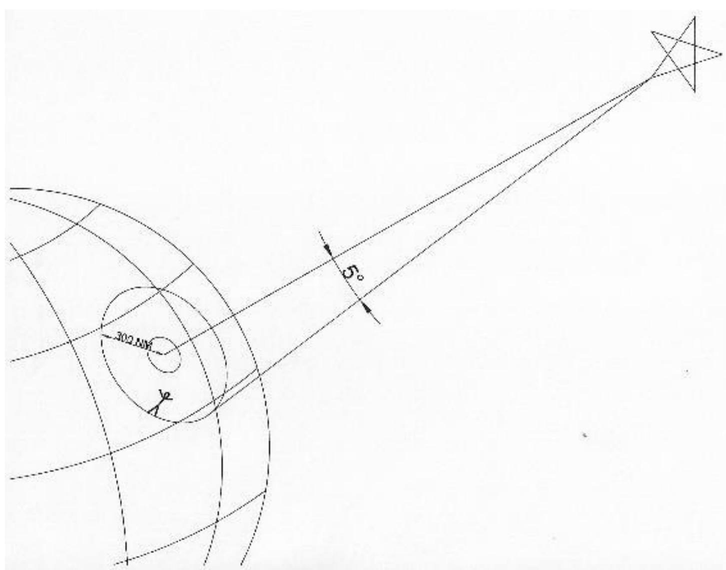
The Trailing Edge

February 2024

Celestial Navigation in Theory and Practice

"And all I ask is a tall ship and a star to steer her by..." That is a line from the immortal work "Sea Fever" by John Masefield in 1916. But how, exactly, does one steer a ship or anything else by a star, or the moon, or the sun? I spent several years as a celestial navigator aboard the WC-135B in the 55th Weather Reconnaissance Squadron. Let's see if I can answer that question. Let's define the scope of this treatise. I hope to give you an understanding of the theory of why celestial navigation works and an appreciation for how it was done in the US Air Force from its inception until "cel nav," as we called it, was suspended in 1997.

The shape of the earth approximates a sphere. Imagine a celestial sphere with the earth at its center. Let's plot the location of all of the celestial objects in their locations relative to the earth on the inside surface of that celestial sphere. Actually, there are only forty-one stars that are considered useful to the purpose. In addition, we have the sun, the moon, and a few of the planets. Except for the moon, they are all far enough away from earth that we can assume they are infinitely far away. This assumption will become significant later. If I want to determine my position on the earth, and there happens to be one of those objects directly over me, at the "zenith," then I would be standing on the subpoint of that object. If I could compute the object's location on the celestial sphere, that would be my position on the earth.



What if we don't find ourselves standing on the subpoint of any of those useful objects? What if I measure the angle from the zenith to the object and find it's five degrees? Five degrees of latitude is 300 nautical miles on the surface of the earth. So, I can draw a circle on the earth with the center at the subpoint and a radius of 300NM. I am somewhere on that circle. This is useful! I can measure the "altitude" in degrees and minutes of any object I can see and compute the radius of the circle I am on. In this use of the word, "altitude" is the angle observed from the horizon to the celestial body. When I compute the subpoint at the time of my observation, I can locate the center of that circle, and I have a line of position that I must be on. If I can see more than one object, I can get two or more lines of position and determine a "fix." I don't need to draw the entire circle; I only need the portion of it that is near me. Moreover, if the circle is big enough (and it always is), I can approximate my little portion of it as a straight line.

You can imagine that computing the location of any given celestial object at any point in time would involve a whole lot of trigonometry. "But, I need to do this on the fly – literally! The earth is turning under me, and my aircraft is moving over the earth at something close to seven miles per minute." There are two things to note. First, someone has already done the math and built tables. All you have to do is find the right place in the right table and look it up. Second, pick a time in the future and plan for that. Like everything else in navigation, it all starts by throwing out a "DR" or dead reckoning position. Pick a time when you want to "fix" your position. There is some planning and third grade math involved, so give yourself some time. Keep in mind the book (MACR55-135) says you must fix your position every thirty minutes during daytime and every forty minutes at night. There are more observable bodies at night, so the fixes are more reliable. A complex precomputation can take twenty minutes or more, so a celestial navigator gets to be an expert in time management. In the B-52 or the KC-135, the navigator has someone to do the actual shooting. In the B-52, the Electronic Warfare Officer (EWO) uses the sextant and reports the results to the navigator. The boom operator performs that role on the KC-135. That helps with time management.

In addition to my Global Navigation Chart (GNC) (scale 1:5,000,000) and my sextant, I need an Air Almanac for the current calendar year and three volumes of HO249; the red one, the white one, and the blue one. The red one is used for stars at night. The white and blue volumes are for everything else, splitting the latitudes into two volumes, 0 to 40 and 41 to 89. The tables include only whole degrees.

So, I have my DR position for fix time. In order to use the tables in the HO249, I need a whole degree of latitude and a local hour angle (LHA) that appears in the table. It's easy to determine the latitude of my "assumed position." I'll pick the latitude in whole degrees that is closest to my DR. To determine the longitude of my assumed position, I note that the almanac gives me the global hour angle (GHA) of the object for my selected fix time. I must subtract my longitude from the GHA to get the LHA, so I pick an assumed longitude that gives me an LHA that I find in the tables. The HO249 volume of choice gives me the altitude (in degrees and minutes) above the horizon and the true direction (Zn) of my selected object at fix time.

Armed with that, I can stand up to the sextant and shoot my selected body. I crank in the Zn and the expected altitude into the sextant. The sextant has a two minute averager, so I start my shot at one minute prior to the precomputed (precomped) time. Then, the shutter will close at one minute after my fix time. After the shot, the sextant lets me turn the altitude knob until it indicates the average altitude of the shot time. I calculate the difference between the average reading and the precomp altitude. Plotting from my assumed position on the chart, I move the line of position (LOP) toward the body if Height Observed (Ho) was more than the precomp value and away from it if it was less. If the HO is MOre, move it TOward the body. The mnemonic to remember this is HoMoTo. Laying my plotter on the chart so it is perpendicular to the Zn of the body, I can draw my LOP.

However, if I have more than one body to shoot, such as three stars at night, I have to pick different times to shoot. If I plan to have two minutes between shots, that puts four minutes between the center times of each shot. Rather than do three separate precomps, one for each star, I can precomp them all at the same time. Then, I need to account for the motion of the body (MOB) during shot times and the motion of the observer (MOO). The MOO is based on my direction of flight and my groundspeed. The MOB is based on the earth's rotation. How I account for these motions depends on the patch on my flight suit. If I am in Air Training Command (ATC) or the Strategic Air Command (SAC), I add those numbers on the precomp sheet. It's a form printed on a standard piece of paper. If I am in Military Airlift Command (MAC), I account for those motions by moving my assumed position for each shot. A precomp in MAC fits into a space about one inch by three inches on my flight planning form. It is important to note that the motions of the moon are a little weird. If shooting the moon, it's best to shoot it at fix time rather than adjusting for the MOO and the MOB.

Now, I have to mention a bit of a wrinkle. The numbers in the tables are computed as if I am shooting from the center of the earth, not thousands of feet above the surface. However, almost all of those objects are millions of miles, or lightyears away from earth. So, the radius of the earth doesn't matter. If I shoot the moon, that assumption causes problems. Therefore, for moon shots, I have to apply a correction for the parallax in altitude (PinA). There is a table for that correction. If the Ho of the moon is closer to the zenith, the correction is less than if it is closer to the horizon.

There are two more corrections to add. First, the atmosphere refracts the angle of the light from the body. It depends on my altitude in the atmosphere and the Ho. Again, there is a table for that. Second, there is an issue with the rotation of the earth. It isn't as well behaved as one might think. It wobbles a bit. The axis isn't always aligned with the rotation. It nutates. Also, as one might expect of a spinning mass, there is some precession. To compensate, there is a value for the "P and N" correction. I get that from the air almanac and include it in my precomp.

Since I can account for the MOO and the MOB, I will typically plan my shots to be all done before my declared fix time. I will start shooting twelve minutes early for a three star fix. That way, I am sitting at the nav station plotting the results of my shots when fix time occurs. That gives me the chance to press a "hold" button on the INSs to record their position. Then, I can plot the positions of the INSs along with my cel LOPs and assess the accuracy of the INSs against my celestial position. That also gives me a chance to compare the two INS positions and see if they are drifting apart. If I am still at the sextant at fix time, I must ask the pilots or the flight engineer to hold the INSs for me. Asking them to hold the INS typically results in several seconds elapsing before someone says, “Uh.. Say again, Nav.” The time elapsed introduces another error.

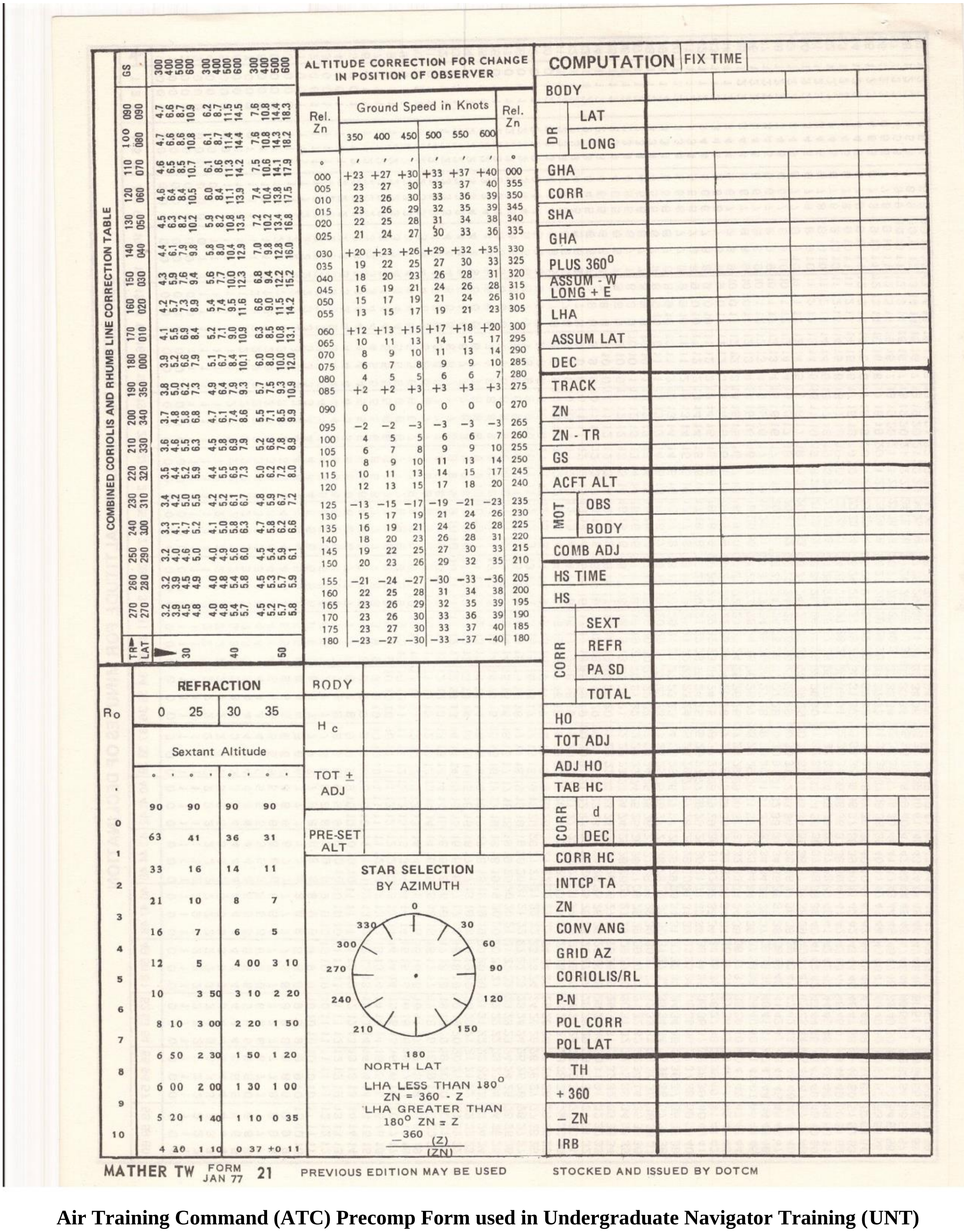
While we’re talking about the flight engineer, it is important that nobody adjusts the throttles during my shot. It won’t change the groundspeed appreciably. However, the slight acceleration or deceleration that follows a power change can significantly move the celestial LOPs. The periscopic sextant doesn’t measure the angle between the horizon and the body like the nautical sextants of old did. Instead, there is a bubble in the view field of the sextant. To shoot a body, you hold the sextant so the bubble is centered in the crosshairs while turning the sextant and adjusting the height knob to keep the body in the center of the bubble. A slight acceleration causes the bubble to deflect forward or aft and moves the position in the direction of the acceleration. The standard practice is to announce on intercom that “Nav is up to shoot.” That is supposed to warn everyone to leave the throttles alone for the time of the shots. Each minute of defection introduces a nautical mile of error.

Clear enough? Well, get back to work. By the time you have everything plotted, it’s time to start planning the next shot. You have to do this for seven to twelve hours. There are some things I haven’t mentioned. There is often some error in the sextant. Not to worry. If you are shooting three stars, the error will be the same for each shot. When you plot the LOPs, they may form a big triangle. Your cel position is still at the center of the triangle. If you are shooting only the sun, you will not know how much the error is. If you are shooting only two objects, say the sun and moon, you will not know how much error is in those shots. Also, the navigator is required to do a heading check at the beginning of the over water leg of the mission. This requires doing a precomp to determine the Zn of a visible body. At the precomp time, use the sextant to read the true heading of the aircraft. At the same time, note the true heading indicted by both INSs and the reading of the N-1 compass at the nav station and ask the copilot to read the value of his J-4 compass. Then, compare all the values, converting the magnetic indications to true with the local magnetic variation. After the heading check, before you get out of range of those nav aids on the coastline, take a fix and call it your Initial Cruise Fix (ICF). Finally, there are times when only the sun is available. With that, you get only one LOP and you can’t call it a fix. With one LOP, look at where that is in relation to your DR, use your best judgement and plot your Most Probable Position (MPP).

As you might imagine, there are some tangible advantages to celestial navigation. It is available anywhere on the globe. It doesn’t require any support systems on the ground. It doesn’t require the aircraft to radiate anything to make it work. Moreover, it can’t be jammed by anything other than cloud cover. However, it has its limitations. It is sensitive to very small accelerations. At its best, it is accurate to only a few miles. That is why it was only used for crossing large bodies of water. If over land in the free world, there are navigation aids available, i.e. Non-Directional Beacons (NDB), Very High Frequency Omnidirectional Radios (VOR), and Tactical Air Navigation systems (TACAN). Without radio navigation aids, the ground mapping radar is still more accurate than cel nav over land. Nevertheless, when everything else is unavailable, there are stars in the heavens.

For what it’s worth, I haven’t mentioned grid navigation. It is mandatory to convert to grid navigation at high latitudes where the magnetic compasses become unreliable, typically above sixty degrees latitude. However, subpolar grid was often used for training and during check rides, of course. The only delightful part of grid navigation that I recall is the puzzled look on the pilots’ faces as they looked at a compass showing a southerly heading as we cruised toward the north pole. I also haven’t mentioned using the APN-59 ground mapping radar to look for weather while enroute over water. Don’t forget your thirty-minute cel pacing.

- Stormy Weathers



COMBINED CORIOLIS AND RHUMB LINE CORRECTION TABLE

TR	LAT 30: GS 300	400	500	600	LAT 40: GS 300	400	500	600	LAT 50: GS 300	400	500	600
090 090	4.7	6.6	8.7	10.9	6.2	8.7	11.5	14.5	7.6	10.8	14.4	18.3
100 080	4.7	6.6	8.6	10.8	6.1	8.7	11.4	14.4	7.6	10.8	14.3	18.2
110 070	4.6	6.5	8.5	10.7	6.1	8.6	11.3	14.2	7.5	10.6	14.1	17.9
120 060	4.6	6.4	8.4	10.5	6.0	8.4	11.1	13.9	7.4	10.4	13.8	17.5
130 050	4.5	6.3	8.2	10.2	5.9	8.2	10.8	13.5	7.2	10.2	13.4	16.8
140 040	4.4	6.1	7.9	9.8	5.8	8.0	10.4	12.9	7.0	9.8	12.8	16.0
150 030	4.3	5.9	7.6	9.4	5.6	7.7	10.0	12.3	6.8	9.4	12.2	15.2
160 020	4.2	5.7	7.3	8.9	5.4	7.4	9.5	11.6	6.6	9.0	11.5	14.2
170 010	4.1	5.5	6.9	8.4	5.2	7.1	9.0	10.9	6.3	8.5	10.8	13.1
180 000	3.9	5.2	6.6	7.9	5.1	6.7	8.4	10.1	6.0	8.0	10.0	12.0
190 350	3.8	5.0	6.2	7.3	4.9	6.4	7.9	9.3	5.7	7.5	9.3	10.9
200 340	3.7	4.8	5.8	6.8	4.7	6.1	7.4	8.6	5.5	7.1	8.5	9.9
210 330	3.6	4.6	5.5	6.3	4.5	5.8	6.9	7.9	5.2	6.6	7.8	8.9
220 320	3.5	4.4	5.2	5.9	4.4	5.5	6.5	7.3	5.0	6.2	7.2	8.0
230 310	3.4	4.2	5.0	5.5	4.2	5.2	6.1	6.7	4.8	5.9	6.7	7.2
240 300	3.3	4.1	4.7	5.2	4.1	5.0	5.8	6.3	4.7	5.8	6.2	6.6
250 290	3.2	4.0	4.6	5.0	4.0	4.9	5.6	6.0	4.5	5.4	5.9	6.1
260 280	3.2	3.9	4.5	4.9	4.0	4.8	5.4	5.8	4.5	5.3	5.7	5.9
270 270	3.2	3.9	4.5	4.8	4.0	4.8	5.4	5.7	4.5	5.2	5.7	5.8

ALTITUDE CORRECTION FOR CHANGE IN POSITION OF OBSERVER

Rel. Zn	Ground Speed in Knots 350	400	450	500	550	600	Rel. Zn
°	′	′	′	′	′	′	°
000	+23	+27	+30	+33	+37	+40	000
005	23	27	30	33	37	40	355
010	23	26	30	33	36	39	350
015	23	26	29	32	35	39	345
020	22	25	28	31	34	38	340
025	21	24	27	30	33	36	335
030	+20	+23	+26	+29	+32	+35	330
035	19	22	25	27	30	33	325
040	18	20	23	26	28	31	320
045	16	19	21	24	26	28	315
050	15	17	19	21	24	26	310
055	13	15	17	19	21	23	305
060	+12	+13	+15	+17	+18	+20	300
065	10	11	13	14	15	17	295
070	8	9	10	11	13	14	290
075	6	7	8	9	9	10	285
080	4	5	5	6	6	7	280
085	+2	+2	+3	+3	+3	+3	275
090	0	0	0	0	0	0	270
095	−2	−2	−3	−3	−3	−3	265
100	4	5	5	6	6	7	260
105	6	7	8	9	9	10	255
110	8	9	10	11	13	14	250
115	10	11	13	14	15	17	245
120	12	13	15	17	18	20	240
125	−13	−15	−17	−19	−21	−23	235
130	15	17	19	21	24	26	230
135	16	19	21	24	26	28	225
140	18	20	23	26	28	31	220
145	19	22	25	27	30	33	215
150	20	23	26	29	32	35	210
155	−21	−24	−27	−30	−33	−36	205
160	22	25	28	31	34	38	200
165	23	26	29	32	35	39	195
170	23	26	30	33	36	39	190
175	23	27	30	33	37	40	185
180	−23	−27	−30	−33	−37	−40	180

COMPUTATION | FIX TIME

BODY					
DR LAT					
DR LONG					
GHA					
CORR					
SHA					
GHA					
PLUS 360°					
ASSUM - W LONG + E					
LHA					
ASSUM LAT					
DEC					
TRACK					
ZN					
ZN - TR					
GS					
ACFT ALT					
MOT OBS					
MOT BODY					
COMB ADJ					
HS TIME					
HS					
CORR SEXT					
CORR REFR					
CORR PA SD					
CORR TOTAL					
HO					
TOT ADJ					
ADJ HO					
TAB HC					
CORR d					
CORR DEC					
CORR HC					
INTCP TA					
ZN					
CONV ANG					
GRID AZ					
CORIOLIS/RL					
P-N					
POL CORR					
POL LAT					
TH					
+ 360					
− ZN					
IRB					

REFRACTION

R_o	Sextant Altitude 0	25	30	35
′	° ′	° ′	° ′	° ′
	90	90	90	90
0				
	63	41	36	31
1				
	33	16	14	11
2				
	21	10	8	7
3				
	16	7	6	5
4				
	12	5	4 00	3 10
5				
	10	3 50	3 10	2 20
6				
	8 10	3 00	2 20	1 50
7				
	6 50	2 30	1 50	1 20
8				
	6 00	2 00	1 30	1 00
9				
	5 20	1 40	1 10	0 35
10				
	4 30	1 10	0 37	+0 11

BODY			
H c			
TOT ± ADJ			
PRE-SET ALT			

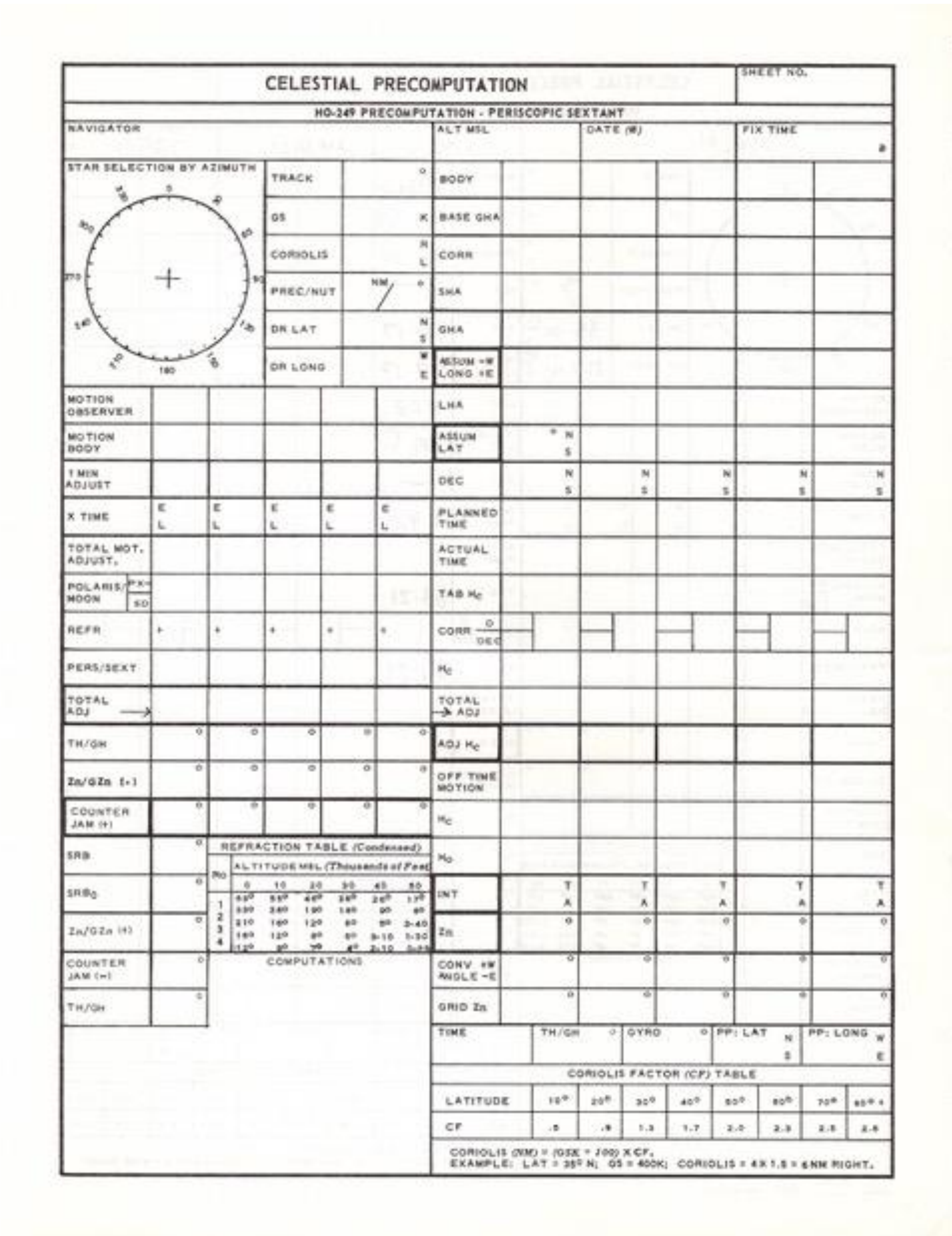
STAR SELECTION BY AZIMUTH

NORTH LAT
LHA LESS THAN 180°
ZN = 360 - Z
LHA GREATER THAN 180° ZN = Z

$$\frac{-360}{(ZN)}\;(Z)$$

MATHER TW FORM JAN 77 21 PREVIOUS EDITION MAY BE USED STOCKED AND ISSUED BY DOTCM

Air Training Command (ATC) Precomp Form used in Undergraduate Navigator Training (UNT) (Mather AFB)



CELESTIAL PRECOMPUTATION

SHEET NO.

HO-249 PRECOMPUTATION - PERISCOPIC SEXTANT

NAVIGATOR | ALT MSL | DATE (@) | FIX TIME

STAR SELECTION BY AZIMUTH

TRACK | GS | CORIOLIS | PREC/NUT | DR LAT | DR LONG

BODY | BASE GHA | CORR | SHA | GHA | ASSUM LONG | LHA | ASSUM LAT | DEC | PLANNED TIME | ACTUAL TIME | TAB Hc | CORR DEC | Hc | TOTAL ADJ | ADJ Hc | OFF TIME MOTION | Hc | Ho | INT | Zn | CONV ANGLE | GRID Zn

MOTION OBSERVER | MOTION BODY | 1 MIN ADJUST | X TIME | TOTAL MOT. ADJUST. | POLARIS/MOON | REFR | PERS/SEXT | TOTAL ADJ | TH/GH | Zn/GZn (-) | COUNTER JAM (+) | SRB | SRBo | Zn/GZn (+) | COUNTER JAM (-) | TH/GH

REFRACTION TABLE (Condensed)

ALTITUDE MSL (Thousands of Feet)

Ro	0	10	20	30	45	50
1	63°	55°	46°	38°	26°	17°
2	33°	24°	19°	14°	9°	6°
3	21°	16°	12°	8°	5°	3-40
4	16°	12°	8°	6°	3-10	1-30
	12°	9°	7°	4°	2-10	[illegible]

COMPUTATIONS

TIME | TH/GH | GYRO | PP: LAT | PP: LONG

CORIOLIS FACTOR (CF) TABLE

LATITUDE	10°	20°	30°	40°	50°	60°	70°	80°+
CF	.5	.9	1.3	1.7	2.0	2.3	2.5	2.6

CORIOLIS (NM) = (GSK ÷ 100) X CF.
EXAMPLE: LAT = 35° N; GS = 400K; CORIOLIS = 4 X 1.5 = 6NM RIGHT.

Strategic Air Command (SAC) Precomp Form

CELESTIAL COMPUTATION

TIME										
BODY										
DR LAT										
DR LONG										
GHA										
CORR										
SHA										
GHA										
PLUS 360										
ASSUM LONG −W +E										
LHA										
ASSUM LAT										
DEC										
HS TIME										
HS										
CORR SEXT										
CORR REFR										
CORR PA SD										
CORR TOTAL										
HO										
TOTAL ADJ										
ADJ HO										
TAB HC										
CORR d										
CORR DEC										
CORR HC										
INTCP (T/A)										
ZN										
TRACK										
ZN − TR										
MOT OBS										
MOT BODY										
COMB ADJ										
GS										
ACFT ALT										
CORIOLIS										
P-N										
POL CORR										
POL LAT										
REMARKS										

MAC FORM 28, SEP 84

Military Airlift Command (MAC) Precomp Form, MAC Form 28