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APOLLO

GUIDANCE AND NAVIGATION

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REPORT E-1068
MONTHLY TECHNICAL PROGRESS REPORT
PROJECT APOLLO GUIDANCE
AND
NAVIGATION PROGRAM
Period September 13, 1961
to
October 4, 1961

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

TABLE OF CONTENTS

INTRODUCTION

During the course of presenting introductory remarks, M. B. Trageser mentioned that there are additional publications by the Instrumentation Laboratory available that would be of interest to the people in attendance at this meeting. The titles and abstracts of three of these reports are included below:

Report R-339, Guidance and Navigation System Information for Apollo Spacecraft Bidders, by Milton B. Trageser.

ABSTRACT

This report is intended to present information for the Apollo spacecraft bidders. The technical approaches which are being followed in the development of the Apollo guidance and navigation system are presented. In our current effort we have made certain assumptions of spacecraft configuration and characteristics. It is our expectation that many of these assumptions could be drastically revised during the interface negotiations between NASA, the selected spacecraft contractor, and MIT. The concepts presented in this report should not be mistaken for constraints. Rather, they are guides to our present thinking.

Report R-342, Development Criteria for Space Navigation Gyroscopes, by C. Stark Draper, William G. Denhard, and Milton B. Trageser.

ABSTRACT

Development criteria for gyroscopes for space use should emphasize the achievement of low power gyroscopic components and inertial measurement units as well as the proper handling of dissipated heat which, in turn, will effect low power operation while maintaining high performance with improved reliability, operating life, and stability of component calibration.

Report R-341, A Statistical Optimizing Navigation Procedure for Space Flight, by Dr. R. H. Battin.

ABSTRACT

In a typical self-contained space navigation system celestial observation data are gathered and processed to produce estimated velocity corrections. The results of this paper provide a basis for determining the best celestial measurements and the proper times to implement velocity corrections.

Fundamental to navigation system is a procedure for processing celestial measurement data which permits incorporation of each individual measurement as it is made to provide an improved estimate of position and velocity. In order to "optimize" the navigation, a

statistical evaluation of a number of alternative courses of action is made. The various alternatives, which form the basis of a decision process, concern the following:

1. Which star and planet combination provide the "best" available observation?
2. Does the best observation give a sufficient reduction in the predicted target error to warrant making the measurement?
3. Is the uncertainty in the indicated velocity correction a small enough percentage of the correction itself to justify an engine restart and propellant expenditure?

Numerical results are presented which illustrate the effectiveness of this approach to the space navigation problem.

He then called on R. Woodbury who stressed the importance of having on this project a group of competent people properly organized with close feedback to insure integrated effort on the Apollo Program.

Trageser then commented on the problem of visibility in using the space sextant. This subject has been under preliminary investigation by R. J. Magee whose presentation follows.

SPACE SEXTANT VISIBILITY PROBLEMS

R. J. Magee

The topic to be discussed is the visibility of stars against backgrounds of high luminance. However, before going into the discussion, I will second the motion for a uniform set of photometric units. The usefulness and desirability to advance a set of units that we all accept need hardly be elaborated upon. As a consequence, Professor Hardy has done considerable work on the subject and has recommended a set of 4 photometric definitions as shown on Table 1. I understand Professor Hardy is working on a report which will go into considerably more detail. The comments of the rest of the project are requested.

Table 1

Photometric Definitions*

	Quantity	Units
1.	Luminous Flux (F)	Lumens
2.	Luminous Intensity (I)	Lumens per solid angle (candle)
3.	Luminance (B)	Lumens per solid angle per meter^2
4.	Illuminance (E)	Lumens per meter^2

* As adopted by Committee on Colorimetry, 1953

The method of observation by means of the sextant has already been discussed, I believe, by Mr. Bowditch. I will review the portion of it that applies to this talk.

The angle between a star and a lunar or terrestrial landmark is measured by superimposing the image of that star upon the landmark by means of the sextant. The angle between the two lines of sight is measured. For example, in this sextant as shown in Fig. 1, the line of sight to the star is reflected from the diagonal mirror through the partial transmission mirror and hence into the objective lens of the telescope. The line of sight from the landmark is partially reflected off this diagonal mirror and also into the telescope. However, whether the observer actually sees the star depends upon

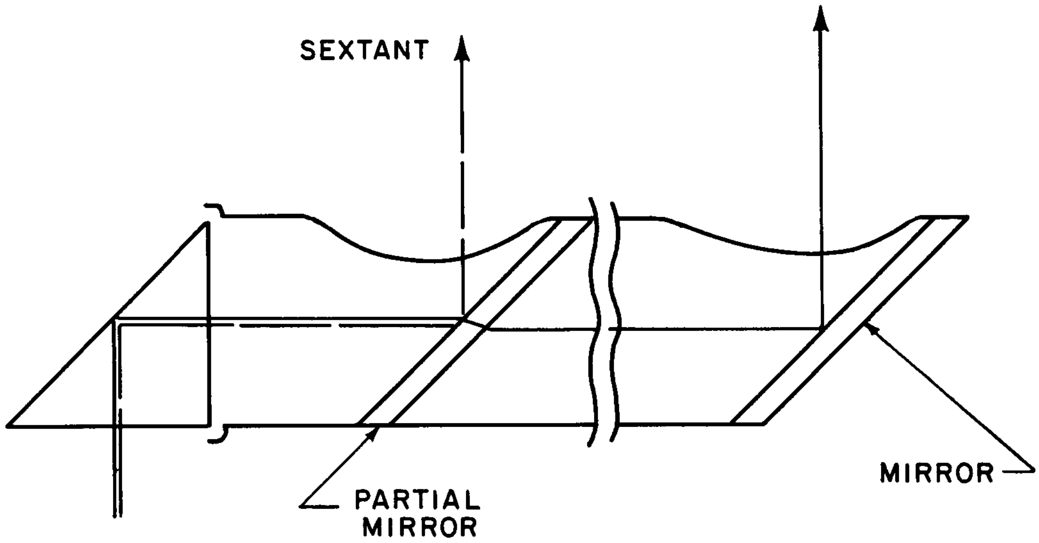
(1) Luminous intensity of the star
(2) Luminance of the background
(3) Observers visual adaption

This topic, the visibility of point sources against a background of high luminance, has been studied by various investigators. I might mention three

(1) Langmuir of G. E. in 1931
(2) Hulburt and Tousey of NRL in 1941
(3) Tiffany Foundation under guidance of Professor Hardy during WW II.

When differences of units and criteria have been adjusted, Fig. 2 results.

The curve can be approximated to within 5% over the range we are interested in by the expression, due to Hulbert, $i = Kb^{0.84}$ where i is the threshold illuminance that can be perceived by the eye against a background of luminance b and K is a constant. Several check points can be noted. One is at the lower limit of the curve where stars



METHOD OF OBSERVATION:

SUPERIMPOSE IMAGES OF <u>STAR</u> AND <u>LUNAR</u> OR <u>TERRESTRIAL MARK.</u>

Fig. 1

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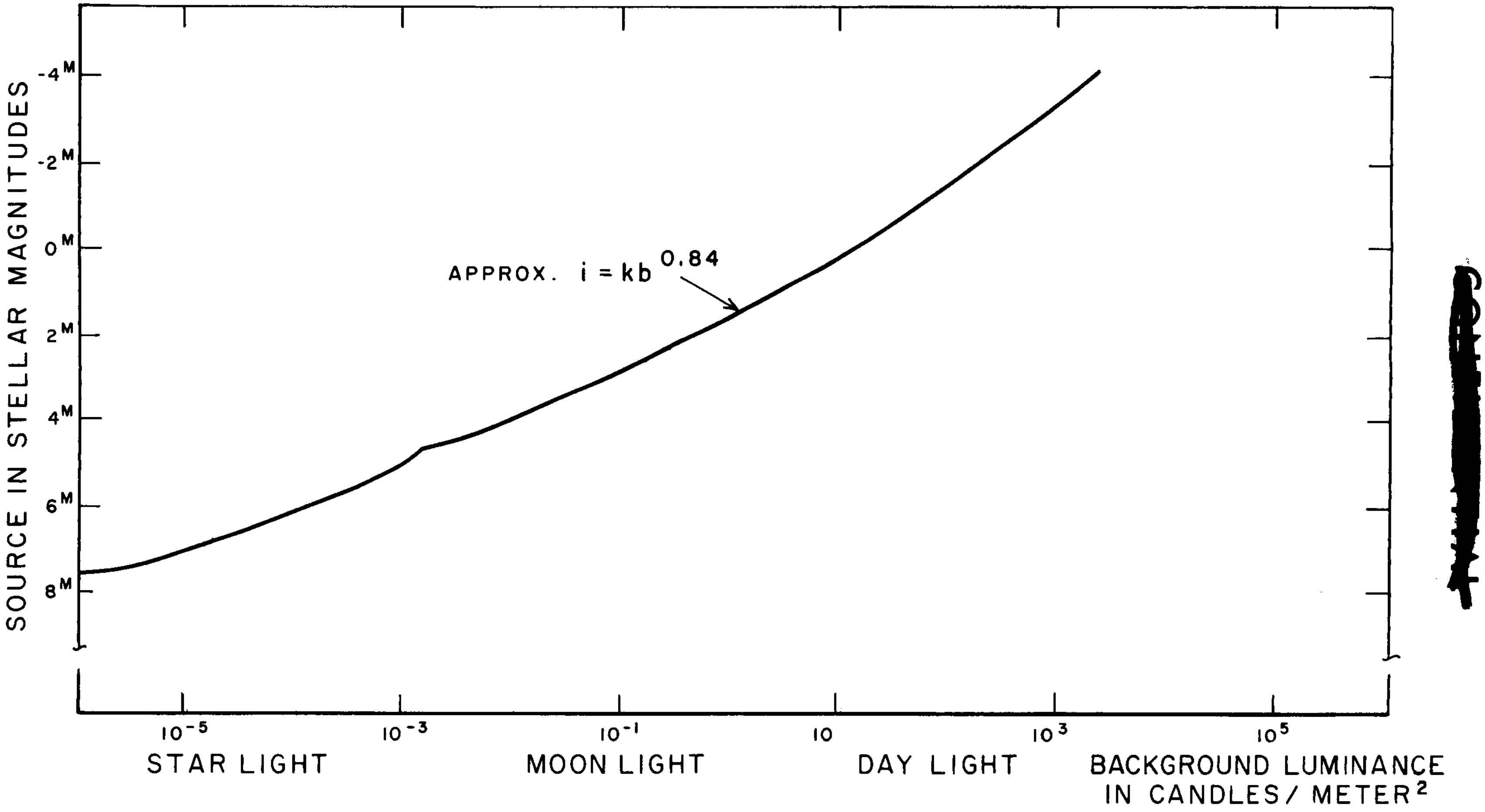

Fig. 2 Threshold for seeing source (E) against background of luminance (B) with 98% probability.

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of 8th magnitude should just be perceived against a completely black background*. Against a starlit sky ($b \approx 5 \times 10^{-5}$ candle/M^2) 5th to 6th magnitude are discernable. Another point is at the upper end of the curve where Venus (magn -3.8) can be seen against the daylight sky.

A telescope can be used to aid an observer in perceiving stars against a high luminance background. To see how this is done, we will discuss telescope optics which are related by the following equation

$$dMD^{-1} = 1 \tag{1}$$

where

d = diameter of exit pupil
D = diameter of entrance pupil
M = magnification power of the telescope

For the case where the diameter of the exit pupil d is equal to or larger than the pupil of the eye, i.e., $d \geq p$, the aided threshold of illuminance i_a is:

$$i_a = tM^2 i \tag{2}$$

where t is telescope transmission. The aided field luminance (b_a) is:

$$b_a = tb \tag{3}$$

Combing Eq. (2) and (3) results in

$$i_a = Kb_a^{0.84} \tag{4}$$

where K is the same constant as before if we assume no change in the diameter of the pupil of the eye while using the telescope. To have images of about the same visibility, we can now substitute the trans-

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* H. N. Russell, Astrophys. Jour. 45, 60 (1917)

mission value of the star sight line t_s, in Eq. (2) and the transmission value of the earth or lunar sight line, t_f, in Eq. (4) and equate them as

$$t_s M^2 i = K(t_f b)^{0.84}$$

or rearranging terms

$$i = K b^{0.84} M^{-2} t_f^{\ 0.84} t_s^{-1}$$

For very high magnifications, when the diameter of the exit pupil is less than the diameter of the pupil of the eye, M^{-2} reduces to $M^{-1.68}$.

When values of transmission for star sight line (t_s) and earth or lunar sight line (t_f) are inserted, a series of graphs of threshold of point source luminous intensity versus background luminance for various magnifications result, as shown in Fig. 3.

These results assume that the observer's eye has been dark-adapted to a light level of no higher illuminance than that presented to him through the sextant telescope. Verification of the above must still be done experimentally here at MIT. Hulburt and Tousey of NRL have experimental evidence in the visibility of stars against the daylight sky for various telescope magnifications but we must obtain similar data for the sextant, where transmissions of field and source vary significantly.

One experiment is shown in Fig. 4 where an image of a point source of known luminous intensity is superimposed upon a uniform field of known luminance by means of a partially reflecting diagonal mirror.

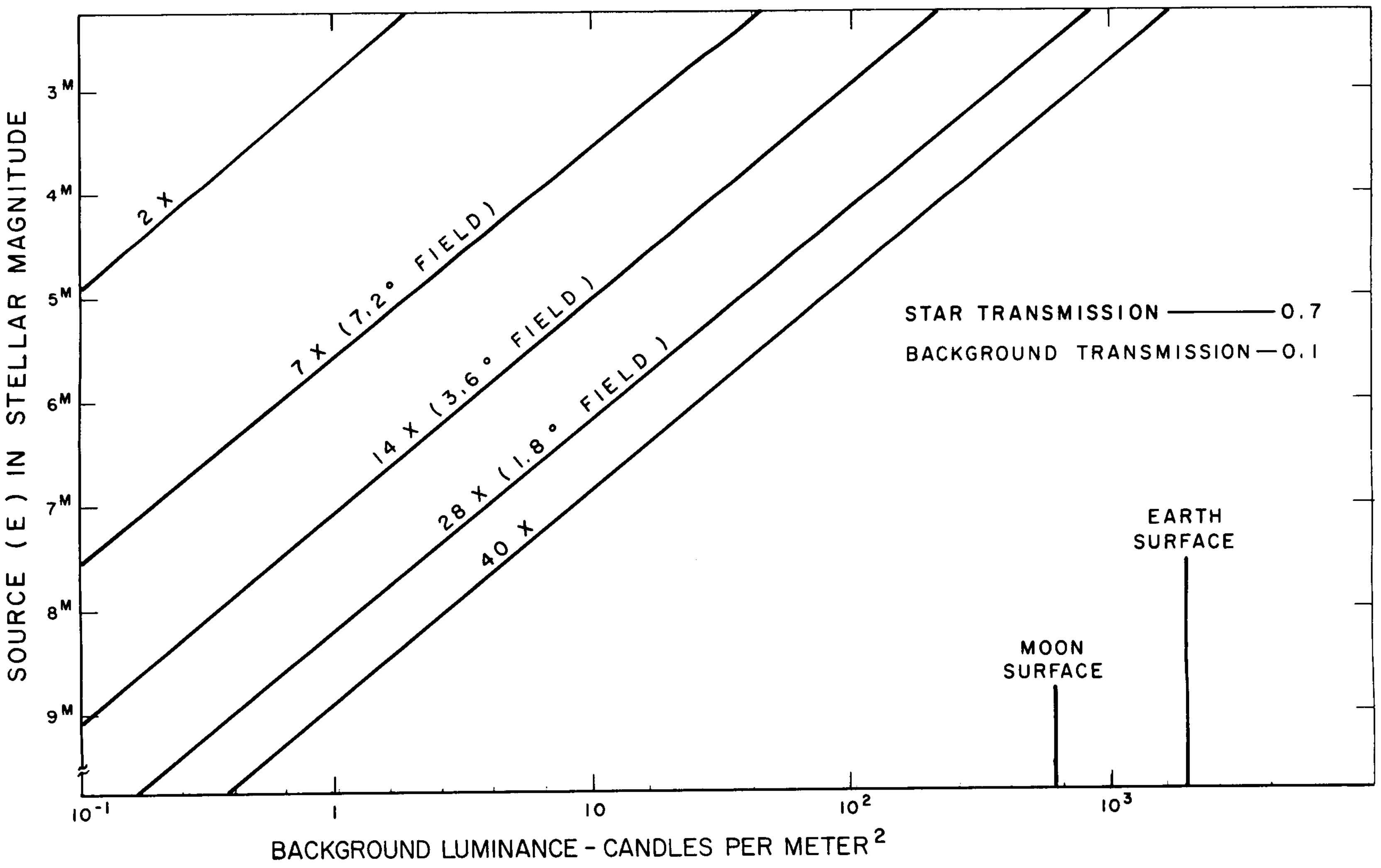

Fig. 3 Star against background in sextant.

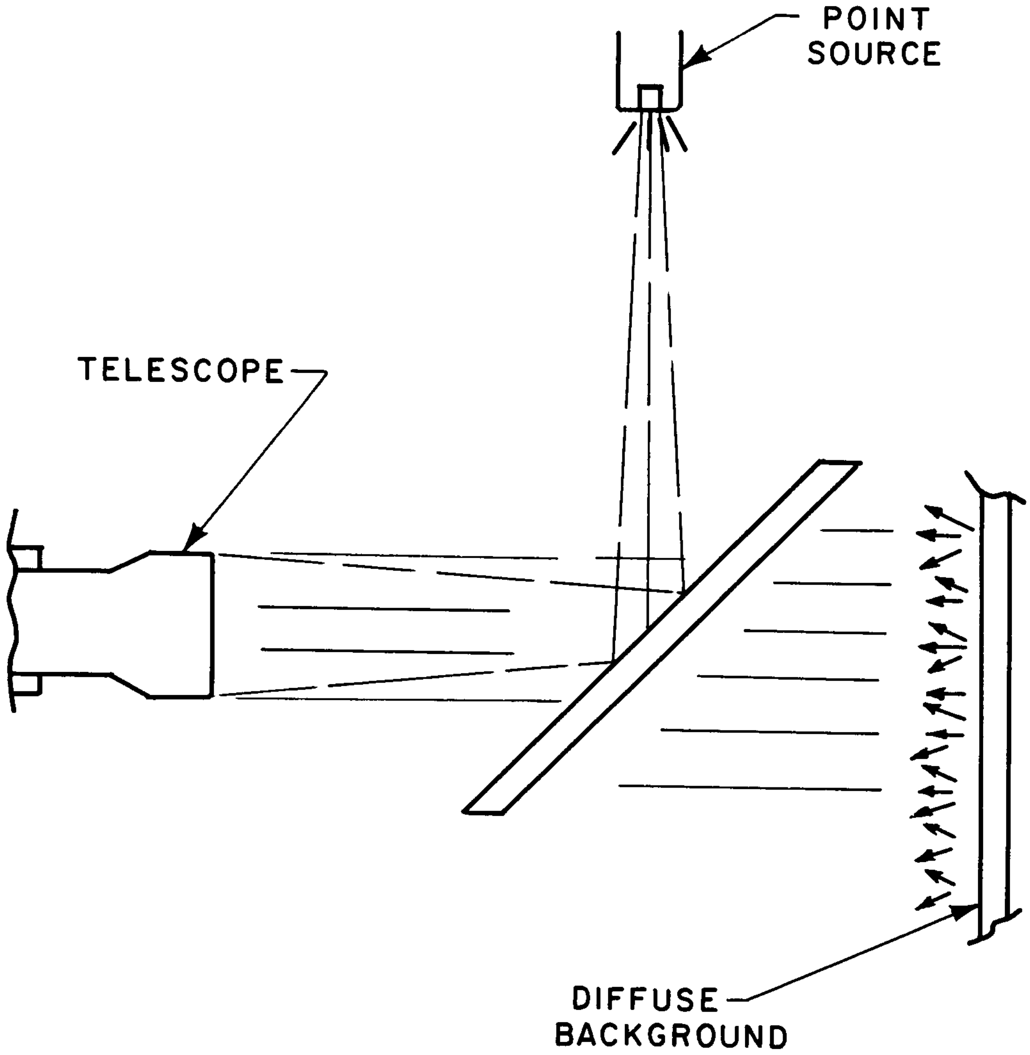

Fig. 4 Experiment

Another is mounting a partially reflecting mirror in front of a theodolite and superimposing images of a star and the moon.

As it appears possible to see the superimposed image of a star on an image of the lunar or terrestrial surface, a star simulated on the earth's surface should also be visible.

In Fig. 5 are shown the beam characteristics of the Army 60" diameter searchlight and the Navy 36" diameter searchlight. Beam candlepower of 4×10^8 translates into the following approximation, namely, at 100 feet or farther from the searchlight, to an observer in the beam, the searchlight appears the same as a 4×10^8 candle luminous intensity source the same distance away.

Knowing the illuminance produced at the earth by a star of first magnitude, the apparent stellar magnitude of a searchlight as seen from various distances can be calculated from this and a curve such as Fig. 6 plotted.

The graph is straight line, of course, because of the exponential character of both the ordinate and abscissa dimensions. It can be seen that from a distance equivalent to that of moon to earth, a 60" searchlight on an otherwise dark earth would appear as a star of 7.3 magnitude, neglecting atmospheric absorption. For an observer near Zenith, a factor of 2 reduction in luminous intensity could be expected due to the atmosphere, so that actually the searchlight would appear as an 8th magnitude star when viewed from that distance.

<u>Comments by Trageser on Magee's Presentation</u>

We do not at the moment recommend searchlights At great

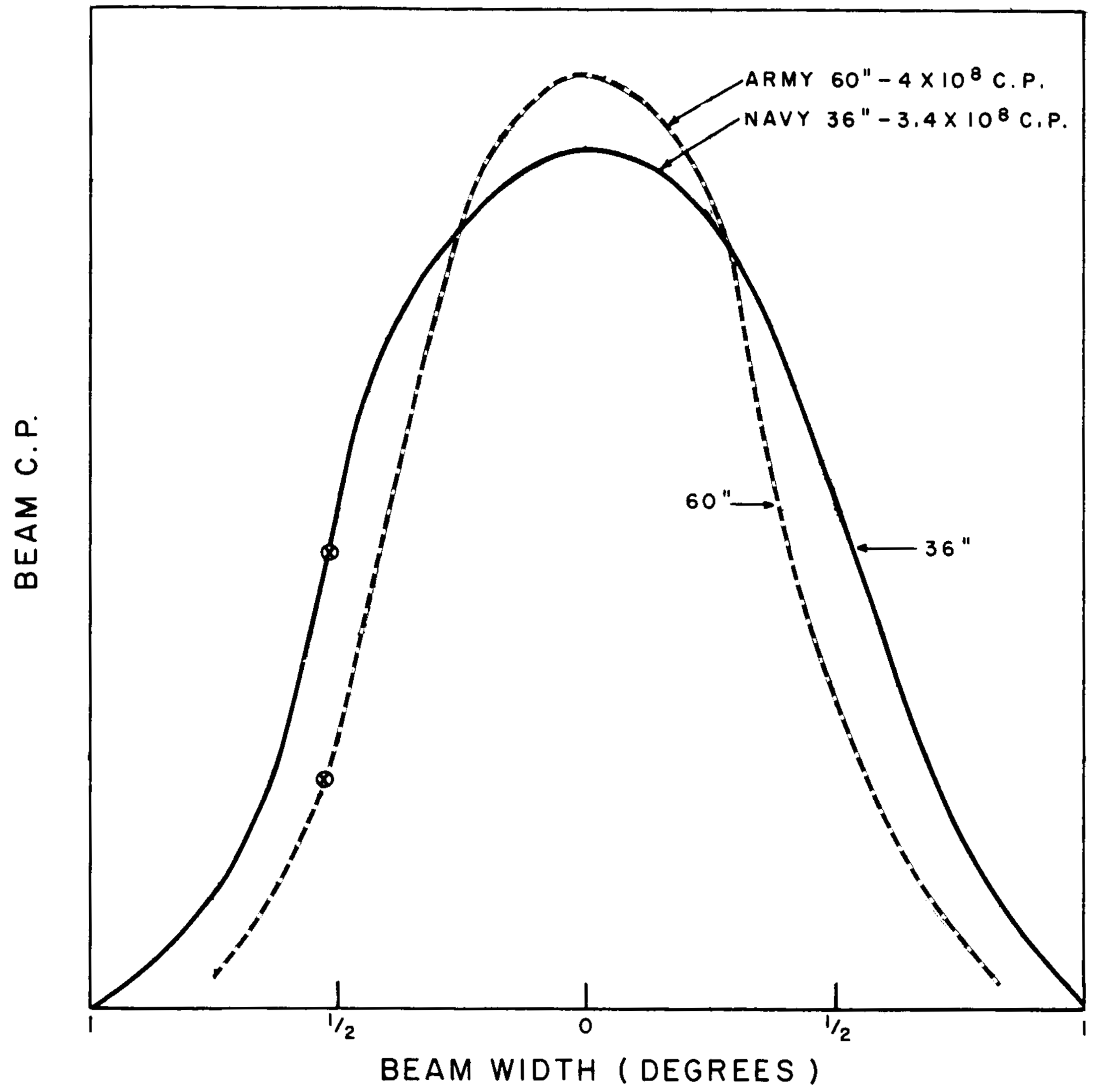

Fig. 5 Beam characteristics of searchlights.

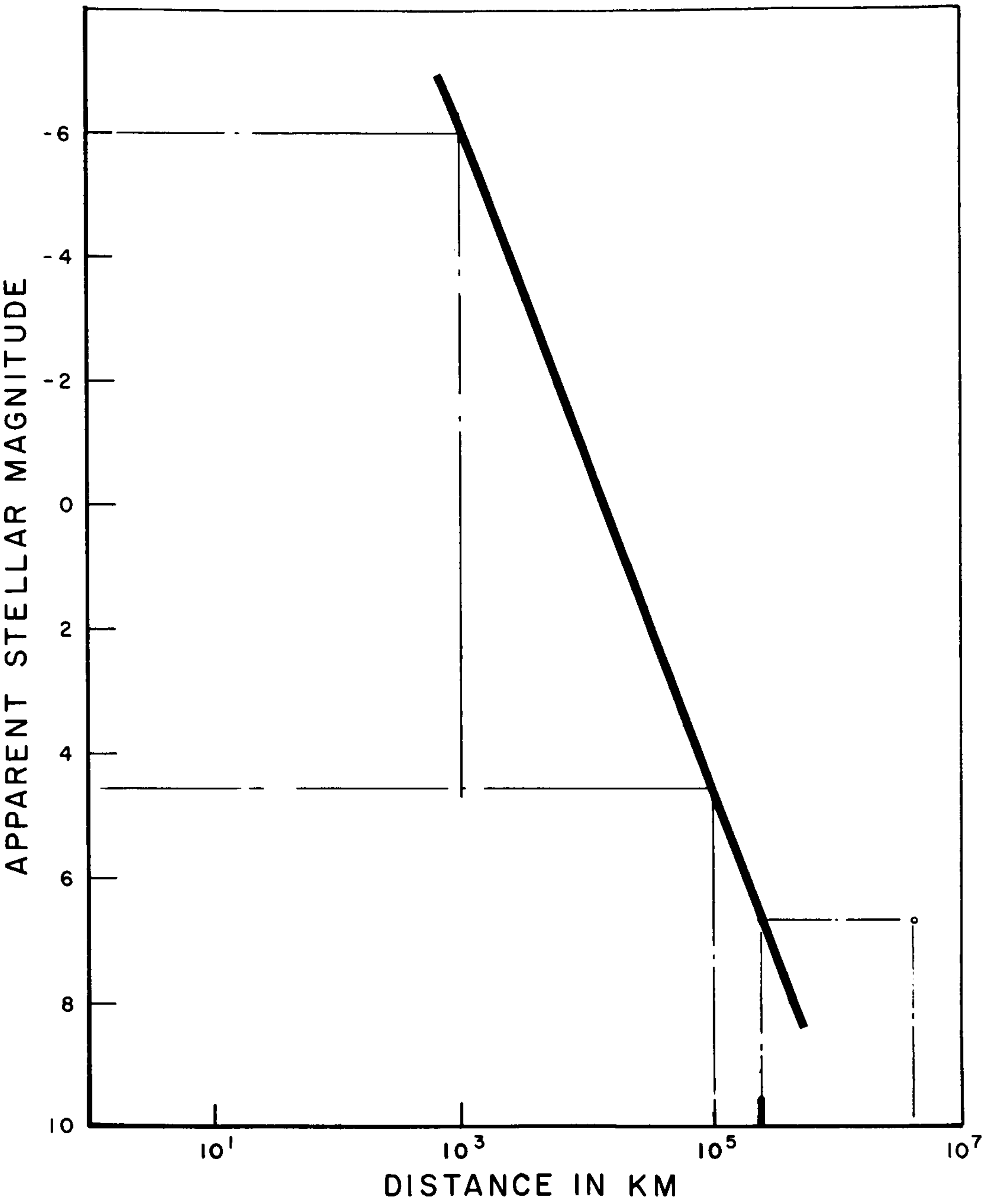

Fig. 6 Apparent stellar magnitude as a function of distance.

distances from the earth, a luminous horizon is nearly always visible and probably will have sufficient accuracy. The use of the very large searchlights required would be unwarrented. Low altitude orbital operations would require too large a number of searchlight beacons. The possibility of using several beacons for certain missions should still be considered, however.

Comments by Trageser Introducing Dahlen's Presentation

The problem of space sextant configuration is very complex. The sextant must provide guidance data in both cis-lunar space and low altitude orbital missions. The instrument must be capable of visual use for measuring landmark bearings; it must also be capable of measuring horizon bearings. Its configuration should minimize attitude maneuvers of the spacecraft. John Dahlen is now going to present some geometrical considerations relating to the configuration presented by Bowditch last month.

SPACE SEXTANT GEOMETRY PROBLEMS

John Dahlen

Meaning: Analysis of interrelationships between space sextant configuration, operating modes and spacecraft attitude control.

The basic task of the sextant is to measure precisely the angle between two celestial objects, such as a star and landmark, by measuring the angle between two telescopes, one of which is pointed at the star and the other of which is pointed at the landmark. To accomplish this, four degrees of freedom are required for pointing the telescopes and may be provided by three axes of vehicle mobility in addition to a precision drive that sets the angle between the telescopes as was the case in the Mars Reconnaissance Probe. The four degrees of freedom may also be provided by fully articulating the telescopes with respect to the vehicle. Many configurations between these two extremes are possible. It was suspected that the case where full vehicular mobility is used would result in a large amount of attitude changing with resulting high Attitude Control System propellant penalty. On the other hand, the sextant having four drives appears to be excessively large and heavy.

For a first serious approach, the configuration explained by P. N. Bowditch at the last monthly meeting was selected.

Roll mobility is employed as one of the required four degrees of freedom. Roll mobility was chosen because it keeps the vehicle sun-oriented which is desirable for thermal balance, and because roll inertia is smallest. Small amount of pitch will be required when it is necessary to look at objects close to the sun.

One important area of analysis concerns the amount of vehicle maneuvering required to make an angle measurement. This is strongly influenced by the sextant configuration and the number of permissible stars. For example if one has a large number of stars to choose from there will be several that can provide satisfactory navigational data at any point on the trajectory. One might in such a case select that star which requires the least attitude change in order to save propellant. This is an important consideration because one will have some time limitation imposed by a required frequency of measurements or by thermal transient considerations, etc. If one is permitted to choose from a large selection of stars, one can also make his choice with the object in mind of reducing the angular travel required of the sextant parts. On the other hand, the larger the selection of stars, the larger one must make the tracker aperture and magnification because one must utilize dimmer stars. We have just begun to make comprehensive trade-off studies of this sort based upon Dr. Battin's guidance simulations. Such studies are required to intelligently evaluate any sextant configuration.

A simplified analysis of the first sextant configuration has been completed in order to get a feel for the numbers involved and to evaluate the merits of the dip angle, and excellent idea by Trageser, shown in Fig. 1.

By driving about the shaft axis and the trunnion axis, the first telescope sight line is fixed on a landmark. Then the second telescope

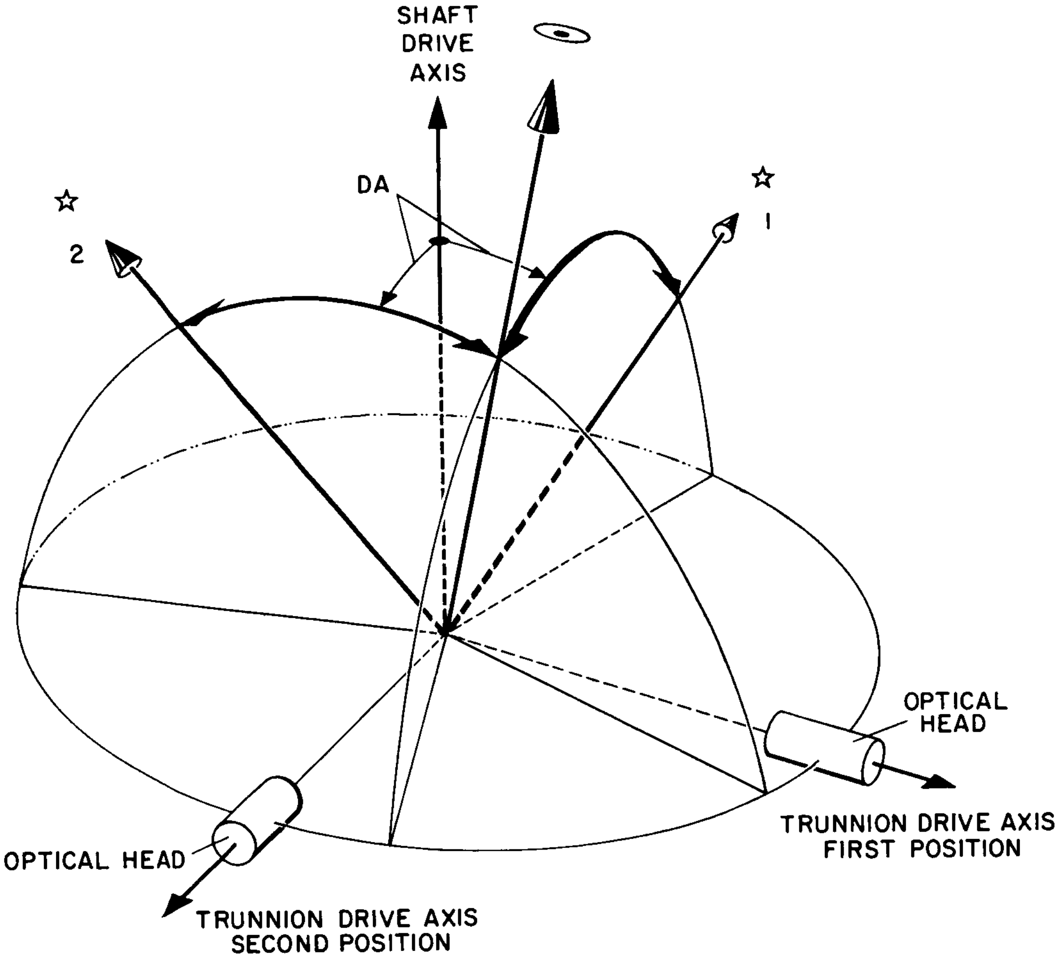

Fig. 1 Sextant operation illustrating dip angle.

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is rotated about the precision axis (collinear with the trunnion axis) until it picks up a desirable star (one of an assumed unlimited selection). The angle between the two telescopes is read out. Now rotate the sextant about the shaft axis, manipulating rotation about the trunnion axis to maintain the sight line of the first telescope on the landmark. Again rotate the second telescope about the precision axis until it picks up a second desirable star and read out the angle between the two telescopes. Because of the dip angle, which is the amount each line of sight is tipped away from perpendicularity with the trunnion axis, the two measurement planes will be nearly orthogonal. This operation requires no roll of the spacecraft and thus has an advantage if the time element were critical.

In Fig. 2 we define the elevation angle as the angle between the mounting plane of the sextant and the sight to a landmark. The initial roll attitude is taken such that the elevation angle is a maximum and the roll position is the preferred. There is a preferred roll attitude in order to point antennas, etc. Fig. 2 shows the regions in which no roll is required. Notice that as long as DA $\geq 12.5^{\circ}$ no roll is required except for very large elevation angles The curves on the chart in the lower half of Fig. 2 show the amounts of roll required as functions of dip angle and elevation angle.

These data are presented as statistically expected roll angles in Fig. 3 which takes into account the probability distribution of the elevation angle. This is only an idealized example and shows what may be expected if one has a large number of permissible navigational stars.

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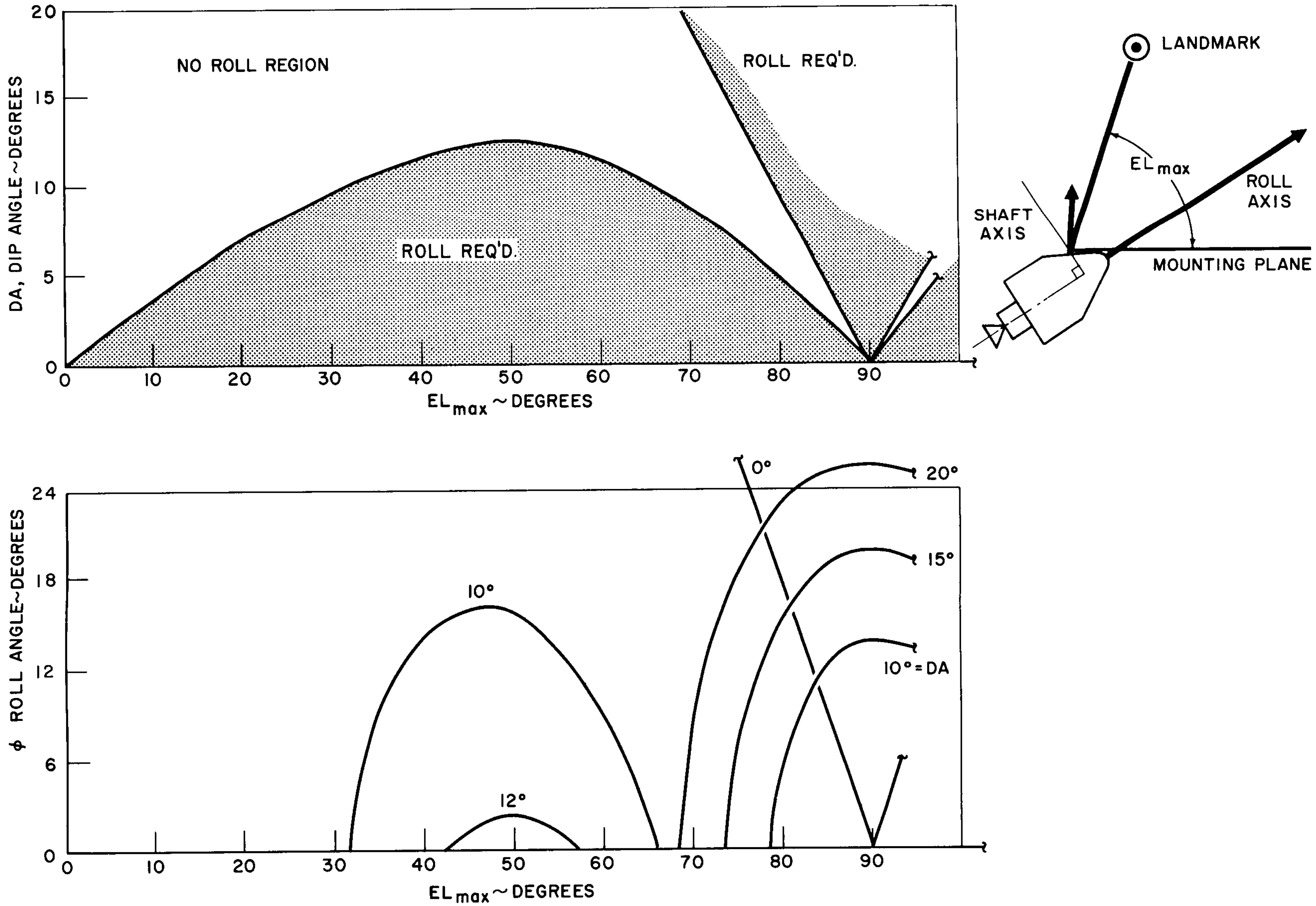

Fig. 2 Effect of dip angle on roll required to measure a suitable pair of angles from a landmark to two stars.

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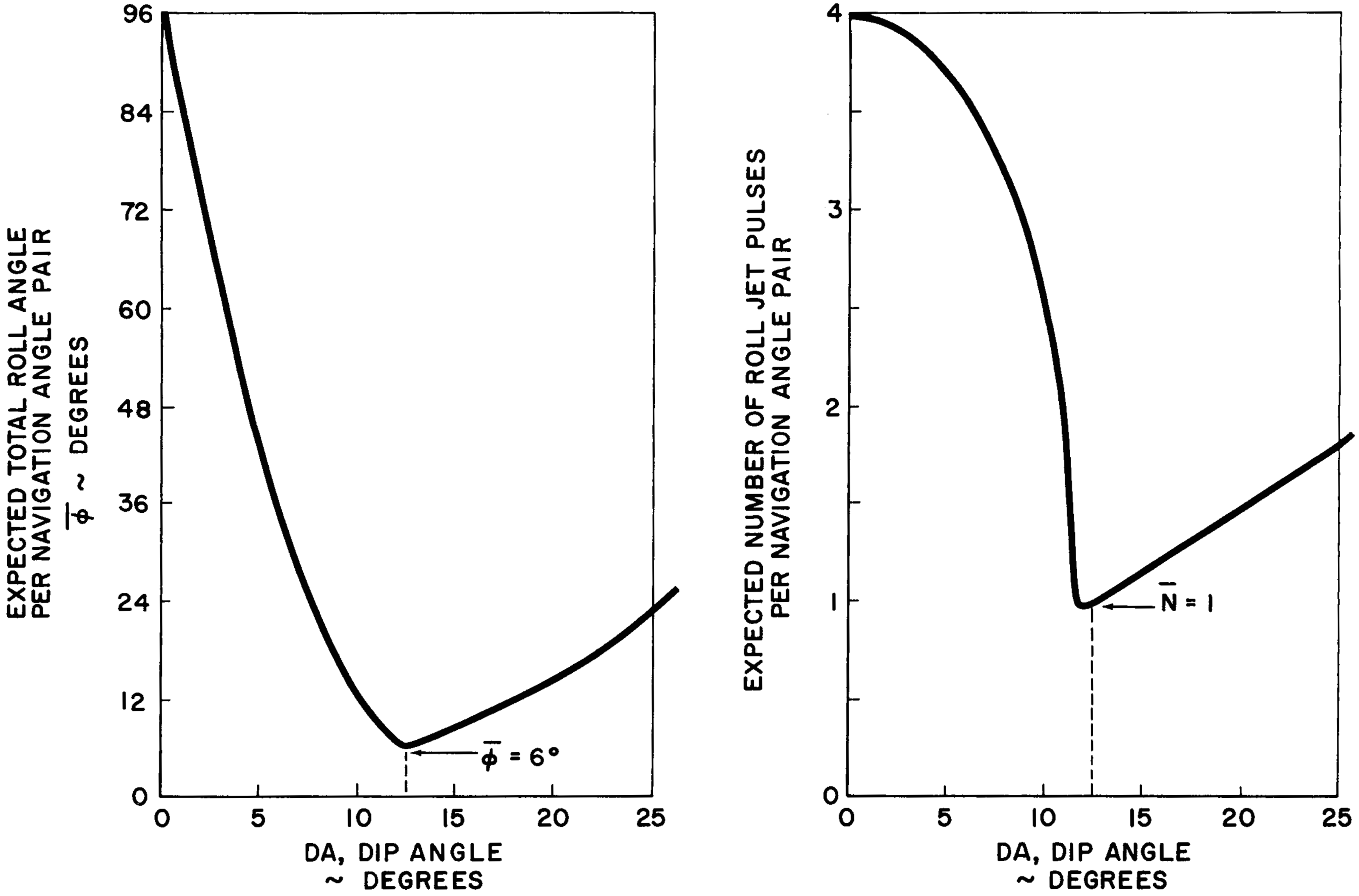


Fig. 3 Roll maneuvering requirement as function of dip angle.

[redacted]

After simulation studies have been completed, more realistic data will be available.

A second important area of analysis in support of the sextant design effort has been the study of aided tracking. By aided tracking is meant that procedure whereby the observer operates the sextant with the aid of a computer.

Figure 4 shows perfect tracking with star and landmark superimposed in the center of the field. This is an idealized condition that is unattainable unless the telescopes are stabilized with respect to inertial space and driven entirely by precision drives.

The design principle of the marine or bubble sextant can be used to minimize the base motion problem. In this design, superposition is not destroyed by base motion except for any component of angular disturbances about the bisector of the two lines of sight which displaces both the images in a nonsensitive direction.

An error in the precision angle is seen by the observer as a display of the images in the sensitive direction. Provided base motions are not excessively fast nor large, it will be possible to take full advantage of the resolving power of the sextant. To illustrate one phase of aided tracking, consider the mid-course example. After acquisition of a sight on some landmark and a star, drive the images to the center of the field. External computation is required to convert the operator's commands to drive voltages on the sextant servomotors and vehicle roll control system.

This procedure is tentative and will be subjected to further theoretical and experimental evaluation. When the spacecraft is near its

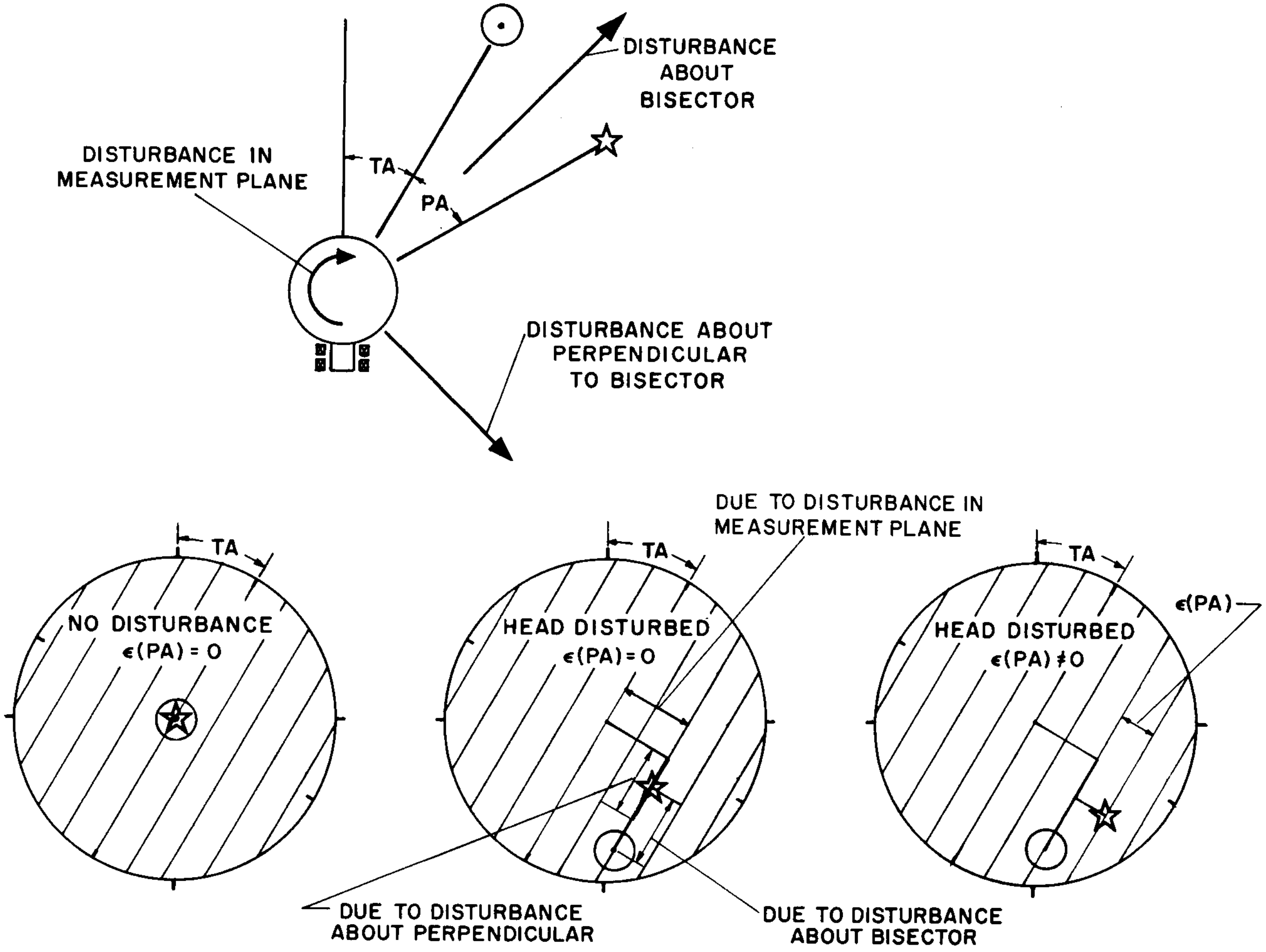


Fig. 4 Detection of measurement error in presence of tracking errors.

destination, the above technique is inadequate because the angular rates are too high. Investigation is being conducted on other ideas of tracking procedure which will be reported at some later time.

Now the vehicle ACS and the sextant drives are turned off. The astronauts remain reasonably still and unbalanced rotating machinery is not allowed to cycle. As a result, the spacecraft will rotate very slowly in space at a constant rate less than 10^{-3} deg./sec. The precision angle is set to the angle which is predicted to occur between the lines of sight some five to ten minutes hence. The observer will now see the images drift slowly and smoothly toward the edge of the field while they gradually approach each other. When they are superimposed, a button is pushed to mark the time. The precision angle is read out visually from the optical scale.

Then base motions need only be kept below certain displacements and rates so that observer can take full advantage of resolving power of instrument.

The question of how to obtain tracking control torques on the vehicle has been considered also. Specifically we compared the ACS jets with a gimballed fly-wheel for roll control during tracking. The large vehicle orientations required for acquisition would of course be accomplished with the ACS jets.

Tracking considerations indicate that residual spacecraft rates of 10^{-3} deg./sec. or less are small enough and perhaps conservative.

A consideration of disturbance torques indicates that spacecraft rates can probably be maintained below this level if the men sit still at critical times and unbalanced rotating machinery is not allowed to cycle during critical tracking periods.

Tracking control might then reasonably be exerted either by gas jets whose minimum pulse would change the spacecraft rate by 10^{-3} deg./sec. or by a gimballed flywheel which changes the spacecraft rate by 10^{-3} deg./sec. when it is tilted about 15°. For the 20,000 lb. Apollo vehicles, these numbers would result if the ACS torques were 10 ft. lb. in roll and 30 ft. lb. about the transverse axis, assuming a minimum thrust duration of 0.01 second. These ACS torques also look reasonable from other points of view so that it may not be necessary to require a special set of small roll jets. A fly wheel (10^{7} wheel) for roll control of this vehicle would weigh about 2 pounds. Each roll gas jet minimum pulse would expend 1/20,000 lb. fuel. An active tracking oscillation in the absence of disturbances of 1 mr half amplitude would pulse every 4 minutes, therefore, burning less than 1/1,000 lbs. fuel per hour, but it is difficult to say how many pulses would be required for further study of the tracking dynamics. However, it is difficult to imagine that the flywheel could turn out to be more attractive than the gas jets.

Comments by Trageser Following Dahlen's Presentation

I'd like to clarify one point that occurred to me during John's talk, in that the example mentioned is a specific combination of times and events that could turn out this way. We realize that these problems have not been defined down to the point where this specific collection of things can be planned before several more months of effort. This is an illustration rather than a definition. Now it is fairly clear that, if one is talking about accuracys of some two to four seconds of arc for measuring an angle, the means of measuring the angle is an optical scale. When the spacecraft is fairly close to the earth with a high angular rate between the landmark and star or the horizon and star, the two seconds of arc is not a practical level of accuracy to seek. The angular rates are too high. The complication of high rates of greater than 40 seconds of arc per second of time precludes obtaining two seconds of arc accuracy.

In this case the bull gear which is in the precision drive is used to measure the angle, or some alternative means of measurement is used. The bull gear looks like the easiest way. We are looking at some other schemes that can be substituted for it.

R. J. Magee has been running a study on a gear train he has from a previous project to determine a fairly good basis for sizing a bull gear of the space sextant with the objective of realizing some 15 to 30 seconds accuracy when it is used for pick-off. I'd like to add that this is one of several gear studies which are underway. The other studies are too premature to report on now.

GEAR TRAIN ANALYSIS

R. J. Magee

As Trageser has already mentioned, sextant measured angle read-out can be accomplished by means of a precision gear train. Although this method is not expected to be as accurate as a manually read optical read-out, nevertheless it has the advantage of speed of operation. The characteristics of this precision gear read-out method are useful for terminal or orbital guidance where speed of read-out is necessary and accuracy requirements are reduced. It might be mentioned that this gear read-out is not expected to be as accurate as the optical read-out because of the use of about a 3" diameter bull gear. The measurement accuracy of the angular position of the gear is generally proportional to the diameter of the gear, that is, the larger the gear diameter the more accurately one can measure with it. In the preceding several months a through analysis has been made on a precision gear drive that is being used in an automatic space sextant.

The analysis that has been made, and based on the data that Mr. Davidson and Mr. Zapf have obtained, will enable us to develop a fairly rigorous analysis of the errors in the gear train. We will get experimental verification of what we have already predicted from the theory.

I might go into the nature and causes of the drive error in a precision gear train. In general there will be two major errors. One is due to the nonconcentricity of the axis of the rotation of the gears with the pitch circle of the gear; this will be roughly a sinusoidal error whose period is equilvalent to one revolution of the gear. The second error is a deviation of tooth form of the gear from the ideal or prescribed shape: this is called tooth-to-tooth error. There are other errors, such as those depending on the method of the manufacture of the gear where there might be recognizable patterns of a 6-8-9 tooth period. Figure 1 illustrates an error, most of which is due to the last two gears in the train, that is, the bull gear which is usually one of the larger gears in the train and its pinion driver. Gears toward the other end of the train have reduced effects in their contributions to errors because of the multiplying effect of the number of teeth on each gear, i.e., the ratio of revolutions that the two gears make. Figure 1 illustrates tooth-to-tooth error of a precision gear drive.

The ordinate of Fig. 1 is the angular position error of a 9" diameter gear. It is the difference between the angular position of the bull gear as predicted from a counter on the other end of the gear train and the actual angle of orientation as measured by autocolumniating with a flat mirror which is attached to the gear. This tooth-to-tooth error has an amplitude of practically six seconds of arc which shows up well as the amplitude is fairly constant. It is an ultra-precision class 1

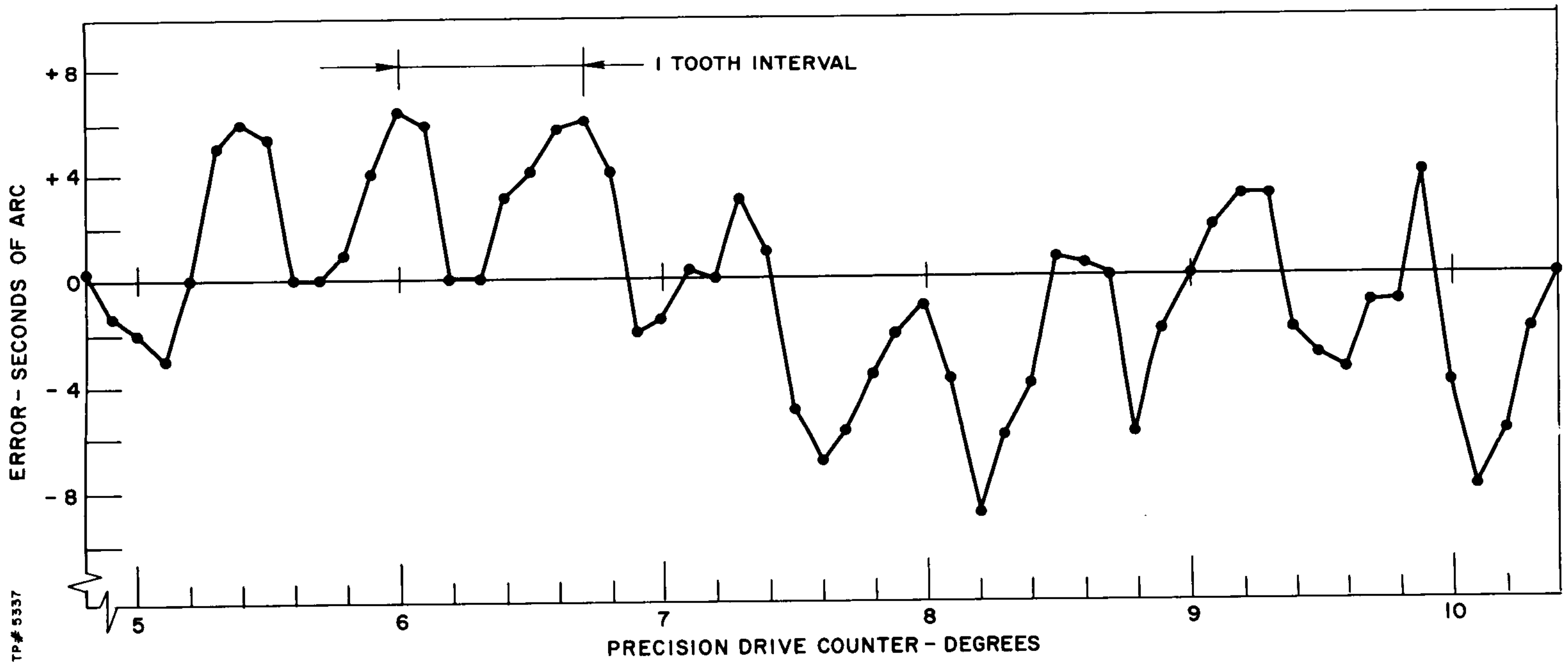


Fig. 1 Tooth to tooth error.

gear. The tolerances on this gear are ± 0.0002. An automatic means of measuring or getting a qualitative estimate of gear train error is by running the bull gear and pinion together and allowing the center-to-center distance between these two gears to vary. A strain gage pick-up will read this variation of distance. The 0.0002 is the amplitude of run-out error.

Figure 2 is a graph of angular gear positioning error in seconds of arc versus the precision drive counter reading in degrees. Both these records are from the automatic space sextant where the bull gear is used to position the line of sight of an acquisition telescope. The angular orientation of the bull gear is read off by means of a counter and dial arrangement at the end of a precision drive gear train as mentioned before. The readings are from the precision drive counter. This figure indicates the 84° of the large bull gear rotation. One revolution of the pinion gear which occupies about 12° of the bull gear revolution is also shown. It is fairly obvious that the pinion gear is not of the same quality as the bull gear, the angular peak-to-peak error being 24 seconds of arc or so. We have through the efforts of Mr. Davidson and Mr. Zapf, a record of the entire gear train. (Exhibited a curve about 15 ft. long).

From the record one can preceive the one period sinusoid, using about four seconds of arc per inch scale and the record is approximately 1 minute of arc in amplitude. This record has been taken 1 point per tooth on the bull gear which has 570 teeth. This

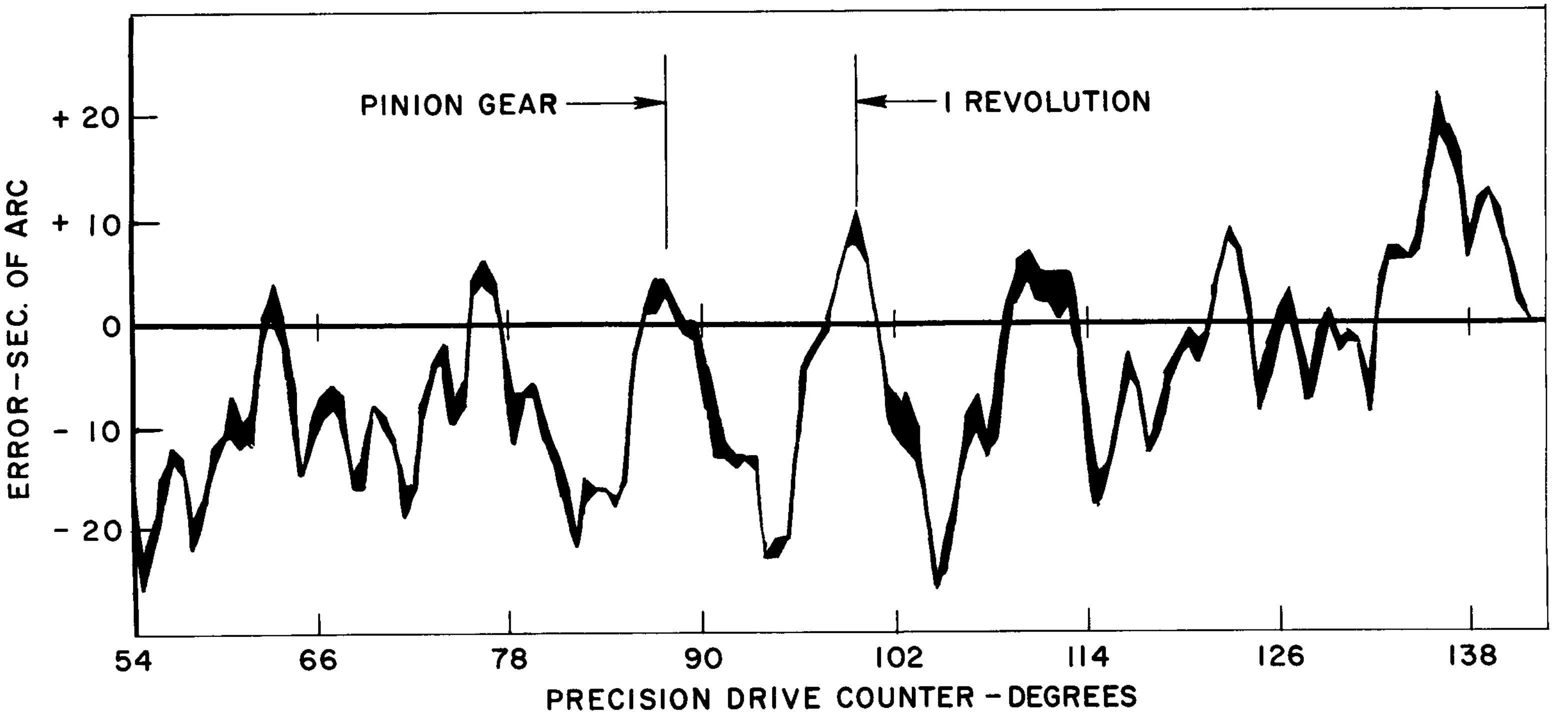


Fig. 2 Gear train error.

has been done so that we might temporarily eliminate tooth-to-tooth error. One may draw a similar curve one half a tooth away which would probably be parallel to this and 6 to 8 seconds below. The record isn"t as clean as theory predicts; instead of one sinusoid for the pinion gear and one sinusoid for the bull gear, there are smaller curves in the record.

Due to the limiting width of the mirror employed, we were able to read a sector of about 12° for a given position of the theodolite. Another mirror arrangement, namely a six-sided mirror, will also be attached to this telescope and by means of this will get the check point every 60° on that curve; thus we can align these 12° sectors. We use a six-sided mirror instead of a four because of the 12° period of the pinions.

Several things will be done with this data. Mr. Dilworth has been working up a Fourier analysis which will give us the components of this error curve. That program is in process now. We hope to synthesize the error curve that we have just seen by adding together all its Fourier terms. By this we will find how many terms of the Fourier series are required to reproduce the repeatable portion of the error curve. These coefficients might possibly be stored in the computer on board the spacecraft to compensate the gear train error.

In answer to the question, width of the error curve, part of this error is the error of observation. The width of the error curve is the difference between successive readings by the theodolite.

However, we do have several re-runs which superimpose almost as well. The repeatable part of the error seems to be large in comparison to the uncompensable residual.

Comments by Trageser on Magee's Presentation

I'd like to emphasize one point before we leave this. The predominent errors that we have seen are bull gear run-out, pinion gear run-out, and tooth-form errors. These are characterised by something like 8 coefficients in the erasable portion of the computer.

Compensating the gear errors does not require a very elaborate nor complex procedure. It requires a modest number of constants stored in the computer. These are used in a simple program occuring at a time the computer is not otherwise rushed.

Now, as I believe was brought out in our last meeting, there are two approaches in the space sextant configuration which are essentially different. We feel that we have to bring both approaches along in the initial period of the effort. In one of these the space sextant is, as John Dahlen's illustration showed, located in a well. The space sextant is in the vacuum of outer space. The advantage of this is the wide cone of coverage so that one can see a star in the low satellite orbit. The disadvantage is that the techniques involved in making this precision equipment work in the vacuum are in rather early stages of technical development. A research program is required to support this space sextant design. We are optimistic about it, but on the other hand it involves some possible pitfalls.

In the second approach one uses the flat window of the order of 10 to 12 inches in diameter which permits only a rather small cone of coverage. These flat windows are, by rule of thumb, generally about a 10th as thick as they are in diameter. If the people who are setting the safety criteria for the cabin pressurization are conservative, they will probably end up with several panes in this flat window so that if one is fractured, loss of cabin pressure does not result. This approach leads to a complicated and heavy window with a very narrow cone of observation. Our primary emphasis is on developing the technology to enable the operation of precision devices outside in space. Mr. Toth has been working on environmental problems of space, particularly the vacuum problem, for two years with the exception of an interruption excursion of this cloud layer business which you heard about last month. This month he is going to discuss the vacuum environmental factors entering the design of the space sextant for operation outdoors.

VACUUM ENVIRONMENTAL APPROACH

W. E. Toth

This will be a general discussion rather than an attempt to include too many details of what the requirements are and their effect, since much of this is documented.

It is important that all of us become aware of the environmental problems so that we do not overlook something in our early designs. Some people who are aware of the serious need for information, P. N. Bowditch, for example, are starting to press for information on how we should build things. What I'll do is indicate in general what environments concern us. I'll pick some of the more important ones, and indicate how I think we can go about getting the information we need as quickly as possible.

First of all, the environments are not completely known. A lot of data is available, rocket data and things we found out in the IGY year. NASA has been doing quite a bit with satellites and various test programs and there are laboratory programs throughout the country. At present no less than 80 groups are known to be working in the difficult environmental areas. The problems are generally unfamilar to designers simply because they are new problems. Their influence on reliability is unknown since things that are reliable in environments we're accustomed to may not be at all reliable on an Apollo type mission. One of the difficulties is in simulating the environments, particularly of high vacuum and micometeorites. Some of the radiation environments cannot be simulated at present.

I am sure everyone classifies environments in a different way. This is the way I chose to classify them today.

1) There are mechanical environments which include shock, vibration, and various loads.

2) The atmosphere, which includes vacuum (no atmosphere). We may have to seal equipment to maintain constant pressure.

3) There are the thermal environments where we must consider energy sources, sinks, heat flow paths, the various mechanisms involved in thermal equilibrium.

4) We have the radiation environment. Solar energy amounts to about 130 watts/sq. ft. There are particles, meteorites, dust, etc. The meteorites are fairly high density, maybe 3-1/2 grams/cc. The dust is, some speculate, 0.05 grams/cc, or a very porous material. Various people have speculated what meteorites and micrometeorites do to materials. Cosmic rays and Van Allen radiation may be troublesome to some things, particularly the men and the computer.

5) There are fields that are important, particularly the gravitation and acceleration fields. For example, heat transfer by free convection will not occur in free fall.

I would like to pick out items of immediate concern. One is mechanical vibration in the vacuum. In landing on, or taking off from the moon, the damping provided by air will not exist. This is important, especially with the space sextant, if it is mounted outside. We don't need an especially high vacuum to perform tests. The air viscosity becomes negligible at about 10^{-3} millimeters mercury.

If we put the space sextant outside, the lubrication of moving parts in the vacuum is very important, probably the most serious problem.

A third problem of importance is that of heat transfer in the combined vacuum and free fall condition. Heat balances in sealed as well as exposed units will be changed considerably and must be properly designed.

One problem in using a vacuum is its ability to clean a surface very quickly and very completely. Surfaces in contact usually have air molecules and oxides on them and as you use them in combination you don't have problems involving intermolecular attractions. In the vacuum, if you have rubbing, or if you have lubricants that are volatile, or if you have gas layers, all these things can disappear very quickly. The result can be molecular adhesion between surfaces, resulting in high friction and very rapid wear.

The main concern right now is the space sextant. It is about the only thing we now see as being out in the vacuum. Thus the most urgent environmental test activity involves the space sextant.

The testing activities to get information can be divided or seem to be separable into about 4 areas. The first is the thermal problem associated with vacuum effects. We need a vacuum of 10^{-4} mm mercury or better which is an easy vacuum to produce. To investigate thermal problems in a vacuum we also need a cold wall. In space the radiations which leave a surface keep going and are not reflected or returned in any way. To simulate this we need a cold wall that is also black so that it doesn't radiate to the parts we are testing and so that it doesn't reflect thermal radiation. A liquid nitrogen or colder wall is necessary for this. I think we have a pretty good design to get a black cold wall.

In regard to solar radiation, it may be that the space sextant will not see the sun at any time during the trip or at least at any time when it is important. However, we must understand the heat balances that we obtain with this environment. A simple carbon arc with a quartz window will simulate spectrum very well for this purpose.

A second area of testing I think we need is shock and vibration tests. While we don't know what the specifications may be, we could probably guess at some. We need to test things like the space sextant mechanisim and the optical assembly that goes into it, to be sure we are not going to jostle things loose. We may have some equipment vibration problems that are a little different in the vacuum and this requires testing.

The third area involves ultra high vacuum testing which I set apart because it is a special area that requires special knowledge and understanding of the phenomena directly associated with the ultra high vacuums. Producing ultra high vacuums in itself is a special area of interest. In addition to the lubrication, friction, wear and adhesion I've already mentioned, material problems, evaporation of certain materials, and condensation would also be under test. The reason I mention condensation is that, in a vacuum, evaporated molecules can travel to distant surfaces and there condense. Thus, materials that were evaporating could get on the sextant optics. We must be careful about the materials surrounding the external optics of the sextant. We must also investigate finishes and adhesives for integrity in high vacuum. Vacuum and thermal effects, and reliability, are so inter-related as to make it difficult if not impossible, to consider each separately.

In regard to reliability, I think the best approach we can take is to run life test on things until they wear out, see why they wore out or broke, and then improve them. In that way we will be doing about as well as we can do to get reliability into prototypes.

The immediate test program to provide design information, particularly for the space sextant, needs to be started right away. I took one space sextant design being considered and outlined a program of tests using this particular device. It turned into a long list of things that we could start doing so I have only summarized them.

First, we would assume that the space sextant is not behind a window. The next thing to assume is that the design is available in detail. We now have sizes and dimensions for everything and we will say that this is the one we are going to build. We would then assume that the vacuum equipment available today is a satisfactory simulation of space. (This equipment is capable of 10^{-10} mm of mercury. Speculations indicate that pressures between here and the moon are 10^{-16} mm of mercury or lower. I am not sure what basis we should use to try to demonstrate that our assumption of 10^{-10} would be good enough.) The test outlined involves testing sextant drive motor and the precision drive motor. We would worry about the thermal balance particularly in the case of a motor whose heat is transferred normally by conduction of air between the motor and stator and to some extent by the bearings and just a little bit by radiation. If we put the motor in the vacuum we find that we do not have convection or conduction of air, but must remove all the heat generated in the rotor by radiation to the stator and by transfer through the ball bearings. Because the contact area of the ball bearings is small and the temperature drop can be quite severe, no significant heat radiation occurs until a high temperature is reached so that thermal equilibrium occurs at higher than normal operating temperature. We will require special designs of bearings and ways to remove the heat from the motors.

A problem with the winding of the motor also exists as the vacuum may affect the insulation, and binder between laminations. The gear box must also go under test. The problem here is lubrication, mainly how to lubricate gears. Frank Siraco tells me that in many of their precision gear boxes no lubricant is put on the gears, which works fine for instrument-type applications in air. This may not work in the vacuum, in fact I don't think it would work at all because the clean surfaces resulting would possibly result in adhesion with high wear. There are some lubricants that might work, solid lubricants particularly, so the problem may not be insurmountable. It is just a matter of making an educated guess at how to design it, try it, and I think we will come out pretty good in many areas.

Bearing failure is in the same category as gear failure. Some bearings, such as in a motor, are high speed while others such as in the precision shaft axis bearings are low speed. P. N. Bowditch had journal bearings in his design so we must test journal bearings also.

Oil vapors on optics present one of the problems of using oils for lubrication. Oils work good, have the lowest coefficient of friction and the best wear properties, but we may not be able to use them where optics are involved. The reason is, again as I stated before, in a vacuum or at reduced pressure molecules leaving one surface will tend to rapidly coat on adjacent surfaces. We will probably want to use solid lubricants, but I think it would be worth while to find out if oil vapor on the optics is a real problem or whether we could satisfactorily use, say, vacuum grease for lubricants.

In regard to using static and dynamic seals, if there were few enough points on the space sextant that could be sealed by dynamic seals, that is, if there were only three or four bearings which when sealed would seal the entire mechanism of the space sextant from the vacuum, this could be a good solution to the problem. As the designs change, we may wind up with something that we could seal with few moving seals. The result would be an enclosure which was not at the high vacuum but was, maybe, at the vapor pressure of something inside. If we have something like gyros, or parts that could be completely sealed with no mechanical moving parts sticking out, then static seals could be used. If we had to worry about the spacecraft leaking enough to get down to low pressure then static seals would probably be important enough that we would want to know a lot about them.

I have some encouragement regarding the lubrication problems and have listed just a few of the things. The CBS labs of Stanford, Connecticut claim to have a bearing that runs at a 1, 000 rpm, no load, room temperature, 10^{-8} mm mercury for 1, 500 hours. This is their claim. I tried to get some of their bearings 8 or 9 months ago but haven't heard from them since. They were having trouble with the process. Some of the bearings worked and some of them didn't.

Miniature Precision Bearings up in Keene, N. H. ran tests on servo motros. They were interested in seeing if conventional lubricants (low vapor-pressure greases or oils) would work on servo motors. They made some tests at 10^{-5} mm mercury (which is low enough pressure to demonstrate the volatile process and get rid of the lubricants). Using only dust covers, they got about a 1, 000 hours out of the best lubricants, which means that many lubricants now available may be useful for this type of life.

Barden Corporation has what they call Bartemp bearing, built with a molybdenum disulfide retainer that rubs molybdenum disulfide on the balls for lubrication. They were interested in bearings at high temperatures so most of the tests were run at high temperature. However, moly-disulfide is known to perform well as a lubricant in a vacuum, exhibiting an extremely low vapor pressure. They ran bearings at 12, 000 rpm for 1,000 hours at almost 600°F. They have just recently, as Frank Siraco pointed out, run some at 10^{-10} mm mercury but they didn't specify how long.

MIDCOURSE GUIDANCE THEORY

Dr. R. H. Battin

Rather than present the involved mathematical formulae of Dr. Battin's presentation, it was suggested that the interested parties refer to Report R-341, A Statistical Optimizing Navigation Procedure for Space Flight, which is Dr. Battin's complete study of the problem. The abstract of that report is reproduced on pages 2 and 3.

[redacted]

INTRODUCTION TO AFTERNOON SESSION

M. B. Trageser

In our work to date we have not concentrated effort on the inertial measurement unit. The laboratory's experience in the design of numerous inertial measurement units in the past makes this a well defined problem compared to the midcourse measurement problem. For this reason our IMU study began only a few weeks ago instead of a few months ago. Dave Hoag will now discuss the IMU.

[redacted]

INERTIAL MEASUREMENT UNIT STATUS

D. G. Hoag

Effort in the design of the Apollo Inertial Measurement Unit, IMU, has been underway too short a time to report any details. This instead will identify the IMU major critical design areas and the factors necessary to resolve them.

First a description of the use of the IMU in the over-all Apollo Navigation and Guidance system... The IMU has two functions:

1. Provide spacecraft attitude signals. These signals will probably be used by the autopilot in an attitude stabilization loop during motor thrust phases. Also these signals might possibly be used to stabilize the direction of optical axes or radar antennas.
2. Measure the specific force (or acceleration with respect to free fall) on the spacecraft for use by the computer in determining velocity changes and steering signals.

As currently conceived the IMU will be operating only during the critical phases of the Apollo mission; at other times all power will be shut down to minimize load on the spacecraft power source. Times when the IMU will be operating will be only when it is being called upon to measure forces on the spacecraft such as motor thrust or re-entry drag. Operation for some period just prior to the measurement phase will be necessary to achieve temperature stability and perform initial alignment.

The critical areas of design decision in the IMU which are listed below must be resolved early in order to meet our schedule:

1. Thermal control scheme.

2. Gimbal order.
3. Gimbal angle takeoffs or signal generators.
4. Inertial components to be used.
5. Stable member configuration.

These areas will be considered in the following discussion.

Thermal Control

Not much is decided in this area. Often this problem is left to last in the design of similar inertial measurement gimbal systems. This cannot be allowed with Apollo since major design criteria are ultimately tied up with thermal control: The over all power economy and heat dissipation.

There are a number of problems due to the Apollo environment. The low cabin pressure inside the command module where the IMU will be located combined with the low acceleration during alignment phases of the operation obviate the use of air convection cooling. Even forced air cooling is impossible during emergency cabin decompression.

The design of the inertial components to help in this area should lean towards a wide range of temperature tolerance as well as low operating power requirements.

Gimbal Order

The present design decision is to have a three degree of freedom gimbal system between the spacecraft and stabilized member of the IMU. This choice of the minimum necessary number of gimbals is based upon the desire for simplicity and the fact that with proper initial alignment no phase of the Apollo mission using the IMU seems to lead to "gimbal lock" conditions.

Figure 1 shows the gimbal order chosen. The outer gimbal axis, OGA, is parallel to the spacecraft roll axis, X_{SC}. This allows unlimited roll motion which is necessary to accommodate the roll control of lift during re-entry chosen in the Apollo Statement of Work.

The middle gimbal axes, MGA, is mounted on the outher gimbal perpendicular to OGA. The middle gimbal supports the inner gimbal axis, IGA, about which the stabilized member is free to rotate.

During each phase of the Apollo mission within which the IMU is making measurements, the spacecraft roll axis orientation required is close to a single inertial direction or at most the roll axis direction required moves roughly in single inertial plane. Thus if the IGA is aligned perpendicular to this plane prior to each use of the IMU, then middle gimbal angles will be kept limited (say 45° or less). In this way gimbal lock is avoided — as long as the roll axis of the spacecraft does not move near 90° out of the inertial plane defined by the aligned direction of the IGA.

Another advantage of this gimbaling order is that it provides a freedom in the trajectory plane for optimum orientation of the inertial components with respect to their effect on accuracy.

Gimbal Angle Takeoffs

Our next subject is the matter of the signal generators or takeoffs on the gimbal axis. There are three considerations which I shall discuss. The first is the interface with the spacecraft attitude controls. The spacecraft manufacturer is to be responsible for controlling

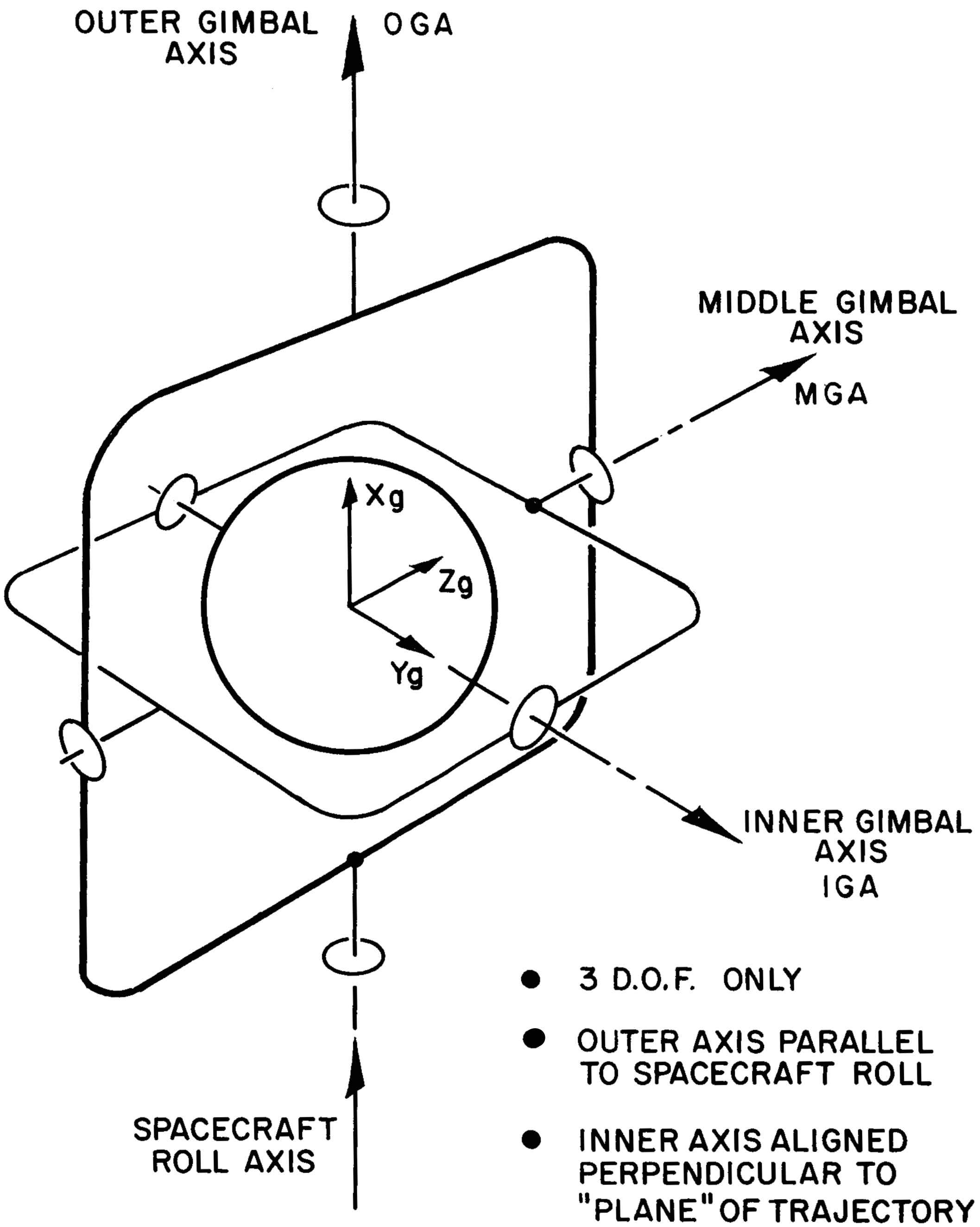


Fig. 1 Gimbal order.

spacecraft attitude during periods of thrusting by use of some sort of autopilot. An attitude reference will undoubtedly be needed and can be provided by the IMU. There must be a compatible interface. The second area of concern that would lead to defining these takeoffs is that of any stabilization function which the IMU must perform: stabilizing antenna, lines of sight, star trackers, or range finders, etc. The IMU must be able to transmit these gimbal angles which present the stabilization signals to these mechanisms.

The third area which will help determine the gimbal angle takeoffs is in the technique of alignment of the stable member prior to its use. Star sightings from the space sextant or midcourse measurement unit, MMU, will provide the inertial directions necessary. Figure 2 shows the geometry involved. The spacecraft roll axis is vertical on this diagram and is labeled as X_{SC}. The Z_{SC} axis is the yaw axis; the Y_{SC} axis is the pitch axis. Also shown is the shaft drive axis, SDA, of the space sextant which is approximately 33^{o} above the Z_{SC} axis. Rotation about the shaft drive axis from a reference produces a shaft angle SDA and positions the trunnion drive axis, TDA, of the MMU. Rotation of the optical line of the mirrors within the sextant about the trunnion drive axis by a trunnion angle, TA, determines finally the direction in which the optics look along a direction fixed by the dip angle, DA. This line of sight when pointed at a star provides for alignment of the inertial measurement unit. The IMU will be mounted in close proximity to the sextant rigidly and firmly

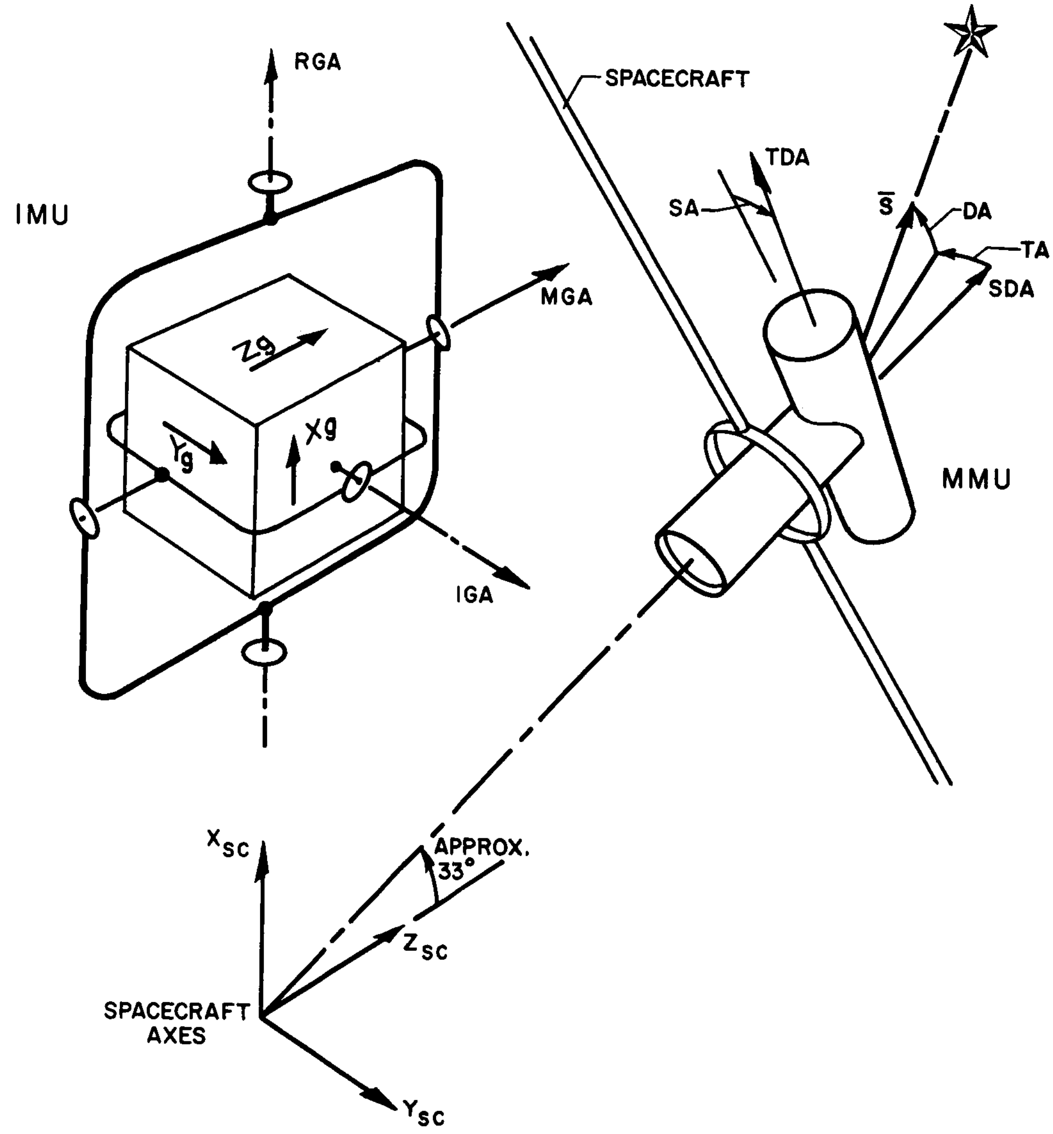


Fig. 2 Gimbal angle takeoffs.

so that there will be hopefully a minimum of flexure between them; thus the sextant angles of star direction can be carried over to the stable member orientation. The gimbal system of the IMU is mounted to the spacecraft and is represented in Fig. 3 as a functional block diagram. There are drives for the roll axis, the middle axis, and the inner axis from which the orientation of the stable member is determined on which sit the three gyros which control this orientation nonrotating as long as there are no torquing currents to these gyros. It achieves this control by error signals generated by the gyros to the gimbal drives. The possibility for unlimited rotation about this inner axis is planned and therefore gyro error signals have to be resolved to get back properly to their drive system coordinates.

There are various possibilities of doing the alignment of the stable member to inertial space using two stars sighted by the MMU. One will be discussed here and is distinctive as being quite simple. Consider that you choose two stars, star #1 and star #2. Star one you will choose in the direction that is determined by the plane within which the trajectory is approximately going to lie. It is parallel to the desired direction of the inner gimbal axis. The second star is chosen approximately 90° from star #1. The plane of these two stars is the plane within which you want the stable member Z axis. Conceive of an operation somewhat like which follows (refer to Fig. 2). You'll pick up star #1 which is in the desired direction of the inner gimbal axis. Keeping the sextant on the star you then maneuver the spacecraft in such a manner that a particular shaft angle and a trunnion angle

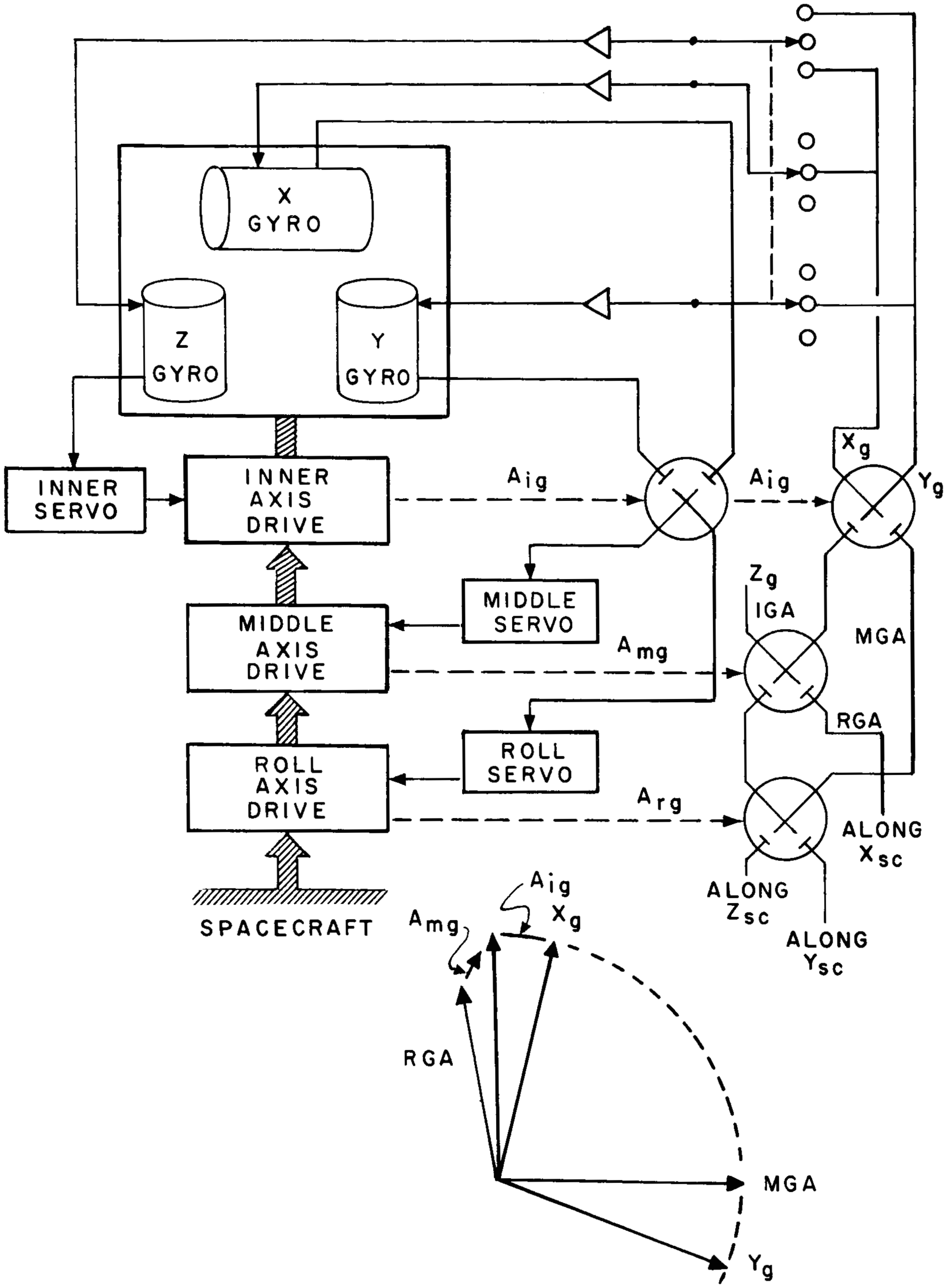


Fig. 3 3 components of the star vector.

result in bringing the spacecraft Z axis close to the star. Alignments to about a third of a milliradian would be required in this simple concept. We can achieve this by commanding appropriate spacecraft attitude rates. Meanwhile error signals generated from the outer gimbal and middle gimbal angle transducers to the gyros bring the inner gimbal axis parallel to the spacecraft Z axis. When you have achieved this the inner gimbal axis is now parallel to star #1 and torquing current to the X and Z gyros should be removed. The gyros will keep this direction of the inner gimbal axis as long as the gyros do not drift.

We then rotate the sextant to pick up star #2 and then rotate the spacecraft so that the Z axis is pointing to this star. The inner gimbal is then about as shown in Fig. 2, i.e., in the plane of these two stars, since the middle gimbal axis is 90° from the roll axis. Then by torquing the third gyro, you can bring the inner gimbal angle transducer to a zero signal. Alignment is now achieved.

Now an obvious question is, are we asking too much to get the spacecraft with sextant on the stars within 1/3 milliradian? I was happy to hear this morning that we were talking about 10^{-3} deg/sec. (0.017 millirad/sec.) as the level of increments you might get from the spacecraft attitude control and very possibly the astronaut looking through the sextant in the optics, once he gets the star in the field of view, can steer the spacecraft so the star passes within 1/3 milliradian of the center of the reticule. When it passes within this range he can simultaneously open up the appropriate gyro torquing loops.

Another possibility would not require getting exactly on the star, but only within a degree or less. Then a simple 1% digital encoding of the gimbal angles could provide information for the computer using the sextant angles to generate the required gyro torquing information to achieve alignment.

It is possible, without requiring any attitude change of the spacecraft other than making sure that you can see a pair of stars far enough apart, to do the job. This would require a resolution chain in which you start with a voltage representing the star vector as shown in Fig. 4. Resolve it by the dip angle with a fixed resolution. Then do the trunnion angle, shaft angle in that order. Another fixed resolution which would be in some booster amplifiers cross feeding into the final resolution, get the star vector components in spacecraft coordinates. Then coming back up the other way, with these spacecraft components of the star vector resolved through IMU gimbal angles, Fig. 3, you get the three components of the star vector in stable member coordinates. Then all you would require to align the gimbal axis along the star would be to torque so that you have no components of the star vector along Y and no components of the star vector along X. Then pick up another star again near 90° from the first star and then torque about the inner gimbal axis to bring either one of these vectors again to zero for the new star. We here achieve the full alignment without any spacecraft maneuver at all. The main difficulty with this is the resolvers and the accuracy from them. I think we would need a state of the art

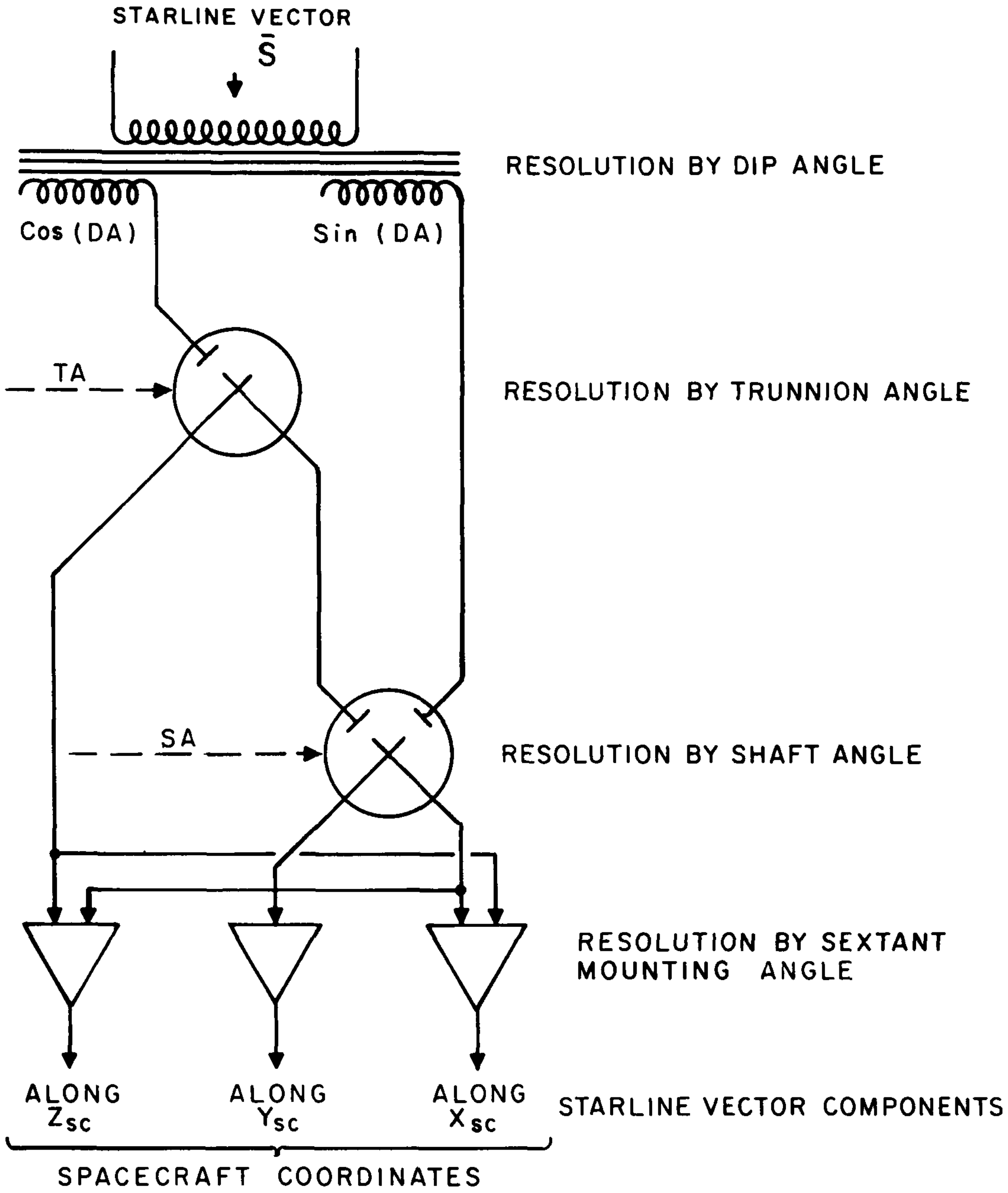


Fig. 4 Resolution of starline vector into spacecraft coordinates.

improvement of about 5 to 1 over what resolvers do as usually employed. There is a lot of difficulty in these resolvers out on the sextant in the space vacuum. Unbuffered resolver chains do have quite a bit of temperature sensitivity. You might have to use buffering and control impedance levels, etc.

The foregoing show the various constraints the IMU alignment scheme can impose on the choice of the gimbal angle transducers. The simplest scheme requires only null signal generator obtainable from synchros, resolvers, or pots. The most complex would require full 360° digital encoding of gimbal angle.

<u>Inertial Components</u>

The following considerations are of concern in the choice of the inertial components, the gyros and accelerometers:

1. Undoubtedly the adequacy of performance for the job cannot be ignored.
2. Availability is very important for AGE 1 due to the tight schedule.
3. Familiarity, while maybe not so obvious, is important also. If our laboratory personnel are involved in instrumentation with which they are not familar, they may not be able to utilize the full capabilities of the instruments within the time limitation imposed by the schedule.
4. Size, power requirements, and temperature sensitivity are quite obvious.

The 2 million berylium gimbal gyro (the MIT 2FBG) has undoubted performance capability, is available, and we are familiar with it. Its size is about 3-1/2" × 5"; the wheel power is about 5 watts. The Mod 1 25 IRIG, about 2-1/2" × 3-3/4", also has the necessary performance but with somewhat less margin. The Mod 1 is in volume production and has about a 3-1/2 watt wheel. A Mod 2, which I feel has easily the performance capability, is not in production yet and has a 4-1/2 watt wheel. We can get a low power wheel, possibly 2 watts in this configuration.

For accelerometers, a 16 PIGA can do what is necessary for Apollo guidance. It has a 1-1/2 watt wheel. The 16 PIPA has a great advantage in size but has a power consumption of about 12 watts as operating in Polaris where it is used in a two-torque-level mode. The PIPA Group in Polaris has studied the operation in a 3-torque-level mode and has achieved performance which is comparable with that achieved from the 2-torque mode of operation. This would cut the power down to around 2 watts. It is a very small device being about 1.6" in dia. The 16 PIGA is a little bit larger than the IRIG in size.

We are not too certain what we need in inertial component performance. Table 1 is an error example rather than an error study, but may give us some early idea of what we need. The right-hand column is the total injection velocity error for a boost, 15 minute parking orbit and injection for a lunar mission. The next column to the left is the total vector position error after you start a re-entry.

The stable member misalignment of 0.1 milliradian is within the order of magnitude considered above. Notice that as would be expected the errors about some of the axes are not as critical as others. The gyro bias drift at 10 meru level is a large error con-

		IMU COMPONENT	RE-ENTRY (FROM MOON) TOTAL VECTOR POSITION ERROR METERS	BOOST, 15 MIN. PARKING ORBIT & INJECTION TOTAL VECTOR INJECTION VECTOR ERROR CMS/SEC.
STABLE MEMBER MISALIGNMENT	0.1 mr.	X	190	22
		Y	450	80
		Z	1080	55
GYRO BIAS DRIFT	10 meru	X	1740	490
		Y	1600	490
		Z	3700	465
GYRO ACCEL. DRIFT	$\frac{10 \text{ meru}}{g(IA)}$	X	835	114
		Y	178	114
		Z	110	204
GYRO ACCEL. DRIFT	$\frac{10 \text{ meru}}{g(SRA)}$	X	400	125
		Y	990	125
		Z	1280	0
ACCELEROMETER BIAS	$0.1 \frac{\text{cm}}{\text{SEC}^2}$	X	1130	240
		Y	1780	476
		Z	880	62
ACCELEROMETER SCALE FACTOR	100 ppm	X	580	164
		Y	590	290
		Z	25	0
		2 STAT MILES →	3200	
		10 ft./SEC →		305

Table 1 An error example.

sumer. At 3700 meters it exceeds the accuracy level desired for re-entry. Therefore, this will have to be 5 meru or less. There is a possibility of leaving a memorized current necessary to achieve and hold the aligned condition in free flight so that this component of drift is compensated. The other possible sources of error are within reasonable limits. The accelerometer bias also lends itself to a simple free fall compensation technique.

J. Nugent has been investigating possible stable member configurations. Fig. 5 assumes that there may be preferred orientations of inertial components. You might say the two critical directions on the preferred orientation are (1) normal to the trajectory plane (the Y direction) and (2) a direction close to the total velocity change for that phase of the mission under consideration, (the X direction). Figures 6 through 8 show several preferred orientations for the stable member.

Figures 9 through 15 show some of the stable member configurations considered to date by Nugent.

Comments by Trageser on Hoag's Presentation

The table that Hoag presented shows errors in the mission due to error levels within the IMU. The errors were chosen as round numbers only to show the relationships to miss-effects produced and cannot be represented as the expected levels. Thus a total over-all combination of all the error sources within the table was not performed.

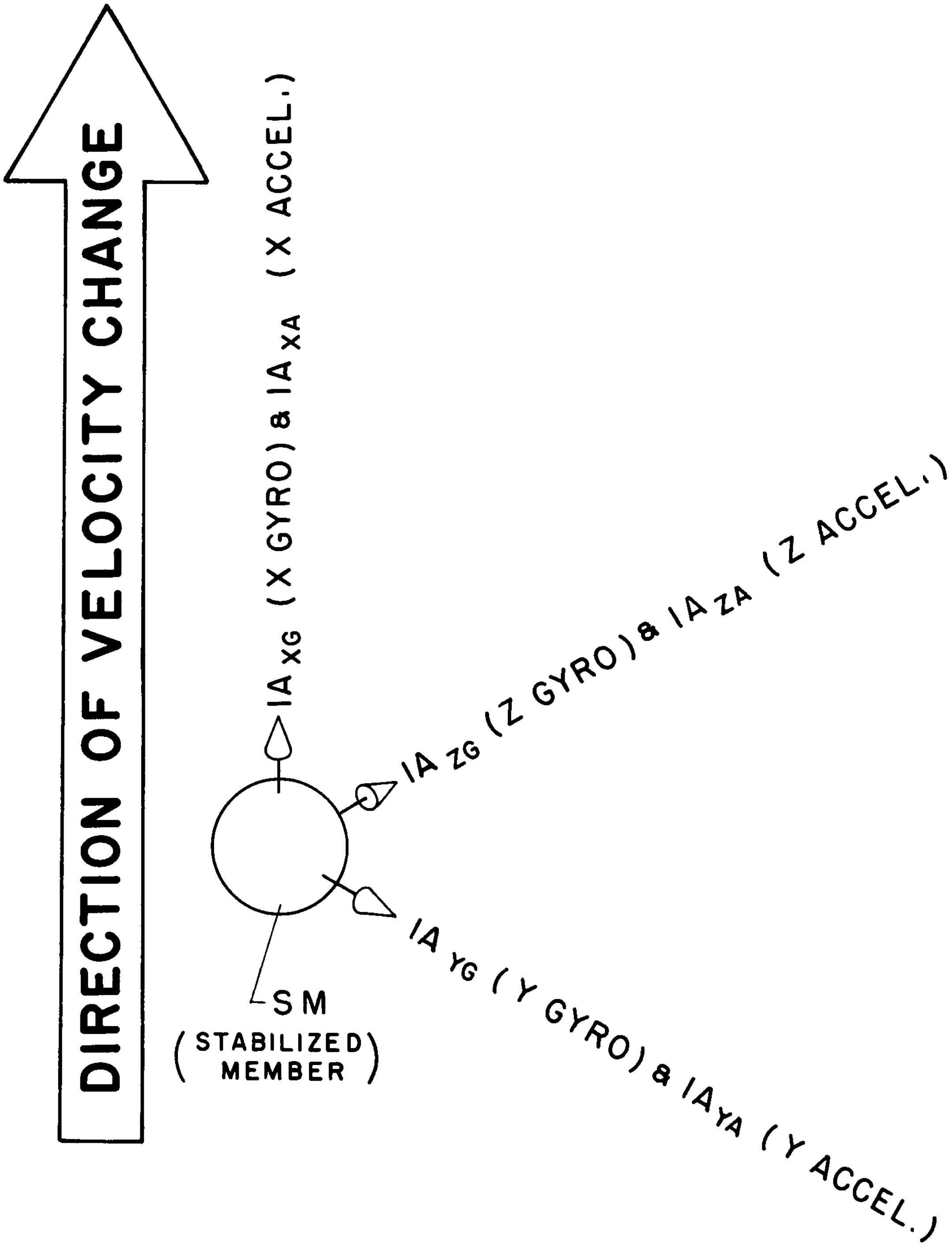


Fig. 5 Inertial components input axes for SM/IMU.

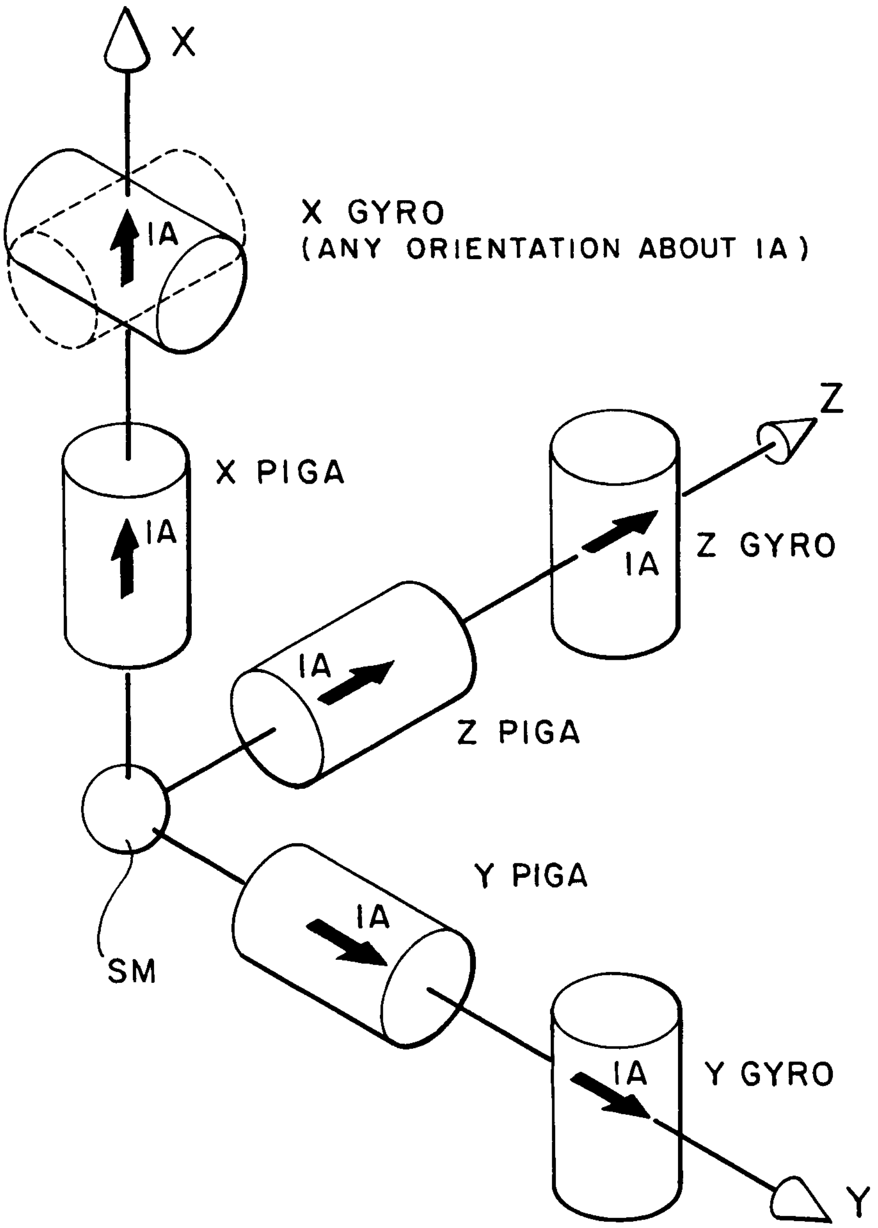
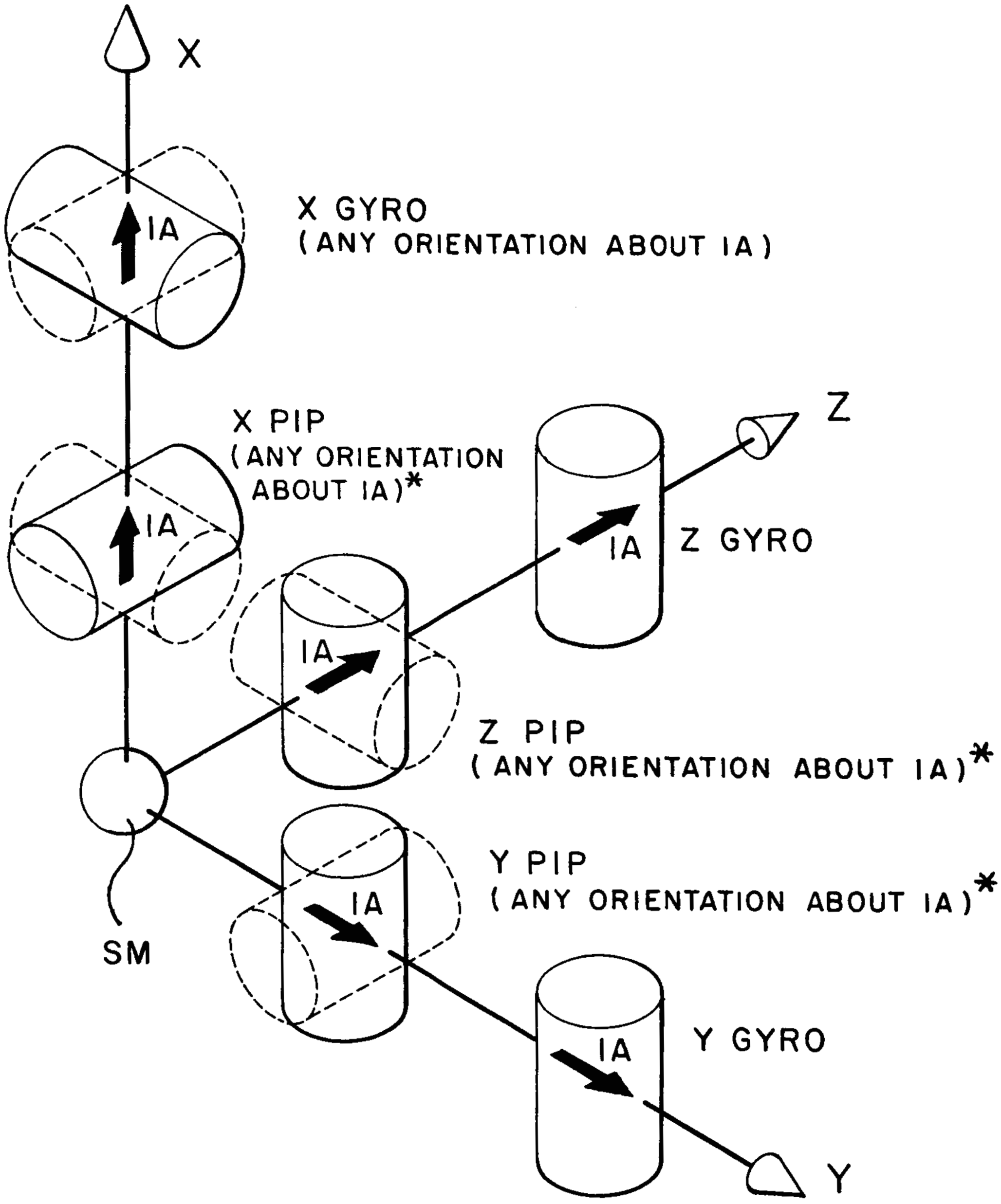
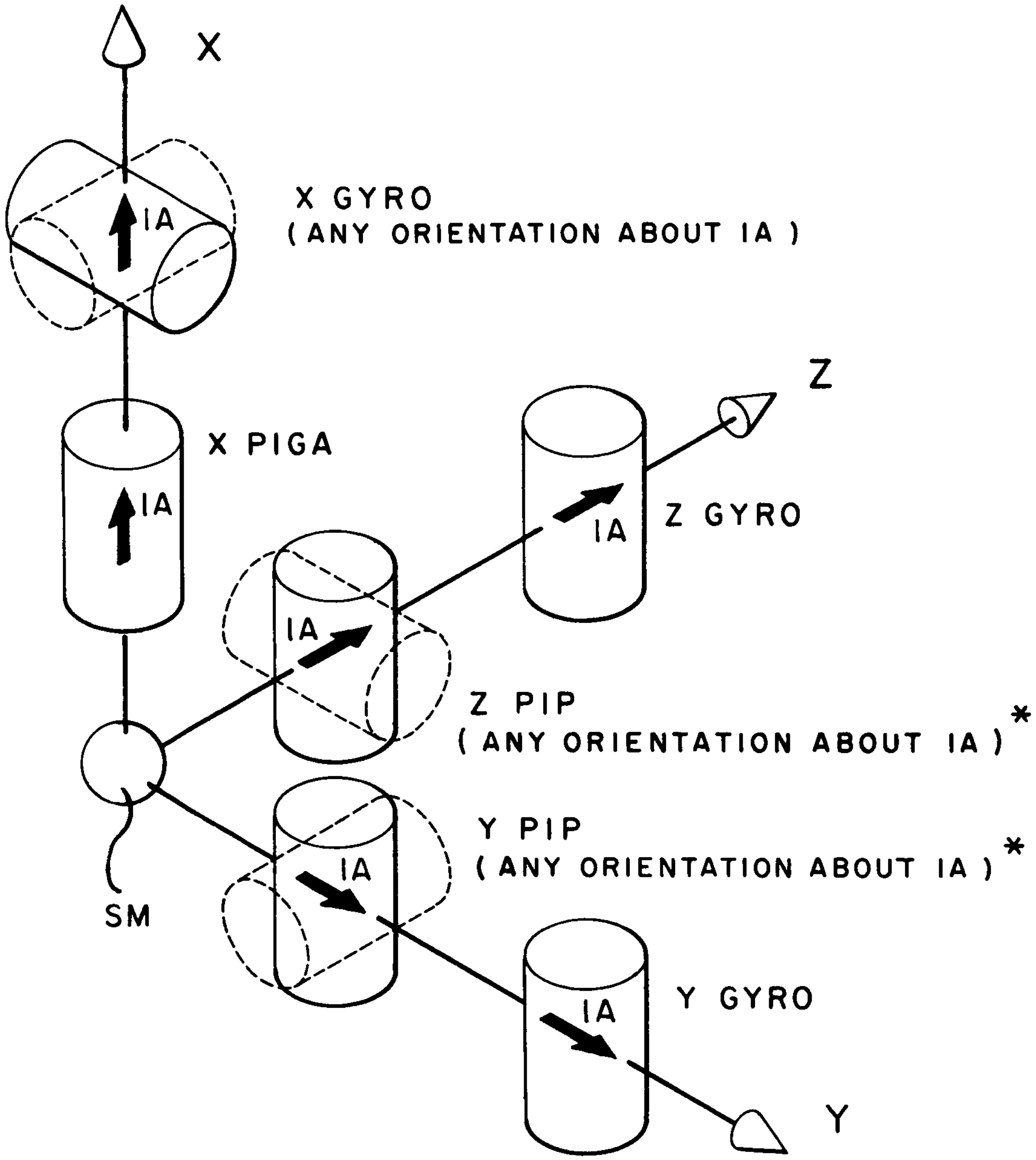


Fig. 6 Preferred component orientations for 3 PIGA and 3 gyro stable member.



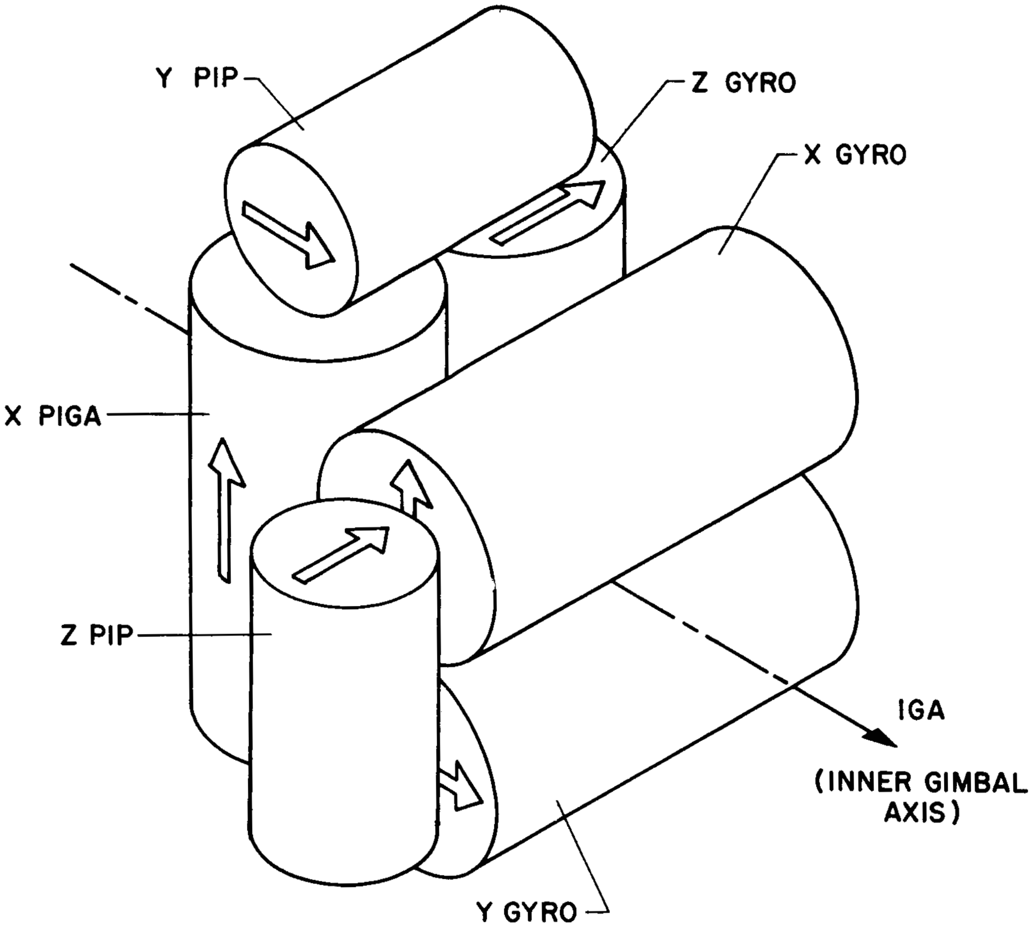
* ERROR STUDIES MAY INDICATE A PREFERRED ORIENTATION OF PIP OA

Fig. 7 Preferred component orientations for 3 PIP and 3 gyro stable member.



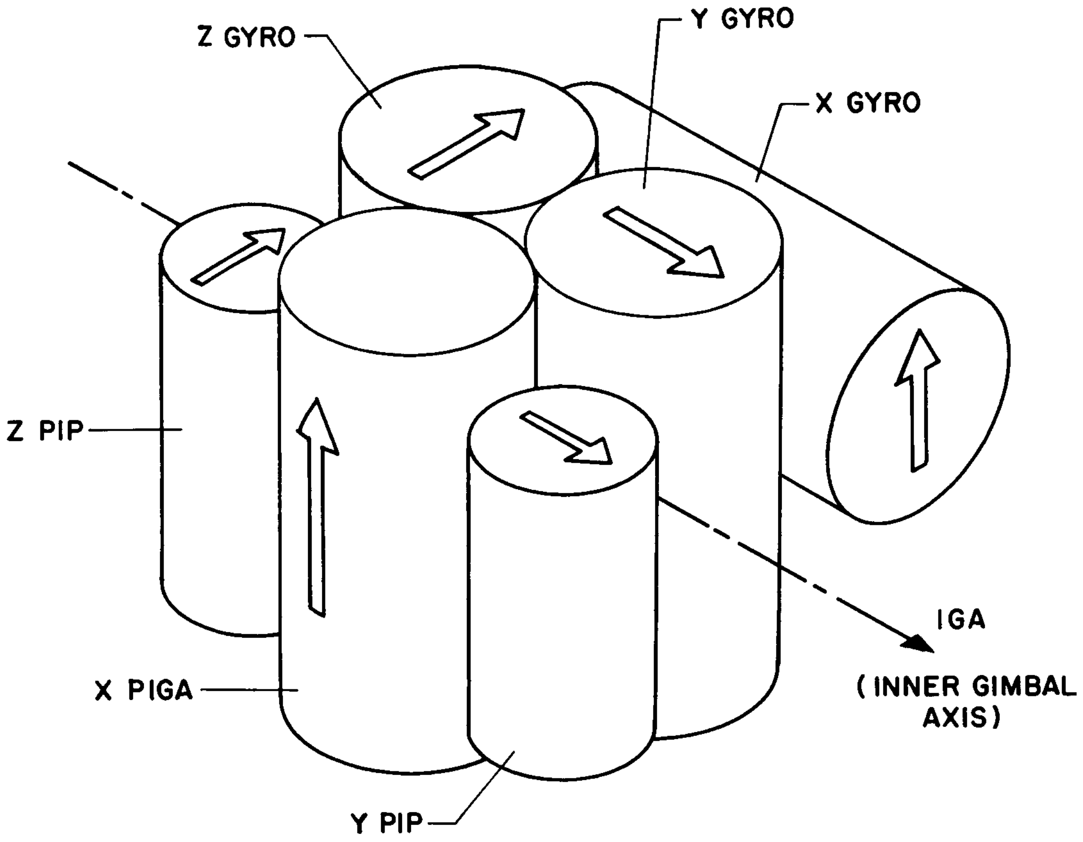
* ERROR STUDIES MAY INDICATE A PREFERRED ORIENTATION OF PIP OA

Fig. 8 Preferred component orientations for 1 PIGA - 2 PIP - 3 gyro stable member.



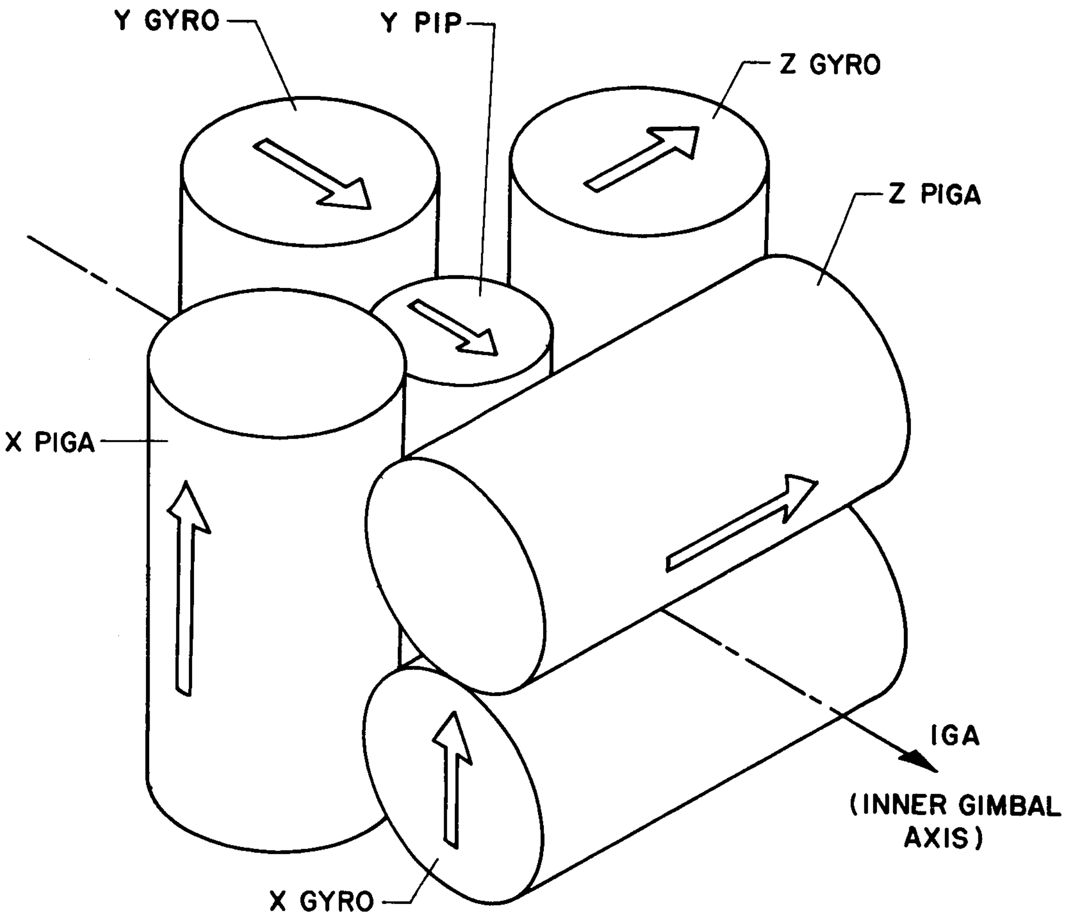
ARROWS INDICATE COMPONENT INPUT AXIS DIRECTION

Fig. 9 Stabilized member for proposed AGE 1 IMU; design 123 conversion (1-16 PIGA, 2-16 PIP, 3-25 IRIG).



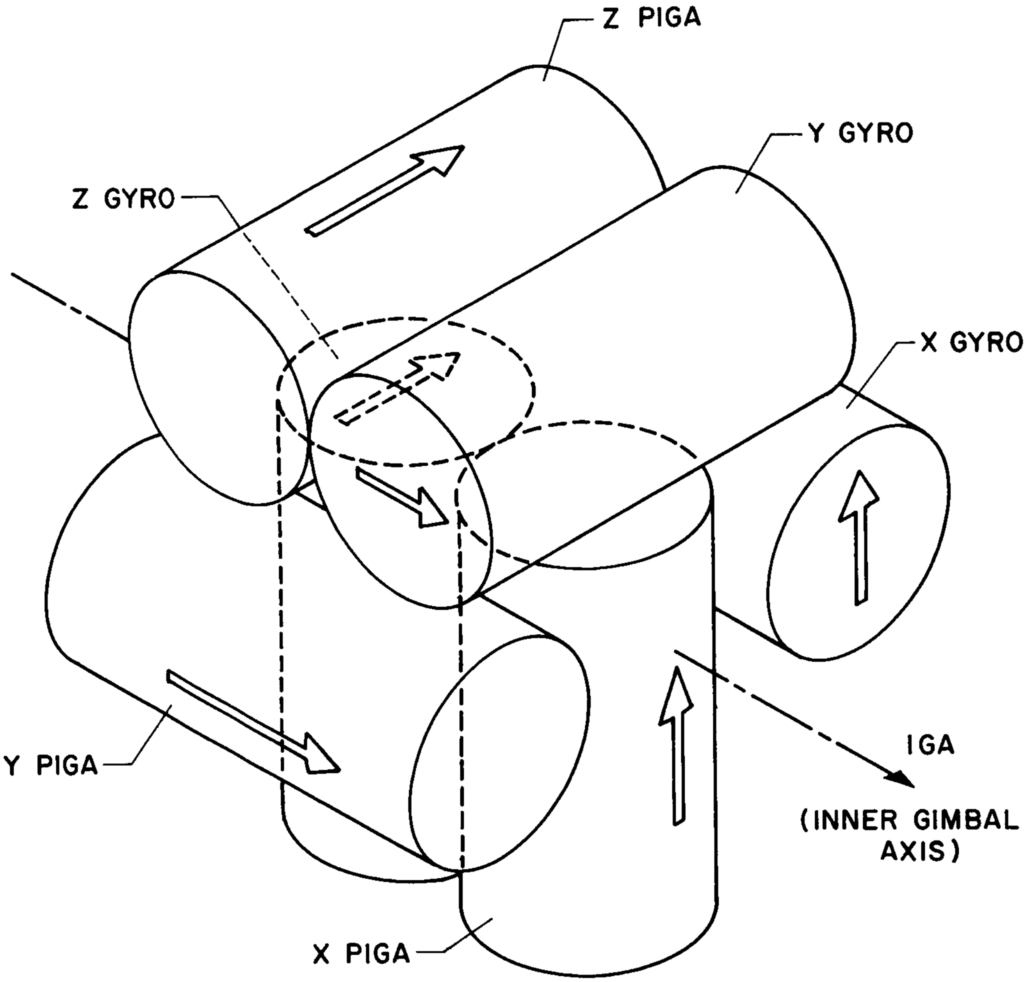
ARROWS INDICATE COMPONENT
INPUT AXIS DIRECTION

Fig. 10 Stabilized member for AGE 1/AGE 2 IMU; proposal "A" (1-16 PIGA, 2-16 PIP, 3-25 IRIG).



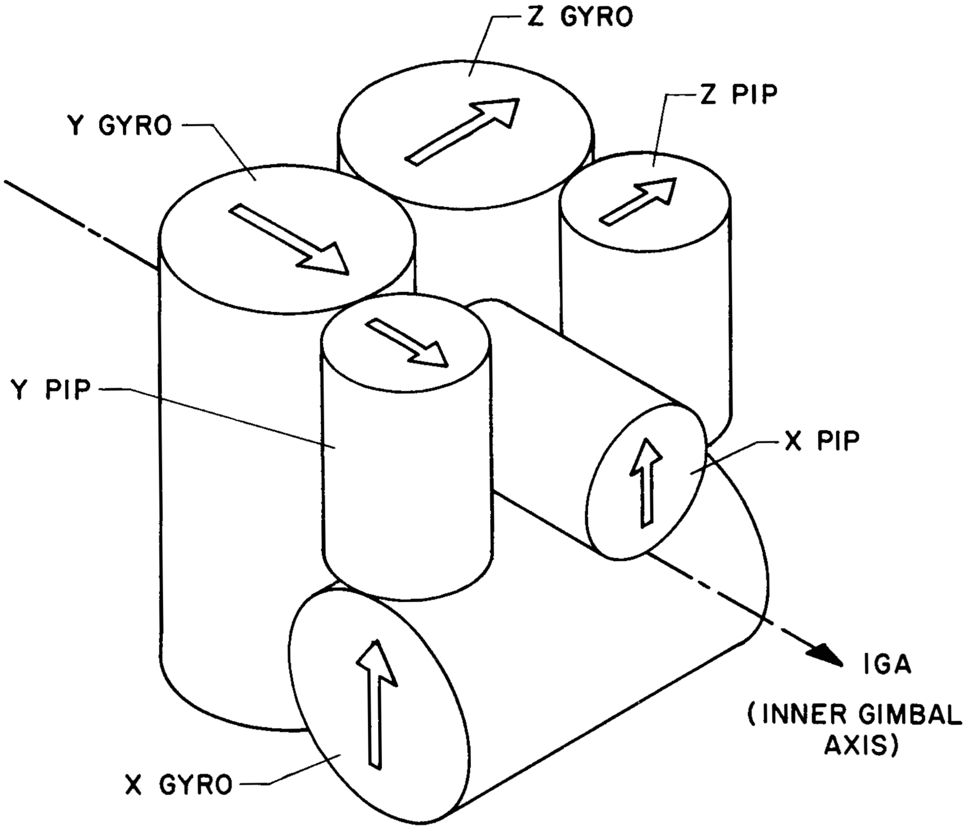
ARROWS INDICATE COMPONENT
INPUT AXIS DIRECTION

Fig. 11 Stabilized member for AGE 1/AGE2 IMU; proposal "B" (2-16 PIGA, 1-16 PIP, 3-25 IRIG).



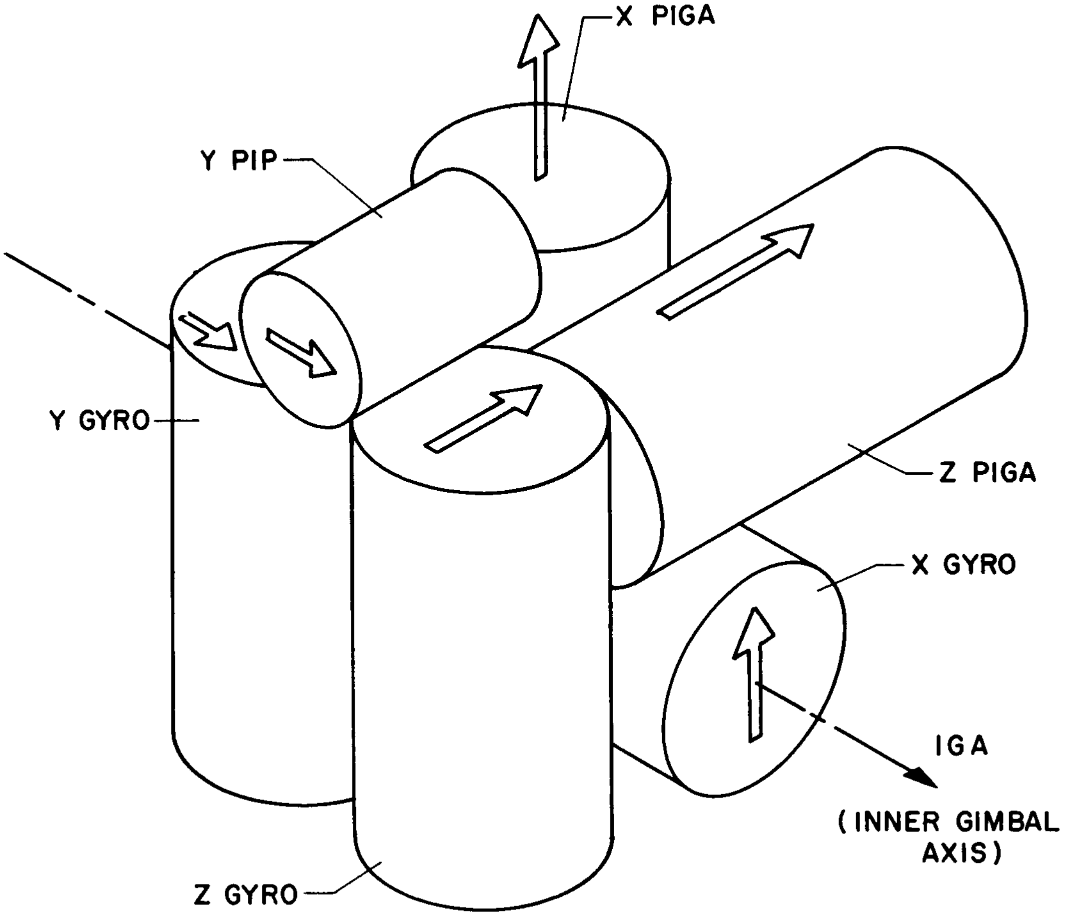
ARROWS INDICATE COMPONENT INPUT AXIS DIRECTION

Fig. 12 Stabilized member for AGE 1/AGE 2 IMU; proposal "C" (3-16 PIGA, 3-25 IRIG).



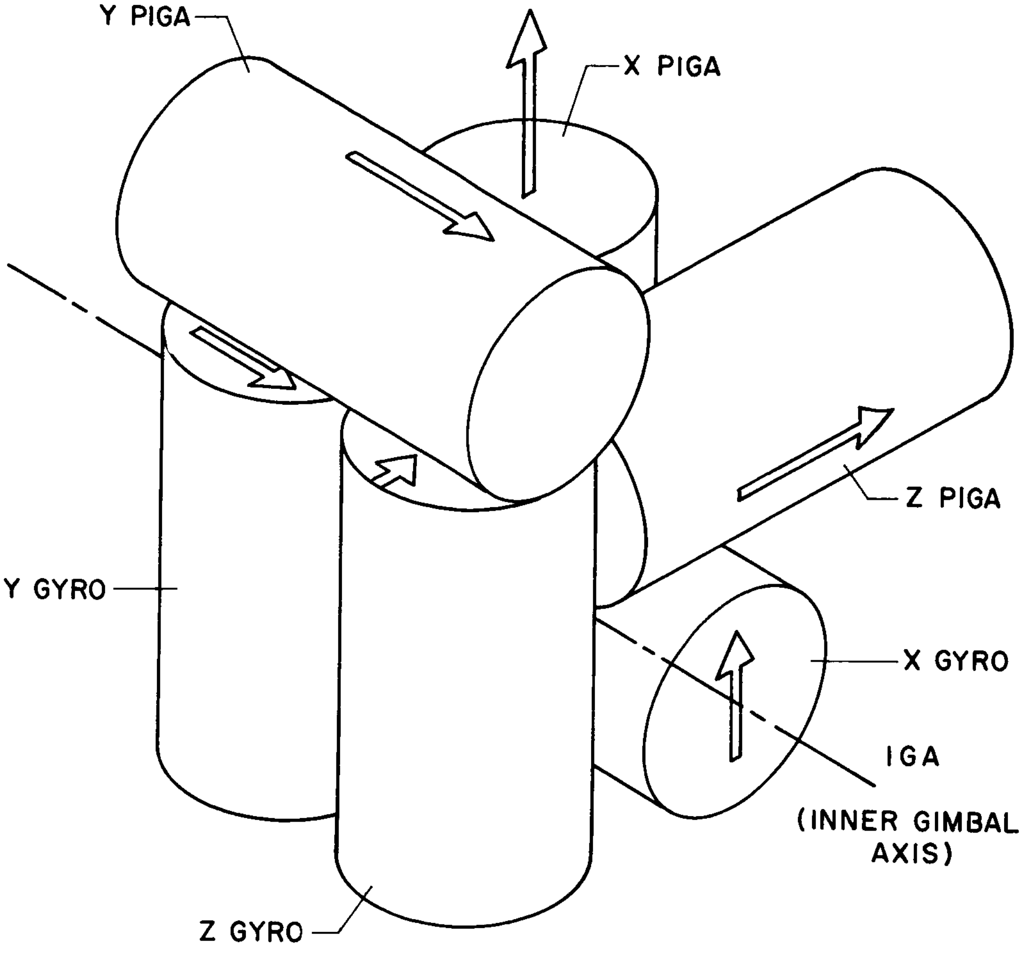
ARROWS INDICATE COMPONENT
INPUT AXIS DIRECTION

Fig. 13 Stabilized member for AGE 1/AGE 2 IMU; proposal "D" (3-16 PIP, 3-25 IRIG)



ARROWS INDICATE COMPONENT
INPUT AXIS DIRECTION

Fig. 14 Stabilized member for AGE 1/AGE 2 IMU; proposal "E" (2-16 PIGA, 1-16 PIP, 3-FBG).



ARROWS INDICATE COMPONENT
INPUT AXIS DIRECTION

Fig. 15 Stabilized member for AGE 1/AGE 2 IMU; proposal "F" (3-16 PIGA, 3-FBG).