OF HORIZON

Dr. M. Peterson

These paragraphs are a condensed revision of remarks made at the Apollo conference September 13, regarding calculations and photometry trials bearing on the appearance of the earth's atmosphere seen as a limb of the sun-lit earth from outside the entire atmosphere. This study was begun under an assignment by NASA for observations by an earth-orbiting astronaut. It pertains to the guidance problems for Apollo in the fact that air observation of the earth's limb for space navigation at landing approach should use all available accuracy. The varied brightness of the earth's limb may be appraised in terms of the intensity of the light scattered by the atmosphere as predicted by scattering theory and the observed attenuation of sunlight under varied circumstances.

The astronaut looking at the earth's limb, or sensing it with some photosensor other than the eye, will be receiving light scattered into a line of sight extending in his direction and grazing the earth at some significant elevation, above sea level, greater, almost surely, than 5 km. Below this elevation many clouds are likely to intrude. If they did not, it is clear from our occasional view of the setting sun itself that at sea level the horizon atmosphere is so nearly opaque, by scattering, that little of the sun-light scattered into this direction would succeed in emerging toward the

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astronaut. What does emerge will have nearly the color of sunlight, will be white, and will not be accountable in terms of single Rayleigh scattering.

In this study only this Rayleigh scattering is considered, that due to pure air, obeying an inverse fourth-power wavelength dependence, and only single scattering has been considered in the calculations here reported.

The geometry from which these calculations proceed is shown by Fig. 1.

Sunlight is considered to fall on the earth's atmosphere in the vertical direction. As it enters the atmosphere it is somewhat attenuated by scatter, wo that any element of scattering atmosphere, such as that marked Δm, is illuminated in an amount dependent on its elevation, — on how much air is between it and the sun. This attenuation is little, but may easily be considered. It is also necessary to know the density of the air in the element of path occupied by Δm, hence its elevation is again involved. Its elevation is got by the rule $X^2 = (h-h_0)2R$ very nearly. h_0 is its elevation at the grazing point, where the path of the beam is perpendicular to the earth's radius. With the value of h one can take from table (A.R.D.C. Standard Atmosphere 1959) the density of the atmosphere at the location of Δm and the mass of air between it and the sun. This latter is to be expressed in kilometers

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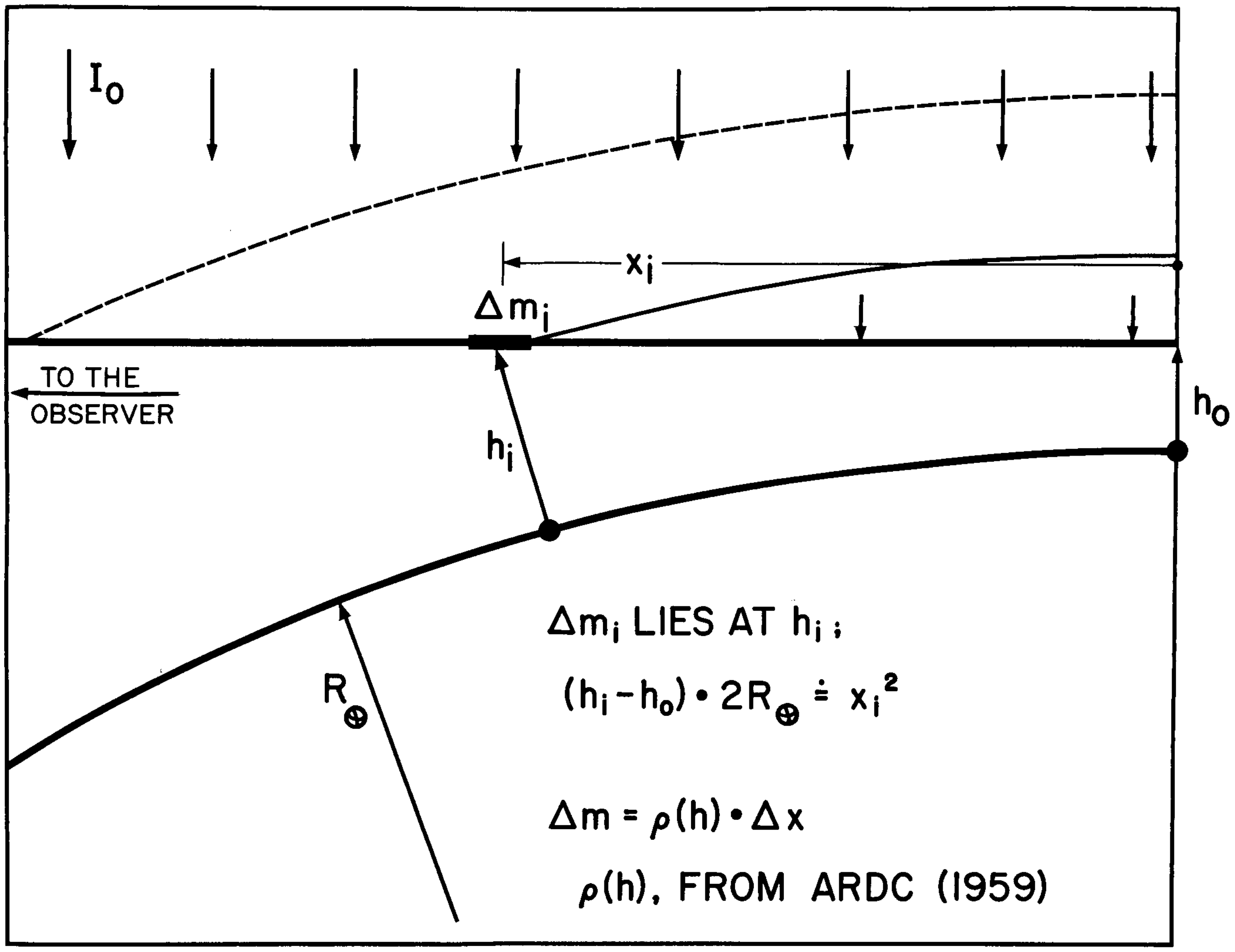

Fig. 1 Geometry of Scattering Lamina in Limb Atmosphere

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of normal density air at sea level pressure. At sea level this quantity is about 8.0 km, varying only a little with the season. It is called the "reduced height" of the atmosphere.

The incident solar illumination on Δm can be written

$$I = I_o e^{-\sigma h_1}$$

in which h_1 is the "reduced height" of the atmosphere above the h elevation of Δm and σ is an extinction coefficient, calculable by theory for pure air, and observable astronomically, under conditions which practically never can be designated as pure air. The observed extinction is always greater. This extinction coefficient depends on the wave-length of the light considered.

The light that the element of air Δm scatters in the observer's direction will be proportional to the illumination and, in the case of Rayleigh scattering, to a scattering coefficient which is directly measured by the extinction coefficient in a manner depending only on the scattering angle, that we have chosen as 90°. The scatter will also be proportional to Δm, and can be written

$$\Delta B_o = I_o e^{-\sigma h_1} \cdot \rho(h)\, \Delta X \cdot S(\sigma)$$

But before this scattered light emerges from the atmosphere toward the observer, it will be attenuated by all the air in its path between Δm and the observer. This attenuation

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can be written

$$e^{-\sigma m'_i}$$

in which

$$m'_i = \sum_{j}^{z} \Delta m_n$$

Then for a chosen scattering angle and value of σ , and on an arbitrary brightness scale, we may write for the total of all contributions ΔB.

$$B = \Sigma\, \rho(h)\, \Delta X \cdot e^{-\sigma (h_1 + m')_i}{}_{\sigma}$$

In so using σ instead of the specific S(o) we only add a factor to the arbitrary brightness scale, but more importantly we conserve the general utility of the comparative calculations until specific wave-length assignment is made to the solar spectrum. This last depends on the real atmosphere's varying deviation from pure air scattering at different elevations. All well established data have been taken from high mountain observatory sites. More recent balloon observations require study.

Each calculation for a given σ and h_o gives one point on a curve describing the brightness profile of the earth's limb in one color; and must be repeated for several values of h_o to enable drawing the curve. Such calculations have been made for seven values of h_o and for five values of σ, assignable to various colors of light. The curves derived from these calculations appear in Fig. 2.

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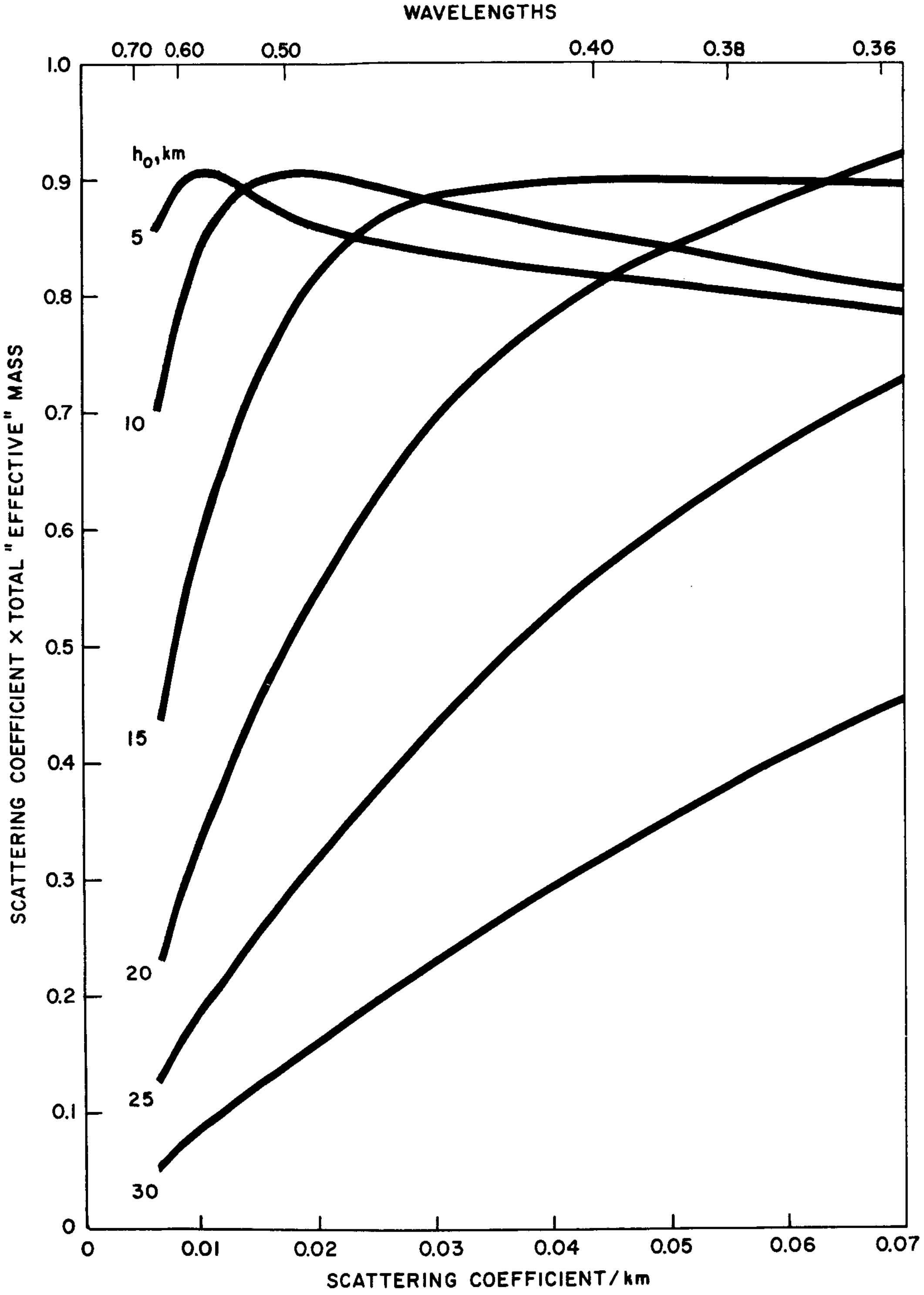

Fig. 2 Profiles of Rayleigh Atmosphere

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These curves show that for the scattering considered:

(a) The peak brightness for any scattering value changes very little, assuming a unit brightness of solar illumination of the same wave-length, but with increasing scattering coefficient this peak brightness occurs farther up in the atmosphere.

(b) The depth difference in the atmosphere between full brightness and 1/10 of it is only slightly variable, being about 20 km.

(c) The maximum brightness gradient is about 0.053/km.

The recession of brightness at low values of h_o and higher values of σ will not be actually realized because, in these cases, secondary scattering will enhance the total scattering phenomenon. This occurs most pronouncedly when for any given optical path the effective product $\sigma \cdot m_{eff.}$ is greatest. m_{eff} is the total mass weighted according to its transmission factor.

The curves of Fig. 3 show the individual contributions of the several Δm elements along any one optical path of fixed h_o, for the scattering coefficient 0.0175/km, which for pure air applies to wave-length 5000 A, in the blue-green. These show that $h_o = 5$ km almost none of the received scattered light comes from beyond the grazing point; at 10 km not much more. At 30 km the far side contribution is nearly half of the little that there is. These curves illustrate the

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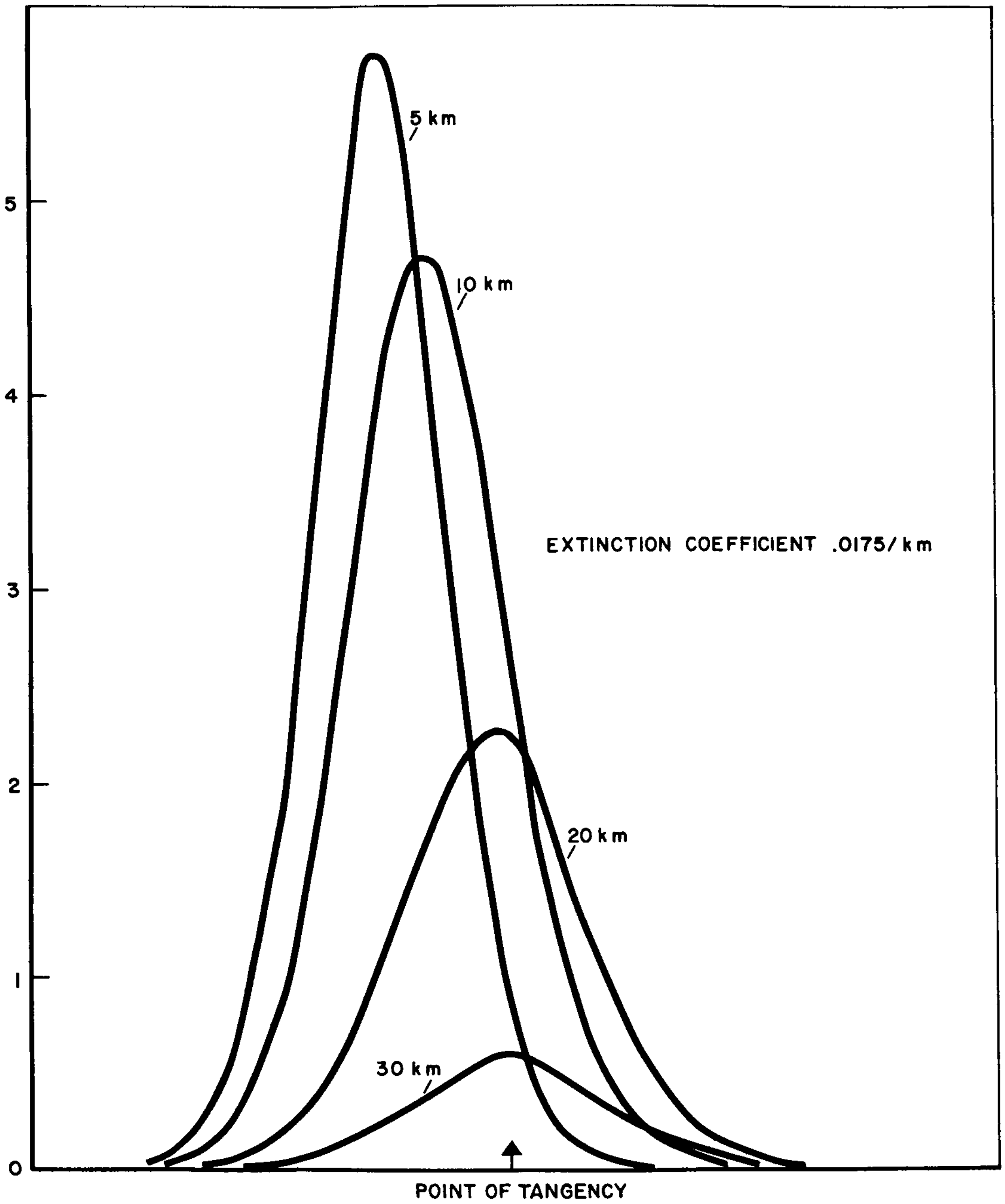

Fig. 3 Distribution of Transmitted Scatter in Line of Sight

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opacity of the horizon atmosphere due to scattering.

The curves of Fig. 4 show, in a general way, the approach for low values of h_o, of the several components of the spectrum to being a "white" match for sunlight. The curves have as a parameter the several values of h_o. Ordinates represent proportional brightness; abscissae the scattering coefficient and wave-lengths assigned as for pure air Rayleigh scattering.

Further studies in this domain involve:

(a) Some generalization of the scattering angle.

(b) Addition of Mie scattering in the lower atmosphere, due to water and dust.

(c) The role of polarization in the scatter.

Of these, (a) and (b) are in progress.

Further Discussion on Photometric Observations

To develop some concrete ideas for photometric observations by an astronaut of the sun-lit earth's limb, experiments have been made with several forms of illuminometers. A luminous simulated earth's limb has been measured, as well as a spray-painted simulation done after suggestions by Professor Arthur C. Hardy. This latter employs a very fine scattering medium on a black ground, and should be a physical replica of the real thing, if a good medium can be employed

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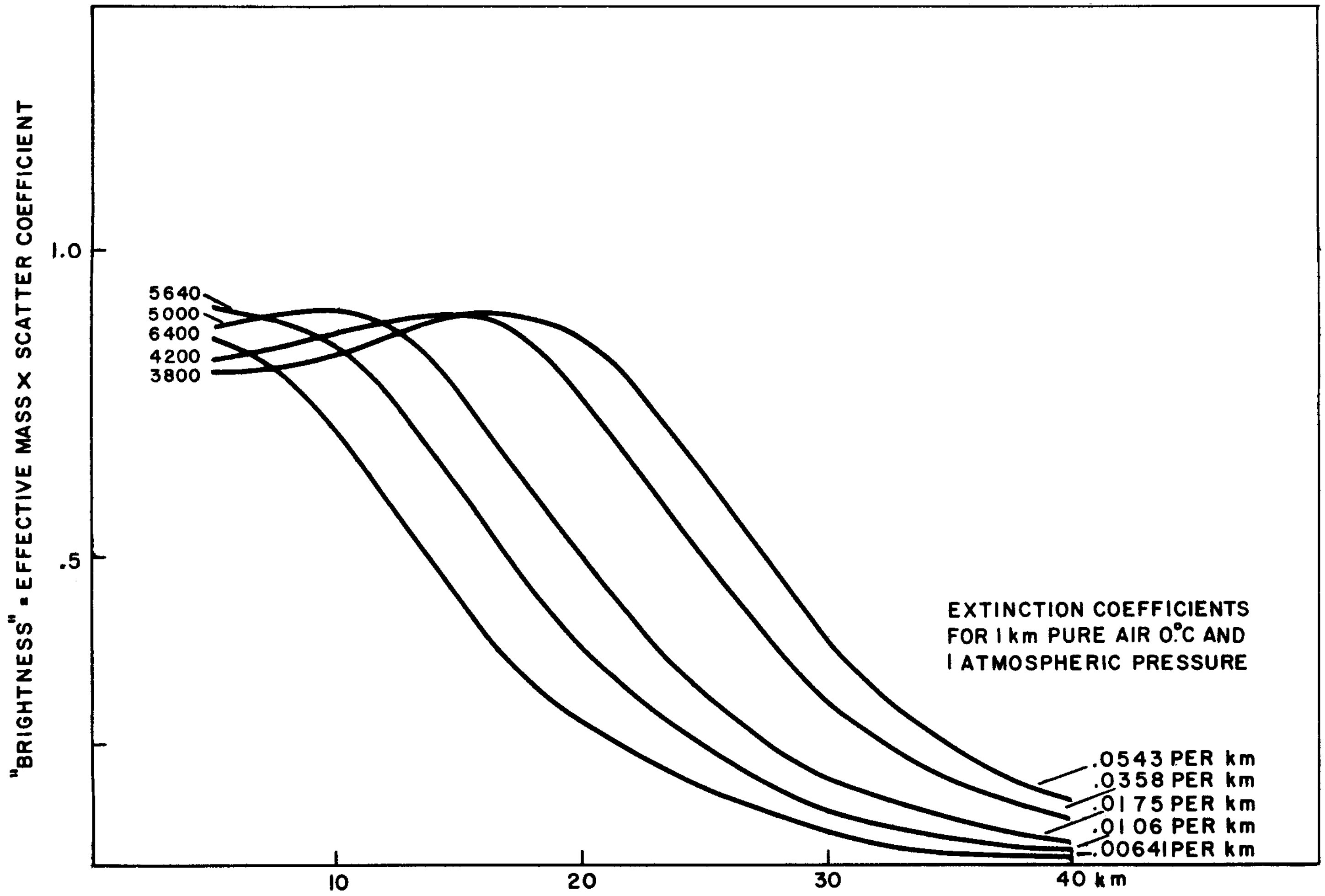

Fig. 4 Spectral Profiles of Rayleigh Atmosphere

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The curves of Fig. 5 display the results of these measures, using a visual file-photometer, and a photo-electric (S-4) sensor in the same device. In this photometer, the brightness of a narrow band of the horizon, perpendicular to the gradient was visually matched to a variable comparison field got from a small incandescent lamp. The instrument was stand-supported. It is not thought that a hand-held instrument could get such smooth data. The un-smoothness of the visual curve for the scattered light simulated was evidently partly real, due to the perception of local irregularities that the photo-cell averaged.

Professor Hardy, who was present at the conference, made some pertinent comments regarding this simulation of the earth's limb employing light scattering paint.

Comments by Mr. B. Trageser on Dr. Peterson's Presentation

I'd like to spend five minutes trying to relate the previous remarks to the over-all navigation problem. As Dr. Peterson's charts indicate, the brightness of the atmosphere diminishes by a factor of two approximately every 17,000 feet, just as does the air density. One scheme is to make either visual or nonvisual photometric determination of a certain altitude in the atmosphere. Meteorological conditions at the altitudes under consideration - some 90,000 - 100,000 feet - make this altitude move up or down photomet-

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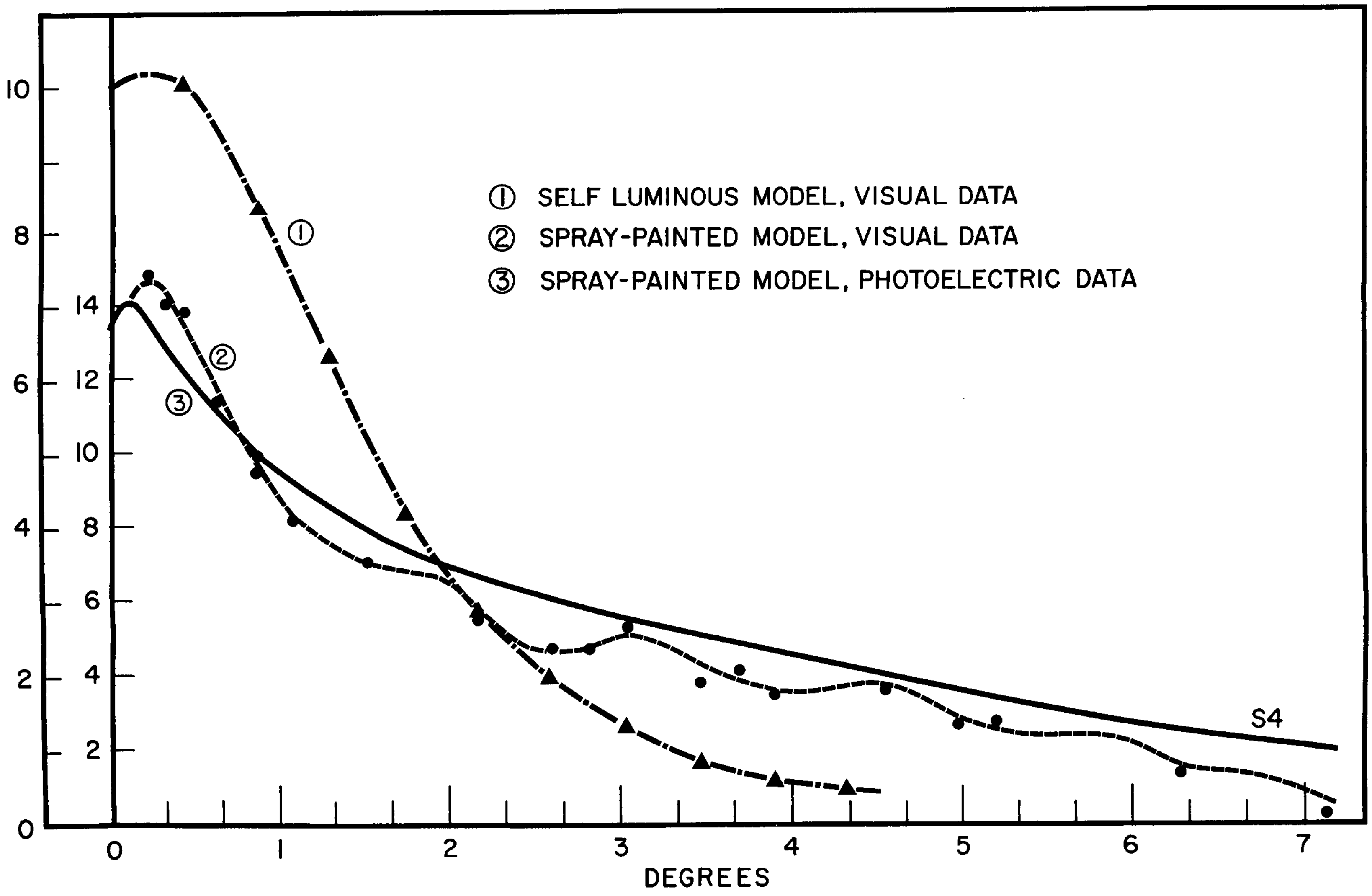

Fig. 5 Photometric Observations of Simulated Horizons

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rically by something like ten per cent of the pressure; in other words, a couple of thousand feet. We expect this method of navigation will have at best an accuracy limitation of some 2,000 feet because of this pressure variation resulting from meteorological conditions. At worst, atmospheric layers could result in a several or five mile accuracy for this method.

An important question that must be answered is, "Of what anomalies in the atmosphere are we uninformed?" Consideration has been given to using Project Mercury and the astronaut to make visual measurements to determine the nature of the atmospheric anomalies. We must determine what technique is highly effective, moderately effective, or useless when observing the limb of the earth. Experiments in Mercury might determine the effectiveness of this method for position determination.

In reply to Mr. Ragan's question, several schemes are contemplated to determine relative brightness. One method is to use photometric comparison. One can not state positively that a certain relative brightness determines a certain altitude.

The next topic is landmarks. The fix by landmark promises the most accuracy. It also promises more complexity in its operation and in storing computer data.

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W. E. Toth has been analyzing trajectories and meterorological data and has outlined the method of approach for the problem.

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VISUAL OBSERVATION OF LANDMARKS

W. E. Toth

It is possible for an observer, outside the earth's atmosphere, to view landmarks on the earth's surface or to view a horizon formed by the atmosphere. Involved in the choice of what to look at is the question of observation uncertainties. Consider this question with the aid of Fig. 1. (This figure shows the uncertainty distance at the object versus distance from the object.)

Uncertainty Distance at Object is defined as the distance, at the object, corresponding to the angular uncertainty assumed for the observation. The object refers to the thing observed. The angular uncertainty refers to the uncertainty associated with the observation (bull gear error, instrument resolving power, uncertainty of readout, etc.).

The diagonal lines apply to instruments exhibiting various angular uncertainties. Horizontal lines are drawn to illustrate uncertainties assumed to exist in the location of landmarks and the earth's horizons. For illustrative purposes, let us assume an instrument uncertainty (due to bull gear, optics, readout, etc.) of 10 seconds of arc. One can now infer the following from Fig. 1.

1. When closer than 1700 miles from the earth, the most accurate measurement would be made sighting landmarks. Mapping errors would limit accuracy to 500 feet at the object.

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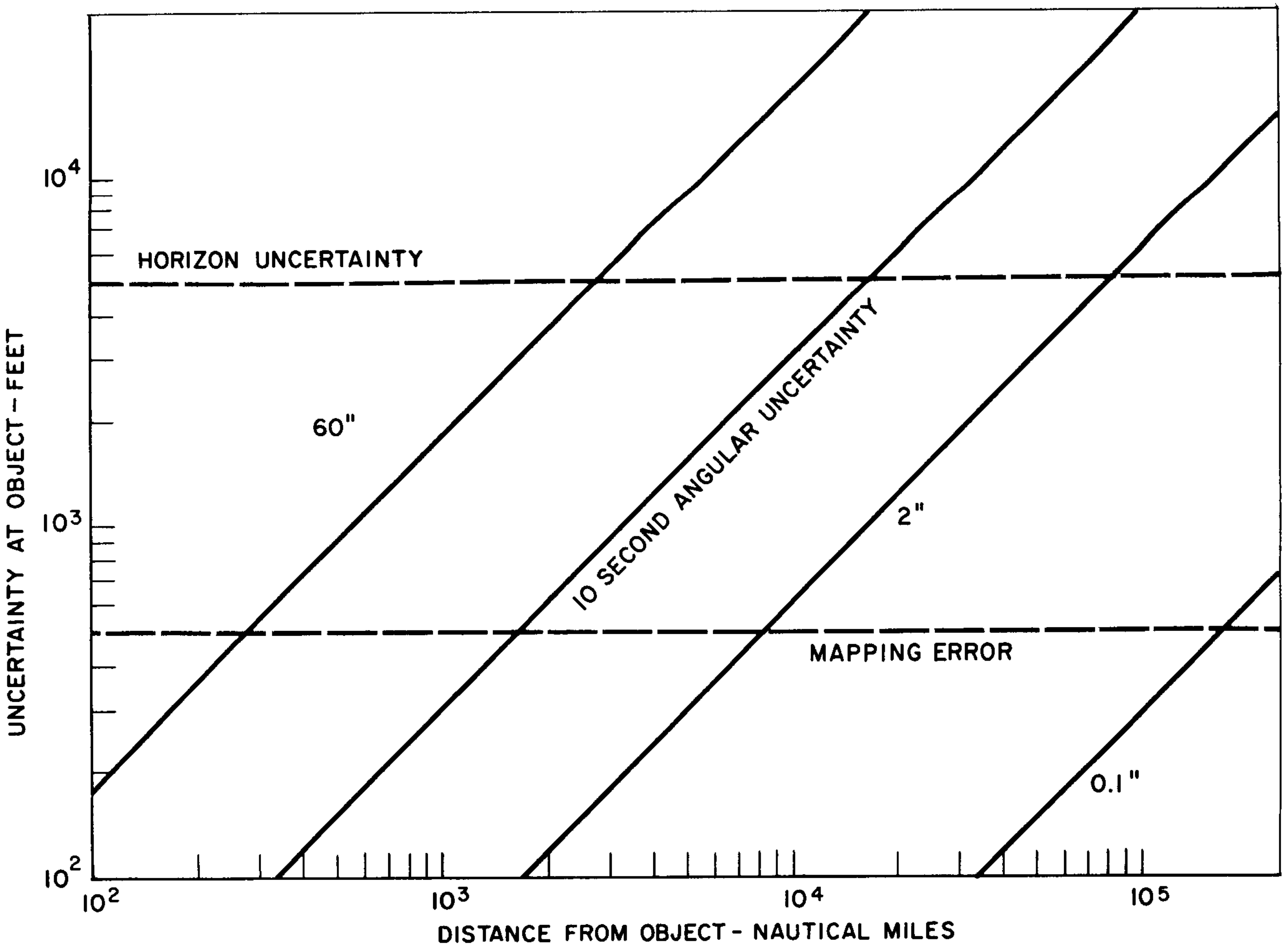

Fig. 1 Uncertainty Distance at Object vs Distance from Object

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2. When beyond 1700 miles from the earth, the most accurate measurement would be made sighting landmarks. Instrument error would be the limiting factor: 500 feet at 1700 miles and 5,000 feet at 17,000 miles.

3. Beyond 17,000 miles the accuracy is limited by instrument errors, and either the horizon or landmarks can be viewed. Landmark observation and identification problems might make the horizon a better choice at these distances.

There are other factors that must also be considered when determing what to look at and how. Relative motion of the observed object and time available to take a sight are two considerations, not discussed here, which will influence observation accuracy, recognition of objects, and choice of observation procedure.

There are a great many variables involved in questions of what one sees when looking at the earth from beyond the atmosphere. A procedure that will minimize the number of variables to consider, and eliminate useless generalization is

1. Determine the trajectories which might be selected for the Apollo mission.

2. From the trajectories, plot the earth and moon tracks for the entire trip. Note the vehicle's position, distance from earth or moon, and aspect of the sun at various times along the tracks.

3. Consider geometrical limitations to viewing landmarks along the ground tracks.

4. Consider weather conditions on the earth along the ground tracks.

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5. Consider problems of visibility involving the atmosphere, color, contrast, lighting, etc., along the ground tracks.
6. Conclude as to the probability of being able to take appropriate "fixes" and the practicality of using landmarks along the ground tracks.

An illustrative trajectory is reproduced in Fig. 2. An earth track is shown for a launch from Cape Canaveral toward the moon, at about midnight, during the month of January. Several specific times after launch are selected, and noted on Fig. 2. Estimated distance along the track and altitude above the earth are shown.

Fig. 3 shows the relative positions of the earth, moon, sun and the vehicle during this trip to the moon and back. From this figure, one obtains a rough idea of the lighting and view at various times during the journey. Several interesting things are observed using Figs. 2 and 3. A parking orbit is achieved after approximately 6 minutes, placing the vehicle at about 100 miles altitude. For the next 20 minutes the vehicle moves toward Africa at constant altitude. The earth below is dark during this time. Thus, passive sun-lit landmarks are not available during the period before injection, for the orbit shown. Even if something were available, say a light on the earth, the angular rate at which the light appeared to move might preclude the possibility of accurate tracking from the vehicle.

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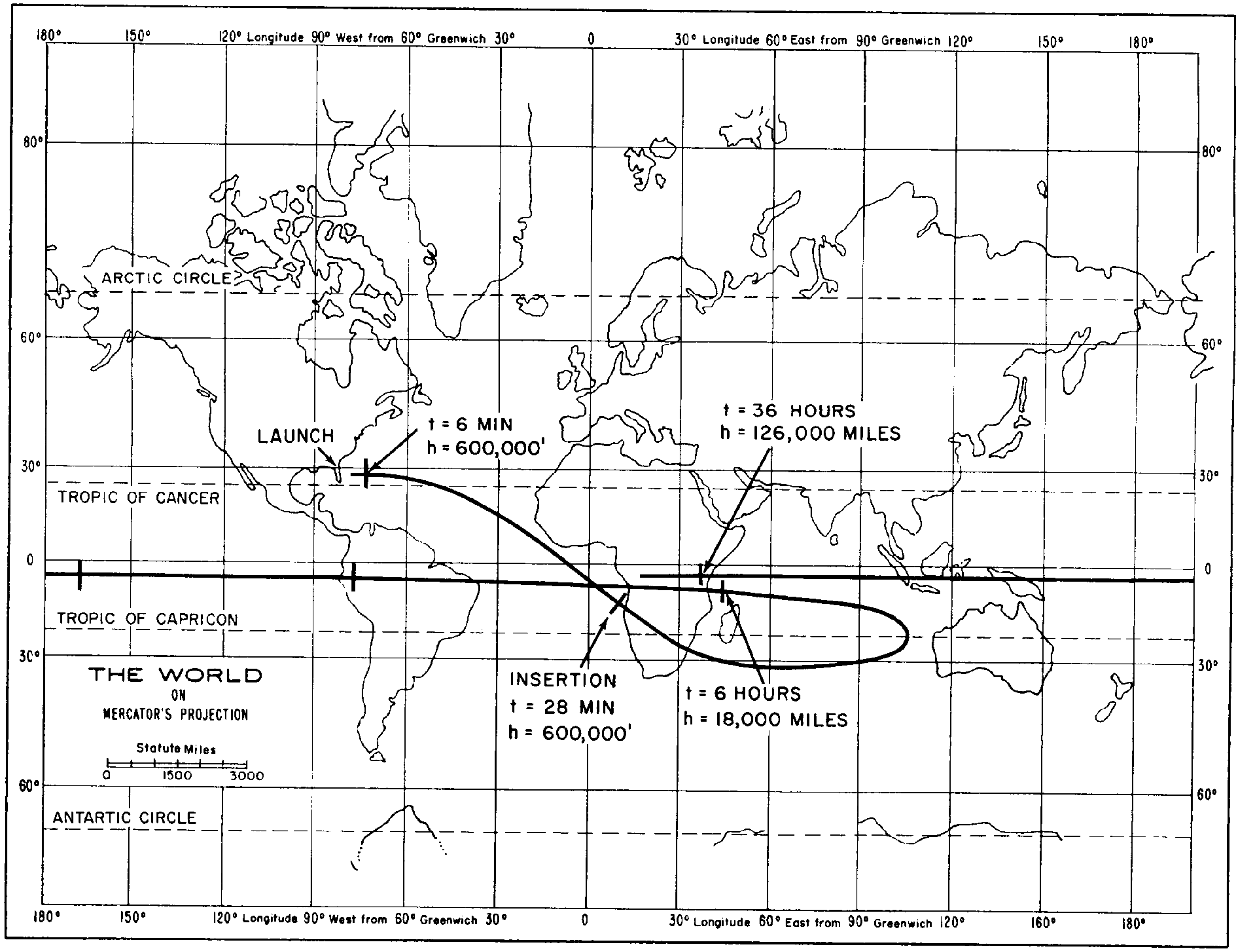

Fig. 2 Illustration of Trajectory from Cape Canavaral

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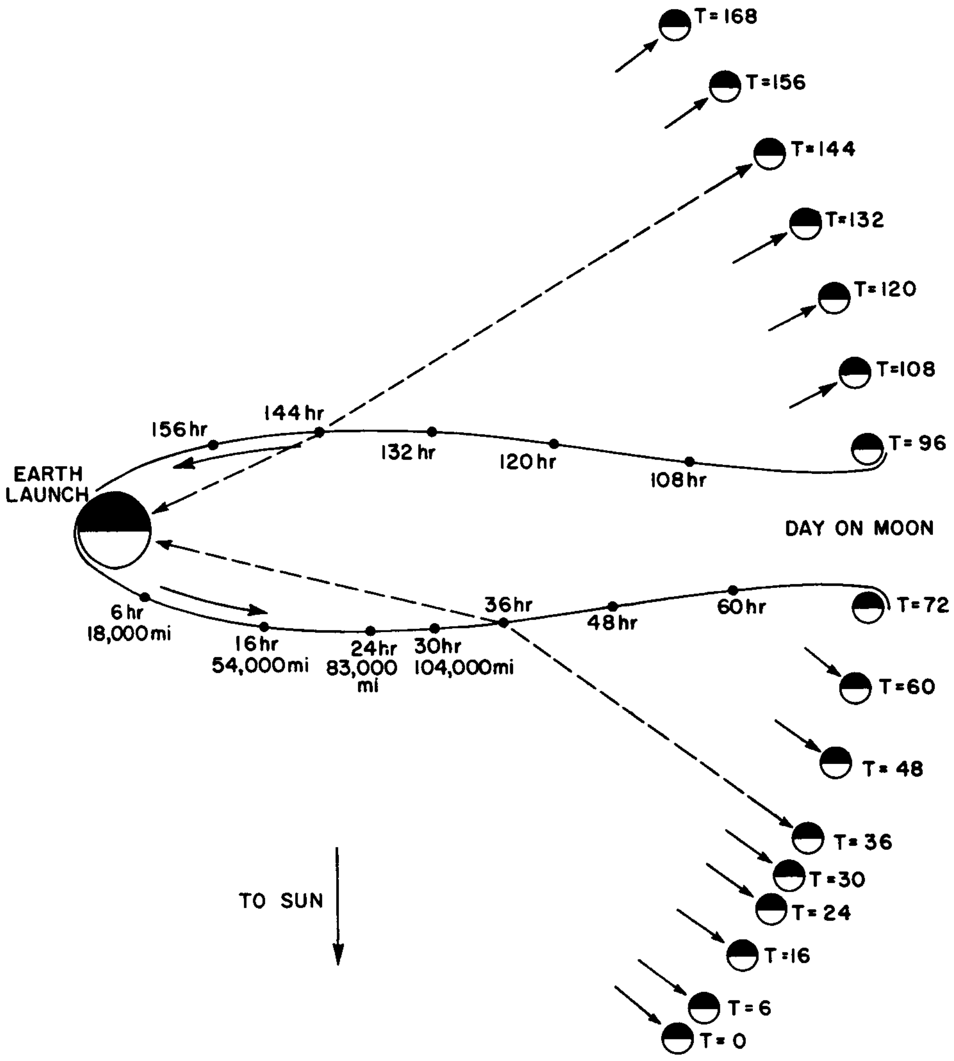

Fig. 3 Illustration of Visual Observations

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This rate is about 2.5 degrees per second of time.

Three hours after launch the earth below appears to be stationary. Six hours after launch the vehicle is approximately 18,000 miles from the earth's surface. The earth appears to rotate at nearly earth rate for the remainder of the trip to the moon. We note also that the earth is well lit during the translunar trip. Thus slowly moving, well-lit landmarks may be available for mid-course guidance to the moon (for the illustrated trajectory). The same is true of the moon, except that only a crescent will be seen, with landmarks almost stationary.

The trajectory back to the earth appears less favorable for this orbit since much smaller sun-lit portions of the earth are available, and one now looks toward the sun instead of away from it. At this point one thinks of the possible usefulness of lights placed on the earth. Landmarks of this type are entirely feasible, and may provide the best type of landmark under the circumstances. At this phase of the study, however, they are not being investigated. It is interesting to note the possibility, however, as follows. A high intensity arc light having a brightness of 300,000 lamberts, ignoring effects of the earth's atmosphere, having an aperture of 45 cm would be just perceptible to the unaided, dark-adapted eye, at the moon.

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Limitation due to Geometry

Fig. 4 shows the limitation to viewing landmarks due to the geometry of the situation. Complete absence of an atmosphere is assumed. An angle θ_M between the line of sight and the normal to the plane of the landmark is shown. For angles exceeding about 70°, landmarks will be difficult or impossible to recognize because of elongations and distortions of the view. This limitation can be shown graphically along with the earth and moon tracks. The resultant tapering area over the earth and moon will indicate the areas which, in the absence of all other limitations, could be observed at various times during the trip.

Limitation to Viewing due to Adverse Weather Conditions

Some portions of the possible viewing area on the earth may exhibit particularly poor weather situations, on the average, for the times important to the Apollo mission. These areas should be deleted from the area of possible landmark observation.

Limitation to Viewing Landmarks due to the Effects of a Clear Atmosphere

The earth's atmosphere scatters light, accounting for a reduction in contrast of the observed scene. This reduction in contrast will make it impossible to distinguish some landmarks. The exact change in contrast depends upon the scene, the amount of atmosphere involved, and the kind

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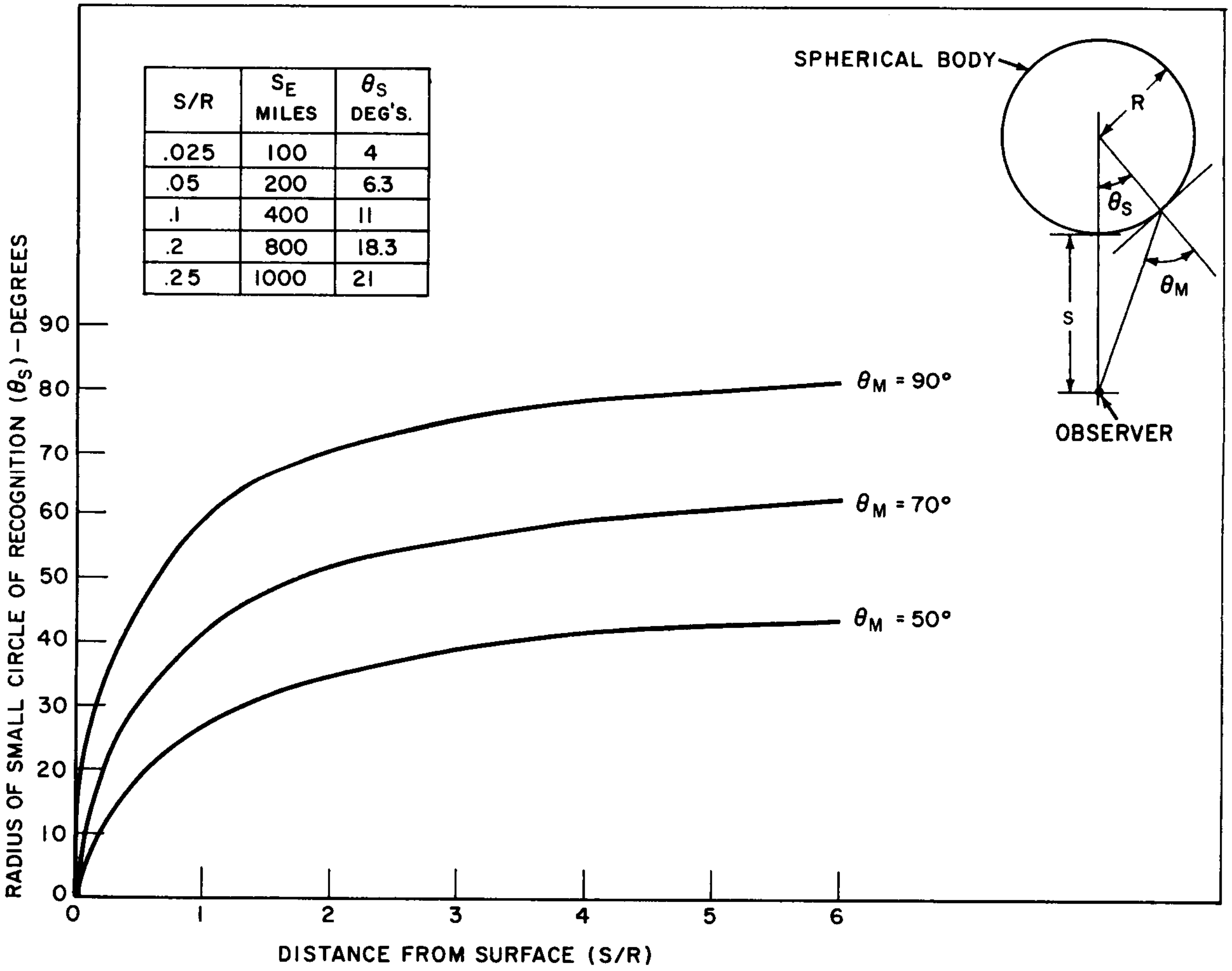

S/R	S_E MILES	θ_S DEG'S.
.025	100	4
.05	200	6.3
.1	400	11
.2	800	18.3
.25	1000	21

Fig. 4 Geometrical Limitation to Area of Recognition vs Distance from a Spherical Body

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of atmosphere considered. The effect can be investigated point by point along the ground tracks. Thus, at a particular time the view might be of a coast line in th Pacific. If one assumes some average kind of atmosphere for the area involved; contrast values for things of interest; lighting conditions of scene and background; then the influence of the atmosphere on one's ability to distinguish landmarks can be calculated. The details of this analysis will be treated by Mr. F. Martin shortly. This limitation will narrow further the areas of possible landmark observation.

Limitation to Viewing Landmarks due to Position of Sun

Since only passive landmarks are under investigation here, it is necessary that areas of observation be sunlit. Those areas in darkness must be deleted from the map of landmarks available for possible observation. Thus, on Fig. 2 the landmarks along the earth track from Cape Canaveral to the coast of Africa would be deleted for the early part of the mission.

We might now draw a map showing, at any time, the areas suitable for observing landmarks if weather conditions permit. One can select, in these areas, a number of specific landmarks for further analysis. We must determine on the basis of meteorological data, the probability of seeing specific places at the times in question. We are considering, then, the problems of cloud cover, incidence

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of fog, haze and mist, and visibility through an atmosphere.

Meteorological data is available in various forms for stations throughout the world. As one might suspect, however, the exact information we require for this study is not readily available. Meteorological information which can be processed to give the necessary information may be available from a number of sources. Sources in the U.S. Air Force, Tiros data, and Mercury data. Outside the U.S. are the meteorological data centers of the governing countries involved; another source is IGY data taken for a period of at least 18 months starting in June, 1957, for weather stations throughout the world, and recorded on micro cards. Assuming we now have meteorological data, what do we do with it? We must determine, for each station, if the incremental time period in question were a time during which the station could or could not be seen from beyond the atmosphere. To do this it is necessary to establish a criterion which, when applied to the available meteorological data, gives the desired information. The criterion for selecting periods of good seeing might include

1. No fog
2. Not more than 0.1 cloud cover
3. Horizontal visibility not less than D miles, where D is selected for each location. D would correlate with the previously mentioned "type of atmosphere" assumed in computing limitations to viewing landmarks through a clear atmosphere.

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4. Station illuminated by bright sunshine.

All times not satisfying these conditions would be discounted. Then, with a knowledge of the length of time of good seeing and the number of daylight hours, the probability of being able to see the station during daylight hours is computed (the ratio of the two).

The probability data, found for many points along the earth track, can be noted on a map showing all important weather stations. Sufficient information is available on this map to determine the best and poorest times for viewing landmarks and to determine the practicality of using landmarks for navigation. The information will also be an aid in determining the specific data the astronaut should carry (maps, tables, etc.).

It is noted (Table I) that values greater than (0.7) are rare for individual stations. Hopefully, the chance of seeing a useful landmark will be considerably greater than this. The reasoning to support this hope goes as follows: Consider a group of stations, each with a probability of being seen equal to (P). If the meteorological conditions at each station are statistically independent of conditions at all other stations, one can compute the probability of seeing at least two stations, for example, out of the group. This probability will be considerably greater than (P), as in-

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TABLE I

PROBABILITY OF SEEING PARTICULAR STATIONS DURING MONTH OF JANUARY

STATION	PROBABILITY*
Nemuro, Hokkaido (Japan)	0. 16
Maebashl, Honshu (Japan)	0. 37
Kobe, Honshu (Japan)	0. 10
Taihoku, Formosa	0. 07
Madrid (Spain)	0. 52
Lisbon (Portugal)	0. 47
Rome (Italy)	0. 38
Athens (Greece)	0. 49
Cairo (Egypt)	0. 70
Miami (Florida)	0. 65
Atlanta (Georgia)	0. 51
Charleston (S. Carolina)	0. 58
Montgomery (Alabama)	0. 52
Phoenix (Arizona)	0. 75
Pueblo (Colorado)	0. 76
New Orleans (Louisiana)	0. 49
Houston (Texas)	0. 48

* Calculated as hours of bright sunshine divided by total possible hours of sunshine.

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dicated in Fig. 5. Actually, some dependence of weather at one station to weather at another station does exist. If the relationship is known it is possible to compute the important probabilities. This type of analysis has not been carried out.

Experimental Program

It is an absolute necessity that an experimental program be conducted to establish the validity of the ideas discussed here. This program must accomplish the following:

1. Demonstrate the validity of calculations of visibility through a clear atmosphere.

The question of realistically defining a typical atmosphere is involved here. We ask, for example, if continuous layers of thin cirrus clouds, invisible from the ground, existing at high levels (50,000 feet) are present on most "clear" days.

Calculations involving color, lighting, contrast and recognition must all be tested by experiment.

2. Meteorological data taken by land and sea stations are used to calculate the probability of seeing any station. These probabilities must be varified.

3. Assumptions involving statistical dependence or independence of weather conditions at a number of stations must be checked, or established.

4. The existence of an atmospheric phenomenon, unsuspected but interfering with visibility from beyond the atmosphere, must be checked.

5. The question - How accurate is the information derived from observing a landmark? - must be answered for various landmarks.

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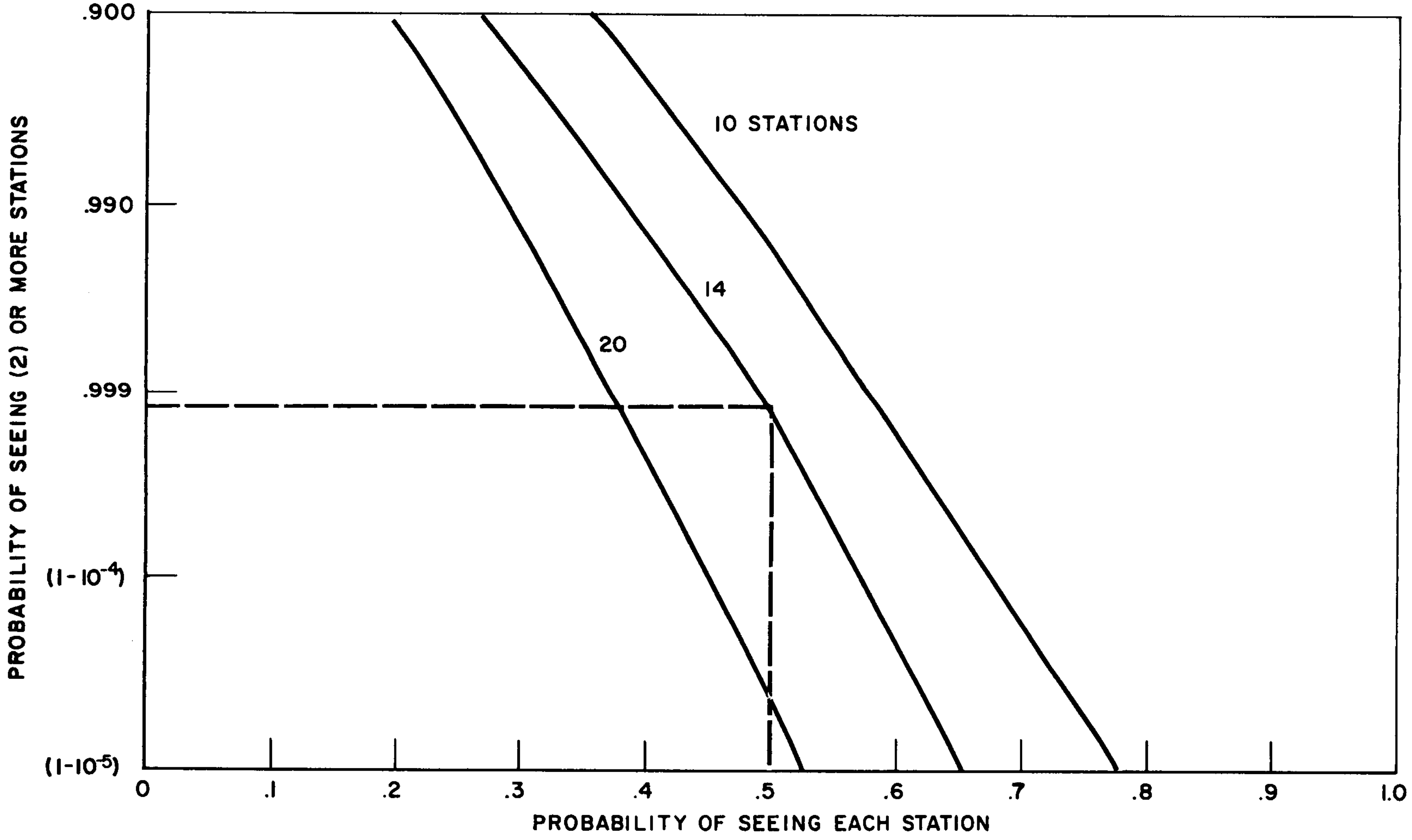

Fig. 5 Probability of Seeing (2) or More Stations

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Several means for carrying out experimental programs suggest themselves. They are balloons, U-2 aircraft, satellites, the Mercury vehicle, and rockets. The use of balloons and U-2 aircraft is reasonable since most of the phenomenon affecting visibility through the atmosphere occurs below about 50,000 feet. Known exceptions to this are the Nacreous clouds, occuring at altitudes of 75,000 feet to 100,000 feet, and Noctilucent clouds occuring at altitudes of 250,000 feet to 300,000 feet. In addition it is interesting to note that at 75,000 feet one is above 96% of the atmospheric mass.

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VISIBILITY OF LANDMARKS

F. H. Martin

Herein is presented an initial approach to the study of seeing landmarks through the atmosphere. It is only concerned with the deterioration of visibility due to atmospheric density and disturbances while cloud cover and the recognition of landmarks will be the subject of other investigations.

The phenomenon which contributes to the reduction in visibility through the atmosphere is the scattering of light into the path of vision. This scattered light reduces the contrast of the landmark scene and therefore its visibility. The first section following deals with a definition of terms and a short presentation of the basic concepts involved. This is followed by an attempt to quantitatively classify landmarks and an application to the seeing of landmarks from a spacecraft.

1. Basic Concepts

The brightness of an object at a distance is materially affected by the column of atmosphere presenting itself between observer and object. Figure 1 illustrates this situation for horizontal vision. Each element of the intervening atmosphere is illuminated by surrounding sky-light, sun light and reflected light. Some of this incident light is scattered [1*] (through molecular and/or particle action) in

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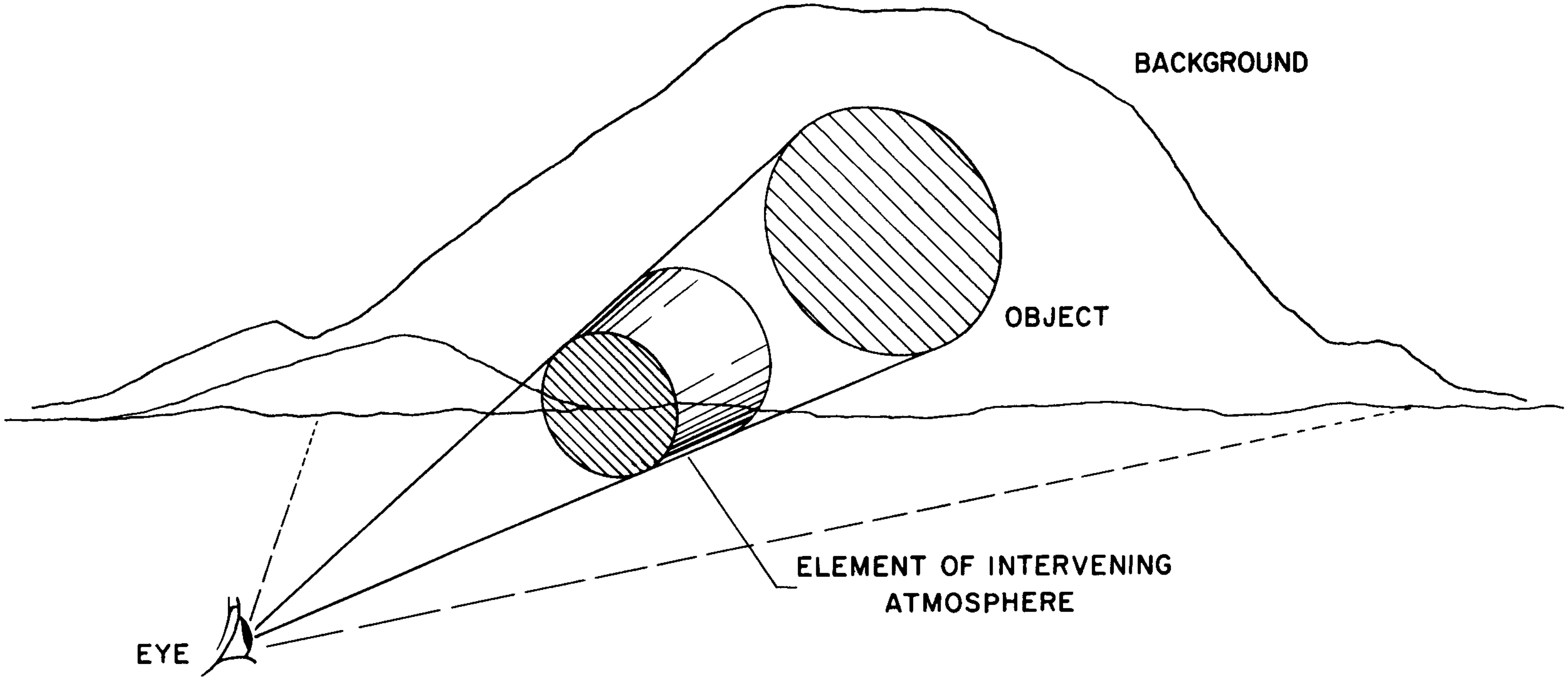

BLACK OBJECT $B_b = B_h (1 - e^{-br})$

ANY OBJECT $B = B_h (1 - e^{-br}) + B_o e^{-br}$

Fig. 1 Horizontal Vision - Scattering of Light

[redacted]

the direction of the observer, contributing to his perceived brightness of the object. The transmission characteristic of the scattered light is exponential and the brightness at a distance can be shown to be equal to

$$B = B_o e^{-br} + B_h(1 - e^{-br}) \qquad (1)$$

where B_o is the inherent (or up-close) brightness of the object, b is the scattering coefficient, and B_h is the brightness of the object at infinity which is assumed to be equal to the brightness of the horizon sky. Equation (1) indicates that even a perfectly black object, i.e., $B_o = 0$, will "appear" at a distance to have a brightness between zero and that of the horizon.

If we assume that the scattering coefficient is proportional to atmospheric density then the slant vision situation (Fig. 2) is complicated by the varying air density with altitude. An equation similar to Equation (1) may be utilized if the concept of "reduced height of atmosphere" is introduced. First, a horizontal column (constant density) must be found which contains the same mass of air as the slant path. If the density of the atmosphere is exponential with height then the mass contained in a slant path extending through the entire atmosphere is

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* Refer to similarly numbered references in the bibligraphy at the end of this presentation

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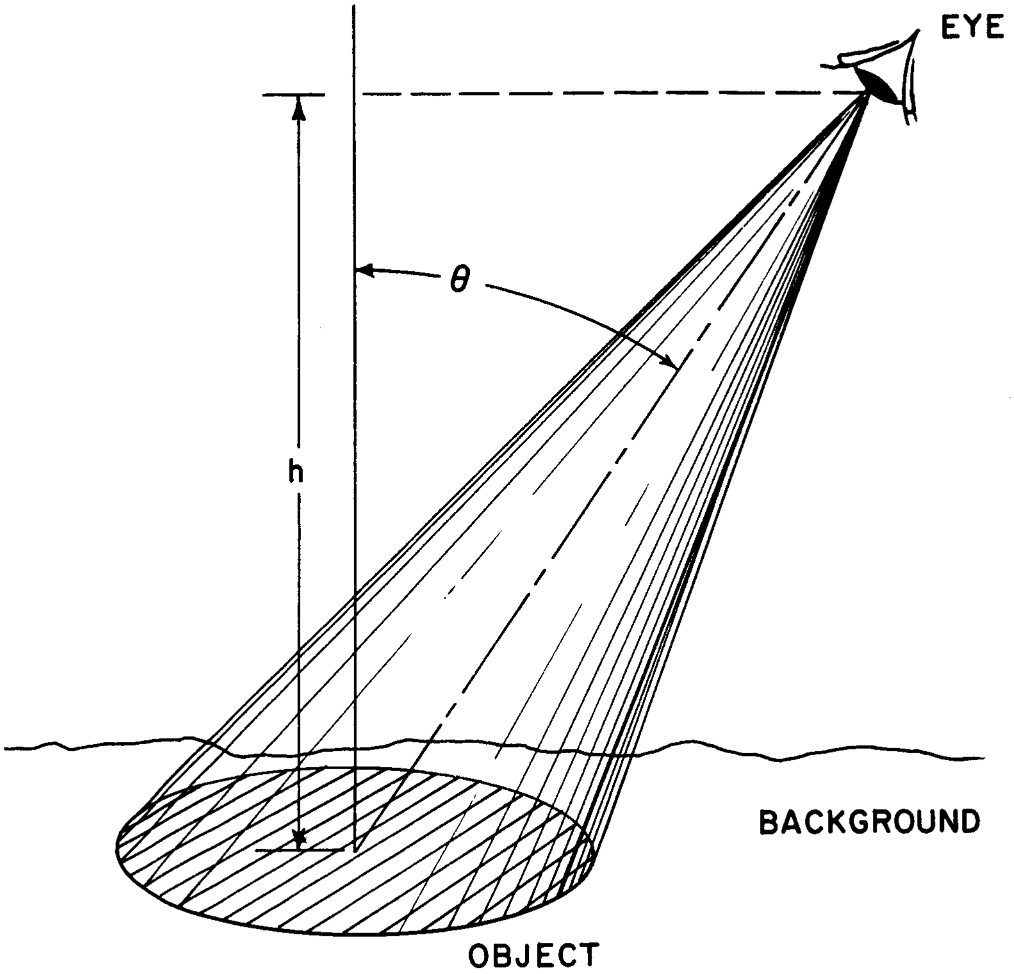

$$B = B'_h (1 - e^{-b_o \overline{R}}) + B_o e^{-b_o \overline{R}}$$

Fig. 2 Slant Vision

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$$M = \int_{o}^{\infty} \rho_o \, A \, e^{-ar \cos \theta} \, d\theta = \frac{\rho_o A}{a \cos \theta} (\text{kgs}) \qquad (2)$$

where ρ_o = Density at sea level

A = Cross sectional area of column

θ = Angle from normal

a = Constant

For a horizontal path at sea level

$$M = \rho_o \, A \, \bar{R} \, (\text{kgs}) \qquad (3)$$

Equating (2) and (3), it is found that the equivalent or reduced height $\bar{R}$ is

$$\bar{R} = \frac{\text{Sec } \theta}{a} (\text{km}) \qquad (4)$$

If the path is normal to the atmosphere, i.e. $\theta = 0$, $R \approx 8$ km[*2] Using the reduced height $\bar{R}$, a constant scattering coefficient may be associated with the slant path, i.e., the scattering coefficient at sea level. A form similar to Equation (1) may now be postulated

$$B(r) = B_o e^{-b_o \bar{R}} + B_h' \left(1 - e^{-b_o \bar{R}} \right) \qquad (5)$$

B_h' must now be interpreted a little more carefully than being just the brightness of the horizon sky. Equation (5) indicates that B_h' is the brightness emanating from an infinitly thick atmosphere. If the earth were considered a

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* Assuming a plane parallel atmosphere

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black object and viewed from outside the atmosphere, B_h' would approximate the brightness seen. This quantity has been shown[3] to be dependent on the aspect of the sun in a rather complicated fashion. It has also been postulated that there are specific azimuth directions[4] on the ground (with respect to this sun) at which the horizon sky approximates B_h'. The brightness in these directions will henceforth be called the "sky-brightness".

The salient[*] feature of visibility is the contrast of the landmark scene as presented to the observer. Contrast is defined as the percentage difference in brightness between an object and its surroundings. It is expressed as

$$C_o = \frac{B_o - B_o'}{B_o'} \qquad (6)$$

where B_o' is the inherent contrast of the surroundings or background. At a distance, or course

$$C_R = \frac{B(r) - B'(r)}{B'(r)} \qquad (7)$$

Substituting Equation (5) appropriately for object and background, the following important relationship for contrast at a distance is deduced

$$C_R = C_o \left[1 - \frac{B_h'}{B_o'} \quad 1 - e^{b_o R} \quad {}^{-1} \right] \qquad (8)$$

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[*] In this elementary first approach

[redacted]

[redacted]

The ratio B_h' / B_o' is now defined as the "sky-ground ratio", and $b_o R$ as the "optical thickness τ", a pure numeric.

The human eye possesses a psychological contrast threshold of 2% which must be exceeded in order to just see distinction between object and background. For the purposes of viewing landmarks a factor of safety may be desirable to insure detectibility. If this new threshold (including safety factor) is designated as T_R, it is evident that the contrast at a distance of a landmark C_R, (Equation 8) must exceed T_R for visibility of that landmark.

2. Classification of Landmarks

In order for a landmark to be seen $C_R \geq T_R$ or from Equation (8)

$$1 - (sk)_R \quad 1-e^{\tau} < \frac{C_o}{T_R} \tag{9}$$

where $(sk)_R$ = sky-ground ratio

Further manipulation yields

$$\tau \leq \ln \left[\frac{A - 1}{(sk)_R} + 1 \right] \tag{10}$$

where $A = \frac{C_o}{T_R}$ = contrast ratio

Since the right hand side of Equation (10) does not depend upon qualities of the atmosphere but only upon features of the landmark scene, it will be called the landmark number, N_L. Then, in order for a landmark to be seen, the

[redacted]

optical thickness of the parth of vision must be less than or equal to the landmark number N_L.

Landmarks may now be classified according to landmark number N_L, where

$$N_L = \ln \left[\frac{A - 1}{(sk)_R} + 1 \right] \qquad (11)$$

For the purpose of illustration, two types of landmarks are now considered.

(a) <u>Black object surrounded by fresh snow</u>

Since the object is black, the inherent contrast of the scene $C_o = 1$. If a threshold is chosen at five times the liminal value (for sure detection) then $T_R = 5\,(0.02) = 1$. The contrast ratio A is then $A = \frac{C_o}{T_R} = 10$. For a clear day and fresh snow (sk) $(sk)_R = 0.02$[*]. Equation (11) determines N_L, which for this case is $N_L = 3.8$.

(b) <u>Light forest surrounded by darker forest</u>

For this case, let $C_o = 0.5$ in which case for the same T_R, $A = 5$. For a clear day and forest $(sk)_R = 5$.[*] Equation (11) now yields $N_L = 0.59$

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[*] See Reference 4, p. 73

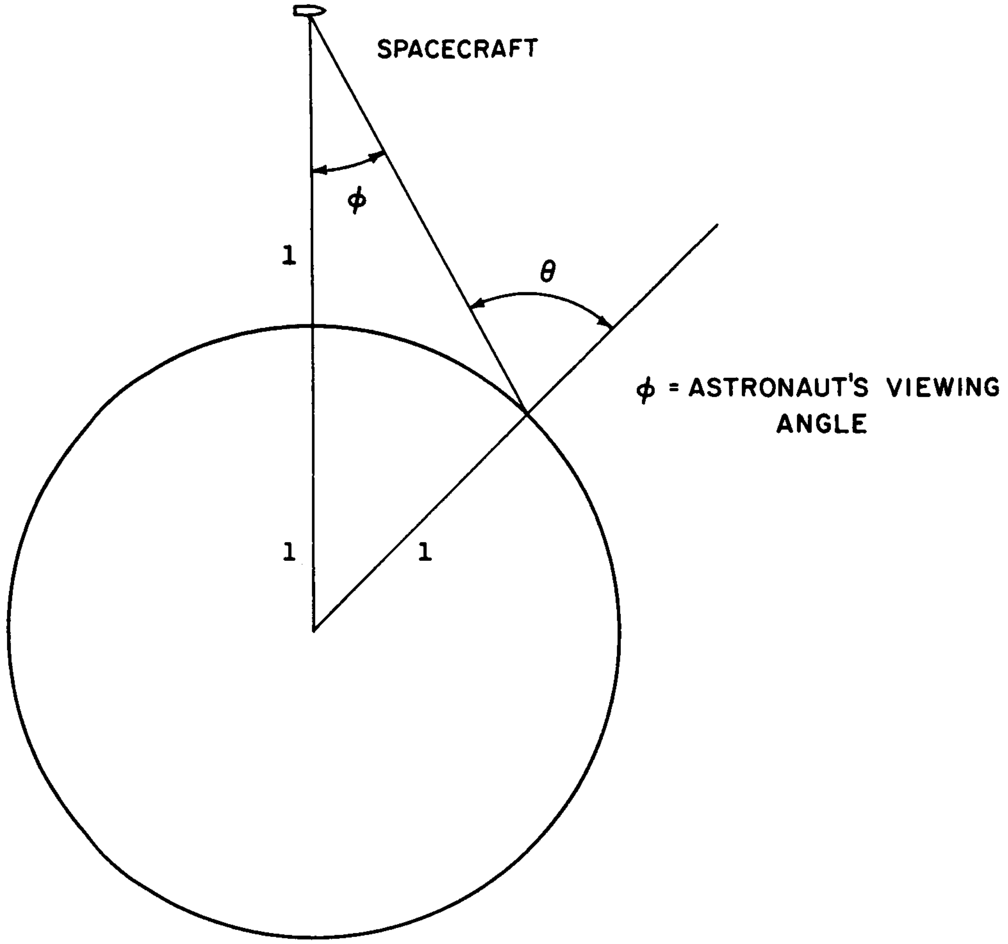
In this manner various familar landmarks may be evaluated and tabulated according to their landmark number. Possible landmarks might be: islands in the water, objects on a desert, coast line beaches or shapes, lakes surrounded by farm land, mountains, etc.

The important concept here is that a landmark number is not unique but simply represents a combination of terrain features. Different types of landmarks having the same number may be treated alike as to their visibility from outside the earth's atmosphere.

3. Application to the visibility of landmarks from a space craft

From the altitude of a spacecraft, the earth will subtend a particular viewing angle, for the astronaut, which is dependent upon the craft's distance from the earth. A visual path normal to the earth's surface will penetrate the least amount of atmosphere and hence posses a minimum optical thickness. It is evident that as the visual path approaches the earth's horizon the optical thickness will increase. Figure 3 illustrates the geometry of the situation. The spacecraft is shown at a distance of one earth radius.

The astronaut's viewing angle is defined as ϕ, and the angle from the normal to the visual path as θ. The law of sines quickly indicates that



GEOMETRY: $\phi = \sin^{-1}\left[\frac{1}{2}\sin\theta\right]$

Fig. 3 Visibility of Landmarks from Spaceship at One Earth Radius

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$$\sin\phi = \frac{1}{2} \sin\theta \qquad (12)$$

Recalling Equation (4) appropriately for optical thickness,

$$\tau = \frac{8b_o}{\cos\theta} \qquad (13)$$

The landmarks defined in the previous section may now be considered from the point of view of their visibility from the spacecraft. The black object on snow ($N_L = 3.8$) requires that

$$\tau = \frac{8b_o}{\cos\theta} \leq 3.8 \qquad (14)$$

i.e., that the optical thickness be less than the landmark number. If a very clear day is chosen ($b_o = 0.06$)* then from Equation (14), $\theta \leq 83^o$, which indicates from Equation (12) that the viewing angle is close to 30^o(almost at the horizon for one earth radius).

The forest landmark requires that

$$\frac{8\,b_o}{\cos\theta} \leq 0.59 \qquad (15)$$

or $\theta \leq 35.5^o$. In this case the astronaut's visibility is limited to $\phi \leq 16.8^o$. Figure 4 illustrates the results of these calculations. It is seen that for the very good landmark $N_L = 3.8$ visibility practically includes all of the available earth surface. The poorer landmark $N_L = 0.59$

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* See Reference 2, p. 52

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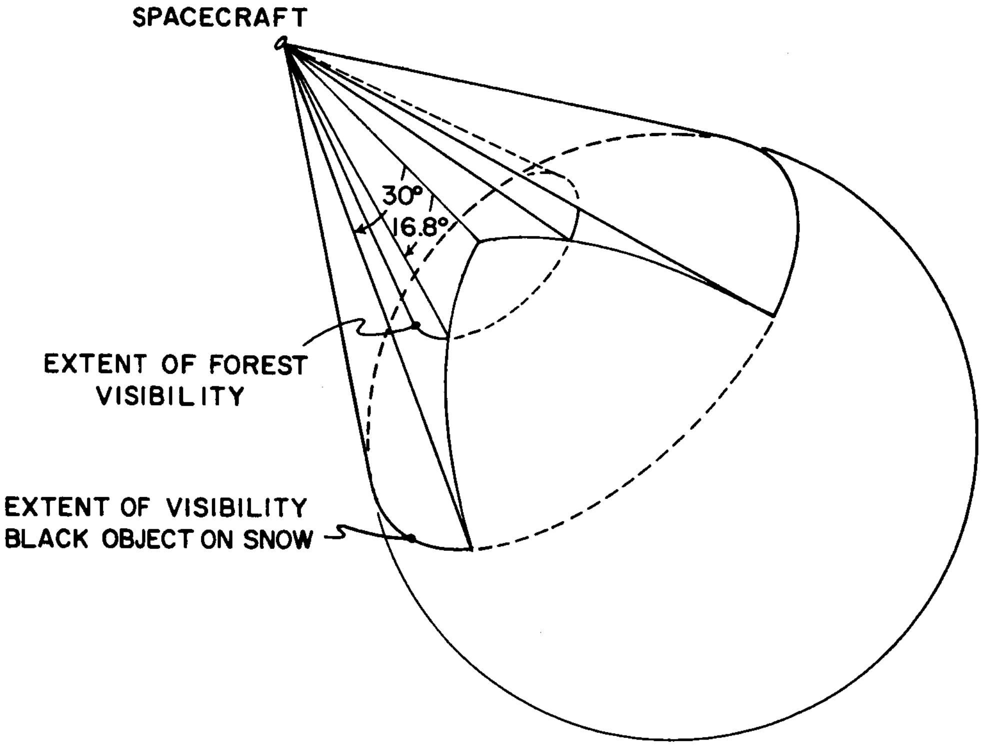

Fig. 4 Landmark Observation

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can only be seen over a portion of the surface.

In summary, each prospective landmark may be assigned a landmark number which depends upon the features of the terrain. As a function of the conditions of the atmosphere - clear, light haze, haze, etc. - the landmark may be seen through longer or shorter visual paths through the atmosphere. Based on a little geometry, each landmark may then be ascribed as being visible over a definite portion of the earth's surface for any spacecraft altitude.

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SPACE SEXTANT

W. E. Bowditch

We have been attempting to reduce the concepts of a space sextant to a working piece of hardware. Fig. 1 shows the first iteration which will probably be reworked several times before a fully satisfactory solution is reached. In addition to the sextant covered in this report, we have several other studies under consideration, as well as proposals of various companies.

The sextant described in this report is not to be considered as final. I plan to present other configurations at the next meeting, at which time I will point out the advantages and disadvantages of the various schemes from a mechanical view point.

The space sextant is required to measure within two to five seconds of arc an angle between a star and landmark, or between a star and the horizon. An aperture of one and one half inches at the objective lens is required. Two lines of sight are identified (see Fig. 1), which are dipped off at an angle slightly less than 90° from the trunion axis. Both lines of sight move in cone angles, the apex of the cone being along the trunion axis. By rotating the diagonal mirror of line of sight number one, its image will be superimposed on the image of line of sight number two, thus allowing us to get

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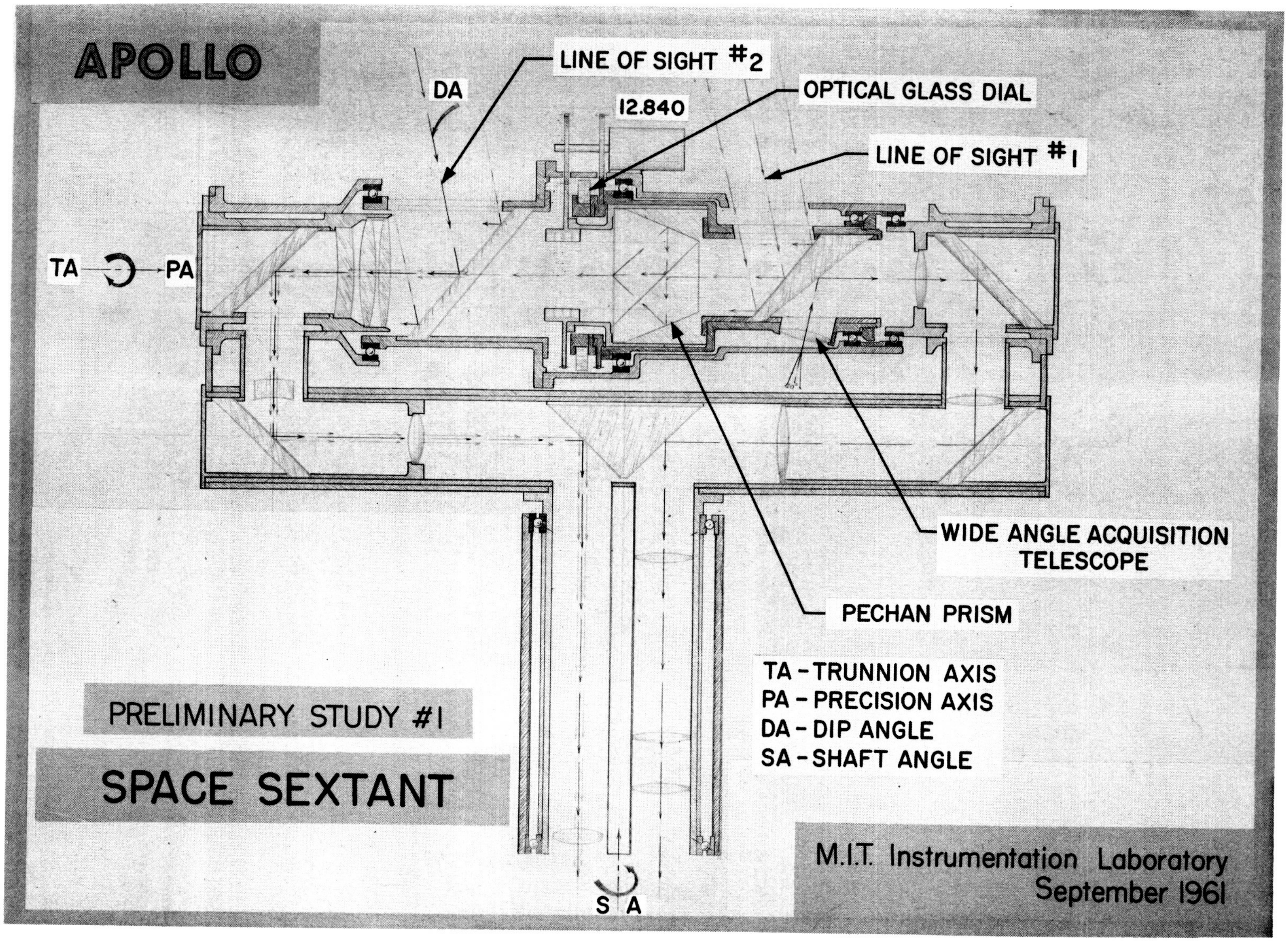

APOLLO

PRELIMINARY STUDY #1

SPACE SEXTANT

TA - TRUNNION AXIS
PA - PRECISION AXIS
DA - DIP ANGLE
SA - SHAFT ANGLE

M.I.T. Instrumentation Laboratory
September 1961

Fig. 1

[redacted]

[redacted]

an angle sight between two objects. The diagonal mirror of line of sight number two is partially silvered; allowing both images to be brought down by an optical train to the observer in the space ship. A Pechan prism is placed on the optical axis between mirrors of the two lines of sight. It is driven at one half the rotational rate of the diagonal mirror of line of sight number one preventing the image of line of sight number one from rotating with respect to image of line of sight number two. An analysis of the gearing accuracy of the required drives will be presented at the next meeting. The angle between the two lines of sight is measured optically by means of a glass dial similar to a theodolite angle reader. The lens of the optical bridge, which read the glass dial, are fixed to the rotating housing of the trunion axis; and the reading is optically brought down, through the shaft, to the observer in the spacecraft.

Encompassed in this design is a 20° wide angle telescope of low magnification, mounted in the same cell as the diagonal mirror of line of sight number one with its line of sight rotated 180°. Its separate optical path is brought down to the observer as shown. Having acquired or identified a landmark or star with the wide angle telescope, its cell is rotated 180° placing the diagonal mirror of line of sight number one on target. This same telescope will have been previously used for acquiring the target for sight number two.

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The degrees of freedom are identified. Trunion axis and precision axis are coaxial. The shaft axis is normal to the trunion axis. The roll axis of the spacecraft is defined as another degree of freedom. The only angle which has to be read to a high degree of precision is the angle formed by the two lines of sight on the precision axis.

The approximate size of the space sextant is 12.8 inches long and 4 inches high. A possible method of mounting within the command module is shown in Fig. 2; the included angle of observation is tentatively limited to 140°. The T-shaped sextant is mounted in a small well, with movable covers, to afford protection during blast-off and re-entry. The inertial measurement unit is structurally tied closely to the sextant since it probably will be erected with data from the sextant for re-entry. The navigator's console display panel will be easily accessible to the sextant operator.

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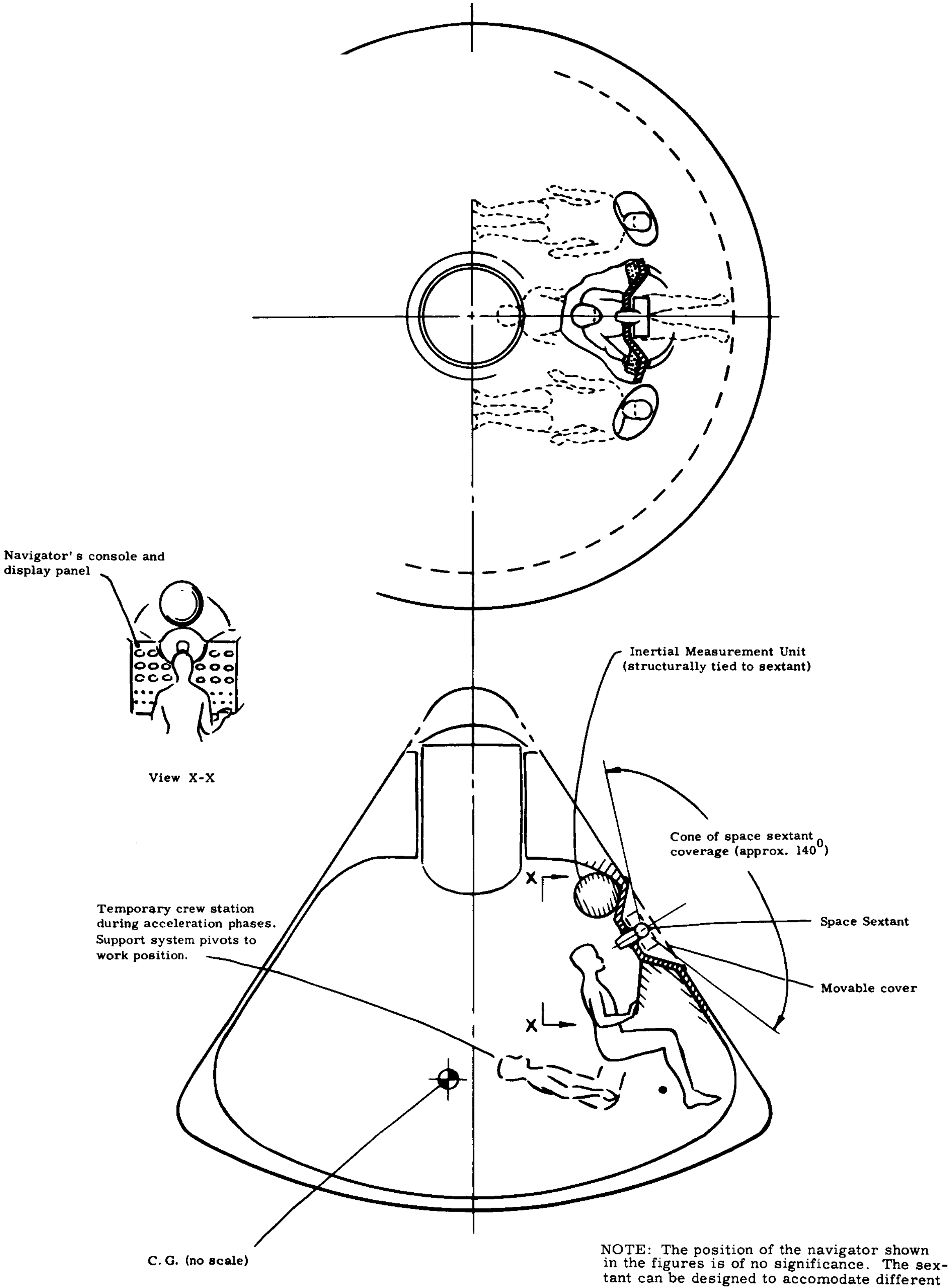

NOTE: The position of the navigator shown in the figures is of no significance. The sextant can be designed to accomodate different observer positions.

Command Module

Fig. 2 Arrangement of guidance and navigation equipment

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