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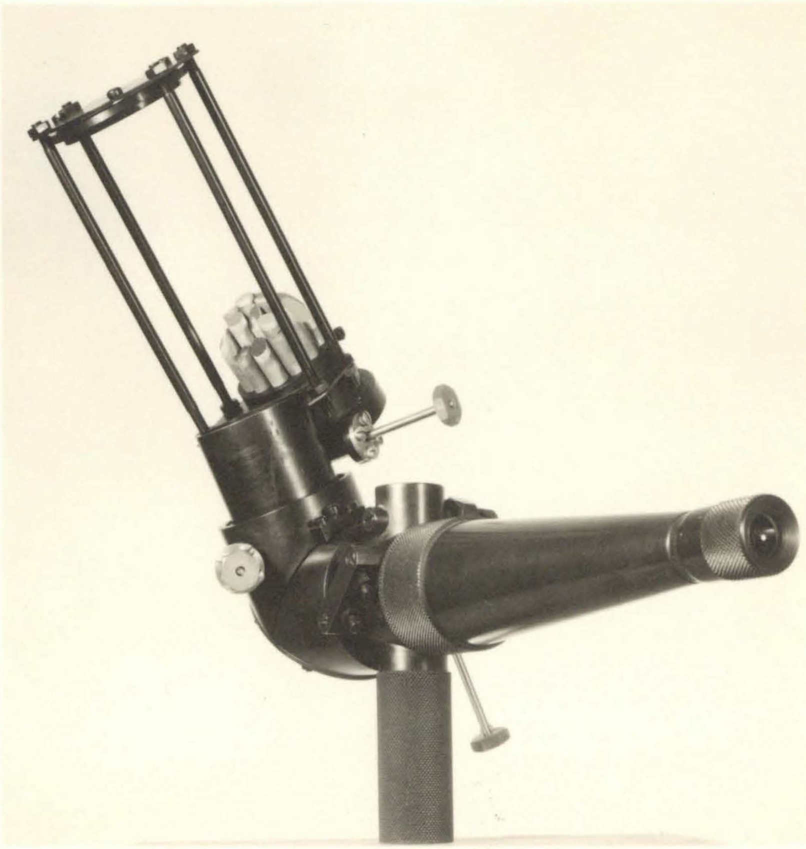

ASTRO-NAVIGATOR

DEVELOPMENT OF A PORTABLE CELESTIAL NAVIGATION INSTRUMENT FOR THE DIRECT-READING OF TERRESTRIAL POSITION

Thesis by

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DEVELOPMENT OF PORTABLE NAVIGATION INSTRUMENT FOR DIRECT-READING OF TERRESTRIAL POSITION

I. Objective

Today with the remarkable developments in speed and range of aerial transportation, its precise control is essential. Navigation--the determination of a moving position on the earth--is receiving careful attention from many investigators with widely various points of view. As a result, useful improvements are appearing with growing frequency.

The radio beam and the new air position indicator have contributed much to the ease of aerial navigation. But there is still need for a method of determining latitude and longitude independent of dead reckoning. This need was nicely expressed by representatives of the Army Air Force Materiel Command At Wright Field.

"Give us," they said, as if asking the impossible, "an automatic device which, held in the hands and directed toward the stars, will read the observer's latitude and longitude.

This thesis was undertaken to develop a portable celestial navigation instrument for direct-reading of terrestrial position.

II. HISTORY OF NAVIGATION BY INSTRUMENTS

The progress of navigation has been an interdependent development in its three fields: piloting, dead reckoning and celestial navigation. Starting from primitive observation with crude tools or none at all, each has increased in accuracy with the addition of new concepts and more carefully worked-out instruments.

A. PILOTING

Piloting--tracing a course from land mark to land mark--was the system used by the first small vessels of the Egyptians in 3,000 B. C., by the early Chinese, and by the Phoenicians. This method using the sounding pole and the weighted line led to the development of maps and charts of the coast line and then of the entire world.[1]

Except in their crudest form, maps and the whole science of cartography depend upon accurate measurement of distance and direction, and finally upon the geographic coordinate system for our round earth. Developments in piloting follow quickly upon improvements in other fields. Witness especially the use of radio, radio beams, and radar to extend the range and accuracy of our piloting method.

B. DEAD RECKONING

Dead reckoning--by independent measurement of direction and distance--was fathered by the lode stone. The Chinese, Arabs and

1 See Appendix A for all footnotes.

ancient Greeks knew of the magnet, but the earliest genuine record of a marine compass in use is A.D. 1297.[2] The chip log was first used to indicate speed for sailing vessels, and developed into various patent logs for modern vessels.[3]

Given the map obtained by the piloting method, the time and the distance travelled, position may be determined from any starting point. The direction is obtained from the earth's magnetic field with the magnetic compass or from the motion of the observer in space with the gyro-compass. In each case, fundamental technical difficulties limit the possible accuracy. Distance is usually determined from the time and speed. The most troublesome problem is to correct for drift, the motion of the sea or air itself. This requires special instrumentation on its own account. The correlation of dead reckoning with geographic position is further complication ed by the convergence of the meridians.

Most of these difficulties have been nicely solved by a new instrument, the Air Position Indicator, now used on our B-29 Superfortress. It is a quart-sized device which fits on the instrument panel and figures latitude, longitude, nautical miles flown and correct compass bearing automatically from dead reckoning data.[4]

C. CELESTIAL NAVIGATION

Celestial Navigation--by observation of heavenly bodies--progressed with astronomy and mathematics, especially as the need appeared in the limitations of the other two methods.

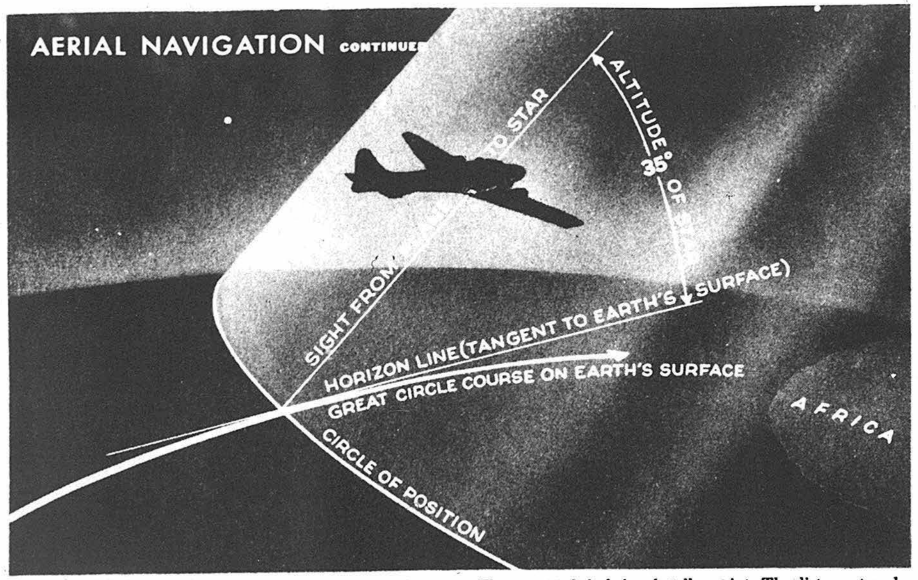
The primitive Polynesians, in their remarkable expansion in the South Sea islands, had no tools at all--only their knowledge of the stars.[5] The Europeans began their use of star sight measurements only after their ships pushed beyong the Mediterranean. In the fifteenth century, the Portugese, under Prince Henry the Navigator, took the lead in compiling tables and inventing nautical instruments. Columbus had only a cross-staff and an astrolabe,[6] in addition to his compass.[7]

Then came Copernicus, Galileo and Newton, opening vast new areas in our knowledge of the universe.[8]

In 1620, trigonometry was applied to navigation, followed closely by logarithmic tables. Columbus's cross-staff and astrolabe developed into the forestaff, backstaff, double quadrant, and, finally, in 1731, the sextant.[9]

Then, in quick succession, came three developments which led to the foundation of modern celestial navigation: In 1837 Captain Thomas H. Sumner of the United States Navy made his unique voyage on which he discovered the "Sumner line of position".[10] In 1865, Harrison, the Englishman, brought forth the chronometer.[11] In 1875, Saint-Hilaire, the Frenchman, published his method of calculated altitude.[12] Figure 1 illustrates basic ideas involved.

Because this fundamental principle of Sumner and Saint-Hilaire is unchanged, the labor and ingenuity for each improvement since has been focused on devising shortcuts, on simplifying tabulations, and on pre-computing the elements of the astronomical triangle. Within the last twenty years, five successive methods of celestial navigation



SEXTANT SIGHT measures angle of star above horizon, places navigator on circle of position, on which height is constant. The center of circle is substellar point. The distance to substellar point can be read from sextant: 1° = 60 nautical miles.

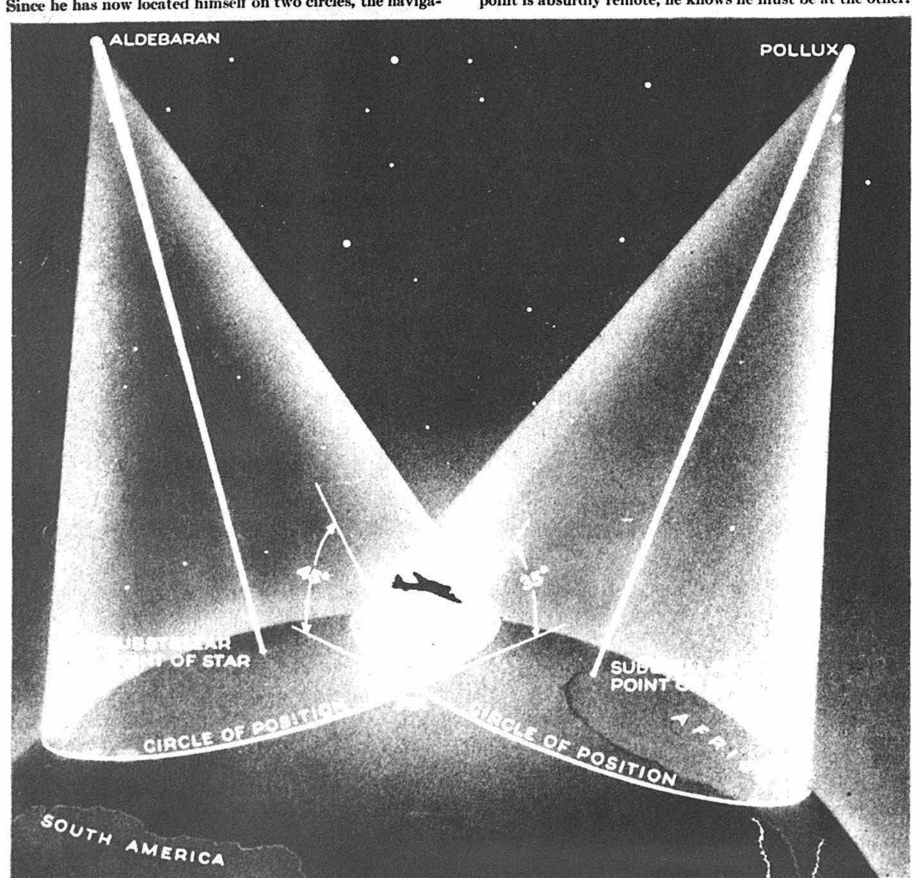
BY THE STARS

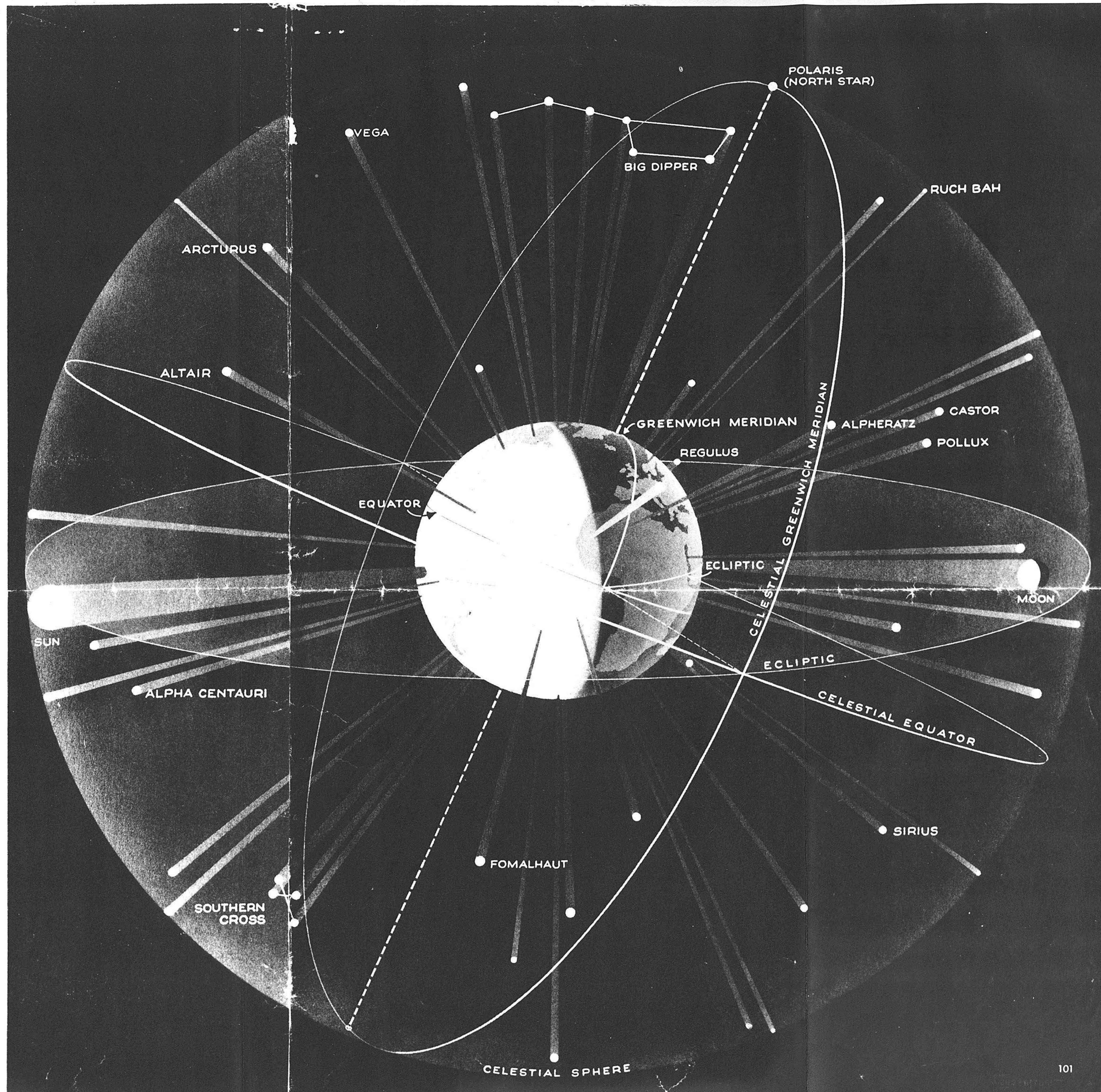
Because he knows his way among the stars, the aerial navigator can find his way to any point on earth. In the night sky, out beyond the sight of pilotage points and the hearing of radio beacons, beyond his faith in his instrument-reading and log-keeping, the navigator can take up his sextant and fix his position within a radius of 15 miles.

This feat can be performed by anyone who has had a high-school education. The navigator travels in the symmetrical universe of Ptolemy, in which the earth is the exact center (*see opposite*). The sky is a star-studded sphere. Except for the sun and its satellites, which move along the line of the ecliptic, all the stars are fixed in their positions relative to the celestial coordinates, just as points on earth are fixed on the terrestrial coordinates of latitude and longitude. As the earth rotates, the celestial sphere, its axis through the north star, appears to revolve from east to west around the earth—with the earth apparently remaining fixed.

Once this ancient concept of the universe is comprehended, the trick of celestial navigation resolves itself from complication to simplicity. Beneath every star at any given moment is a point on earth, the substellar point, at which the star is directly overhead. These points move as the stars move, parallel to the lines of latitude around the earth. The positions of the sun, moon and planets, and of 50 navigation stars and hence of their substellar points are listed in the almanacs relative to Greenwich, England, for every instant of the day. By measuring the height above his horizon of two or more stars, the navigator locates their substellar points relative to his dead-reckoning position. He locates these points in turn by consulting his almanac and his chronometer, an accurate watch set on Greenwich time. He can now locate himself relative to Greenwich and plot his position on his chart.

POSITION IS FIXED by measuring the altitude of second star. Since he has now located himself on two circles, the navigator must be at one of their points of intersection. Since one point is absurdly remote, he knows he must be at the other.

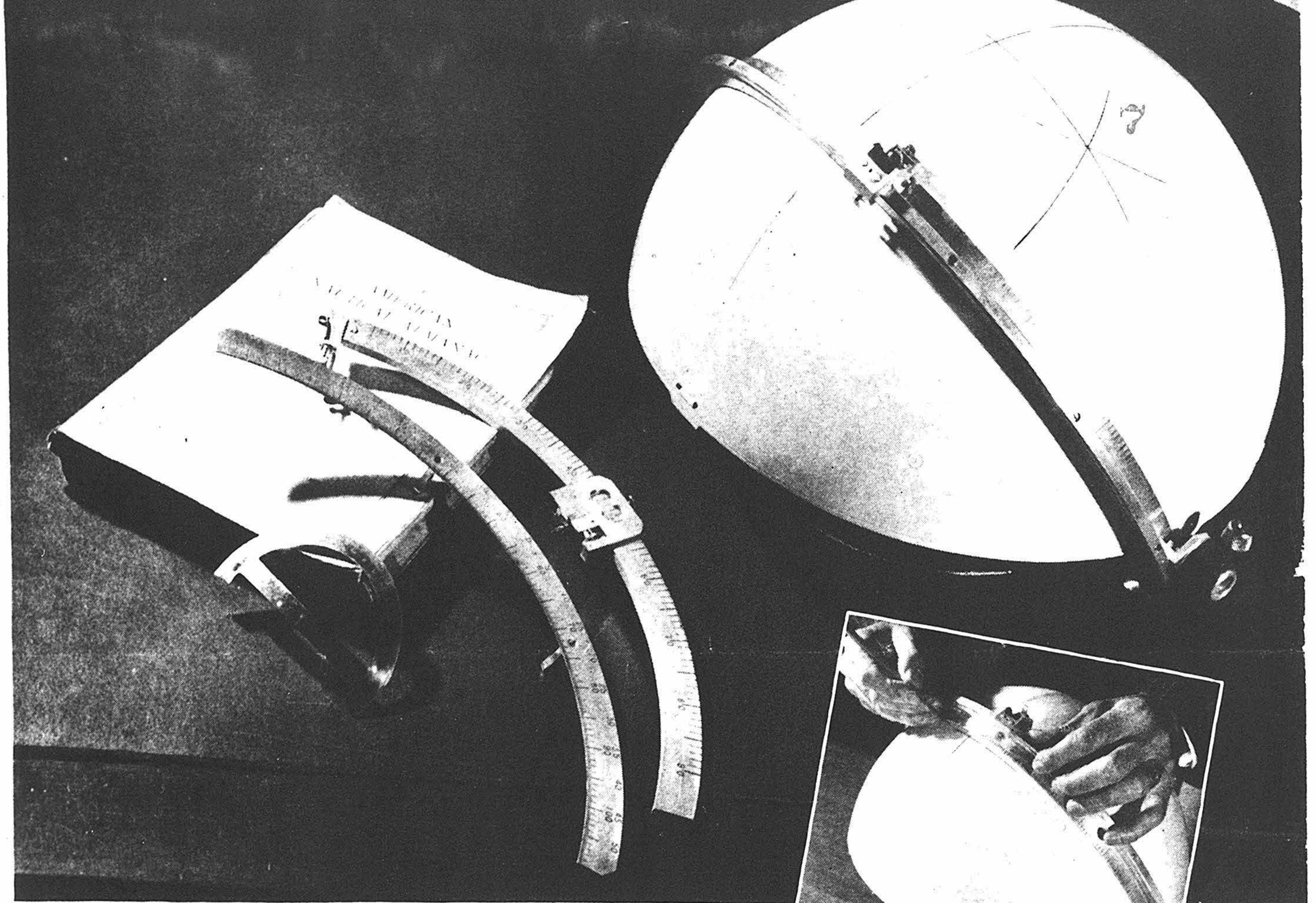




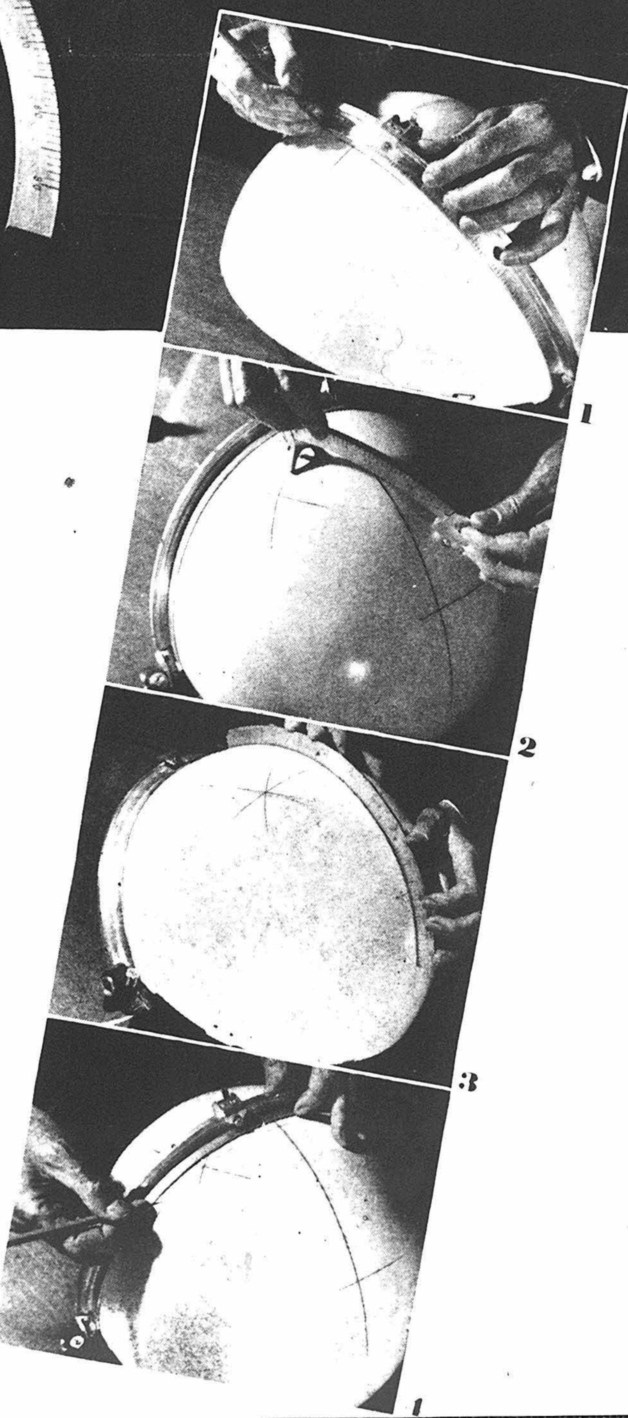
have been taught our officer candidates at the Naval Institute in Annapolis. Of these, Ageton's method, and the new Altitude-Azimuth Tables[13] seem outstanding today. These Hydrographic Office publications have reduced the intricacies of spherical trigonometry to simple interpolation in the tables.

Attacking the problem of celestial navigation from a different point of view, Captain P. V. H. Weems prepared charts[14] covering the earth showing lines of constant altitude for several selected stars in each region. Given the actual observed altitudes of these stars, the lines of position may be plotted directly by graphical interpolation on these charts. The newest tabular methods accomplish much this same end. The Astro-Graph which has been used for navigating our Flying Fortresses projects these star altitude curves from photographic film directly onto the navigator's table, to the scale of his chart. This device also provides mechanical adjustment between the star altitude curves and the longitude coordinates of the chart, corresponding to the sidereal motion of the stars and of their respective curves of equal altitude relative to the earth.

Recently, Drury A. McMillen, the Brazilian engineer, raised a minor tempest when he introduced his Sphero-graphical Navigation in sensational and provocative statements to the press.[15] He returned to the fundamental sphere, and by the use of precise instruments shown in Figure 2 was able to obtain results by simple and clear graphical construction approaching in accuracy the requirements of



SPHEROGRAPHICAL navigation needs these tools which were offered the Government at $5,000.00 a set. Across the globe moves a meridian hoop, used to draw lines of latitude and longitude. A spherical protractor, great-circle ruler and a spherical compass rest on the indispensable 50¢ *American Nautical Almanac*. Any slight warping or damage to these instruments would put the navigator many miles off his course



1
2
3
4

Plotting by the Spherographical System

1. The navigator uses a meridian hoop to draw the Greenwich meridian line on any convenient section of the globe. This line and the equator, permanently marked, become the base lines since latitude is measured north and south of the equator and longitude east and west of the Greenwich meridian. A slip of one-eighth inch in drawing these lines would mean the difference of over sixty miles.

2. After consulting the *Almanac*, to find the substellar point of a star at the instant when he observed it, the navigator marks its position on the globe. Two or three stars can be observed and their positions plotted on the globe. Intersection of three circles is the fix. in daytime, there is only the sun. Between sights of the sun, dead reckoning would have to be figured, which would be difficult on the globe because straight compass courses would have to be plotted as a curve with a change of direction at every meridian making the advantages of the system doubtful in the daytime.

3. After the navigator has a fix—the intersection of the distances from the substellar points of two or more stars—he must measure latitude and longitude in order to transfer the airplane's position to a regular geographical flying map. This operation offers opportunity for error. If the globe were held on the knees of a tired, shaken avigator, a slight slip of a pencil might mean missing an island in the broad ocean.

4. Finally, the navigator must find his longitude by measuring with a great-circle ruler along the equator from the Greenwich meridian to the meridian of the fix. In this, he must compute his time just as in all navigation. The McMillen System does not cut down the necessary operations such as shooting the sun, consulting the *Almanac*, consulting the chronometer and the major preliminaries to determining a position. Notice the

the navigator. The advantages in the pictorial representation of the relations in the problems of spherical trigonometry have long been recognized, both for the clear appreciation of the factors, and for teaching. However, precise graphics on a sphere require a skilled and steady hand, and ideal circumstances, conditions which do not always obtain in military aircraft. Difficulties in accuracy and manipulation prevented the enthusiastic adoption of this graphical method.

Mechanical instruments have been designed and some put on the market to simplify celestial navigation.[16] Nathaniel Bowditch puts the situation nicely: "Such instruments are costly and subject to instrumental errors, but they are very useful for checking computations and may some day be devised in a form useful to the navigator".[17]

It was the Bowditch prediction which the author had in mind when he designed and built the Navigator-Sphere, described in Chapter III, which led to the conception of the direct-reading device described in Chapter IV.

III. THE NAVIGATOR-SPHERE

A. PURPOSE

The Navigator-Sphere is a calculating machine for the problems of celestial navigation. It is designed specifically to give the latitude and longitude directly from simultaneous star altitude sights. Given two star sights, and Greenwich sidereal time, these three values are set on scales of the instrument, the selected stars plugged in, and latitude and longitude read off their scales. That is all.

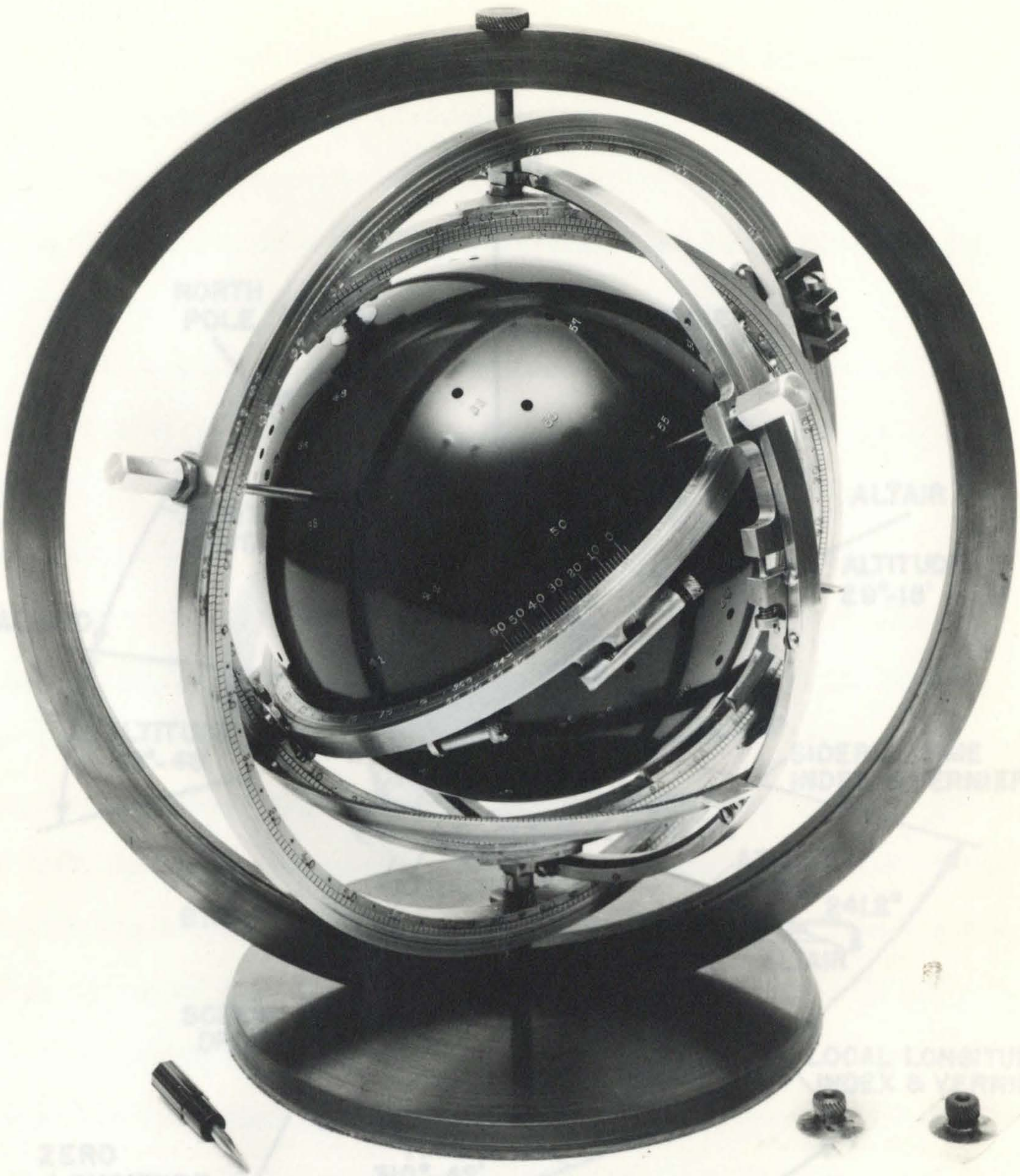
The position is determined in the time it takes to tell it.

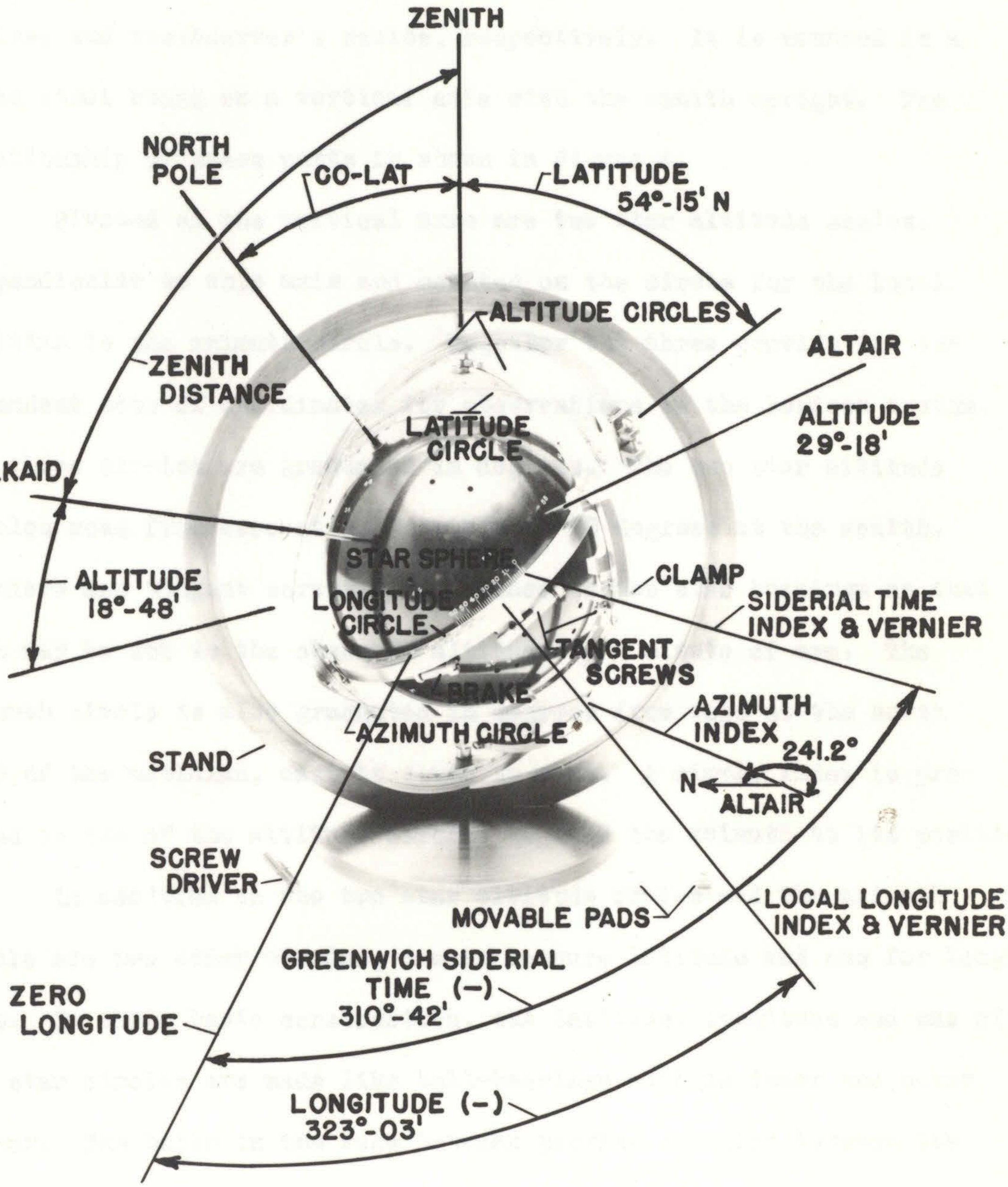
Using the development model, hand-made by the author, results for any given data are repeated consistently with a standard deviation of two minutes. The position so determined is absolutely independent of any dead reckoning or plotting on the chart. Thus it gives the ideal check on the dead reckoning.

The instrument may also be used with similar speed and accuracy to determine the conventional lines of position, to calculate great circle sailing data, and to establish fix from long distance radio compass bearings.

B. DESCRIPTION

The Navigator-Sphere, shown in Figure 3, looks like an intricate maze of bright steel rings surrounding a black sphere. Essentially it is a scale model incorporating the relations and relative motions involved in the simplified astronomy of celestial navigation. The




ZENITH
NORTH POLE
CO-LAT
LATITUDE 54°-15' N
ALTITUDE CIRCLES
ALTAIR
ZENITH DISTANCE
LATITUDE CIRCLE
ALTITUDE 29°-18'
ALKAID
STAR SPHERE
CLAMP
ALTITUDE 18°-48'
LONGITUDE CIRCLE
SIDERIAL TIME INDEX & VERNIER
TANGENT SCREWS
BRAKE
AZIMUTH INDEX
AZIMUTH CIRCLE
241.2°
STAND
N
ALTAIR
SCREW DRIVER
MOVABLE PADS
LOCAL LONGITUDE INDEX & VERNIER
GREENWICH SIDERIAL TIME (–) 310°-42'
ZERO LONGITUDE
LONGITUDE (–) 323°-03'

instrument provides the three customary systems of spherical coordinates--siderial, geographic, and horizon--in the star sphere, the geographic scales, and the observer's scales, respectively. It is mounted in a blued steel stand on a vertical axis with the zenith upright. The relationship of these parts in shown in Figure 4.

Pivoted on the vertical axis are two star altitude scales. Perpendicular to this axis and mounted on the circle for the local meridian is the azimuth circle. Together the three provide two independent sets of coordinates for observations in the horizon system. All three circles are graduated in degrees. The two star altitude circles read from zero at the horizon to 90 degrees at the zenith. Verniers and tangent screws are attached to the star bushings so that each may be set to the observed altitude to a minute of arc. The azimuth circle is also graduated in degrees from zero at the north limb of the meridian, east to south to west. A simple index is provided on one of the altitude circles to read the azimuth to its position.

In addition to the two star altitude scales and the azimuth circle are two other circles, one to measure latitude and one for longitude. In their basic construction, the latitude, longitude and one of the star circles are made like ball-bearings with an inner and outer member. The balls in the race between provide rotation between the two members in the plane of the ring.

The other member of the latitude circle is pivoted on the vertical axis of the sphere. The inner member of the circle carries the pivot bearings for the polar axis. Thus the latitude circle, containing both the zenith and the polar axes, determines the plane of local meridian. It provides for the angular motion between the zenith and the pole which gives the latitude for the zenith. The inner circle is graduated from zero at the equator to 90 degrees at both poles, while the outer carries a vernier at the zenith with which the angle of the latitude there may be read to a minute of arc.

Fastened to the inner latitude circle perpendicular to the polar axis and circling the sphere near the equator is the circle which determines the longitude of the plane of the local meridian. The outer member of the circle is fixed perpendicular to the inner member of the latitude circle. It carries the vernier by which the local longitude, that of the zenith, is determined. The inner member of the longitude circle is graduated clear around in degrees from zero to 360 from east to west, and thus gives readings of west longitude from Greenwich.

Inside all these rings is the star sphere, made from a black, five- inch, bowling ball. It is freely pivoted at the poles and fits snugly within the longitude circle. Its position relative to the longitude is determined by the sidereal time for the observation. A brake and tangent screw between the sphere and the circle permit the accurate setting of the sidereal time vernier against the longitude scale, thus placing the Greenwich meridian in its proper position relative to the stars for the given instant. The sphere itself is a bakelite ball in which have been drilled small radial holes with the center of each at the exact right ascension of declination for the sixty-one principal navigation stars. A number stamped in the sphere surface near the hole, and a printed table, shown in Figure 5, provide a positive index for unfamiliar stars. Two inlaid steel bushings provide a ball-bearing set for the polar pivots.

Because, for purposes of navigation, the appreciable changes of stars' positions in right ascension and declination are due to precession only, these changes are made on the star sphere by moving the polar axis the approximate 50 seconds of arc per year toward the vernal equinox, and by setting the sidereal time vernier ahead. On the development instrument this adjustment is accomplished by applying progressively more eccentric polar bushings as the years pass. Thus the pole is moved and the stars are fixed.

To correlate the observed altitudes with the definite position for the stars on the star sphere, cylindrical star pins are passed radially through bushings in the star altitude circles into the holes in the star sphere. For a particular altitude for a certain star, the setting is made on the star altitude circle and the star pin plugged into its proper hole. The arc of the altitude circle will then maintain the appropriate zenith distance between the star and the zenith. The several degrees of freedom for the star sphere are reduced to one, and the sphere may only move so the zenith traces a circle of position over the sphere. Coordinates for points on this circle may be read off as desired on the latitude and longitude scales, and the corresponding azimuth to the star on its scale.

With any other star, one can do the same thing with the second

Figure 5

NAVIGATOR - SPHERE

Development Model - ' - W.F. Hiltner

STAR INDEX

#	Star	Name	Mag.	R.A. °	R.A. '	Decl. °	Decl. '	Star	#
1	α Androm.	Alpheratz	2.2	1	23	+28	47	Acamar	9
2	β Cassiop.	Caph	2.4	1	34	+58	51	Achernar	7
3	α Cassiop.	Schedir	2.4	9	21	+56	14	Acrux	32
4	β Ceti	Deneb Kaitos	2.2	10	13	-18	17	Adhara	19
5	γ Cassiop.		2.0	13	21	+60	25	Aldebaran	11
6	δ Cassiop.	Ruchbah	2.8	20	33	+59	57	Alioth	35
7	α Eridani	Achernar	0.6	23	55	-57	31	Alkaid	38
8	α Arietis	Hamal	2.2	31	01	+23	12	Al Na'ir	59
9	θ Eridani	Acamar	3.4	44	03	-40	31	Alphard	26
10	α Persei	Marfak	1.9	50	06	+49	40	Alphecca	44
11	α Tauri	Aldebaran	1.1	68	11	+16	24	Alpheratz	1
12	β Orionis	Rigel	0.3	77	59	- 8	16	Al Suhail	24
13	α Aurigae	Capella	0.2	78	09	+45	57	Altair	55
14	γ Orionis	Bellatrix	1.7	80	33	+ 6	18	Antares	46
15	β Tauri	El Nath	1.8	80	42	+28	34	Arcturus	41
16	α Orionis	Betelguex	0.5	88	03	+ 7	24	ε Argus	23
17	α Argus	Canopus	-0.9	95	41	-52	40	Bellatrix	14
18	α Can.Maj.	Sirius	-1.6	100	41	-16	38	Betelguex	16
19	ε Can.Maj.	Adhara	1.6	104	07	-28	54	Canopus	17
20	α Geminorum	Castor	1.6	112	47	+32	01	Capella	13
21	α Can.Min.	Procyon	0.5	114	06	+ 5	22	Caph	2
22	β Geminorum	Pollux	1.2	115	29	+28	10	γ Cassiopia	5
23	ε Argus		1.7	125	21	-59	20	Castor	20
24	λ Argus	Al Suhail	2.2	136	30	-43	13	β Centauri	39
25	β Argus	Miaplacidus	1.8	138	09	-69	29	θ Centauri	40
26	α Hydrae	Alphard	2.2	141	13	- 8	25	β Crucis	34
27	α Leonis	Regulus	1.3	151	22	+12	15	γ Crucis	33
28	β Ursa Maj.	Merak	2.4	164	38	+56	41	Deneb	57
29	α Ursa Maj.	Dubhe	2.0	165	05	+62	03	Deneb Kaitos	4
30	β Leonis	Denebola	2.2	176	34	+14	53	Denebola	30
31	γ Ursa Maj.	Phecda	2.5	177	44	+54	00	Dschubba	45
32	α Crucis	Acrux	1.1	185	53	-62	48	Dubhe	29
33	γ Crucis		1.6	187	02	-56	48	El Nath	15
34	β Crucis		1.5	191	08	-59	23	Enif	58
35	ε Ursa Maj.	Alioth	1.7	192	54	+56	15	Etamin	51
36	ζ Ursa Maj.	Mizar	2.4	200	26	+55	13	Fomalhaut	60
37	α Virginis	Spica	1.2	200	34	-10	53	Hamal	8
38	η Ursa Maj.	Alkaid	1.9	206	21	+49	35	Kaus Austr.	52
39	β Centauri		0.9	209	59	-60	07	Kochab	43
40	θ Centauri		2.3	210	52	-36	06	Marfak	10
41	α Bootis	Arcturus	0.2	213	17	+19	28	Markab	61
42	α Centauri	Rigil Kent.	0.1	218	58	-60	37	Merak	28
43	β Ursa Min.	Kochab	2.2	222	43	+74	23	Miaplacidus	25
44	α Cor.Bor.	Alphecca	2.3	233	06	+26	54	Mizar	36
45	δ Scorpii	Dschubba	2.5	239	16	-22	28	Nunki	54
46	α Scorpii	Antares	1.2	246	31	-26	19	Peacock	56
47	α Tri. Aust.		1.9	250	42	-68	56	Phecda	31
48	η Ophiuchi	Sabik	2.6	256	48	-15	40	Pollux	22
49	λ Scorpii	Shaula	1.7	262	28	-37	04	Procyon	21
50	α Ophiuchi	Rasalague	2.1	263	06	+12	36	Rasalague	50
51	γ Draconis	Etamin	2.4	268	50	+51	30	Regulus	27
52	ε Sagit.	Kaus Austr.	2.0	275	08	-34	25	Rigel	12
53	α Lyrae	Vega	0.1	278	46	+38	44	Rigil Kent.	42
54	σ Sagit.	Nunki	2.1	282	58	-26	22	Ruchbah	6
55	α Aquilae	Altair	0.9	297	02	+ 8	43	Sabik	48
56	α Pavonis	Peacock	2.1	305	20	-56	55	Schedir	3
57	α Cygni	Deneb	1.3	309	53	+45	05	Shaula	49
58	ε Pegasi	Enif	2.5	325	22	+ 9	37	Sirius	18
59	α Gruis	Al Nair	2.2	331	12	-47	14	Spica	37
60	α Pis.Aust.	Fomalhaut	1.3	343	39	-29	55	α Tri. Aust.	47
61	α Pegasi	Markab	2.6	345	30	+14	55	Vega	53

star-altitude circle. Setting both circles locks the sphere, so that the zenith is located correctly relative to the stars. The latitude of the observer is then already indicated on the latitude scale. To find the longitude, it is further necessary to set the inner member of the longitude circle at the correct sidereal time. Then the longitude index shows the observer's longitude.

The local latitude and longitude provide a fix. This fix is at the intersection of the two circles of position described by the zenith for each of the two stars separately. On the Navigator-Sphere, this intersection is automatically established in the hinge at the zenith axis.

C. OPERATION

The Navigator-Sphere was designed primarily to solve the problem of simultaneous star altitude sights; it is also adapted to solution of other problems involving positions on a sphere, or measurements on a spherical surface. Those with which the author is acquainted are described herewith. With reflection, and some ingenuity, the reader may very well solve other such problems as he meets them.

1. Position from Simultaneous Star Altitude Sights

<u>Given:</u> Corrected altitude observed for two stars, and Greenwich sidereal time.

<u>Find:</u> Latitude and longitude of position.

Set Greenwich sidereal time in degrees and minutes of arc on the inner scale of the longitude circle, using the vernier on the sphere.

Clamp and adjust precisely with the brake and tangent screw.

Set the given star altitudes on each circle with its vernier, using the clamp and tangent screw.

Insert star pins through bushings in the star altitude circles into the holes for the given stars.

The zenith axis is now mechanically locked in the required position at the co-altitude or zenith distance from the substellar point for both stars.

Latitude, and longitude west of Greenwich, for the fix are read directly from their scales.

This position corresponds to the point of interesection of the circles of position around the two stars. Theoretically there are two such points of intersection, but this second point offers no confusion in practice. Usually the spurious point is thousands of miles away from the known vicinity of the observer. However, if the approximate azimuth of each star is noted, say within 30 degrees, or the sphere oriented so that the stars are more or less in their obvious relation to the zenith, the correct fix is established without question.

The best intersection of the circles or lines of position is obtained when the azimuths of the two bodies differ by 90 degrees. For a difference of 0, or 180 degrees the circles are tangent and thus do not intersect at a definite point. These relations are easily demonstrated on the instrument. They should be considered in choosing the stars for observation.

Checks of the fix are readily obtained with additional sights.

Sights of three stars will give three independent fixes, four sights, six fixes, and so on. The instrument gives each fix for every pair of stars, by readings of latitude and longitude without the intermediate plotting of lines of position. However, these lines of position may be drawn, by connecting the several plotted fixes, or as in the following problem.

2. Line of Position Data for a Single Star

Given: Observed altitude of star, dead reckoning latitude and longitude, and time.

Find: Line of position.

Set sidereal time, star pin and star altitude. Turn sphere to nearest degree in latitude and read corresponding longitude (and azimuth). Plot this point on chart. Turn sphere to nearest degree of longitude and read corresponding latitude. Plot this point on chart. These two points determine the line of position. For check, this line should be perpendicular to azimuth noted above. Also, any number of other points on the line of position may be had by selecting appropriate values of latitude or longitude.

Alternate method:

Given: D. R. Latitude and longitude and time.

Find: Altitude and azimuth of any visible star.

Set sidereal time on inner scale of longitude circle with brake and vernier on sphere. Turn sphere to given longitude, tilt polar axis to latitude. Loosen star altitude circle, and set bushing over chosen star. Insert star pin through bushing into hole for star position, clamp star altitude circle and adjust star altitude tangent screw and azimuth to exact given latitude and longitude. Read altitude and azimuth for star, for this given position. Draw line of position in the usual way: Azimuth line through D. R. position, line of position perpendicular to azimuth line at a distance toward star equal to difference between observed and calculated altitude of star.

3. Running Fix

The running fix is available by the usual methods of plotting on the chart, by advancing a previous line of position for run. Generally the run between sights is not sufficient to introduce serious error from the curvature of the surface.

Though the instrument was designed primarily for fixes from simultaneous star altitudes, it may also be used to reduce observation on the sun and planets, and for problems of great circle sailing. Auxiliary fittings are provided for the solution of these problems.

4. Observations on the Sun

Line of position from the sun may be determined just as for any star except that the position of the sun, in right ascension and declination must be established on the star sphere, for the instant of observation. A movable locating pad is provided which is set in position under the zenith axis, measuring declination and right ascension on the latitude and longitude circles respectively. In this development model, the position of the longitude circle may require the use of a bridge attachment for the eight degree band near the equator.

Line of position from sun sight may be found more directly using solar time. The position pad for the sun is set at the declination for the instant, along the index meridian on the sphere. (This corresponds to the equinoctial colure for stars and sidereal time.) Greenwich Apparent Time in degrees and minutes of arc, instead of Greenwich Sidereal Time, for the instant of observation is set on the inner longitude scale with the vernier on the sphere. This places the sun at the correct hour angle for every longitude. The line of position is then determined just as described above for the stars. Considering the importance of sun sights in actual navigation, an additional scale, inlaid in the sphere on the index meridian, may well be provided on which to set off the variable declination of the sun.

5. Observations on Planets

Line of position may be found from sights on planets or moon using adaptions of the methods described for the sun.

If position by simultaneous altitudes is desired, the first method employing sidereal time and position would be chosen. After locating the movable pad for the planet, it serves just as a star.

6. Great Circle Sailing

Given: Origin and destination.

Find: Course and run for each heading, plot of route.

Clamp longitude circle relative to sphere in any arbitrary position. Set pads at origin and destination, using zenith axis to locate geographic latitude and longitude coordinates. Insert star pins, and set each star altitude circle at 0 degrees. The zenith axis is now at the pole for the desired great circle. Set another pad to mark this spot. Shift one of the star pins to the pole for the great circle, keeping its star altitude circle locked at 0 degrees. The other star altitude circle now lies in the plane of the desired great circle. By releasing the clamp, the zenith may be set at any desired point on the great circle route, reading the distance from the fixed point, origin, or destination, from the graduations on the great circle scale, reading the bearing of the course from the azimuth circle, and the latitude and longitude from their usual scales. Any desired number of points may be taken, and a flight table prepared. From these data, using the Navigator-Sphere, the relative motion plot for the flight may be traced through the heavens. Also, stars near the horizon may be chosen to steer by.

D. PECULIAR PROBLEMS

In the construction and the development of the first model of the Navigator-Sphere, several peculiar problems were encountered. Because of the war, no skilled machinists could be found in Seattle, where the author was then living, to help with this project. However, he was allowed to use the equipment and facilities of the College of Engineering of the University of Washington.

Materials were also hard to get with the priority red tape and depended in part upon the size of the projected instrument. Considering the precision desired--to one minute of arc, one mile--and the probable skill and accuracy of the author and the available machines (a thirteen-inch lathe and a new mill), a five-inch bowling ball was selected for the star sphere.

These balls had not been manufactured for months and were completely out of stock. One of the local bowling alley proprietors had several cached. Caught off guard in a sober moment, he parted with one, "for the advancement of science," and at twice the list price. Scraps of mild steel plate were begged from a sheet metal fabricator. It remained only to machine the steel into a precise instrument.

The ball bearing arrangement of the rings was selected for accuracy and ease of manufacture. This design turned out well. Two rings acting together greatly improved their strength and stiffness. Some difficulty was encountered in attaching fittings to these rings without warping them, but these difficulties were mostly due to the restricted materials and restricted facilities at hand. Dovetailed rings were used for one of the star altitude circles but the ball bearing device proved much the better.

One member of each pair of rings was graduated all around the circle in full degrees. The other member carried the corresponding vernier, reading to two minutes of arc. Because the rings were offset from the axis of their pivots, they were right or left handed, depending on which semicircle was used. Thus, though only 180 degrees is needed to cover the whole range of latitude and only 90 degrees for altitude, the graduations are carried on around so the rings may be used on either hand if any ring interferes with another.

All the scales were graduated in the lathe, scribing the lines with the horizontal motion of the lathe tool. The 360 degree circles were marked off using a 360-tooth gear attached to the outboard end of the lathe spindle by inserting a dog into the successive teeth.

The trick used for graduating the verniers with this same equipment may have practical value to the reader in the construction of some similar device. Thirty equal divisions were required in the space for twenty-nine degrees of arc. To accomplish this end, the ring for the vernier scale was set eccentric in the lathe so that these thirty divisions could be marked with the thirty teeth on the gear in the space for twenty-nine degrees on the ring. This geometric relation is shown exaggerated in Figure 6. Thus by simple trigonometry the exact amount of the eccentricity may be calculated and the work set accordingly off-center in the lathe. On the six verniers graduated thus by the author, no error could be detected when the thirty spaces on the vernier were matched with the twenty-nine on the corresponding graduated circle. Strictly speaking, the thirty divisions made thus are not exactly equal. However, a rough calculation showed the maximum cumulative error to be about one hundredth of a minute of arc, hardly significant in this instrument.

E. SUMMARY AND CRITICISM

The Navigator-Sphere incorporates in one simple instrument adaptions of the valuable features of previous celestial navigation computers and has several new features of its own which add to its own which add to its convenience and usefulness.

First, a two-star fix is produced mechanically, with all the essential elements in their true relations.

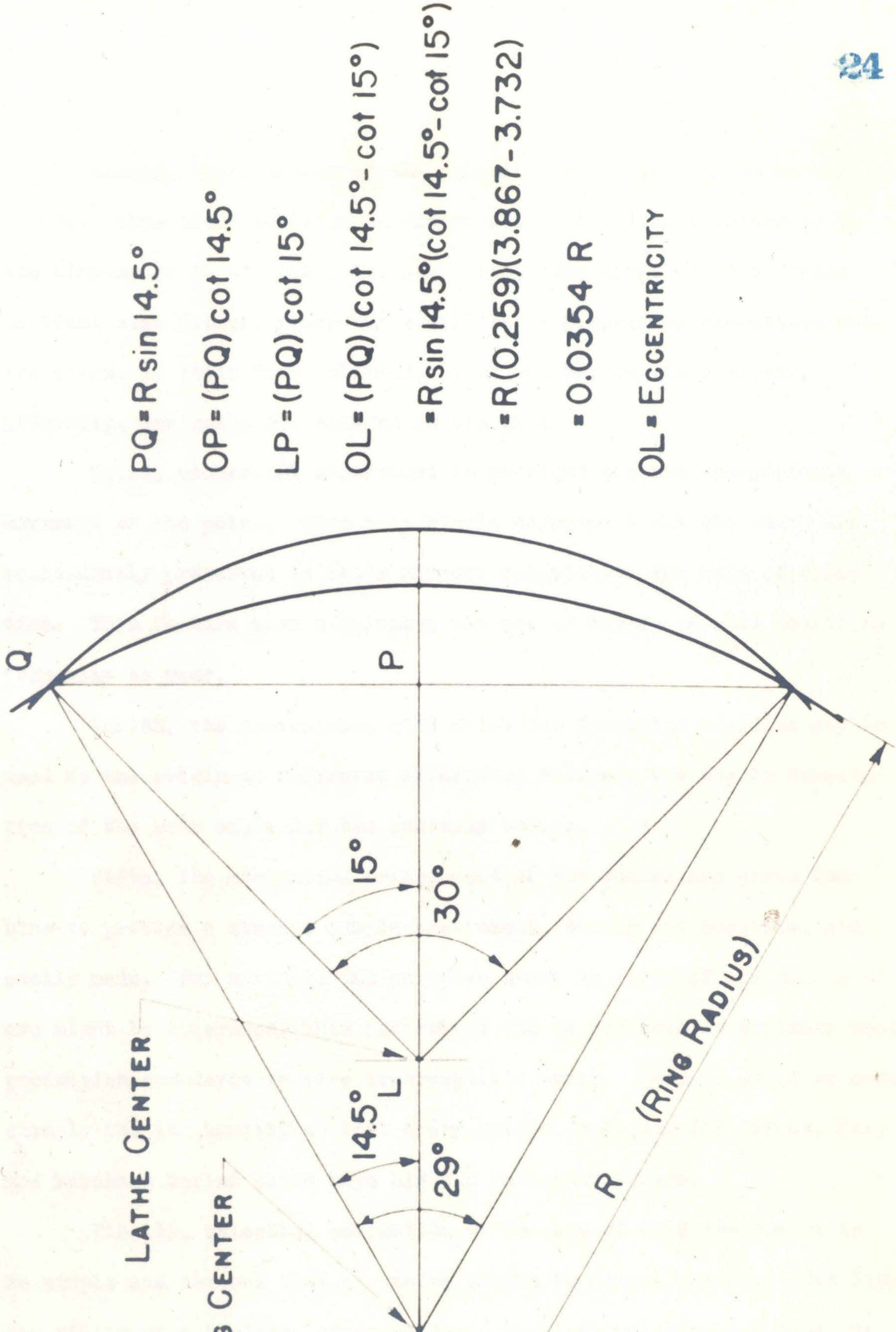

PQ = R sin 14.5°
OP = (PQ) cot 14.5°
LP = (PQ) cot 15°
OL = (PQ)(cot 14.5° - cot 15°)
= R sin 14.5°(cot 14.5° - cot 15°)
= R(0.259)(3.867 - 3.732)
= 0.0354 R
OL = Eccentricity
Q
P
15°
30°
Lathe Center
L
14.5°
29°
Ring Center
O
R
(Ring Radius)

Figure 6

Second, the position of the principal stars is plotted on the sphere. Thus their position is always available without reference to the almanac or to any other tables. Also, this arrangement provides an ideal star finder, since there will be no projection distortion and the stars, in their true relation, stand out before the observer. Literally, one holds the heavens in his hand.

Third, mechanical adjustment is provided for the precessional movement of the poles, With this single adjustment all the stars are continuously preserved in their correct relation to the axis of rotation. This feature also eliminates the use of tables of star positions from year to year.

Fourth, the convenience with which the Greenwich meridian may be used as the origin or reference eliminates entirely the use or computation of the hour angle for the heavenly bodies.

Fifth, the mechanical arrangement of the scales and parts combine to provide a sturdy, simple instrument, strong and accurate, and easily made. For navigational purposes where an error of one minute of arc might be tolerated, this instrument can be produced by ordinary mass production standards to give imperceptible error. This it could be made cheaply and in quantity so that every navigator in our air forces, Navy and Merchant Marine could have his own Navigator-Sphere.

Finally, celestial navigation by the use of this instrument is so simple and obvious that it can be taught to almost anyone. Just like the riding of a bicycle, once the basic physical relations of time and space are impressed on the manipulative and visual senses, they are simply not forgotten. Also, as in the case of the bicycle, it is difficult to learn from the printed pages without the machine, but understanding comes quickly from experience with the device in hand.

In December, 1943, the Navigator-Sphere was examined by Dr. S. M. Burka, Captain J. G. P. Callahan, and Lt. Dion Hoy, under direction of Colonel G. V. Holloman of the Engineering Division of the Army Air Forces Materiel Command at Wright Field. They made the following criticism of the Navigator-Sphere:

1. "The device as constructed uses angular scales and verniers. These are definitely difficult to use in the air".

2. "The device is limited to use at night and then only for selected star sights. The sun, the moon, and the planets cannot be used except with difficulty and special plotting".

3. "The device is inherently fragile if kept to minimum weight. Exposed arcuate members are subject to bending and misalignment in handling".

4. "Accuracy is directly a function of the precision of manufacture and, for usuable size, extreme precision and careful choice of materials is required".

5. "The device solves for simultaneous sights on two stars and no provision is made in the instrument for allowing for time difference or run between sights".

6. "The use of the device does not afford as much time and effort-saving as might appear at first sight since the instrument replaces only one part (H.O. 218) of the equipment and operations

required in celestial navigation. The taking of sextant observations and the plotting of the data require most of the labor and time, and the computation with the proposed device or with H. O. 218 are simple and rapid in any case".

"Give us", said Dr. Burka, "an instrument which will read latitude and longitude directly".

In response to this request, work was begun on the Astro-Navigator, which, it is hoped, will be to celestial navigation what the radio beam is to piloting and the Air Position Indicator is to dead reckoning.

IV. FINAL INSTRUMENT: ASTRO-NAVIGATOR

A. PURPOSE

The Astro-Navigator is an optical instrument which, by observations on the stars, directly and continuously gives the local position in latitude and longitude. No additional instruments, no tables, spherical trigonometry nor graphical methods are needed.

Latitude is measured simply as the altitude of the elevated pole. Longitude is determined by direct comparison in the instrument of local sidereal time and Greenwich sidereal time.

The Astro-Navigator differs from the preliminary instrument in that the position of the stars is taken directly from the heavens instead of mechanically located on the on the sphere. In answer to an oft-expressed need it provides an independent, self contained, portable celestial navigation instrument.

B. BASIC PRINCIPLES

Fundamentally, the problem of navigation from the stars is that of correlating the horizon coordinate system with the celestial coordinate system. Therefore, we need to establish in the instrument the orientation of the celestial coordinate system and the origin for the horizon system, and measure the angles between them.

For spherical coordinates only two reference planes are necessary. In the celestial sphere, these are determined by the polar axis and the direction of the vernal equinox; in the ecliptic system by the pole of the ecliptic and the vernal equinox. In the terrestrial system, these are the plane of the equator and of the Greenwich meridian. On the other hand each star optically marks a particular axis which is related to the coordinate axes by angular differences; for example, in the celestial sphere the right ascension and declination of the stars.

Given the stars in the sky, using their known positions, the instrument determines the orientation of the celestial coordinate system. With a clock drive in the instrument, these are related to the terrestrial system. By means of the micrometer drives, the coordinates of the zenith are measured in this terrestrial system.

Consider the conventional equatorially mounted telescope where by rotation around the polar axis following a star at a given declination, one can keep track of the passage of time with the rotation of the earth. Suppose the equatorial mounting, with the declination clamped, were reversed and the axis of rotation provided about the line to the stars. At some point in the rotation of the system about the star axis, the polar axis would be parallel to the earth axis. One star restricts the rotation to a single axis but does not uniquely determine the orientation of the polar axis. Of course the same is true for any individual star. However, two stars taken together would limit the direction of the polar axis to only two possible positions, one of which is correct and the other completely wild. These separate solutions correspond to the two points of intersections of circles of positions in the conventional navigation technique. The use of three stars will, however, uniquely determine the direction of the polar axis without any possibility for error.

In order to measure the position of a number of stars at once, it is most convenient to see the images in coincidence. Therefore a multiple reflector is incorporated as the first step in the optical train. We use nineteen reflectors carefully adjusted at the start so that the light from each selected star will be reflected into a parallel bundle along any desired axis in the celestial coordinate system. The multiple reflector device is key to the operation of the instrument and provides a number of basic simplifications to the technique of celestial navigation.

The right ascension and declination for each star is incorporated in the orientation of the mirrors and is independent of any tabular values. Besides, all the bright stars wherever they appear in the heavens will contribute their share to the determination of the position with a single sight, instead of the repeated observations now required. The orientation so determined is completely unique.

The immediate objections that would be raised at this place are that the stars change their position in right ascension and declination, and that refraction errors will not be accounted for by any fixed arrangement of the mirrors.

To take care of the precessional change of position of the stars, we use the axis of the ecliptic as the main reference axis for these mirrors. Relative to the ecliptic coordinates, adjustment for precession is readily provided by a simple rotation about the ecliptic axis of approximately 50 seconds of arc per year. This is possible because the stars do not change their relative positions except for proper motion. The largest proper motion for stars used will be for Arcturus, in the neighborhood of two seconds per year. Considering the desired precision of the instrument this is negligible.

The effect of refraction, however, is more serious. Its elimination depends upon the desired degree of precision of the instrument. If one minute of arc is satisfactory in the result, the stars can be used as low as 30^{0} above the horizon and a mask can be used to prevent light from any of the stars lower than 30^{0} elevation from entering instrument. In any event, the stars near the zenith will produce an exact coincidence and the stars near the horizon will be deflected from this exact coincidence depending upon their altitude and their corresponding refraction. Other items in high precision position determination which are neglected in this instrument include the effect of nutation, parallax, and aberration.

Experienced navigators will immediately notice that all reference so far has been to fixed stars. This excludes two classes of observations, on the sun and on the planets. In the case of the planets, it is more convenient in a simple instrument to neglect them than to try to take account of the variations of their position in the mechanism of the device. This restriction is not as serious as might be presumed from the prominence of the planets, because the observed coincidence of a number of stars will be as bright as any of the planets. A useful by-product from the use of the ecliptic axis is the simplicity with which the motion of the sun may be traced. The reflector for the sun is set at 45 degrees to the ecliptic axis and is rotated about the axis relative to all the other stars at a rate of about one degree per day. The orientation of the sun mirror for any particular time of the year may be obtained from the almanac.

In review, the simplifications in the Astro-Navigator involves the assumption of negligible proper motion and negligible refraction, but provision is made for precession and for the sun's motion.

C. DESCRIPTION

The instrument has three essential parts: The multiple reflector, the micrometer drives, and the artificial horizon. The relative arrangements of these parts in the development model of the Astro-Navigator is shown in the assembly drawing, Figure 7.

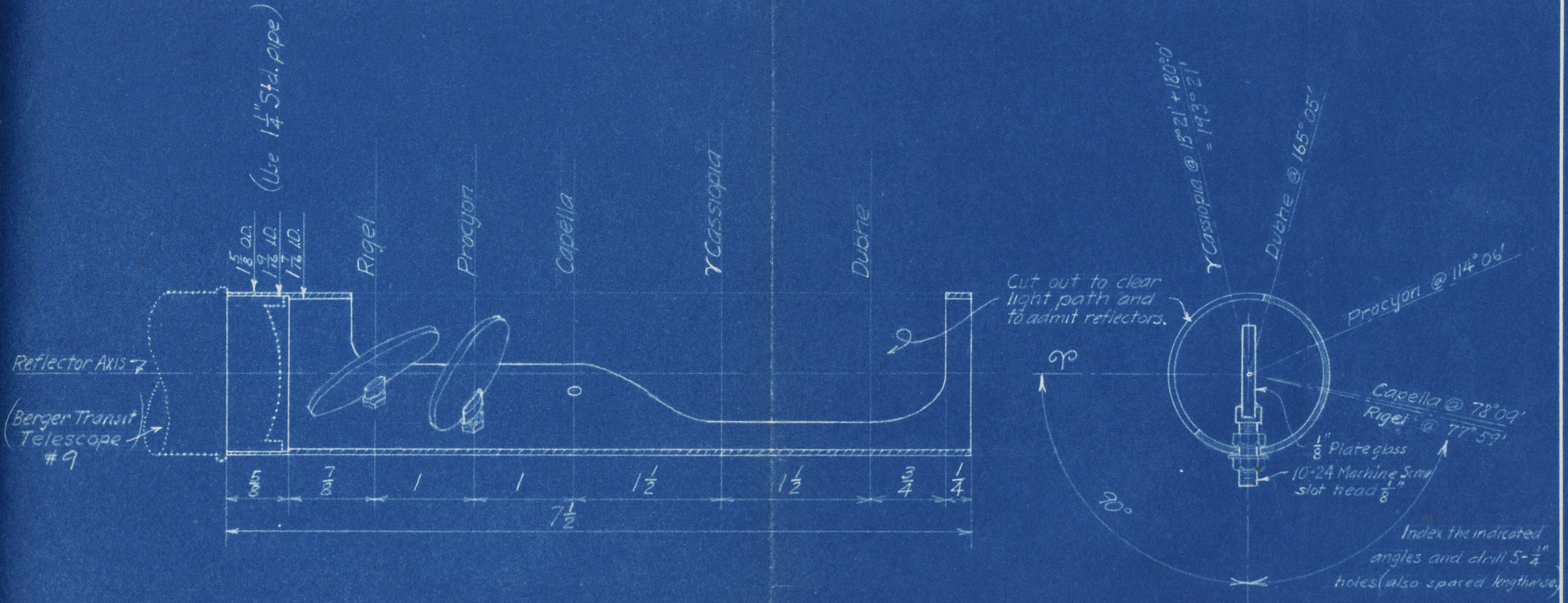
1. Multiple Reflector

There are several possibilities for the design of the multiple reflector:

a. A single prism might be cut so the light would be refracted at the entry window for a given star, and internally reflected from the entry windows for each succeeding star, coincident with the refracted beam there. Then the images for all the stars would appear superimposed. The use of such a prism, besides its mechanical simplicity, might have had an added advantage derived from the dispersion caused by the glass, producing, in effect, chromatic astigmatizers to aid in the setting of coincidence. However, the difficulty of cutting the prism and probable excessive loss of light makes it necessary to rule it out.

b. A series of plane-parallel glass plates may be arranged along the polar axis, each to reflect the light for its particular star and transmit the light already directed along the axis. A multiple reflector unit for four stars was built using this method. The use of the plane parallel plates was thought to be simpler for preliminary construction. The arrangement of this reflecting system is shown in Figure 8. It was installed upon the objective end of a 30-power Berger surveyor's transit in place of the sun shade. When the transit was pointed toward the north pole, rotation of the reflector around this polar axis took care of the time. This preliminary instrument demonstrated conclusively in practice that a unique orientation was determined by such a reflector and that the coincidences of the star images so formed was a very sensitive indicator of the direction of the desired axes. The angles of the glass plates for this preliminary reflector were set by hand, using the stars themselves as the basis of measurment. This preliminary device was not satisfactory because the plane parallel plates scattered much too much light in passing through only four plates. The light from Dubhe was so greatly diminished as to be barely visible in the telescope with 1-3/8 inch objective. For the proposed instrument with nineteen reflectors, the use of plane parallel plates in series was shown to be completely out of the question.

c. The arrangement ultimately chosen uses nineteen total reflecting mirrors laterally distributed across the field of view. The details of their construction is shown in Figure 9. They produce a number of



PART NO.	NAME	NO. RQD.	MATERIAL DESC.	MATERIAL SPEC.	WEIGHT

ALL DIMENSIONS IN INCHES
LIMIT ON DIMENSIONS UNLESS OTHERWISE NOTED: ANGULAR ± ½° ; FRACTIONAL ± 1/32 ; DECIMAL ± .010

NUMBERS ARE SURFACE ROUGHNESS IN MICROINCHES
R ROUGH MACHINE FINISH — 16 FINISH GRIND
250 SMOOTH MACHINE FINISH — 2 FINE GRIND, LAP
40 ROUGH GRIND — ½ POLISH

FINISH: 250

HEAT TREAT: None

CALIFORNIA INSTITUTE OF TECHNOLOGY

TRIAL MULTIPLE-REFLECTOR ASTRO-NAVIGATOR

DRAWN BY W. H. Hiltner
TRACED BY
CHECKED BY
APPROVED BY
DATE Feb. 20 '45 SCALE Full
COURSE NO.
SECTION NO.
DWG. NO. 8

DIEPO 1000H CLEARPRINT

FORM 302

parallel rays which must be concentrated by the conventional optical system of a telescope so as to enter the pupil of the eye. Figure 10 shows details of the short 8-power telescope.

The light from eighteen stars or the sun is reflected from the small multiple reflectors, to a 23-1/2 degree mirror, to the 45 degree mirror, through the artificial horizon and the telescope to the eye. When the polar axis is correctly oriented, all the stars will appear fused into a single point at the east horizon, and the index for the vernal equinox will be in its correct position to give local siderial time.

In addition to the small mirrors of the multiple reflector, a large mirror is mounted at the intersection of the ecliptic axis and the polar axis so that the light reflected along the ecliptic axis is again reflected, changed in direction by 23-1/2° so that the light proceeding along the polar axis is directed toward the south pole. This whole assembly, the multiple reflector and the ecliptic reflector, is mounted together as a unit and is arranged to rotate about the polar axis.

2. Micrometer Drives

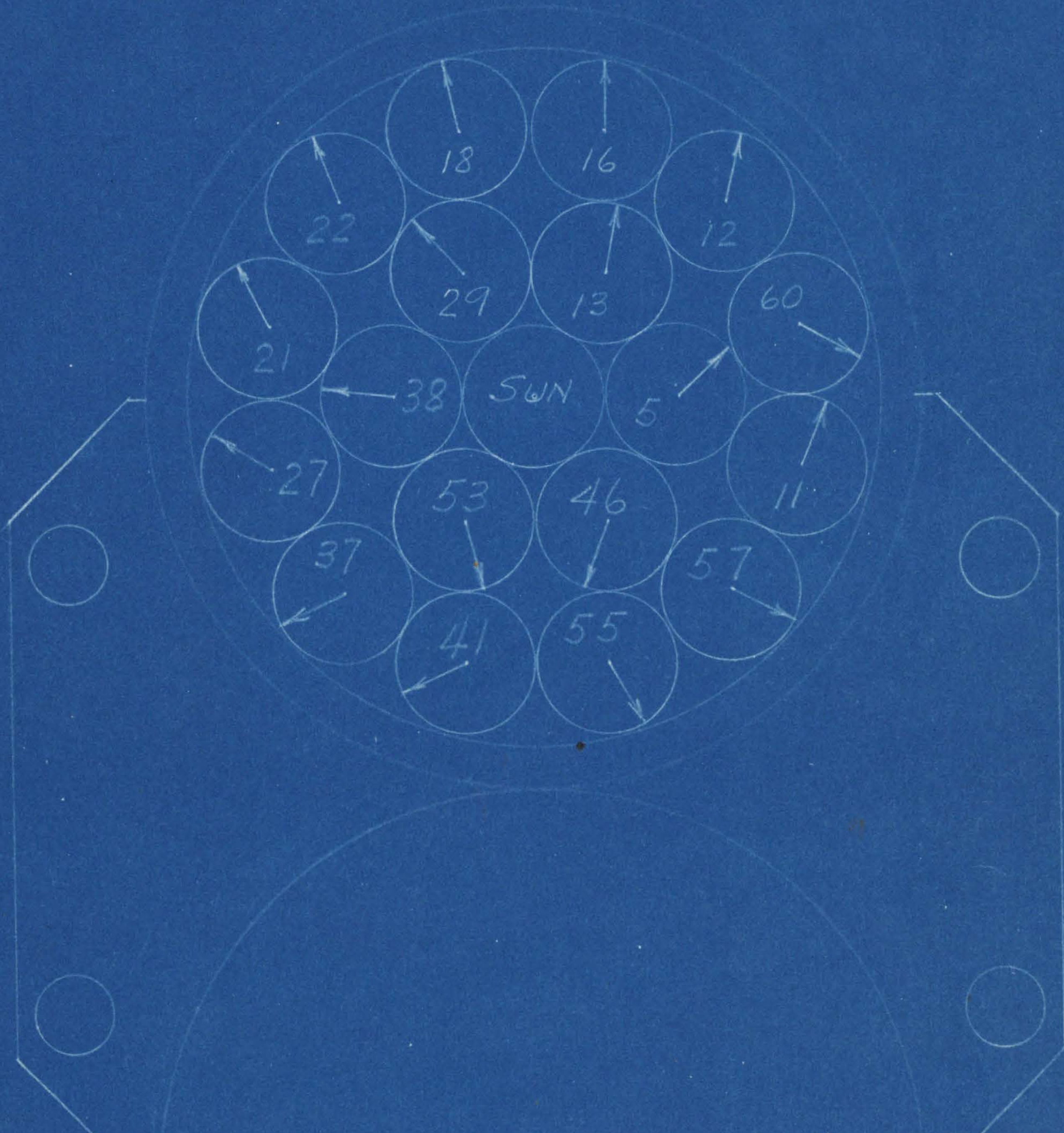
The micrometer drives provide rotation of the multiple reflector around the polar axis and rotation of the polar axis about the east-west axis. The arrangement is shown in Figure 11. The rotation about the polar axis and the rotation about the horizontal east-west axis relative to the zenith is measured to determine the latitude and the local hour angle of the vernal equinox. From this local hour angle and siderial time, the longitude is obtained. These two drives are perpendicular to each other and provision is made to adjust the angle to exactly 90°.

Approximate Ecliptic Coordinates

for the

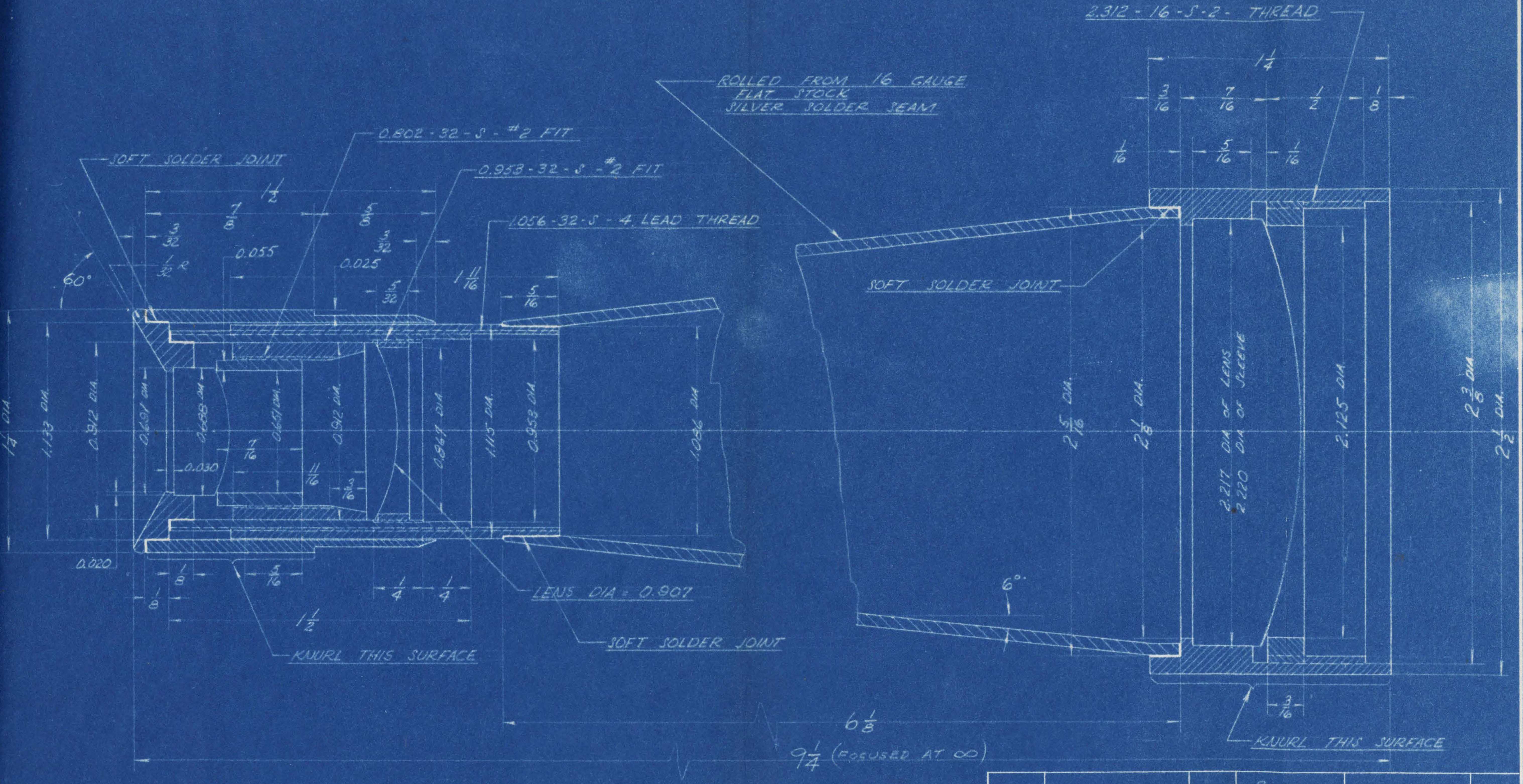
18 Selected Bright Stars Distributed Throughout the Sky above Latitude 40° South

Index No.	Name	Mag.	Celestial Latitude °	'	Celestial Longitude °	'
5	Gamma Cassiopia	2.0	48	46	47	0
11	Aldebaran	1.1	- 5	40	21	20
12	Rigel	0.3	-31	30	14	0
13	Capella	0.2	22	35	9	10
16	Betelguex	0.5	-16	50	1	50
18	Sirius	-1.6	-40		347	30
21	Procyon	0.5	-16	0	335	20
22	Pollux	1.2	6	28	337	40
27	Regulus	1.3	0	16	301	0
29	Dubhe	2.0	49	29	315	40
37	Spica	1.2	- 2	02	247	0
38	Alkaid	1.9	54	14	273	50
41	Arcturus	0.2	30	46	246	40
46	Antares	1.2	- 4	24	201	0
53	Vega	0.1	61	52	165	50
55	Altair	0.9	29	24	149	20
57	Deneb	1.3	60	0	115	40
60	Famalhout	1.3	-21	20	117	30



ARRANGEMENT OF MIRRORS

NUMBERS REFER TO STAR INDEX.



			BRASS		
PART NO.	NAME	NO. RQD.	MATERIAL DESC.	MATERIAL SPEC.	WEIGHT

ALL DIMENSIONS IN INCHES
LIMIT ON DIMENSIONS UNLESS OTHERWISE NOTED — ANGULAR ± 1/2° FRACTIONAL ± 1/32 DECIMAL ± .010

NUMBERS ARE SURFACE ROUGHNESS IN MICROINCHES

R ROUGH MACHINE FINISH — 16 FINISH GRIND
250 SMOOTH MACHINE FINISH — 2 FINE GRIND, LAP
40 ROUGH GRIND — 1/4 POLISH

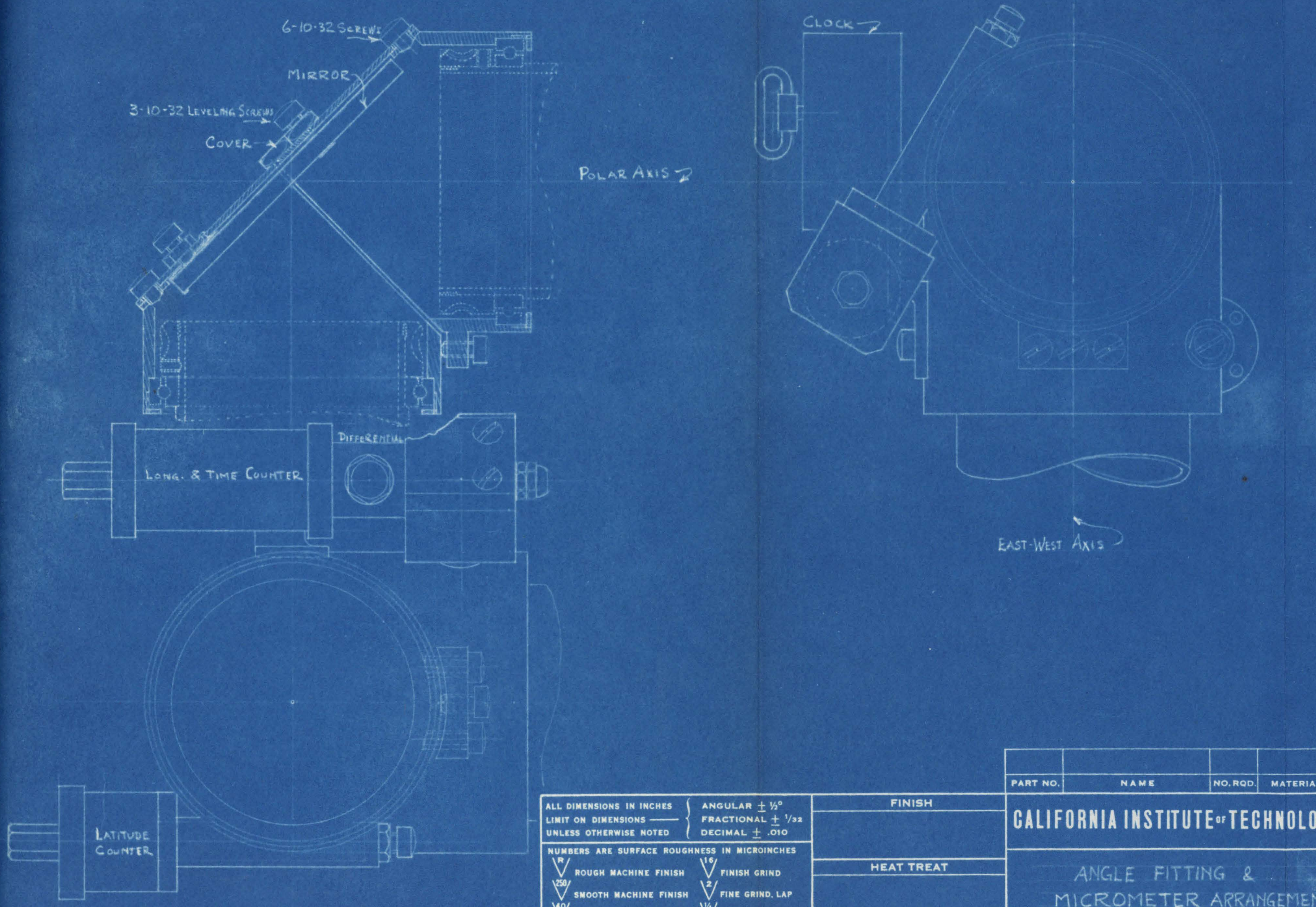
FINISH

HEAT TREAT

CALIFORNIA INSTITUTE OF TECHNOLOGY

TELESCOPE

DRAWN BY P. Jenson
TRACED BY
CHECKED BY W.F.H.
APPROVED BY W.F.H.
DATE 5-24-45 SCALE 2 ×
COURSE NO.
SECTION NO.
DWG. NO. 10



PART NO.	NAME	NO. RQD.	MATERIAL DESC.	MATERIAL SPEC.	WEIGHT

ALL DIMENSIONS IN INCHES
LIMIT ON DIMENSIONS UNLESS OTHERWISE NOTED: ANGULAR ± ½° · FRACTIONAL ± 1/32 · DECIMAL ± .010

NUMBERS ARE SURFACE ROUGHNESS IN MICROINCHES

R ROUGH MACHINE FINISH	16 FINISH GRIND
250 SMOOTH MACHINE FINISH	2 FINE GRIND, LAP
40 ROUGH GRIND	¼ POLISH

FINISH

HEAT TREAT

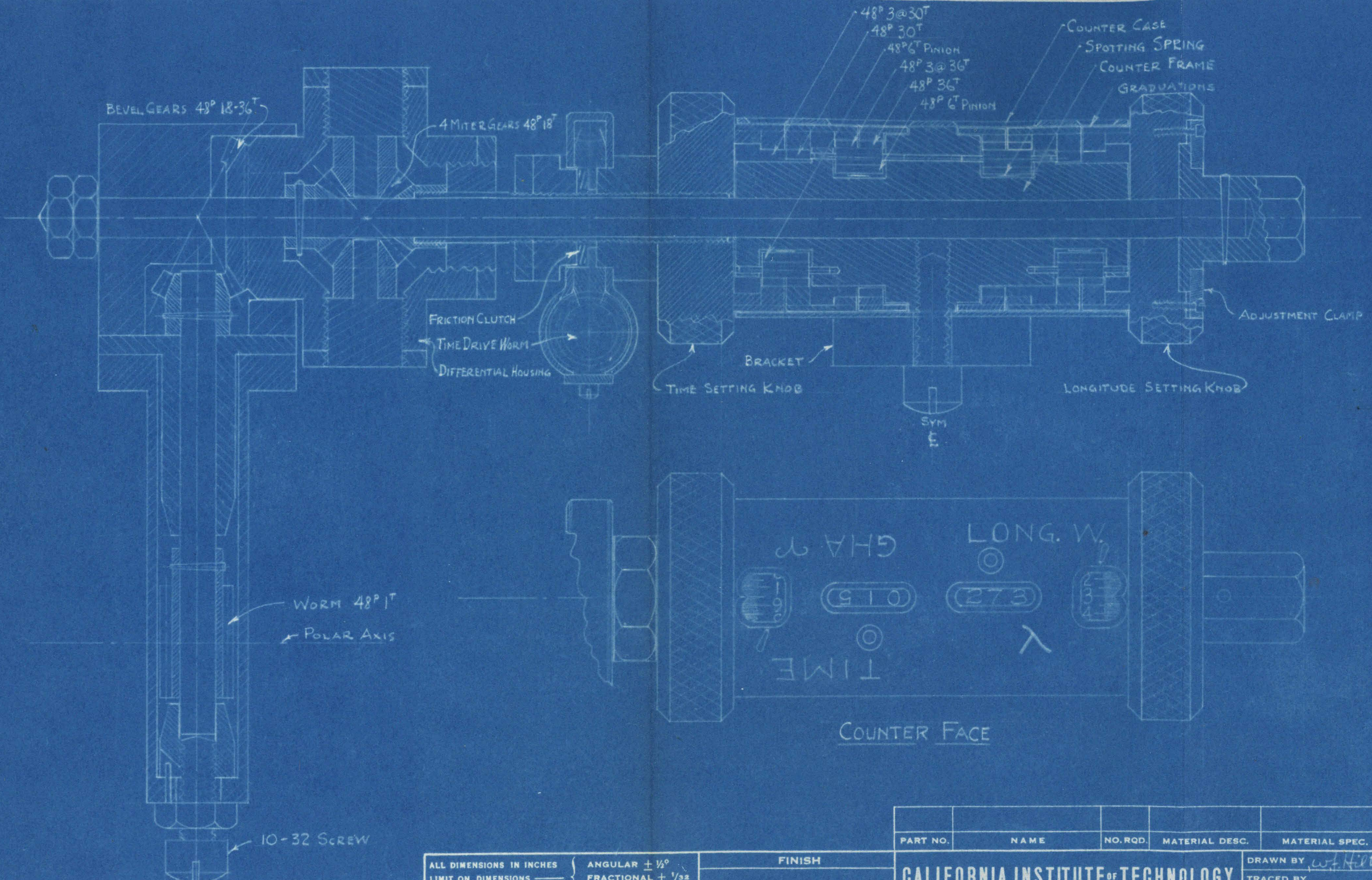
CALIFORNIA INSTITUTE OF TECHNOLOGY

ANGLE FITTING & MICROMETER ARRANGEMENT

DRAWN BY	W F Hiltner
TRACED BY	
CHECKED BY	
APPROVED	
DATE	8-20-45
SCALE	FULL
COURSE NO.	
SECTION NO.	
DWG. NO.	11

DIEPO 1000H CLEARPRINT

FORM 302



PART NO.	NAME	NO. RQD.	MATERIAL DESC.	MATERIAL SPEC.	WEIGHT

ALL DIMENSIONS IN INCHES
LIMIT ON DIMENSIONS UNLESS OTHERWISE NOTED — ANGULAR ± 1/2°, FRACTIONAL ± 1/32, DECIMAL ± .010

NUMBERS ARE SURFACE ROUGHNESS IN MICROINCHES

R ROUGH MACHINE FINISH	16 FINISH GRIND
250 SMOOTH MACHINE FINISH	2 FINE GRIND, LAP
40 ROUGH GRIND	1/4 POLISH

FINISH

HEAT TREAT

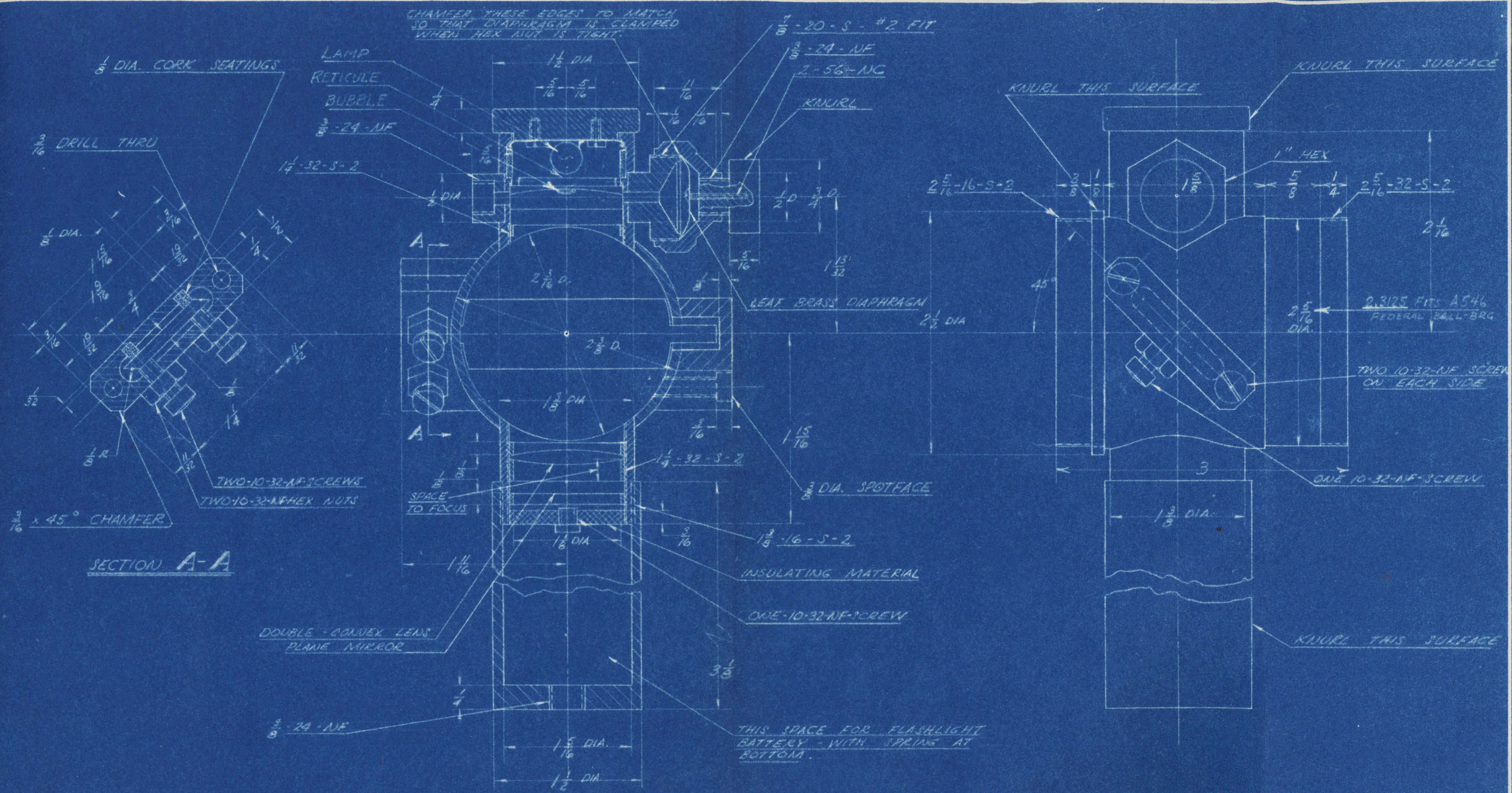
CALIFORNIA INSTITUTE OF TECHNOLOGY

LONGITUDE & TIME COUNTER ASSEMBLY

DRAWN BY w. f. Hilton
TRACED BY
CHECKED BY
APPROVED BY
DATE 8-27-45 SCALE DOUBLE
COURSE NO.
SECTION NO.
DWG. NO.

DIEPO 1000H CLEARPRINT

FORM 302



PART NO.	NAME	NO. RQD.	MATERIAL DESC.	MATERIAL SPEC.	WEIGHT
			BRASS		

ALL DIMENSIONS IN INCHES
LIMIT ON DIMENSIONS UNLESS OTHERWISE NOTED — ANGULAR ± 1/2° FRACTIONAL ± 1/32 DECIMAL ± .010

NUMBERS ARE SURFACE ROUGHNESS IN MICROINCHES
R ROUGH MACHINE FINISH — 16 FINISH GRIND
250 SMOOTH MACHINE FINISH — 2 FINE GRIND, LAP
40 ROUGH GRIND — 1/4 POLISH

FINISH

HEAT TREAT

CALIFORNIA INSTITUTE OF TECHNOLOGY

ARTIFICIAL HORIZON

DRAWN BY R. Jenson
TRACED BY
CHECKED BY WFH
APPROVED BY WFH
DATE 5-26-45 SCALE FULL
COURSE NO.
SECTION NO.
DWG. NO. 12

DIEPO 1000H CLEARPRINT

FORM 302

Both motions are ball bearing mounted and worm driven. Each worm is connected to a specially designed counter so that the angles are read in the sexigesimal system in degrees and minutes without scales or verniers. Along the worm shaft for the longitude motion is a differential drive, one of whose elements records longitude and the other sidereal time. Clock work mechanism is also incorporated so that the sidereal time can be maintained during the use of the instrument.

3. Artificial Horizon

The artificial horizon must provide the zenith, the origin from which to measure the altitude of the pole and the local sidereal time, and show in the field of view when this origin is true.

As in the Army Air Force sextant, the Astro-Navigator has a bubble under a spherical surface with lenses and reflectors to bring it into focus in the field of view. Its construction details are shown in Figure 12. A reticule is also required to show when the instrument is level.

D. ADJUSTMENT

The details in the construction of the instrument must also provide for adjustment of the optical elements. The specific devices for this purpose are shown in detail in the working drawings of the parts. The problem is much the same as that of planning the adjustment of precise surveying instruments. The adjustments must be simple, strong, and easily checked.

The specific steps in the adjustment are outlined below:

1. Bubble. Set up a remote target at the same elevation as the instrument. This is most easily done with an engineer's level. It may also be done with the instrument itself by using the bubble, even though out of adjustment, to set two targets at the same elevation, if they are the same horizontal distance from the instrument. Adjust the three set screws which press on the 45° glass plate until the bubble is centered on the target. This centering should be checked for the whole field of view. The bubble should appear to remain at the same elevation for small inclination of the instrument.

2. Reticule. Support the instrument by the micrometer drive assembly. Rotate the telescope and artificial horizon using the latitude micrometer. The cross hairs should appear to rotate about their intersection as seen against any distant field. The line of sight passes through the hole in the large 45° mirror. Move the reticule with jacking screws until correct.

3. Polar Mirror. Support the instrument at the artificial horizon. Set two targets on a straight line through the instrument. Rotate the mirror, (and the whole micrometer drive) through 180°, using the latitude micrometer. Adjust mirror with three leveling screws until cross hairs bisect the target for each direction. The line of sight will pass through the hole in the $23\text{-}1/2^{\circ}$ mirror.

4. Polar Axis. Support the instrument by the polar axis tube. Rotate the rest of the instrument around the polar axis using the longitude-time drive. The reticule should appear to rotate about its center on the distant field. The line of sight will emerge through the hole in

the 23-1/2^{o} mirror. Adjust angle with the three push-pull screws. This adjustment depends upon the accuracy of step 3, and may affect its adjustment slightly. Repeat steps 3 and 4 until both are satisfactory.

5. Ecliptic Mirror. Support micrometer drive and artificial horizon with polar axis horizontal. Set two target with included angle of 46^{o} 54'. Using longitude-time micrometer rotate the polar axis tube 180^{o}. Adjust ecliptic mirror until cross hairs bisect the target in each position. The line of sight emerges through the bearing for the sun mirror's shaft.

6. Axis of Multiple Reflector. Affix the special adjustment mirror perpendicular to the sun reflector shaft. Determine that it is perpendicular to the shaft by rotating the shaft with the sun micrometer. The distant field seen through the hole in the ecliptic mirror should appear stationary. Rock the special adjustment mirror on its spherical seat until it is true, and then clamp in position. This adjustment is independent of all the others and may be made first, in preparation for step 8.

7. Ecliptic Axis. Same as step 5 except light is now reflected back on itself, and the line of sight emerges along the ecliptic axis through the hole in the ecliptic mirror. Steps 5 and 7 are also interdependent, and must be repeated until both are satisfactory.

8. Multiple Reflector Mirrors. Support the instrument with the polar axis exactly parallel with the axis of rotation of the earth and rotate about the polar axis to track the stars. This is most easily done by attaching the instrument to an equatorially mounted telescope with a

tracking drive, in which case this adjustment depends only upon step 6. If such a mounting is not available, all the other steps must be taken, and the orientation of the polar axis is found approximately from the latitude and longitude of the adjustment station, and precisely by trial. Once the polar axis is oriented, set the mirror for each star by rocking and rotating its mirror pedestal until the star image appears at the cross hairs.

9. Latitude Counter. For an adjustment station of known latitude, turn the counter knob on the micrometer drive shaft until it reads correctly. Tighten set screw.

10. Sidereal clock. Adjust rate so that instrument tracks accurately.

11. Longitude-Time Counters Start Tracking Clock. Set sidereal time on its counter. Turn longitude counter knob to known longitude of adjustment station and tighten set screw.

This initial adjustment is quite distinct from the use, in which the dials are set for a particular observation.

E. USE

The whole purpose of the instrument is to make its use as simple as possible.

The Astro-Navigator is held in the hand, the telescope pointed toward the east, the polar axis toward the pole, and the vernal equinox toward its position in the sky. The tracking clock is started and the sidereal time set on the clock's counter. By rocking the instrument gently, the images for the visible stars are brought to coincidence.

Then the latitude and longitude micrometer drives are adjusted until the bubble shows the vertical axis of the instrument is correct. Latitude and longitude of the observer is read off the appropriate counters.

In the course of routine observations, the presumed position may be set into the instrument first, and quickly checked as above.

For very precise use in the air it will still be necessary to correct the position as obtained by development model of the Astro-Navigator for the effect of slow continuous turns, and for Coriolus acceleration. These corrections are tabulated and explained in detail in the Air Almanac.

V. SUMMARY

A portable celestial navigation instrument for the direct-reading of terrestrial position has been designed and reduced to practice. Its primary purpose is for use in aircraft navigation, where the need is urgent today. It may also find application in the field of surveying.

Latitude is measured by the altitude of the elevated pole. Longitude is given by the difference between the local sideral time as shown by the hour angle to the vernal equinox, and Greenwich sidereal time. The direction of the polar axis and the vernal equinox are obtained by manipulation of the instrument.

The device has three essential elements: the multiple reflector, the micrometer drives, and the artificial horizon.

The multiple reflector is a fixed array of small mirror which reflect light from every one of the visible bright stars to produce for a particular orientation in space a parallel bundle of rays. This orientation is determined by observing the coincidence of all the star images with a telescope.

The micrometer drives provide the necessary angular motion and its measurement, directly in terms of latitude and longitude.

The artificial horizon provides the zenith, as the origin for the measurements of local latitude and longitude.

In use, the observer will orient the instrument to obtain coincidence for all the star images, adjust the latitude and longitude micrometers until the buble shows true, and read off the position.

APPENDIX

A. BIBLIOGRAPHY AND REFERENCES

B. NAVIGATOR-SPHERE CORRESPONDENCE

C. EVALUATION OF NAVIGATOR-SPHERE BY ARMY AIR FORCES MATERIEL COMMAND

D. ASTRO-NAVIGATOR CORRESPONDENCE

E. PATENT AGREEMENTS

APPENDIX A

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APPENDIX B

NAVIGATOR-SPHERE CORRESPONDENCE

W. F. Hiltner to Drury A. McMillen (Sketch of "Celestial Position Finder")	March 2, 1943
D. A. McMillen to W. F. Hiltner	April 20, 1943
W. F. Hiltner to National Inventors Council	March 3, 1943
National Inventors Council to W. F. Hiltner	March 30, 1943

UNIVERSITY OF WASHINGTON
Department of
GENERAL ENGINEERING
SEATTLE

March 2, 1943

Mr. Drury A. McMillen
Sao Paulo
Brazil

Dear Mr. McMillen:

FORTUNE for January 1943 carried an interesting article describing your Spherographical System for celestial navigation and your efforts to introduce it to use in our armed forces. Evidently you have progressed far in its development to be actually contracting for the production of the instruments.

Two important difficulties were not brought out clearly in the FORTUNE article. Doubtless you are aware of these. The first difficulty is physical. The accuracy of results by your method is limited by the care and skill in the graphical construction. The best accuracy claimed for the size of sphere and scales you use is a minimum error of three minutes. The "navigators" think they can do better than that, neglecting perhaps the question of the possible accuracy in the initial observation of the star's altitude.

From this first limitation arises a psychological impasse. Graphical methods always irk those with an accounting aptitude and an analytical bent. They are the ones who become the "navigation authorities". De gustibus non disputandum est.

Perhaps both of these difficulties might be reduced by using the sphere as a map, a map on which are permanently located all the stars convenient for navigation. Using two great-circle scales, hinged at their intersection, one could lay off on each scale from the center of the hinge, the observed zenith distance for a star. With these points on the scales placed simultaneously on the corresponding stars on the sphere, the axis of the hinge would indicate the zenith. (Same exception is found here as in the case of the two intersections of the circles of position as mentioned in the above article.) The location of the zenith is thus independent of clocks and of dean reckoning.

To come down to earth, if the hinge is mounted to slide freely on a meridian hoop, the latitude of the position may be read directly on the meridian scale. The right ascension may be converted directly into longitude by arithmetic, or by setting the zero (Greenwich meridian) of a graduated equatorial circle at the appropriate hour angle from the vernal equinox and reading the longitude vernier.

Mr. Drury A. McMillen - March 2, 1943

The suggested instrument has several advantages. All the required measurements and settings are adapted to the use of the vernier and tangent screw--the accuracy may be as fine as warranted, easily within one minute of arc.

The star points are permanently and accurately located beforehand by the instrument maker. Since they do not change their relative positions in the celestial sphere (choosing stars with negligible proper motion) the use of tables of right ascension and declination is obviated.

These points could be marked with circular holes, and the zero end of the two great circle scales fitted with mating conical pins to insure accurate measurement to the centers. Provision can be made for the small correction to the position of the pole to allow for the precession of the equinoxes.

The time required for obtaining the fix is reduced even from the graphical method. With simple instructions and a little practice the navigator should be able to find his position immediately after taking the star sights.

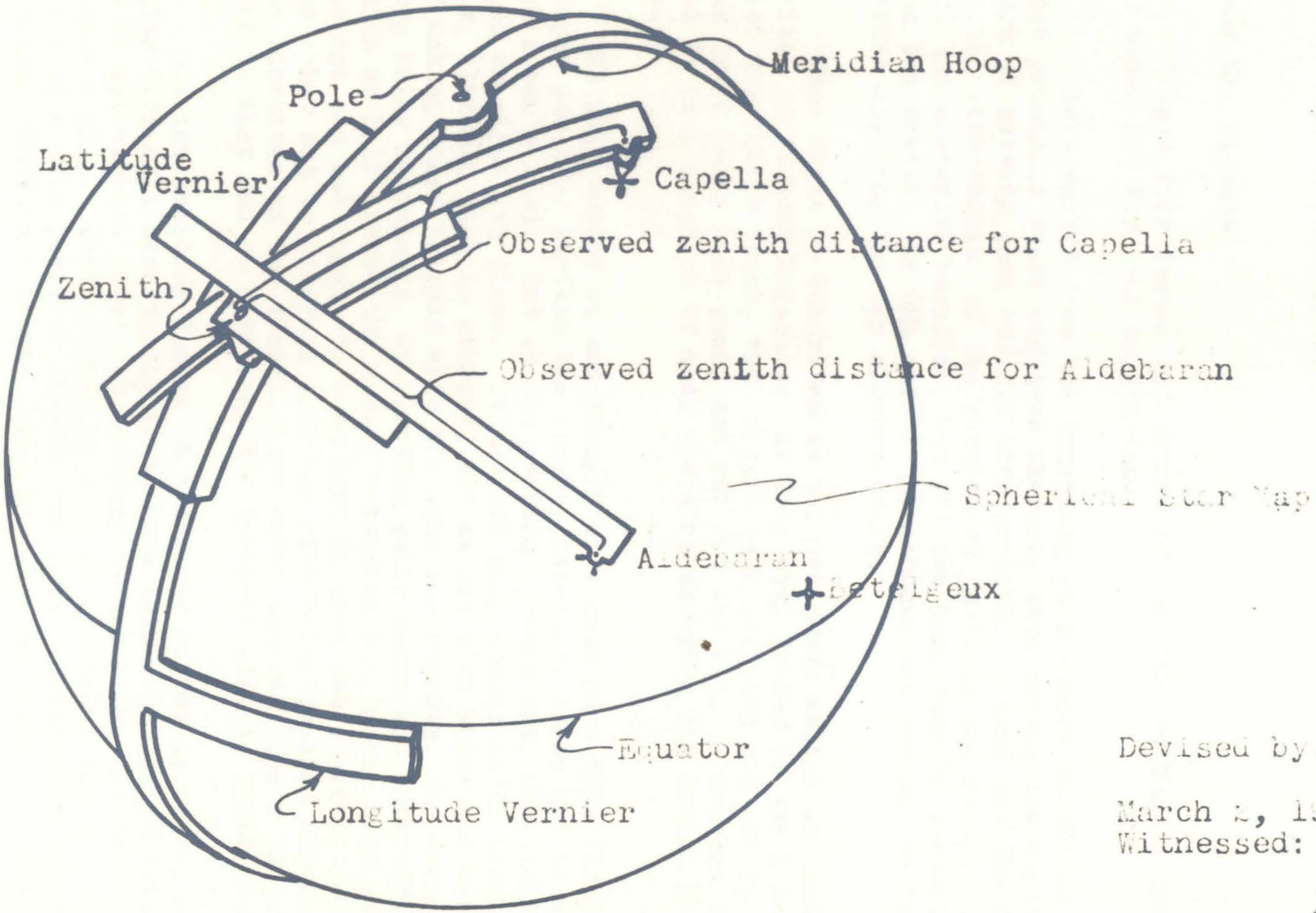
Perhaps the greatest advantage is the compactness and ruggedness that could be built into such an instrument for any required degree of precision. A six inch sphere would readily provide an accuracy to one minute of arc.

I am sending copies of this letter to FORTUNE Magazine and the Inventor's Council in Washington. I would be very glad to work with you on this extension of your ideas.

Very truly yours,

/s/ Walter F. Hiltner
Walter F. Hiltner
Instructor

WFH:b



CELESTIAL POSITION FINDER

Devised by: Walter F. Hiltner

March 2, 1943
Witnessed:

John R. Wallace Jr.
E. P. Wilcox.
[illegible]

Figure 13

Cia DOS ANNUNCIOS EM BONDS
Rua Do Carmo 41
Sao Paulo

April the 20th. 1943.

Walter F. Hiltner,
Instructor, Department of Engineering
University of Washington,
Seattle.

Dear Mr. Hiltner,

I have your letter and sketch of the 2nd. of March, and wish to thank you for your suggestion.

I have worked from the beginning on a sphere which has the 31 most prominent stars engraved thereon, thus saving the duplicate work of setting them out for each problem. I thus get the Latitude by the intersection of two circles of position and do not even set out the Greenwich Meridian, but get the Longitude by measuring the LHA and reading the GHA out of the Almanac and adding the two, or rather applying the two algebraically.

What might be described as the New Haven Method is that described in Fortune Magazine. At Yale they prefer to use a half globe plot the entire track, then obtain each position and set it off on the Track being made good, and rub out the fix. I suppose in the end it is a question of each operator choosing the method he likes best.

We have worked on and thought of a good many substitutes for a simple plotting surface the sphere, necessary tools but no more, and a man's hand. But as the problem spreads out, simplicity must also be given its place. We are not only concerned in obtaining a fix, although that is primary, but we are also under the necessity of making polar flights with the same instruments, the Meridian Hoop being detachable, of plotting radio beams and intersection which go half around the world, obtaining sun, moon, star and planet risings and settings. We even have in mind two spheres, one inside the other set to sidereal time and with holes punched through at the locations on the translucient outer sphere. There is not limitation to what can be done once the inherent idea is understood.

But the deciding factor in the whole matter is use by navigators under difficult conditions, so we have laid down the principle that we do not wish to obtain an accuracy of one mile. No navigator ever docked a ship. That is done by a pilot who takes the ship in from its 2 to 4 mile position outside the port. Navigation never landed a plane. That is a pilots job. On the other hand if I can take a plane straight over the pole from New York to Chung King and get within 20 miles of Chung King air port I would feel that I had accomplished the desideratum of the spherographical system. And allowing 10' for sextant errors, and 10' for bad plotting, that is an error of half a millimeter which a man can see standing on his head or drunk, we feel we have averaged the possibilities of the system with universal application and ease of operation, although each point could be developed to a more accurate degree.

Be assured on the other hand that I have no wish or intent to disparage your suggestion. I wish there were more people like you who thought about and talked about and tried to improve on the original idea. Later on when instrument makers and manufacturers in the States come to their senses, and have not such a burden of war work, something like you suggest may be manufactured.

I shall be in the States in May, and at the Yale Club of New York where I would be glad to hear from you again.

Sincerely yours,

/s/D. A. McMillen
D. A. McMillen

March 3, 1943

National Inventors' Council
Washington, D. C.

Dear Sir:

You are probably acquainted with Drury A. McMillen's Spherographical Method for celestial navigation as described in the January 1943 FORTUNE. Enclosed is a copy of a letter describing an instrument to further facilitate navigation, as based on his suggestions. It should be of considerable aid to the aircraft navigators if it were made available to them.

I call this to your attention too, to speed the successful prosecution of our war.

Very truly yours,

Walter F. Hiltner
Instructor

WFH:b

DEPARTMENT OF COMMERCE
The National Inventors Council
Washington

March 30, 1943

Mr. Walter F. Hiltner
University of Washington
Seattle, Washington

Dear Mr. Hiltner:

The disclosure of a variation of the McMillen system of navigation which you have submitted to this office has been examined with interest. However, we do not believe that it overcomes the basic objections to McMillen's system which have been discussed at some length in the issues of Fortune Magazine and elsewhere.

Since the Navy Department is not interested in the McMillen system, it does not appear that any further consideration of your variation is justified. Accordingly, I am placing the correspondence carefully classified in our files where it will be immediately available should some future interest in this category develop.

Very truly yours,

J. C. Green
Assistant Chief Engineer

APPENDIX C

EVALUATION OF NAVIGATOR-SPHERE BY ARMY AIR FORCES MATERIEL COMMAND

ARMY AIR FORCES
Materiel Command
Office of the Commanding General

Wright Field, Dayton, Ohio
11 Jan 1944

Mr. Walter F. Hiltner,
University of Washington,
Seattle, Washington.

Dear Sir:

Attached for your information is one ozalid copy of Engineering Division Memorandum Report No. ENG-54-655-886 dated 8 December 1943, subject: Proposed Navigation Devices.

Very truly yours,

G. V. HOLLOMAN,
Colonel, Air Corps,
Chief, Equipment Laboratory,
Engineering Division.

1 Incl.
Copy M.R. ENG-54-655-886.

ARMY AIR FORCES
Materiel Command
Engineering Division SMB:dh:54-2

MEMORANDUM REPORT ON

Date: 8 December 1943.

SUBJECT: Proposed Navigation Devices.

Equipment Laboratory Expenditure Order No. 655

SERIAL No. ENG-54-655-886

A. Purpose.

1. To report on visit of Mr. Walter F. Hiltner from the University of Washington on 26 and 27 October, 1943.

B. Factual Data.

1. Mr. Hiltner exhibited at Instrument and Navigation Branch office a model of a navigational computer of his design and described a proposed sextant. Those present were:

Captain J.G.P. Callahan, Equipment Laboratory
Dr. S. M. Burka, Equipment Laboratory
Lt. Dion Hoy, Equipment Laboratory
Mr. Walter F. Hiltner, University of Washington
Mr. G. Wright Arnold, Attorney

2. This visit was reported previously in the Daily Activity Report covering the above dates.

3. The device proposed by Mr. Hiltner was gone over in great detail with him. The basic principle of the instrument is sound but is not new. It is based on a mechanical reproduction of the celestial sphere with the hour angle, altitude, azimuth and other arcs duplicated by movable metal arcs carrying angular divisions. Two LHA arcs are provided for simultaneous solution of two sights. Among others, Mr. Aylesworth of Los Angeles submitted an almost identical device to Materiel Command about 1930. Mr. Hiltner's scheme has one new feature, that of locating the navigational stars by holes drilled into the central sphere.

4. The device has the advantages of such mechanical computers of simplicity in operation and the possibility of making the reduction with minimum mistakes. It is not of military value due to the following disadvantages:

a. The device as constructed uses angular scales and verniers. These are definitely difficult to use in the air.

b. The device is limited to use at night and then only for selected star sights. The sun, the moon, and the planets cannot be used except with difficulty and special plotting.

c. The device is inherently fragile if kept to minimum weight. Exposed arcuate members are subject to bending and misalignment in handling.

d. Accuracy is directly a function of the precision of manufacture and, for usable size, extreme precision and careful choice of materials is required.

e. The device solves for simultaneous sights on two stars and no provision is made in the instrument for allowing for time difference or run between sights.

5. It was pointed out that the use of the device does not afford as much time- and effort-saving as might appear at first sight since the instrument replaces only one part (H.O. 218) of the equipment and operations required in celestial navigation. The taking of sextant observations and the plotting of the data require most of the labor and time, and the computations with the proposed device or with H.O. 218 are simple and rapid in any case.

6. Mr. Hiltner also described a proposed sextant using a reflector floating on a mercury pool for altitude measurements, and a vertical mirror moved by a magnetic needle for bearing measurements. It was pointed out to him that even if the equipment functioned (which is highly improbable) the operations required, namely simultaneous settings and orientation to obtain coincidence of two reflected images and a cross hair for altitude, and at the same time coincidence of two other reflected images for azimuth, are impossible of performance in the air.

7. Mr. Hiltner and Mr. Arnold were given the original of the abstract of the discussion attached as Appendix 1 for their records.

C. Conclusions.

1. The devices proposed are of no military value.

D. Recommendation

1. That no further consideration be given to the devices.

Prepared by: S. M. Burka

Approved by: G. V. HOLLOMAN, Colonel, A.C.
Chief, Equipment Laboratory.

Approved by: F. O. CARROLL, Brig. General, U.S.A.
Chief, Engineering Division.

Distribution:
Major General Branshaw;
Mr. Walter F. Hiltner, University of
Washington.

APPENDIX D

ASTRO-NAVIGATOR CORRESPONDENCE

Correspondence with Office of Scientific Research and Development

W. F. Hiltner to Dr. Vannevar Bush	December 18, 1943
Carroll L. Wilson to W. F. Hiltner	December 23, 1943
Theodore Dunham, Jr., to W. F. Hiltner	January 14, 1944
W. F. Hiltner to Dr. Dunham	January 26, 1944
W. F. Hiltner to Dr. Dunham	April 27, 1944

Proposed Thesis Program at California Institute of Technology

(Sketch of Essential Elements of Astro-Navigator)

December 18, 1943

Dr. Vannevar Bush
Office of Scientific Research & Development
1630 P. Street
Washington, D. C.

Dear Dr. Vannevar Bush:

One summer evening a few years ago, I called at your New Hampshire farm with Professor F. Alexander Magoun. We helped you make a spliced rope halter for a new calf.

I am still making things with a nautical slant. The most recent is the Navigator-Sphere, built last summer and briefly described in the enclosure. It was examined at Wright Field at the direction of General Giles, Gene Branshaw, and Colonel Holloman. There it was pronounced scientifically correct, a definite improvement in instrumental navigation calculators, but, in its present form, probably not acceptable to the service branches because of their difficulty in reading the five verniers. However, the authorities at the Army Air Base, Ephrata, Washington, are still considering adopting the device for use by the crew should the navigator become a casualty.

With the service requirements in mind, I have worked out a new celestial navigation instrument which might help our Air Force over Europe this winter. The instrument reads geographic latitude and longitude directly from sights on the stars. It incorporates a new type of artificial horizon. Hand held, this device should show the actual position continuously, and even more accurately than the present octants determine the star altitudes. Gyroscopically stabilized, the system might well give position to a fraction of a mile, perhaps even close enough for accurate bombing through the clouds.

My associate here, Dr. Donald H. Lougheridge, with whom I have discussed the physics aspects of the problem, suggested that I write to you about this project. To develop this device rapidly just now, I need priority standing, financial support, and relief from more than a full schedule of classes. Can you advise me how to proceed in this matter?

Very truly yours,

W. F. HILTNER, Instructor

OFFICE FOR EMERGENCY MANAGEMENT
OFFICE OF SCIENTIFIC RESEARCH AND DEVELOPMENT
1530 P Street NW.
Washington, D. C.

December 23, 1943

Dr. W. F. Hiltner
Department of General Engineering
University of Washington
Seattle, Washington

Dear Dr. Hiltner:

Dr. Bush has asked me to thank you for your letter of December 18th in which you describe the navigation instruments on which you are working. These sound interesting, and at Dr. Bush's suggestion, I am writing to Dr. Theodore Dunham of Division 16 of NDRC and asking him to get in touch with you to obtain more complete information concerning these devices and to ascertain whether this is a matter on which the OSRD can help. I might say that a considerable amount of research effort has been devoted to devices for the purposes you outline, and Dr. Dunham is fully acquainted with the several projects on this subject.

I am sending your letter and a copy of this letter to you to Dr. Dunham at Mount Wilson Observatory, Pasadena, California, and you may expect to hear from him at an early date.

Very sincerely yours,

Carroll L. Wilson
Executive Assistant
to the Director

CC Dr. Theodore Dunham

OFFICE FOR EMERGENCY MANAGEMENT
NATIONAL DEFENSE RESEARCH COMMITTEE
Of The
OFFICE OF SCIENTIFIC RESEARCH AND DEVELOPMENT
1530 P Street NW.
Washington, D. C.

6-105 Massachusetts Institute
of Technology
Cambridge, 39, Massachusetts
January 14, 1944

Dr. W. F. Hiltner
Department of General Engineering
University of Washington
Seattle, Washington

Dear Dr. Hiltner:

At Dr. Bush's request, Dr. Carroll L. Wilson has forwarded to me a copy of your letter to him dated December 18, 1943, describing the work which you have been doing on a navigating device. I would be very glad indeed to have details regarding this instrument, so that our Section of NDRC can assess its possible usefulness for military use.

Would it be convenient for you to send sketches and photographs of any model which you may already have made? Does this device include a telescopic system for sighting on the stars, or is it intended only to expedite calculation of geographical position from sextant observation?

I expect to be at the Mount Wilson Observatory, Pasadena, California for about ten days beginning on January 24th. After January 18th, would you therefore be so kind as to address me in Pasadena?

Very truly yours,

Theodore Dunham, Jr.
Chief, Section 16.1
Optical Instruments

TD s
cc: Dr. Wilson

January 26, 1944

Doctor Theodore Dunham, Jr.
Chief, Section 16.1
Optical Instruments
National Defense Research Committee
Mount Wilson Observatory
Pasadena, California

Dear Dr. Dunham:

In my letter to Dr. Bush, December 18, 1943, I mention two distinct instruments.

The navigator-Sphere is designed to determine the geographical position mechanically, from simultaneous star altitude sights with sextant and clock. It is a computing device. A photograph of the working model I built myself is enclosed. Original features include: precise location of relative position of the navigation stars by accurate holes in star sphere, correction for precession by moving location of polar axis, automatic mechanical intersection of lines of position at zenith, (the vertical axis in the photograph). A patent for this instrument has not yet seemed justified and no formal action has been instituted. Therefore, I must require that you consider the photograph and these comments as confidential. The design and construction of the Navigator-Sphere and my subsequent contact with military service requirements is background for my continuing work in celestial navigation instrumentation.

My other celestial navigation instrument is entirely different from the Navigator-Sphere. It includes an optical system for sighting on the stars (or on any body), a new type of artificial horizon, and appropriate means to measure the necessary angles, including the geographic latitude and longitude of the observer. The device gives the actual position directly, and continuously. It may be hand held, or gyroscopically stabilized like the bomb sights. Sketches or photographs of this new instrument are not yet available. However, my work is beyond the "good idea" stage. The theory, principles, and essential details have been discussed with, and critically examined by several of my associates here, including Dr. Donald W. Loughridge, director of our OSRD project and Theodor S. Jacobsen, Professor of Astronomy. I am prepared now to build the development model, given the necessary priority standing, financial support, and relief from my teaching load. Dr. Wilson, of OSRD, tells me that you are well acquainted with other projects in this field. I would welcome your comments and suggestions.

My purpose in writing to Dr. Bush was to discover how I could most effectively and rapidly perfect this new celestial navigation instrument for our war effort. I presume that you are in some position to cooperate in the development of such devices. On what basis is such cooperation arranged? Should I come to work in your laboratories? Do you have funds available for such projects? How are an individual's interests considered and protected? I would appreciate your advice.

In making similar arrangements, I have found the long distance telephone a great economy in time and an aid to mutual understanding. I can be reached at the University, MElrose 0630, Extension 440 or 296, or at my home, KEnwood 8052.

Very truly yours,

Walter F. Hiltner

WFH:b

April 27, 1944

Doctor Theodore Dunham, Jr.
Chief, Section 16.1
Optical Instruments
National Defense Research Committee
6-105 Massachusetts Institute of Technology
Cambridge, 39, Massachusetts

Dear Dr. Dunham:

As you can see, I've moved down to the California Institute of Technology in Pasadena and have not been able to give any attention to the matter of navigation devices. I had written to you on January 26 about this device and since I have had no reply, I write now to bring this matter to your attention again.

In my letter to Dr. Bush, December 18, 1943, I mention two distinct instruments.

The navigator-sphere is designed to determine the geographical position mechanically, from simultaneous star altitude sights with sextant and clock. It is a computing device. A photograph of the working model I built myself is enclosed. Original features include: precise location of relative position of the navigation stars by accurate holes in star sphere, correction for precession by moving location of polar axis, automatic mechanical intersection of lines of position at zenith, (the vertical axis in the photograph). A patent for this instrument has not yet seemed justified and no formal action has been instituted. Therefore, I must require that you consider the photograph and these comments as confidential. The design and construction of the Navigator-Sphere and my subsequent contact with military service requirements is background for my continuing work in celestial navigation instrumentation.

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My purpose in writing to Dr. Bush was to discover how I could most effectively and rapidly perfect this new celestial navigation instrument for our war effort. I presume that you are in some position to cooperate in the development of such devices. On what basis is such cooperation arranged? Should I come to work in your laboratories? Do you have funds available for such projects? How are an individual's interests considered and protected? I would appreciate your advice.

Very truly yours,

Walter F. Hiltner

WFH:jc

Program of Study and Research For Degree of Doctor of Philosophy at the California Institute of Technology

Proposed by: Walter F. Hiltner December 29, 1944

Thesis: Development of Portable Celestial Navigation Instrument for Direct-Reading of Terrestrial Position.

This thesis on the development of a portable celestial navigation instrument for direct-reading of terrestrial position requires the application of principles of astronomy, optics, and instrument design to the practical problem of quickly determining local position on the earth. Its primary purpose is for use in aircraft where the need is urgent today, but it may also find application in the field of surveying.

The proposed instrument will be composed of three essential parts:

1. Optical head to gather and direct the light.
2. Mechanism providing variation and measurement of latitude and longitude.
3. Artificial horizon as origin for measurements.

The optical head will gather the light from the visible bright stars and direct the rays from every star into a parallel bundle. It is made with a fixed arrangement of mirrors or prisms, so that a particular orientation is required to produce the parallel bundle of rays. This orientation is determined by observing the coincidence of all the star images in a telescope.

The bundle may have any predetermined orientation in the celestial system whatsoever, but for convenience we will direct the bundle parallel to the polar axis.

The altitude to the polar axis as thus defined by the bundle of rays determines the latitude of the place. The local hour angle of Aries compared with Greenwich hour angle of Aries (Greenwich Sidereal Time) gives the longitude.

The mechanism of the instrument permits the required angular motions and their measurements. The optical head is mounted on the polar axis of the instrument so it may be rotated 360 degrees about this axis, and its position measured from the horizontal east-west line along which the bundle of rays is further bent through 90 degrees from the polar axis. To facilitate the use of the instrument, a clockwork "following" mechanism may be provided to continue rotating the optical head about the polar axis in time with the apparent motion of the stars.

The polar axis is in turn mounted on the east-west axis so it may be turned 90 degrees up and down from the horizontal to provide for the variation in latitude and its measurement.

Both of the angular measurements depend upon the artificial horizon: the longitude for the horizontality of the east-west axis, and the latitude for the origin of its scale.

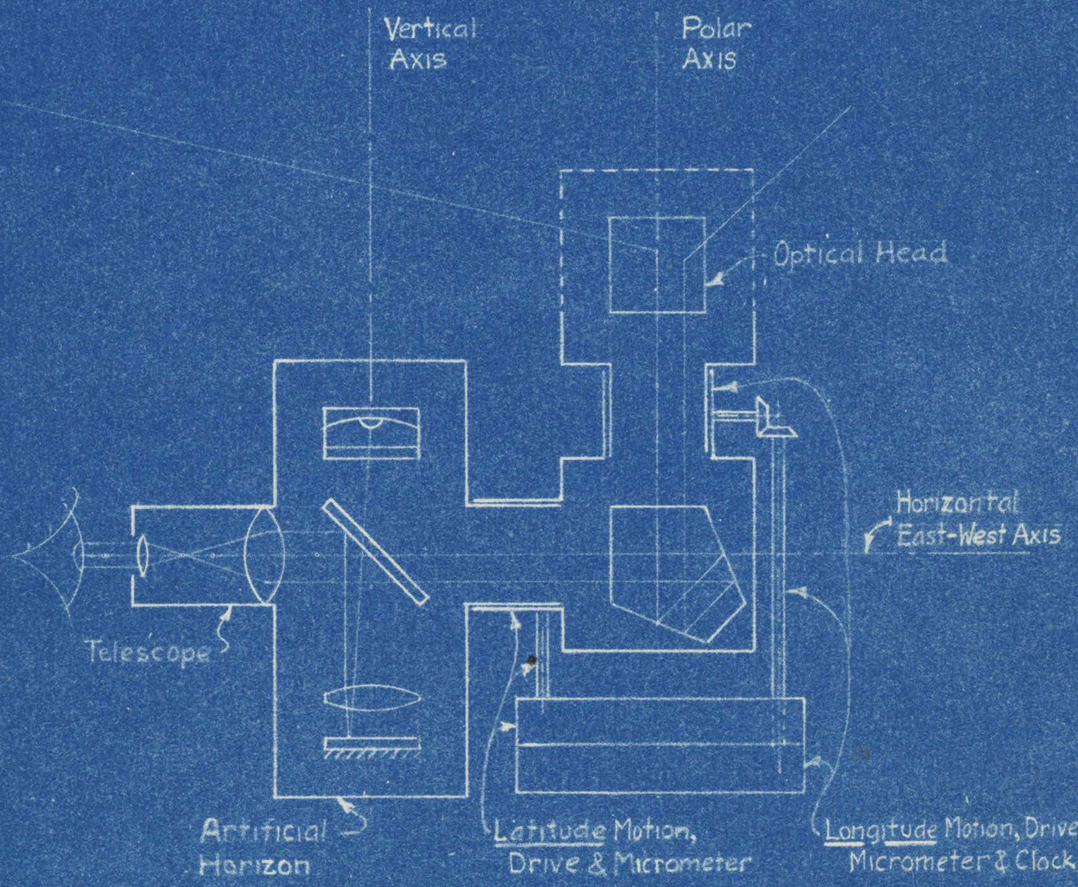
A simple bubble under a spherical surface will provide the horizon for both coordinates. Its arrangement is nicely perfected in the new Army Air Force sextant which also uses a horizontal sight direction as in this instrument.

The observer will then orient the instrument to obtain coincidence for all the star images, adjust the latitude and longitude micrometers until the bubble shows true, and read off the position. Averaging dials are required for use in the air. Corrections for course-drift and Coriolus acceleration must be made as at present.

Satisfactory for Thesis in Civil Engineering for Doctor of Philosophy at California Institute of Technology.

Signed: J. A. Anderson

Franklin Thomas



ESSENTIAL ELEMENTS OF ASTRO-NAVIGATOR

By: Walter F. Hiltner December 28, 1944

FIGURE 1.

APPENDIX E

PATENT AGREEMENTS

W. F. Hiltner to J. Paul Youtz	March 5, 1945
Assignment to California Institute Research Foundation	May 5, 1945
J. P. Youtz to W. F. Hiltner	May 14, 1945

Inter-Department Communication

CALIFORNIA INSTITUTE OF TECHNOLOGY
PASADENA

Date March 5, 1945

To J. Paul Youtz

From Walter F. Hiltner

Subject Inventions

As you suggested in our informal conversations, this note is to call to the attention of the California Institute Research Foundation the work which I have begun under the supervision of Dr. John A. Anderson, the development of a portable celestial navigation instrument for the direct-reading of terrestrial position. Arising from this research may be several patentable features which the Foundation might find profitable to exploit.

I am agreeable to assignment to the California Institute Research Foundation, in return for 15% of the gross returns to the Foundation as a result of the exploitation they choose to give the idea.

California Institute Research Foundation
California Institute of Technology
Pasadena 4, California

Celestial Navigation Apparatus as
disclosed in the Doctor's Thesis,
California Institute of Technology,
by Walter Hiltner.

Gentlemen:

I hereby agree to assign to the California Institute Research Foundation, my entire right, title and interest in and to the above-identified invention and any U. S. or Foreign Patent which the Foundation may elect, at its expense, to file thereon, in consideration of payment quarterly to me by the Foundation of 15% of its gross income accruing from said invention for such period as the Foundation desires to hold the patents.

I hereby agree to execute any and all papers and instruments deemed necessary by the Foundation to secure patent protection for such invention in this and foreign countries and to assign the applications and the patents on the same to said Foundation.

This agreement is binding on myself, my heirs and assigns without restriction as to license or sale of the interest which may result.

Walter F. Hiltner

Leonard S. Lyon
Accepted for the Foundation

Dated May 5, 1945

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CALIFORNIA INSTITUTE RESEARCH FOUNDATION
1201 East California Street
PASADENA

May 14, 1945
2890

Mr. Walter F. Hiltner
Division of Mechanical and Civil
Engineering
California Institute of Technology
Pasadena 4, California

Dear Mr. Hiltner:

Subject: Celestial Navigation Apparatus as disclosed in the Doctor's Thesis, California Institute of Technology, by Walter Hiltner

It gives us great pleasure to return herewith a copy of your letter of agreement covering your invention as above described and upon which has been placed the signature of the President of the California Institute Research Foundation accepting your offer for the Foundation.

We appreciate this opportunity to cooperate with you in making this invention available to science and the public and trust you will keep us advised of any suggestions you may have to this end.

Yours very sincerely,

J. P. Youtz
Business Manager

jpy:jb
encl.