

JET PROPULSION LABORATORY

INTEROFFICE MEMORANDUM

10 November 1984

314.8-500

TO: Distribution

FROM: J. D. Callahan *JDC*

SUBJECT: Voyager and Galileo Interactive Picture Planning Programs on  
the Chromatics (vip and gip)

Vip and gip have been successfully transferred from the Graphics Lab's Picture System 2 and PDP11/55, where they were originally developed (Refs. 1 and 2), to our Chromatics 7900 color graphics computer. A number of modifications and improvements have been incorporated into the programs. This memo describes the current system.

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## I. Introduction

The two interactive computer graphics programs vip (Voyager interactive program) and gip (Galileo) are used to support optical navigation picture planning. The programs allow rapid, interactive simulation on a color CRT of a wide variety of possible optical navigation pictures as well as other scenes (Refs. 1 and 2). After being developed in 1982 on an experimental basis using a Picture System 2 driven by a PDP11/55, it became necessary to move the programs. It was decided to buy a Chromatics 7900 color graphics computer as the home for vip and gip (Ref. 3).

The Chromatics arrived in May of 1983, and advanced forms of both vip and gip are now available. Improvements will doubtless be made in the future, but the programs are quite usable at present. The Chromatics is an impressive device considering that it is an entire graphics system contained within a small moveable cabinet with a CRT terminal sitting on top. The primary hardware features consist of a high resolution (1024x768) color CRT (raster), a Motorola MC68000 chip for the CPU, half a megabyte of memory, a 40 megabyte hard disk, and a joystick and bezel keys for interactive inputs. Data, such as ephemeris files, may be transferred from the NAIF VAX (Chico) or the NAV VAX (Groucho) via a slow (1200 baud) hard wire interface. A DMA board does exist on the Chromatics and a fast hard wire interface may be a reality in the future. The primary software features consist of the IDRIS operating system (essentially UNIX), a screen editor, a C compiler, a fortran 77 compiler, and a linker.

Vip and gip are written entirely in fortran 77 except for two small assembly routines (fortran callable). The routines drive the graphics. In addition to vip and gip there are a few much smaller programs used to transfer and set up files. These are written mostly in fortran 77 and a few in C.

The Chromatics system was purchased for under \$50,000. A minimum Picture System/minicomputer system would have cost \$160,000. Surprisingly the Chromatics has the following advantages over the more expensive system: color graphics, more compact, more reliable, more memory, better interactive inputs (joystick and bezel keys versus knobs and switches). The major advantage of a Picture System/minicomputer is speed. The Chromatics is much slower. However by improving and streamlining the code, and by developing new theoretical methods, vip and gip generally run at 2+1 frames per second. This is still fast enough for a highly interactive, useful program. A floating point accelerator board for the Chromatics could be purchased, and this would increase speed three-fold. If a VAX becomes the CPU, the speed could be improved 10 fold to 20 frames/sec. This is the current plan (Ref. 7). Anything over 6 frames/sec is almost like a movie. Among the new methods developed for speed are interesting algorithms for

spacecraft and satellite ephemerides and for camera pointing optimization. These will be described in the theory section of this paper. (A camera pointing optimization algorithm did not exist on the Picture System 2 and PDP11/55 system). The new programs on the Chromatics are actually more accurate than the originals developed on the Picture System, and usually only 2-3 pixel-level errors are encountered. This is quite satisfactory for picture planning.

## II. Input/Output

### II.1 Input

#### II.1.1 voy.eph/orb.eph

These files, voy.eph for vip and orb.eph for gip, contain the spacecraft ephemerides and program start times. The files are originally created on the Univac machines from either a PFILE or OPUS vary file. Then they are transferred to the Vax (Ref. 4) and finally to the Chromatics. The files are small, formatted, and contain a start time (seconds past 1950.0), a set of times past the start time (seconds), and a set of spacecraft positions (1950.0 eme, km) corresponding to the times.

#### II.1.2 urasat.eph/galsat.eph

These files, urasat.eph for vip and galsat.eph for gip, contain the satellite ephemerides. All five of Uranus' moons and the Galelian satellites are on the files. Like the spacecraft ephemeris files the satellite files are first created on the Univac machines by reading a standard cheveychev file. Then they are transferred to the Vax and finally the Chromatics. However once on the Chromatics, these files, which are large and formatted, are converted to a binary, direct access form. Urasat.eph covers Oct. 1, 1985 to April 1, 1986 and is 288, 768 bytes or 564 blocks (1 block = 512 bytes), while galsat.eph covers Jan.1, 1988 to Jan. 1, 1994 and is 2,349,056 bytes or 4,588 blocks.

Within the satellite ephemeris files, each direct access binary record is 4 blocks or 2048 bytes long and contains two orbits. Each record consists of an absolute start time (seconds past 1950.0), a set of 121 times past the start time (seconds), and a set of positions (1950.0 eme,km) corresponding to the times. The last position is duplicated by the first position of the next record on the file. The positions are at approximately  $6^\circ$  intervals of the orbits.

#### II.1.3 star.cat

Star.cat contains the entire SAO catalog of over a quarter million stars (this is better than the equivalent file on the Picture System 2 and PDP 11/55 which contained most but not all of the SAO catalog). The file is first created on the vax as a direct access binary file

by reading two tapes. Then it is converted to a formatted form and transferred to the Chromatics. Once on the Chromatics, the file is converted back to a direct access file. The file is 6,635,520 bytes or 12,968 blocks.

The file is composed of 2592 records, each of which is 5 blocks long and covers  $5^{\circ} \times 5^{\circ}$  field of sky. Contained within a record are the number of stars in the field (up to 426) and the right ascension, declination, magnitude and spectral class for each star. The epoch of the stars is 1 January 1991 referenced to 1950.0 eme.

#### II.1.4 Bezel Keys and Joystick

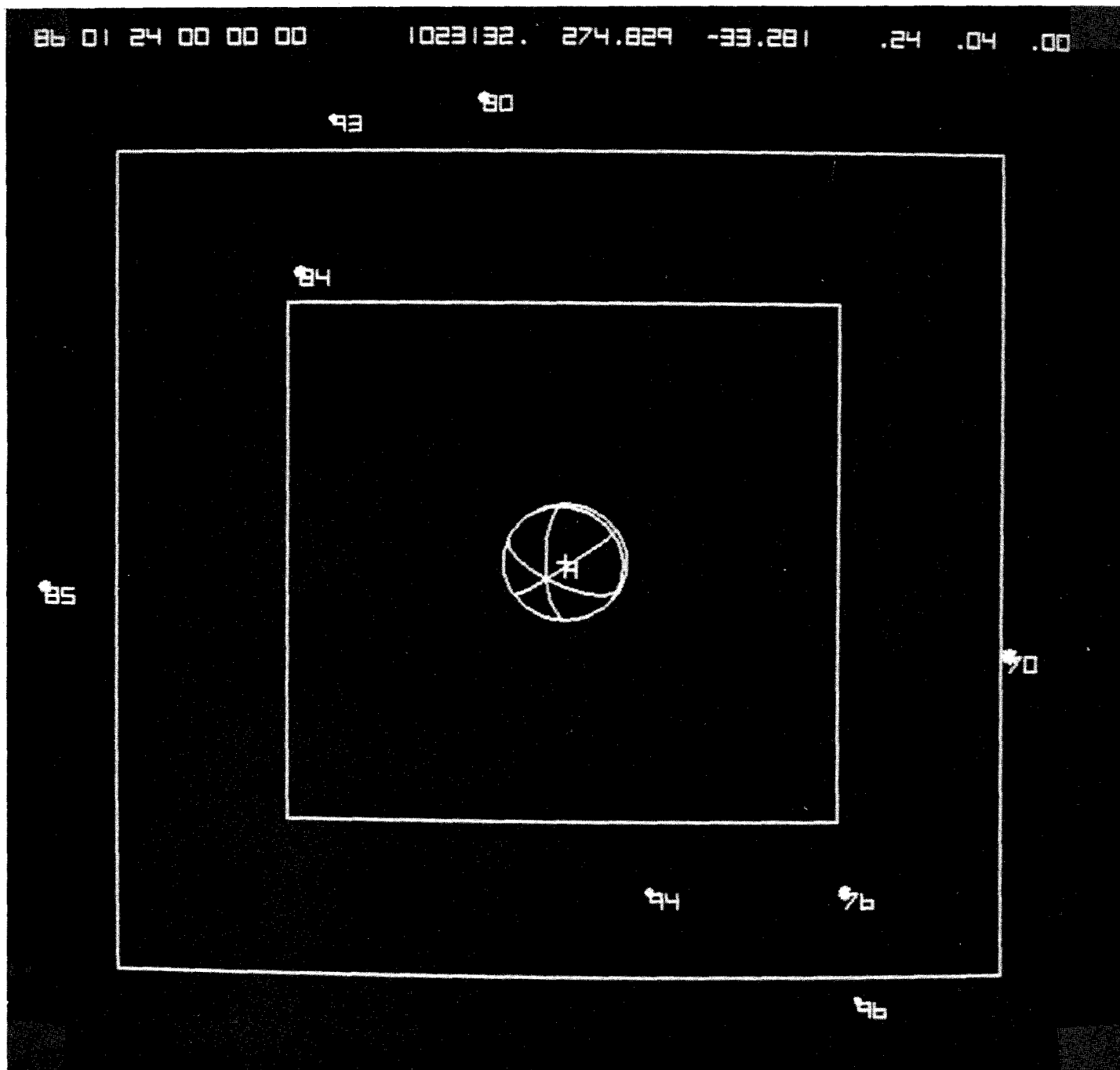
The Chromatics has 8 bezel keys and a joystick. These are the interactive input devices which the user operates to control vip and gip. Most of their capacity is utilized, but there is room to add more functions for them to perform. The operation of the bezel keys and joystick will be explained in the user's guide section of this paper.

#### II.2 Output

##### II.2.1 Chromatics Monitor

The scenes calculated by vip and gip are displayed on the Chromatics 19 inch color monitor (raster device). It draws sharp, pleasant pictures and has a resolution of 1024 horizontally by 768 vertically. Just as with the Picture System Monitor, the planet, satellites, spacecraft and stars may be displayed. In addition, 2 boxes representing camera field ( $.424^{\circ}$ ) and  $3\sigma$  pointing error ( $.682^{\circ}$  for Voyager and  $.814^{\circ}$  for Galileo) are drawn. At the top of the screen may be displayed calendar date (E.T.), distance to observed body (km), pointing angles in right ascension and declination (degrees), and star capture probabilities for 1, 2, and 3 stars.

On the following pages are actual displays from the monitor. These black and white pictures were of course made from the original color. The camera field boxes and all text are green. The stars are colored according to spectral class: O and B = blue, A = light blue, F = white, G = yellow, K = pink, M = red, unknown = green. For the satellites, Io and Miranda are blue, Europa and Ariel are green, Ganymede and Umbriel are light blue, Callisto and Titania are red, and Oberon is pink. For the planets Jupiter is pink, Uranus is yellow.

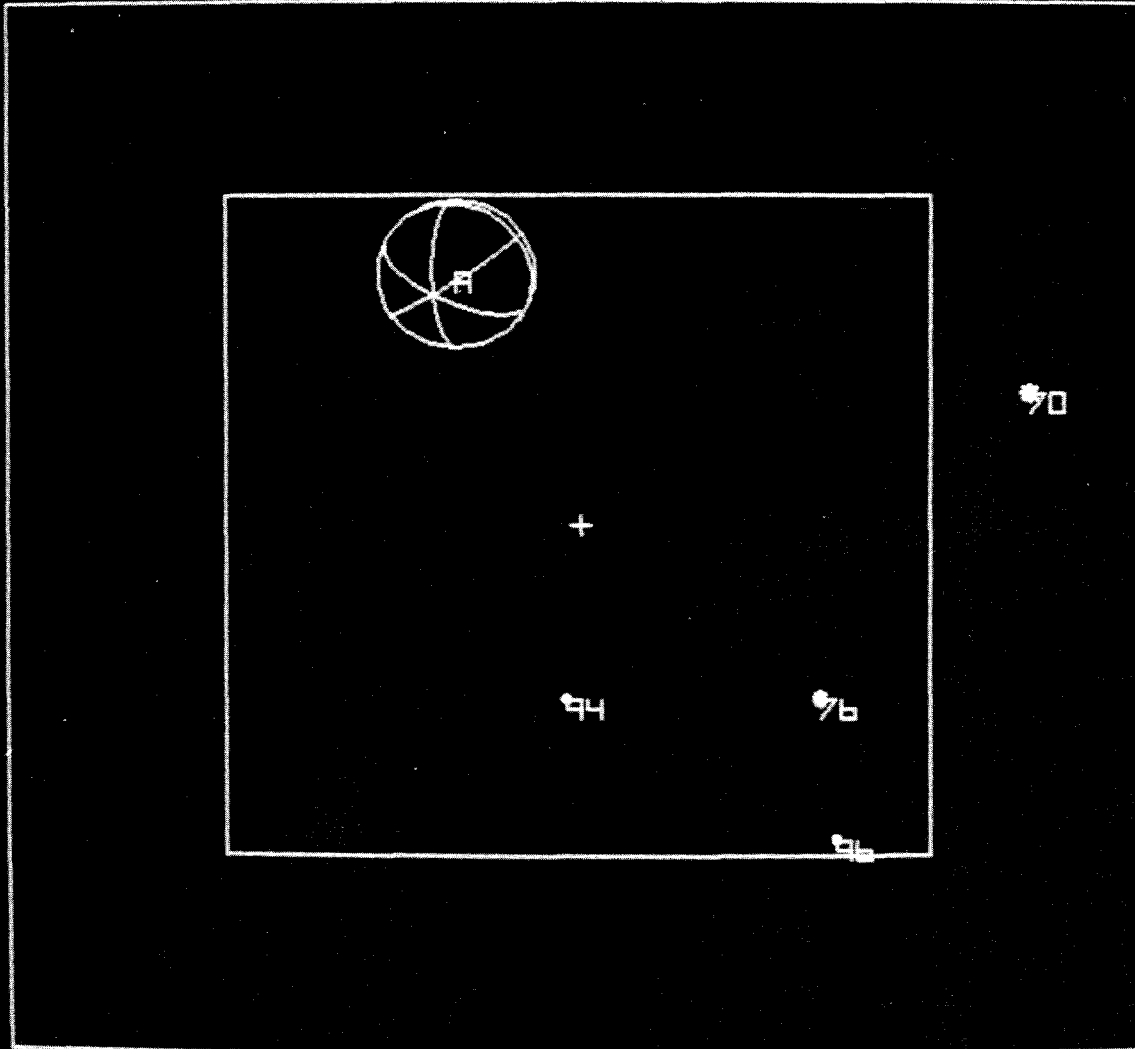


This is a view of Ariel during the Voyager Uranus encounter. Note that the camera is pointed directly at the satellite and there is only a .24 probability of capturing 1 star, and only a .04 probability of capturing 2 stars with the satellite.

86 01 24 00 00 00 1023132. 274.740 -33.441 .87 .82 .46

84

85



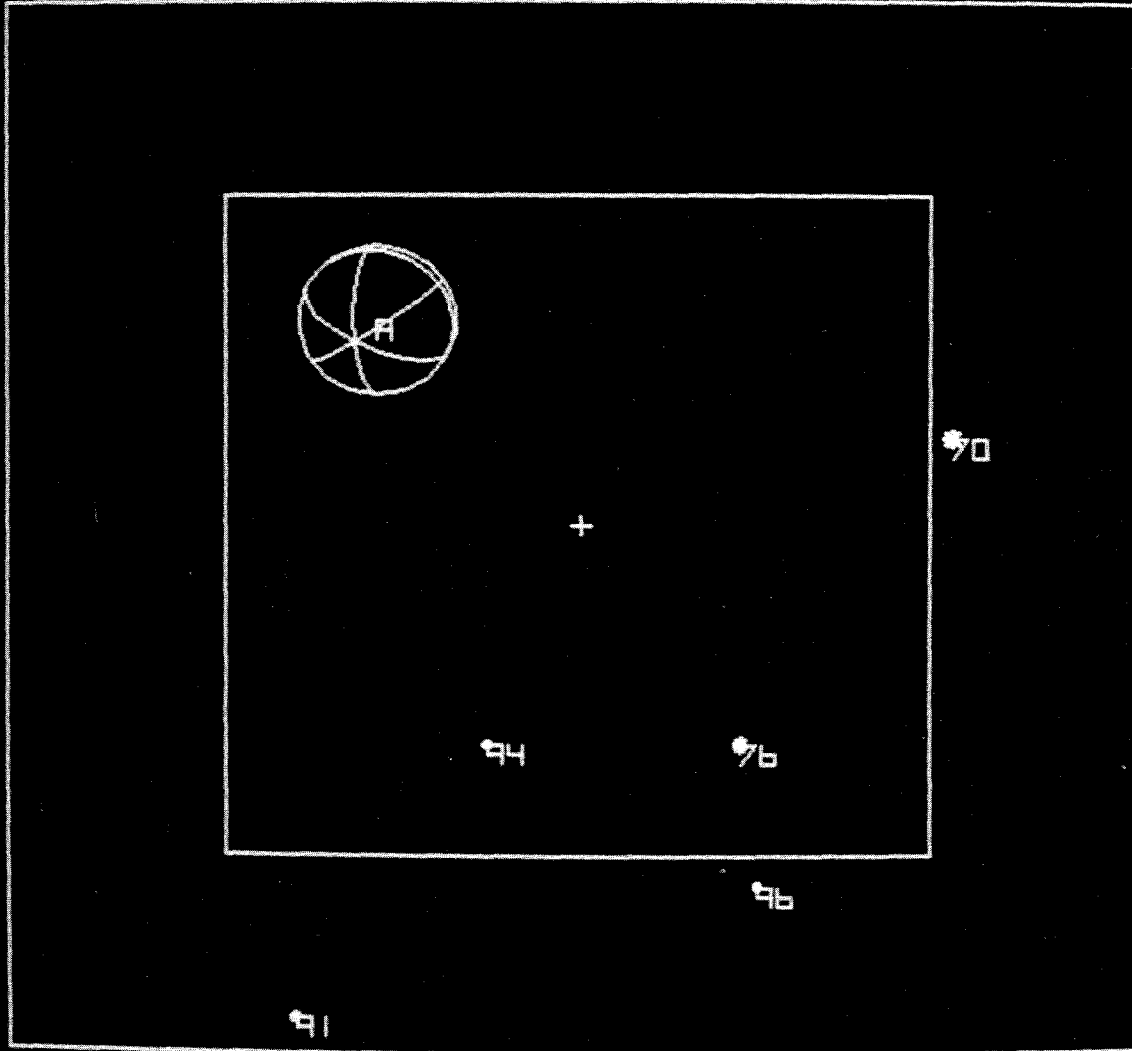
This is the same scene as shown on the previous page. However, the program has automatically pointed the camera. Note the great improvement in star capture probabilities.

86 01 24 00 00 00

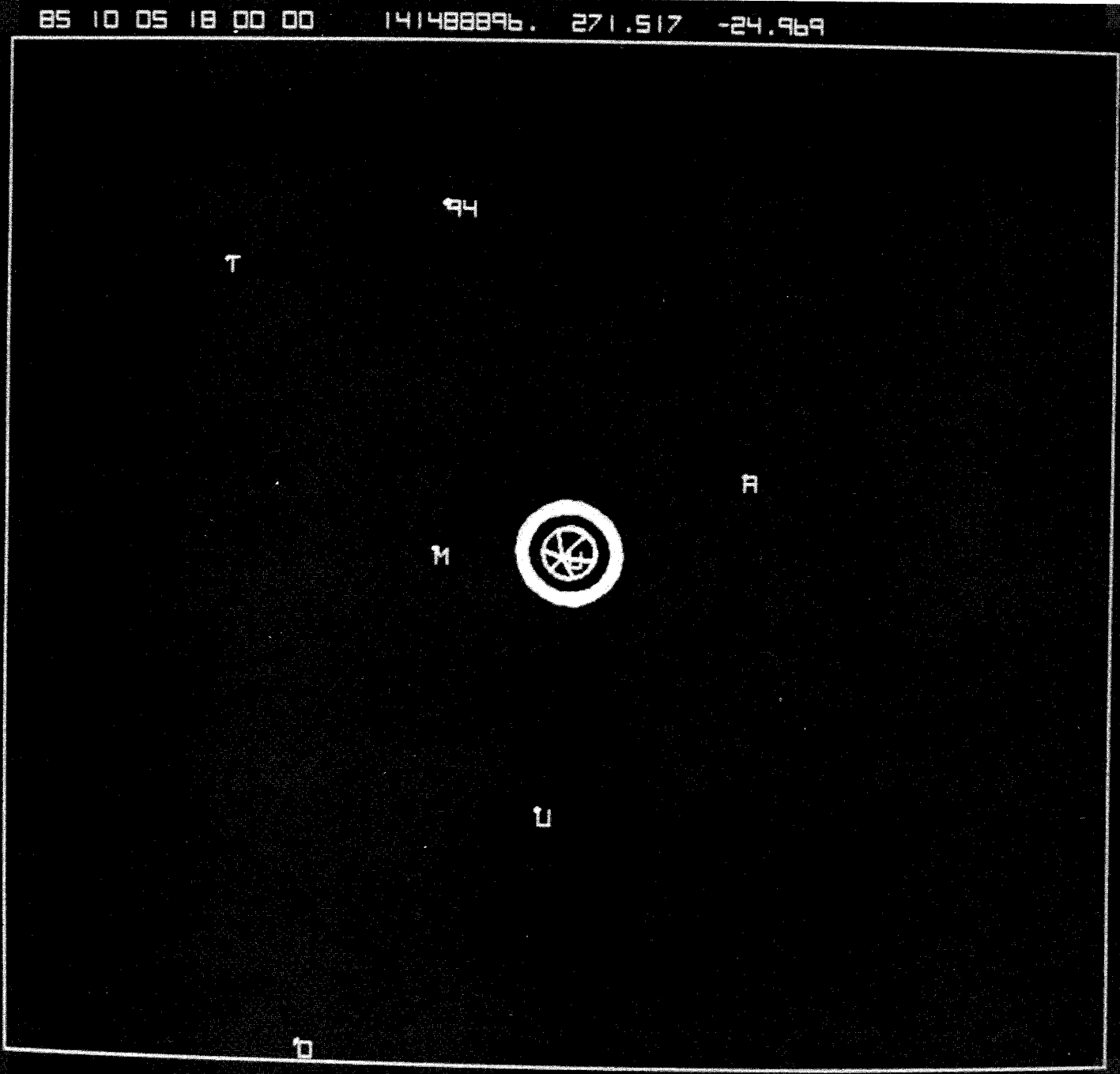
1023132. 274.683 -33.412

.92 .90 .50

84



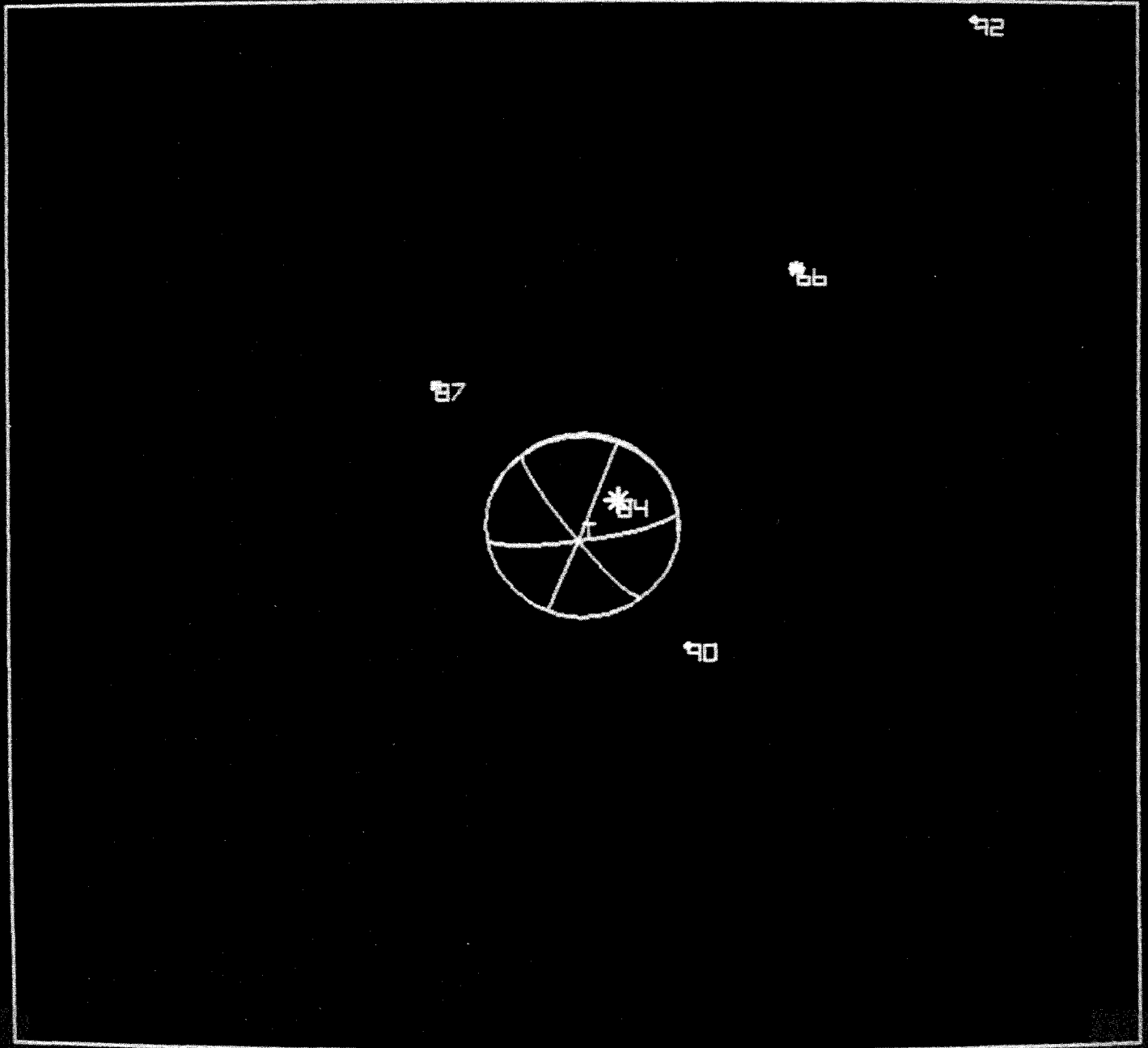
This is the same scene as shown on the previous two pages. Here, however, the user has manually adjusted the pointing. Note the small improvement over auto-pointing.



This is what some of the early pictures from the Voyager Uranus encounter will look like. Note the date in the upper left hand corner. All five of the satellites are seen.

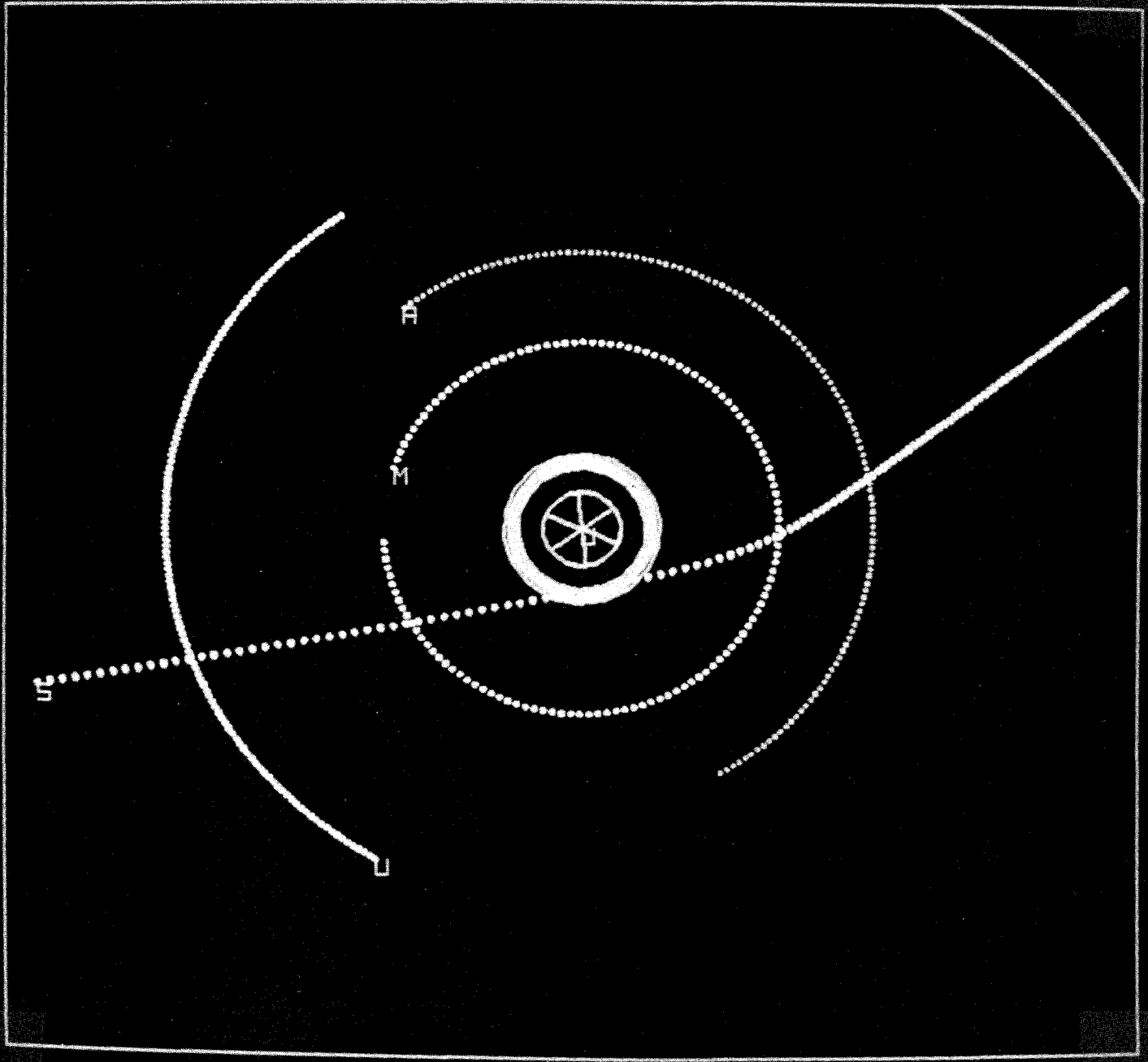


86 01 23 11 30 00 1603423. 259.747 -24.962

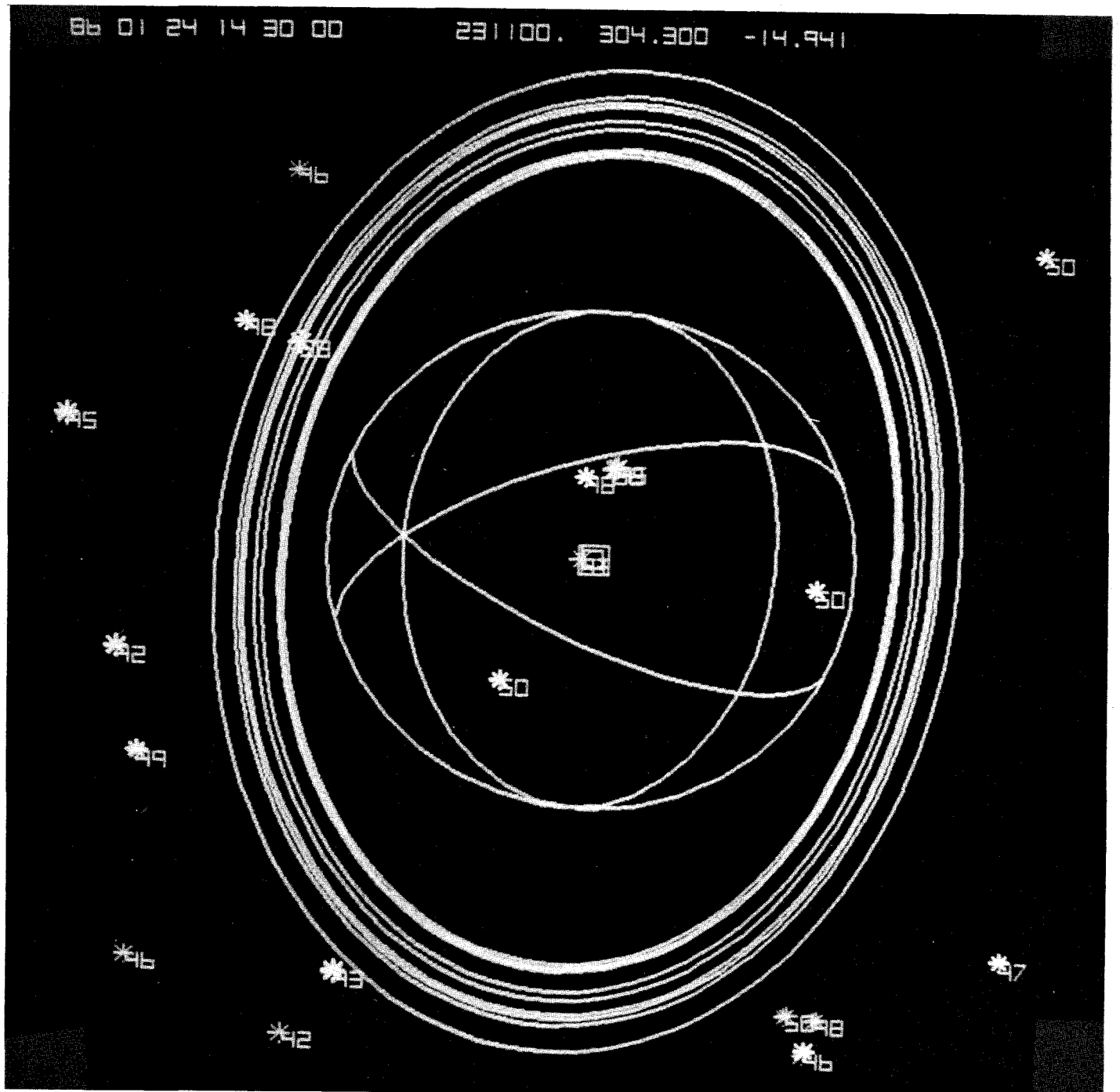


This is the occultation of 3.4-magnitude Theta Ophiuchi by Titania predicted by Bill Owen (Ref. 8). The time is a little more than a day before encounter.

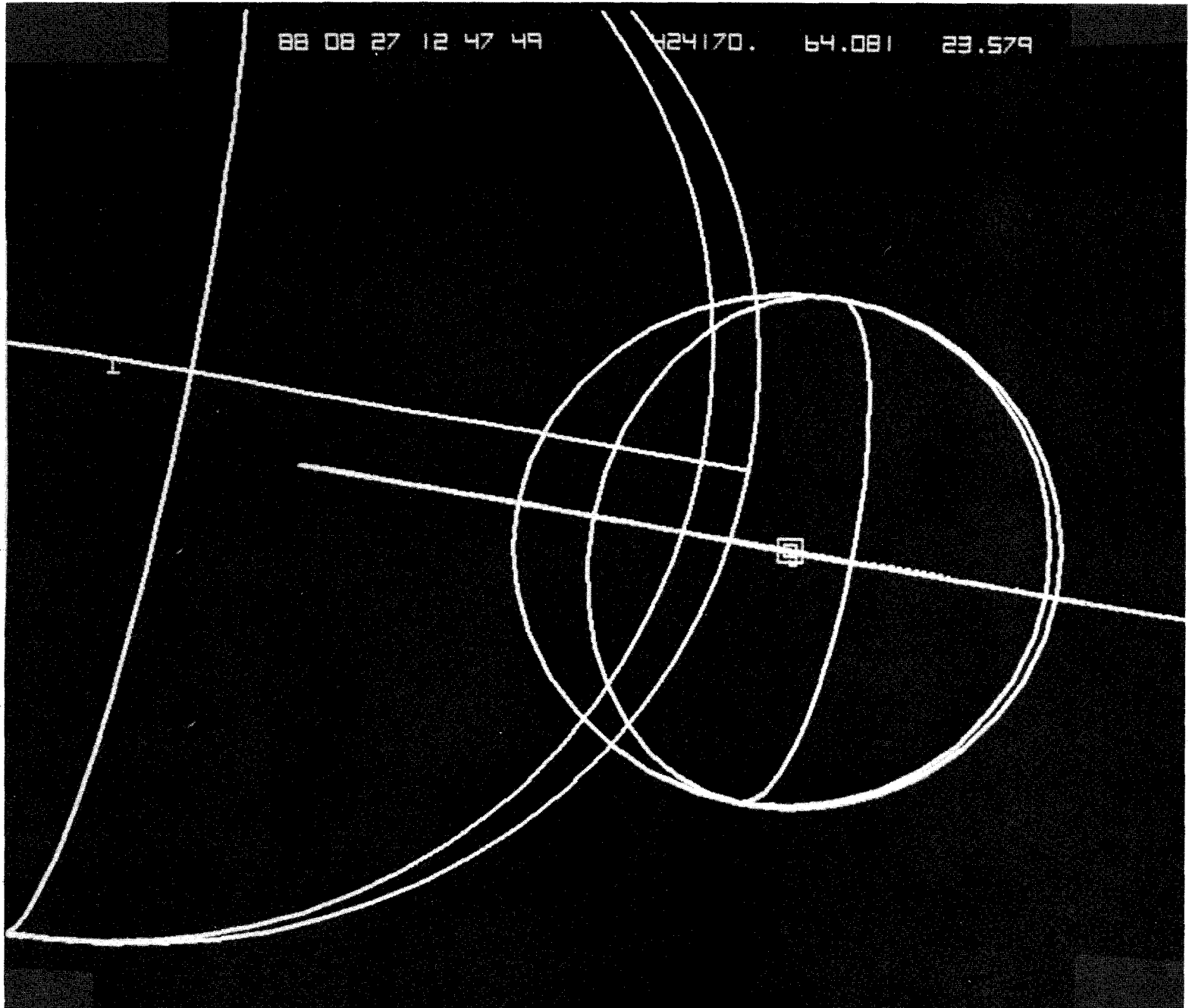
86 01 25 07 45 00 100000016. 256.761 -14.920



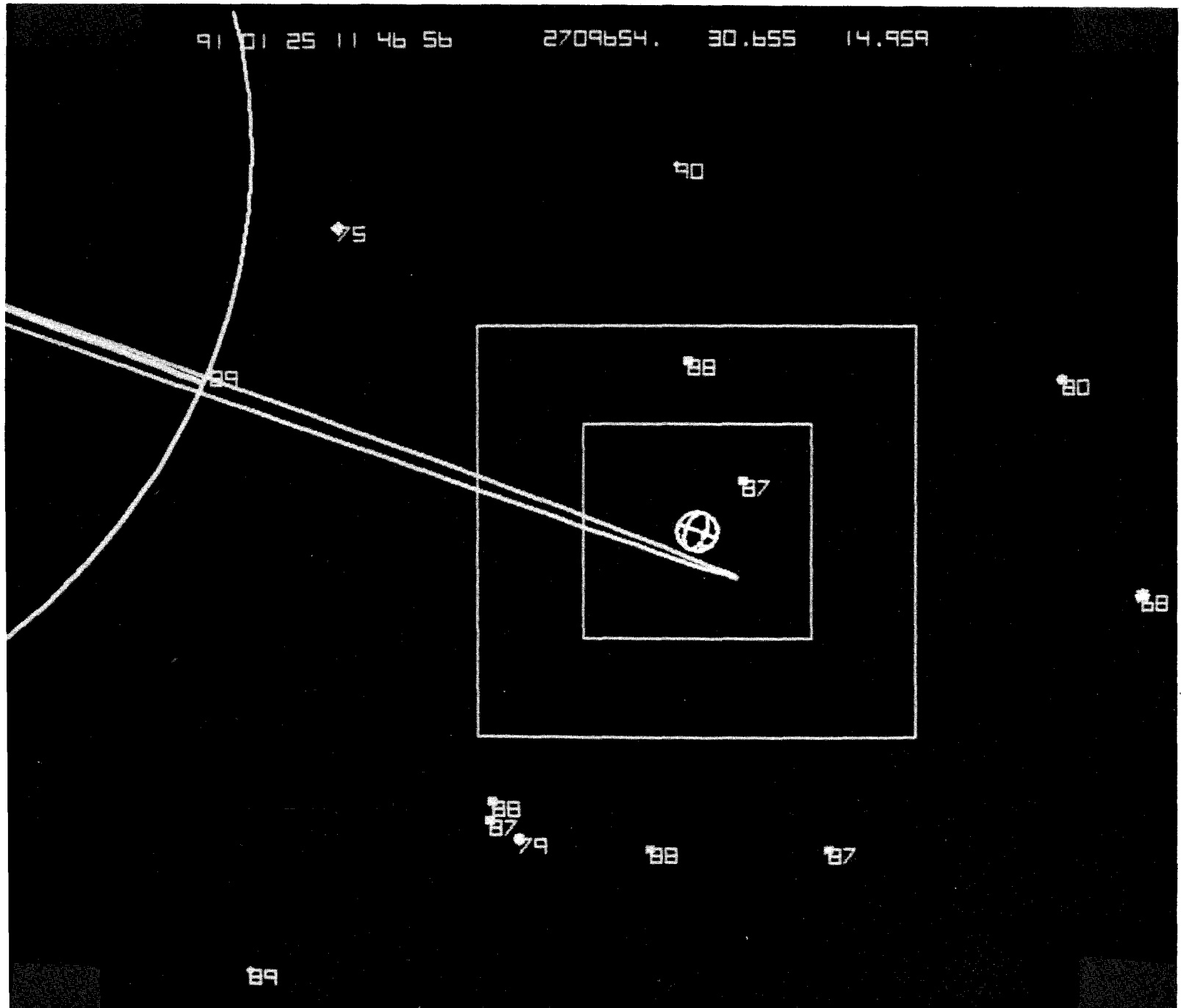
This is a view of the encounter by an observer over the N. pole of Uranus. Note the track of the Voyager spacecraft.



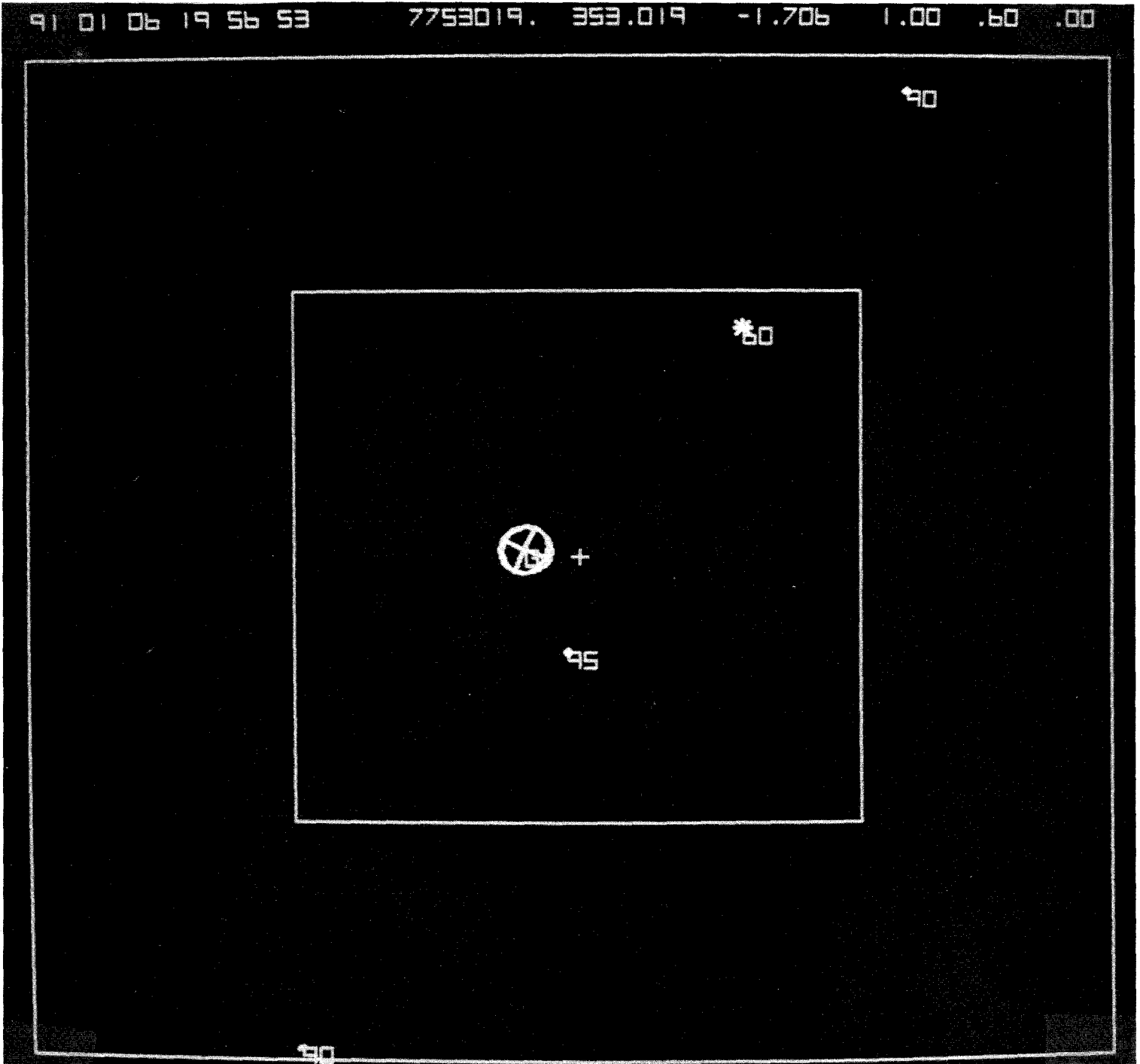
These are some of the bright stars which will pass through Uranus' rings near encounter. The time is only 3-1/2 hrs. before encounter.



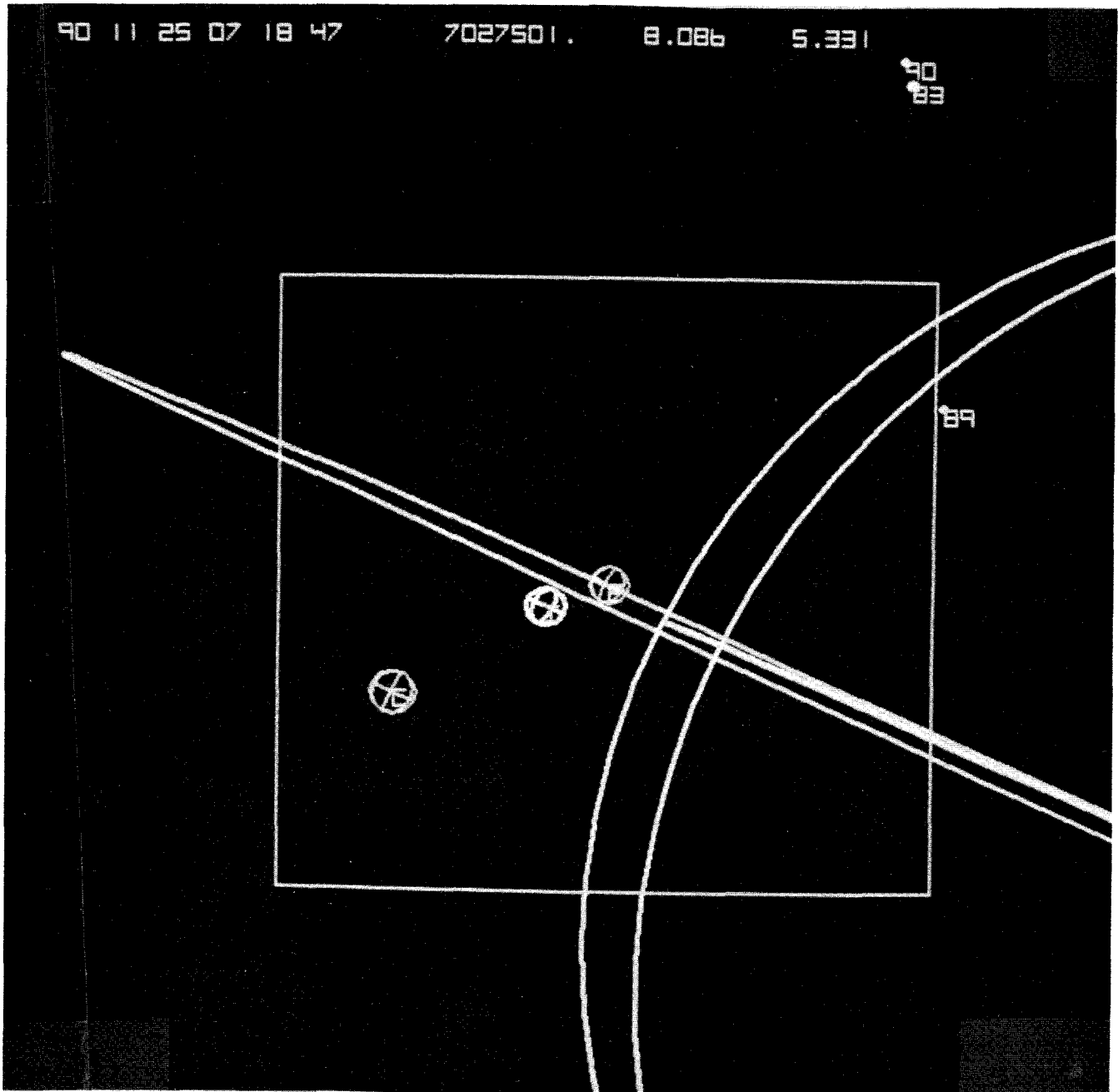
This is a very wide field view from the Galileo spacecraft as it approaches Jupiter just before the Io fly-by.



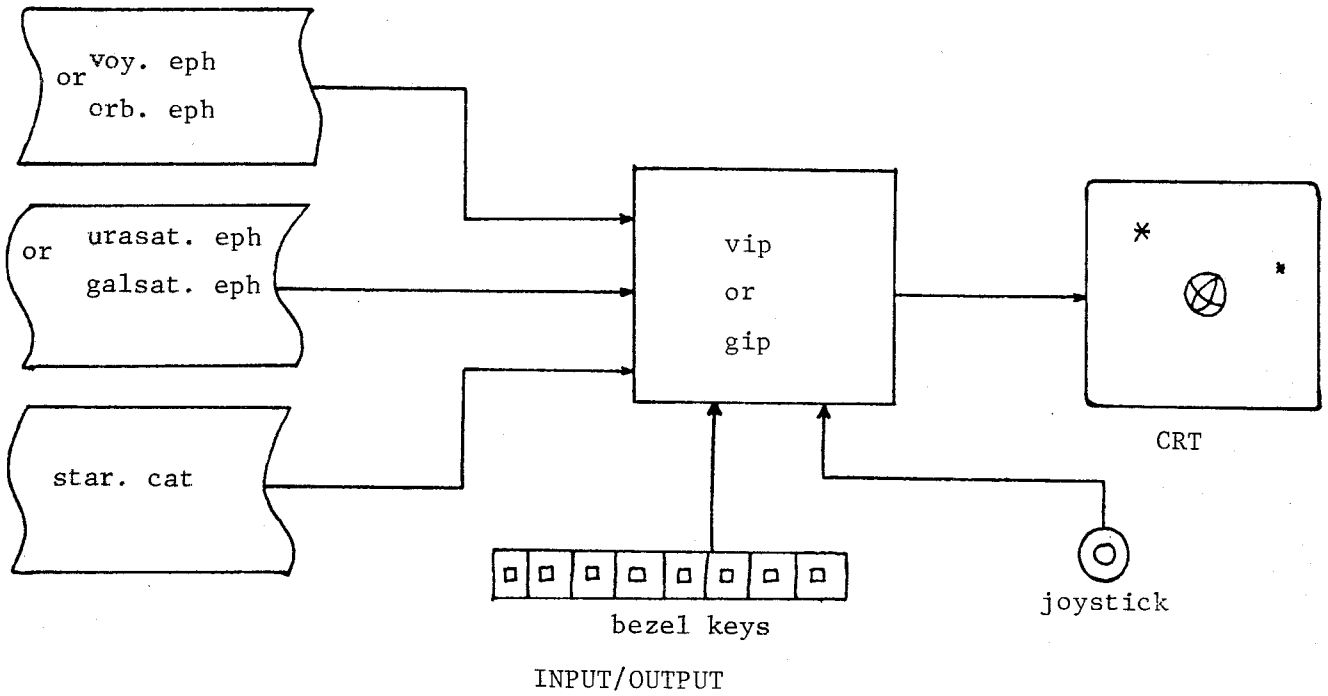
Once Galileo is in orbit, gip will be used to analyze scenes like this one.



This is the equivalent scene as that given in Refs. 1 and 2. (Ganymede G4 encounter, 82-06 mission, view from spacecraft).



Since gip calculates scenes so rapidly, it essentially "sees" in a continuum. This allows it to make interesting discoveries, such as this rare occurrence of three satellites near the limb of Jupiter.



The Chromatics



### III. Program Validity

Vip and gip have been extensively checked out against VUGEOM. The results show that the two programs are in excellent agreement. Picture coordinates of bodies and stars are the most important factor, and these usually agree to within a few pixels. This is a pleasant and surprising result, because the interactive programs were written to be fast and give an approximate idea. They are almost entirely single precision and contain many approximations and new methods (see theory section). On the following pages is given a comparison between VUGEOM and vip for Voyager for arbitrarily chosen points.  $N^*$  is the number of stars which have any chance of being captured with the satellite.  $P_1$ ,  $P_2$ , and  $P_3$  are the probabilities of capturing 1, 2, or 3 stars with the target satellite. The satellite is always at the center of the field in this example..

### VUGEOM, Vip Comparison

Sat	Date (e.t.)	Prog	Range	R.A.	Dec	N*	P1	P2	P3
M	86/01/14 19:20:00	VUG	12744790.	271.475	-24.887	3	.82	.43	.02
		Vip	12744757.	271.475	-24.887	3	.81	.41	.02
M	86/01/17 07:00:00	VUG	9629878.	272.260	-25.563	1	.14	.00	.00
		Vip	9629851.	272.260	-25.563	1	.13	.00	.00
M	86/01/20 21:40:00	VUG	4973385.	273.679	-23.296	7	1.00	.97	.56
		Vip	4973381.	273.680	-23.296	7	1.00	.97	.57
M	86/01/23 15:40:00	VUG	1438765.	277.119	-18.808	4	.96	.14	.00
		Vip	1438759.	277.119	-18.808	4	.96	.14	.00
M	86/01/26 18:35:00	VUG	2590633.	109.975	20.389	2	.52	.06	.00
		Vip	2590624.	109.975	20.389	2	.52	.05	.00
M	86/01/31 04:50:00	VUG	8245284.	113.660	18.368	6	.94	.56	.21
		Vip	8245281.	113.660	18.368	6	.93	.54	.22
M	86/02/03 10:55:00	VUG	12514854.	115.008	18.269	4	.97	.85	.05
		Vip	12514839.	115.008	18.269	4	.97	.84	.05
A	86/01/04 20:20:00	VUG	25427198.	271.693	-24.506	3	.92	.64	.19
		Vip	25427192	271.693	-24.506	3	.93	.66	.21
A	86/01/10 00:00:00	VUG	18873698.	271.943	-24.326	2	.11	.00	.00
		Vip	18873678.	271.943	-24.326	2	.10	.00	.00
A	86/01/17 05:00:00	VUG	9652977.	271.437	-24.072	5	.99	.65	.00
		Vip	9652956.	271.437	-24.072	5	.99	.66	.00
A	86/01/23 15:00:00	VUG	1559767.	280.683	-29.654	9	1.00	1.00	.98
		Vip	1559755.	280.684	-29.654	9	1.00	1.00	.98
A	86/01/27 00:00:00	VUG	3051849.	115.813	19.043	3	.35	.15	.00
		Vip	3051850.	115.813	19.043	3	.36	.16	.00
A	86/02/14 18:00:00	VUG	26788885.	114.632	18.743	1	.38	.00	.00
		Vip	26788866.	114.632	18.743	1	.40	.00	.00
A	86/02/23 00:00:00	VUG	37387580.	114.942	18.257	6	.99	.95	.42
		Vip	37387556.	114.942	18.257	6	.99	.94	.43

### VUGOM, Vip Comparison

Sat	Date (e.t.)	Prog	Range	R.A.	Dec	N*	P1	P2	P3
U	86/01/04	VUG	25513939.	271.916	-25.489	3	.95	.51	.00
	20:30:00	Vip	25513936.	271.916	-25.489	3	.94	.50	.00
U	86/01/10	VUG	18292131.	271.084	-24.619	5	1.00	.59	.03
	10:00:00	Vip	18292108.	271.084	-24.619	5	1.00	.60	.03
U	86/01/18	VUG	7662540.	270.618	-23.994	7	.88	.56	.17
	18:00:00	Vip	7662509.	270.618	-23.994	7	.87	.55	.16
U	86/01/23	VUG	1346524.	278.917	-12.446	4	.83	.30	.02
	17:50:00	Vip	1346528.	278.917	-12.446	4	.83	.31	.02
U	86/01/27	VUG	3094460.	116.856	20.589	1	.96	.00	.00
	00:00:00	Vip	3094461.	116.856	20.589	1	.96	.00	.00
U	86/02/07	VUG	17132441.	114.664	17.742	3	.34	.04	.00
	03:00:00	Vip	17132412.	114.664	17.742	3	.34	.04	.00
U	86/02/13	VUG	25542281.	114.700	19.101	2	1.00	.93	.00
	18:00:00	Vip	25542262.	114.700	19.101	2	1.00	.93	.00
T	86/01/05	VUG	24318610.	270.754	-25.275	6	.54	.18	.00
	16:30:00	Vip	24318576.	270.754	-25.275	6	.53	.19	.00
T	86/01/11	VUG	17414001.	273.238	-25.582	4	1.00	.93	.27
	06:30:00	Vip	17413972.	273.238	-25.582	4	1.00	.94	.27
T	86/01/15	VUG	11365345.	270.387	-23.510	8	1.00	1.00	.96
	19:30:00	Vip	11365315.	270.387	-23.510	8	1.00	1.00	.96
T	86/01/23	VUG	1329801.	257.670	-22.074	2	.02	.00	.00
	16:30:00	Vip	1329797.	257.670	-22.074	2	.01	.00	.00
T	86/01/27	VUG	3375361.	107.148	22.136	4	.97	.43	.33
	12:00:00	Vip	3375345.	107.148	22.136	4	.97	.43	.35
T	86/02/04	VUG	13652599.	113.749	20.126	5	.73	.40	.11
	12:00:00	Vip	13652573.	113.749	20.126	5	.73	.39	.10
T	86/02/13	VUG	24675815.	114.450	19.420	2	1.00	.00	.00
	03:00:00	Vip	24675794.	114.450	19.420	2	1.00	.00	.00

### VUGEOM, Vip Comparison

Sat	Date (e.t.)	Prog	Range	R.A.	Dec	N*	P1	P2	P3
0	86/01/04	VUG	25488084.	273.103	-24.444	4	.56	.03	.00
	22:00:00	Vip	25488076.	273.103	-24.444	4	.57	.03	.00
0	86/01/11	VUG	17067846.	270.041	-25.798	6	1.00	.93	.31
	09:00:00	Vip	17067818.	270.041	-25.798	6	1.00	.93	.32
0	86/01/19	VUG	7433331.	277.350	-24.572	3	.66	.16	.01
	03:00:00	Vip	7433328.	277.350	-24.572	3	.66	.17	.01
0	86/01/23	VUG	1416909.	260.334	-43.513	1	.20	.00	.00
	18:00:00	Vip	1416906.	260.334	-43.513	1	.18	.00	.00
0	86/01/26	VUG	3129608.	121.506	23.038	2	.15	.00	.00
	21:00:00	Vip	3129606.	121.506	23.038	2	.14	.00	.00
0	86/01/31	VUG	7993918.	111.753	21.746	5	1.00	.90	.11
	03:00:00	Vip	7993895.	111.753	21.746	5	1.00	.90	.11
0	86/02/03	VUG	11945008.	112.759	16.936	4	.97	.88	.13
	06:00:00	Vip	11945036.	112.759	16.936	4	.97	.88	.14
		VUG							
		Vip							
		VUG							
		Vip							
		VUG							
		Vip							
		VUG							
		Vip							
		VUG							
		Vip							

## IV User's Guide

On the following pages is given a brief user's guide. It takes a little practice to become proficient with the bezel keys and joystick, so don't be discouraged if at first you have trouble controlling vip and gip.

As was explained earlier in this memo, vip and gip each read 2 ephemeris files, one for the spacecraft and one for the satellites. Vip and gip always read these files with names voy.eph, urasat.eph and orb.eph, galsat.eph respectively. In order to change the content of an ephemeris file one must copy another stored file into it. For example this may be done with the command % cp<sub>b</sub> new.eph<sub>b</sub> voy.eph, and should be done just before typing vip or gip as explained in IV.1.6 below. The following set of preliminary files are on the system. The satellite and the Voyager spacecraft files should be satisfactory. If one wishes to bring over new spacecraft files, he should contact me.

	<u>Voyager</u>	<u>Galileo</u>
satellites	us81.eph (1981 fit)  us83.eph (1983 fit - best)	galsat.eph (1978 fit - good)
spacecraft	bpb.txt (current)	e3.txt (old 82-06 mission) g4.txt (old 82-06 mission) rpd.txt (current approach)

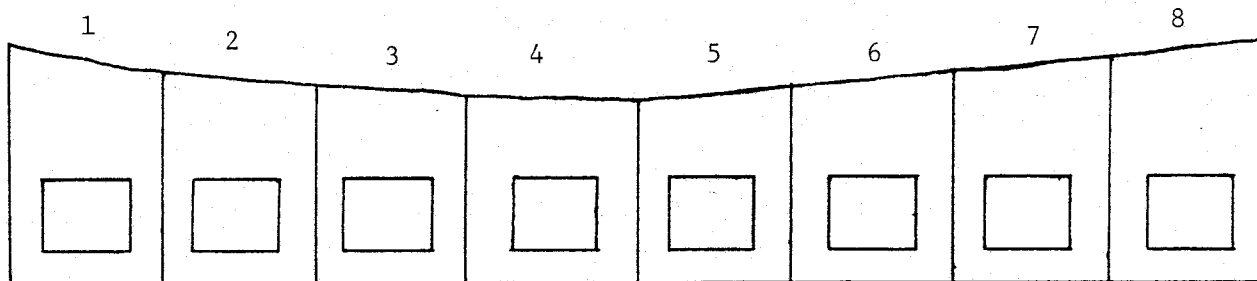
Operation of Vip and Gip on the Chromatics

IV.1 Startup

1. Turn on the Chromatics with the square white button to the right of the floppies and over the joystick.
2. Wait about 15 seconds for the little green light near the joystick to go out and for the system to warm up.
3. Push IDRIS key, which is in the upper set of keys on the left hand side.
4. Wait a few seconds as the system prints some messages and then prompts the user.
5. Make sure the ALPHA key is up (located to the left of the normal keyboard), type JDC, carriage return.
6. You are now logged on. Be sure to press the ALPHA key down and type 'vip' or 'gip', carriage return.
7. Vip or gip (Voyager or Galileo interactive picture planning program) will now be running. It may be controlled with the bezel keys and joystick as explained below.

IV.2 Operation

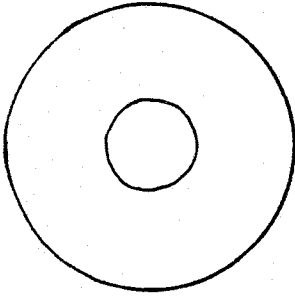
There are 8 bezel keys, which look like decorations, right below the 19 inch color monitor. When a bezel key is pushed it defines the function of the joystick. This function remains in effect until another bezel key is pushed. The bezel keys are shown below, and the corresponding joystick function is summarized on the next page, followed by more pages of explanation.



1

Increase Time

Time Change Sensitivity



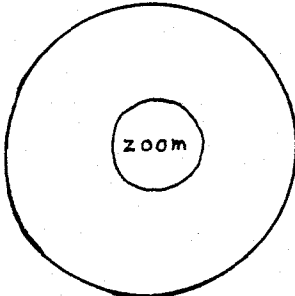
Stop Time

Decrease Time

2

Field of View =  $1.7^\circ$

Field of View =  $.848^\circ$ ; and Pointing Optimization



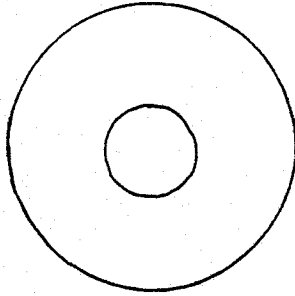
Field of View =  $.424^\circ$

Field of View =  $14.^\circ$

3

View from Position over North Pole

View from Spacecraft



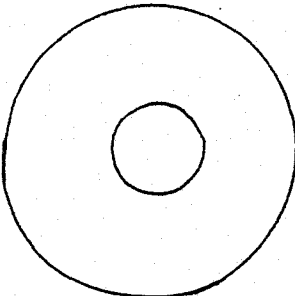
View from Spacecraft

View from Position over North Pole

4

Stop Program

Input Calendar Date



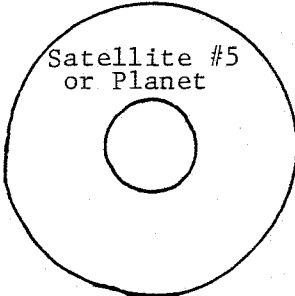
Input Step time (seconds)

Star Magnitude Limit

5

Satellite #3

Satellite #2



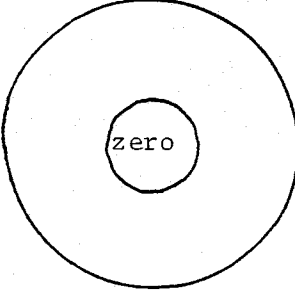
Satellite #1

Satellite #4

6

Change DEC Negative

Change RA Negative



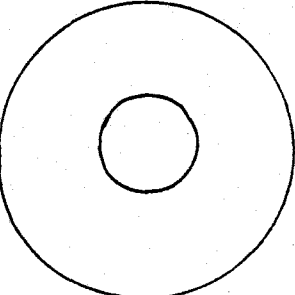
Change RA Positive

Change DEC Positive

7

Remove all Labelling

Display time, Pointing, Distance, Stars and Bodies



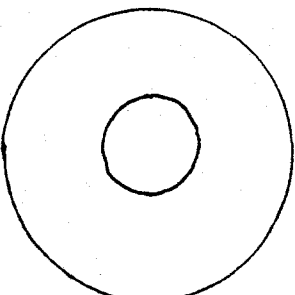
Display Time, Pointing, Distance

Remove all Labeling

8

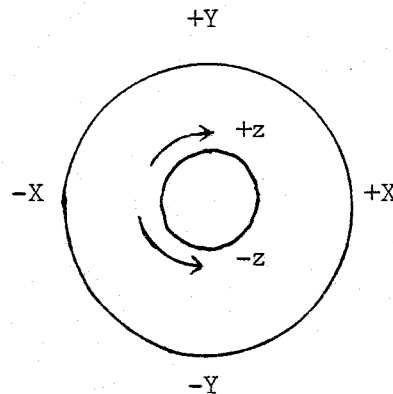
Erase Previous Scenes

Do not draw Grids



Draw Grids

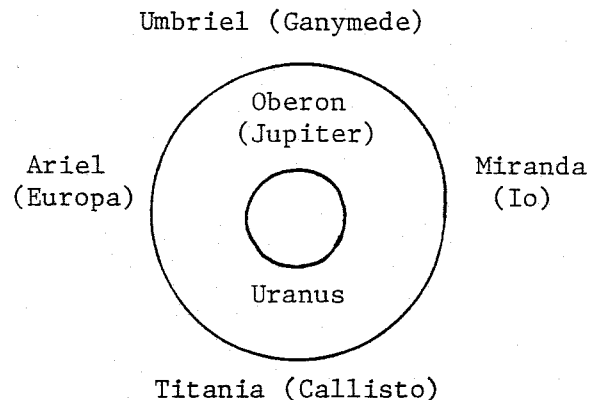
Do not erase Previous Scenes



### The Joystick

1. Bezel key #1 controls time. Pushing the joystick in the +Y or -Y direction increases or decreases the delta time at which the scene is changing. The position of the joystick in the -X direction is also very important, because it affects the sensitivity in the Y directions. Pushing the stick in the +X direction will stop time.
2. Bezel key #2 controls the field of view of the scene. Pushing only in the +X direction will give a field of view of .424 degrees, which is the Voyager camera field. Pushing only in the -X direction will give a field of  $.948^{\circ}$ , and at the same time star capture probabilities will be displayed for an optimized pointing. This pointing may be manually adjusted with Bezel Key #6, see below. Pushing in only the +Y direction will give a field of  $1.7^{\circ}$ . While pushing only in the -Y direction will give  $14^{\circ}$ . In the latter, stars are not displayed because there would be so many. The field of view may be continuously adjusted (zooming) with the joystick knob ( $\pm Z$ ).
3. Bezel key #3 controls the position of the observer. If the joystick is pushed in either a +X or -X direction the scene shown will be that from the spacecraft. If the stick is pushed in either a +Y or -Y direction the scene will be that of an external observer over the north pole of the planet at a distance of 100,000,000 kilometers.
4. Bezel key #4 can be used to stop the program by pushing in a +Y direction. Also the key may be used to input a time. If the joystick is pushed in a -X direction, the program will ask the user for a calendar date (E.T.). Once entered the program will display the scene at this time. Similarly, in the +X direction the user may input a delta time in seconds. In the -Y direction a star magnitude limit may be input.
5. Bezel key #5 is used for pointing. The normal, unadjusted pointing of the scene will be determined by the joystick as shown below.





6. Bezel key #6 is for adjusting the pointing. Pushing the joystick in a +X or -X direction will increase or decrease the RA angle. Pushing in the +Y or -Y direction will decrease or increase the Dec angle. Placing the joystick in any position containing both a large X and Y component will zero the pointing, as will +Z.
7. Bezel key #7 controls labeling. Pushing in the +X direction will display the time, the pointing, and the distance to the body being observed. Star captured probabilities are always displayed if the field of view is  $.848^\circ$ . Pushing the stick in the -X direction will, in addition to the above, display the names of any bodies in the scene and label the stars with their visual magnitude. For example, 89 means 8.9th magnitude. Pushing in the +Y or -Y directions will remove labeling.

For the displayed quantities, time is given in calendar date, E.T., pointing is in right ascension and declination both in degrees, and distance is in kilometers. The spectral classes of the stars may be inferred from their colors: O,B = dark blue, A = light blue, F = white, G = yellow, K = light red, M = deep red, unknown = green.

8. Bezel key #8 controls whether grids (latitude, longitude, and rings) are drawn on the bodies, and also the key determines whether the scene is erased or not between draws. If the joystick is pushed in a +X direction, grids are drawn. If the stick is pushed to -X, grids are not shown. If the stick is pushed in the -Y direction, the scene is not erased. If the stick is pushed in the +Y direction, the scene is erased.

#### IV.3 Helpful Hints

Vip is very forgiving about user mistakes. However it will bomb if it is run outside allowable satellite file time ranges. Also, no other inputs besides the bezel keys and joystick should be attempted while vip or gip is running. The character delete is  $\leftarrow$ , while the line delete is @.

If for any reason the user loses control of program vip or gip do not PANIC, remain calm, and try the following procedures in order.

1. Push bezel key #4 and move the joystick in the +Y direction, hopefully stopping the program.
2. Push the DELETE key (located on the normal keyboard, lower right hand side). This should stop the program. Now to correctly reset the system hit or do not hit the following four keys so that they are lit or not lit as shown below:

OVERLAY	-	lit
CURSOR	-	lit
ROLL	-	lit
PLOT	-	not lit

3. Hold the SHIFT and CTRL keys down together and at the same time push, and release, the RESET key. While continuing to hold the SHIFT and CTRL keys down, note that a green light will come on near the joystick. Wait for the green light to go off and then release the SHIFT and CTRL keys. Now push the IDRIS key and proceed as given in IV.1.3.
4. If the system does not respond to any of the above, do not turn it off. Give up and contact me or Richard Weidner.

#### IV.4 Powering Down

To terminate a session, first push bezel key #4 and move the joystick in the Y direction. Next type sync, carriage return. Now hold the SHIFT and CTRL keys down together and at the same time push, and release, the RESET key. While continuing to hold the SHIFT and CTRL keys down, note that a green light will come on near the joystick. Wait for the green light to go off and then release the SHIFT and CTRL keys. Finally, to turn the Chromatics off, hit the white button described in IV.1.1.

#### IV.5 Additional Information

For now, the user should have no reason to work with or recreate the star, satellite and spacecraft files. In the future better Galileo spacecraft files will become available, but by the time they do, vip and gip will probably be configured differently.

However for the user who is interested in the programs which created the special files, the following summary is given.

Chevechev  
sat file

File PV. is on  
tape K2270 (EZIO),  
must be assigned  
as @ASG,T SATIRE\*KO,  
U9V, K2270

pfile or  
opus vary  
file

UNIVAC

PV.VP or  
PV.GP

PV.BPTL  
PV.GTL

formatted  
file

voy.eph or  
orb.eph  
(formatted)

S A O  
tapes

S F M

star.cat

S I F

SIF.DAT  
(formatted)

The star  
programs  
are in  
NAIFDISK:  
[JDC.STAR]

V A X

vsfm or  
gsfm

sfp

ursat.eph  
or  
galsat.eph

CHROMATICS

star.cat



The subroutine linkages for vip and gip are shown on the preceding page. The main programs and all the subroutines are written in fortran 77 except for hvgi and hvg. A brief description is given below. For more information see the code.

SUBROUTINE	DESCRIPTION
boxes	Calculates screen coordinates for camera field and pointing error ( $3\sigma$ ) boxes
bub	Calculates screen coordinates for center of bodies visible in field
ctime	Converts seconds past 1950.0 to calendar date
dcodi	Returns the individual digits of an I*4 number. For example 403 is returned as 0,0,0,0,0,0,0,4,0,3
drawp	Does the final picture draw after all coordinates have been calculated and stored in a buffer
drwnsg	Gets screen coordinates for a negative sign
drwnum	Gets screen coordinates for the digits 0-9
drwper	Gets screen coordinates for a period
erase	Immediately before drawp is called, erases the previous scene by drawing it in black
galorb	Calculates the position of the Galileo orbiter (1950.0 eme, barycentered, km).
getpar	Reads the bezel keys and joystick to obtain user interactive inputs which control vip and gip
grid	Calculates screen coordinates of latitude and longitude lines for visible bodies
grids	Prepares transformation matrices for grid above
hvg	An assembly routine which drives the graphics
hvgi	An assembly routine which drives the graphics
jupsat	Calculates the positions of the four Galelian satellites (1950.0 eme, barycentered, km).

SUBROUTINE	DESCRIPTION
mul	Multiplies two 3x3 matrices
mult	Multiplies one 3x3 matrix with the transpose of another 3x3 matrix
mulv	Multiplies a 3x3 matrix with a 3x1 vector
nufam	Does final preparation and draw of new scene from calculated picture coordinates
pfunc	Probability routine
pltmde	Causes system to go from terminal mode to plot mode and visa versa
plusc	Gets screen coordinates for a '+' at center
punn	Probability routine
point	Adjusts nominal target body pointing in order to maximize star capture probabilities
pstr	Calculates the probabilities of capturing one, two, and three stars with the target body
rget	Returns the record number within the star file (star.cat) for an input R.A. and Dec
rot	Constructs a 3x3 rotation matrix
sat7	Calculates the positions of the five moons of Uranus (1950.0 eme, barycentered, km).
sdisp	Calculates screen coordinates for stars
stor	Stores in a buffer the final form of the picture data
sup	Calculates screen coordinates for all stars within the field
untime	Converts calendar date to seconds past 1950.0

VI. Theory

The fast geometrical method for obtaining screen coordinates has changed little from ref. 1. However, the Chromatics is a simple 2-D raster device with X coordinate running from left to right between 0-1024 and Y coordinate running from top to bottom between 0-767. There are no hardwired 3-D transformations as with the Picture System 2. For the new versions of vip and gip, therefore, all the calculations are done in software. Whereas before some of the transformations were done in hardware. This is particularly true for orienting and drawing the grids as described on page 25 of Ref. 1. By the way, that equation is incorrect and should read

$$\begin{bmatrix} \delta_T + 90 \\ \alpha_T + 180 \end{bmatrix}_2 \begin{bmatrix} 90 - \delta_J \\ \alpha_J \end{bmatrix}_3 \left\{ \begin{bmatrix} 90 - \delta_J \\ \alpha_J \end{bmatrix}_2 \begin{bmatrix} \alpha_J \end{bmatrix}_3 \right\}^T \begin{bmatrix} -\ell \end{bmatrix}_3$$

The old versions of vip and gip on the Picture System used numerical integration to obtain spacecraft positions and chebvychev polynomial evaluation to obtain satellite positions. Both of these have been replaced by new, faster simpler methods that have never been tried before in any of our software. Because the Chromatics is more or less simply a 'super micro' computer with only a Motorola 68000 chip for the CPU, it does not have vast 'number crunching ability'. In order to make vip and gip run fast it was necessary to try some radical but simple new ideas. It is somewhat amazing that the new methods work as well as they do.

The spacecraft ephemeris is modelled as uniform straight-line motion between a set of points taken from the actual trajectory. The points are chosen such that the departure from straight-line motion caused by the gravitational attraction of the planet and sun cause a field of view error at the target body always less than .001° (.000017 radians). If a point has been chosen at time  $t_n$  then the next point will be chosen at  $t_{n+1}$  according to the equations (refer to Fig. 1)

$$\Delta R = \frac{1}{2} a (t_{n+1} - t_n)^2$$

$$E = \frac{\Delta R}{2 \left| \vec{r}_n \right|} \quad (\text{typically } E = .001^\circ)$$

$$a = \frac{GM_p}{\left| \vec{r}_n \right|^2} + \left| \frac{GM_s}{\left| \vec{r}_c \right|^2} - \frac{GM_s}{\left| \vec{r}_p \right|^2} \right|$$

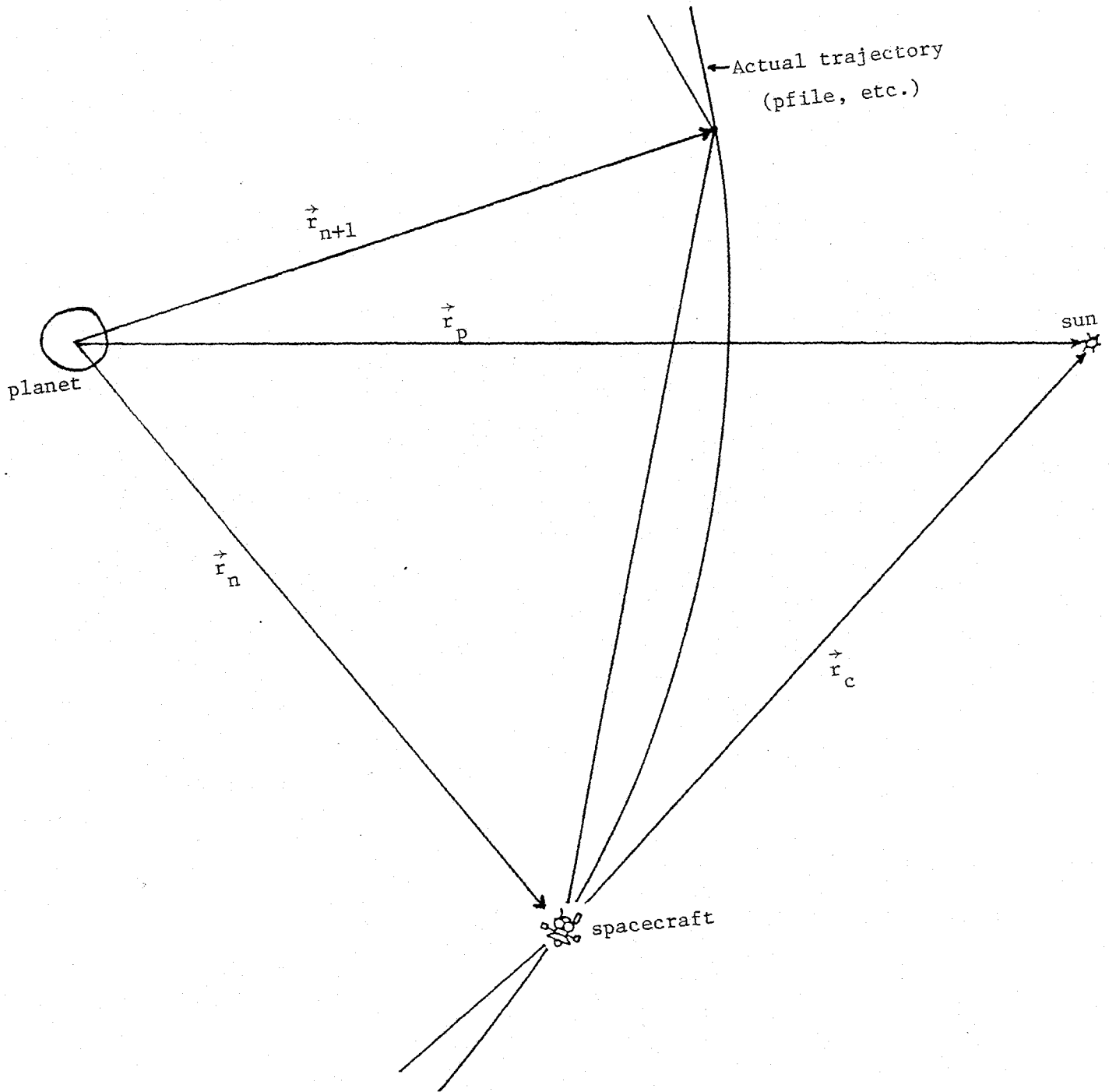


FIGURE 1



where

$\Delta R$  = magnitude of S/C error  
 $a$  = maximum magnitude of gravitational acceleration on S/C  
 $E$  = field of view error at target body as seen from S/C  
 $\vec{r}_n$  = position vector of spacecraft at  $t_n$   
 $\vec{r}_{n+1}$  = position vector of spacecraft at  $t_{n+1}$   
 $\vec{r}_c$  = position vector of sun WRT spacecraft  
 $\vec{r}_p$  = position vector of sun WRT planet  
 $G$  = gravitational constant  
 $M_p$  = mass of planet  
 $M_s$  = mass of sun

Using this method the entire Voyager Uranus encounter spanning approximately 7 months from Oct. 1985 to April 1986 may be represented by a set of only 200-300 spacecraft positions and times. This is few enough that they need be read and stored in vip only once. Then when a spacecraft position is desired it may be calculated with the simple equations

$$\vec{r} = \vec{r}_n + \vec{v}(t - t_n)$$

where

$$\vec{v} = \frac{\vec{r}_{n+1} - \vec{r}_n}{t_{n+1} - t_n}$$

Of course  $t$  must be between  $t_{n+1}$  and  $t_n$  but this is a trivial calculation.  $\vec{v}$  is not recalculated unless  $t$  moves between a different pair of times.

The calculation of satellite ephemerides is a little more complicated than the above but follows the same principle of straight line motion. Points are taken from an actual orbit (usually a chevycyevy file) and uniform straight line motion is used to calculate a position between the points. However instead of using this position one further correction is made. The length of the position vector is adjusted to match a length based on the linear rate of change of length between  $t_n$  and  $t_{n+1}$ . Therefore to calculate a satellite position,  $\vec{r}$ , at time,  $t$  between  $t_n$  and  $t_{n+1}$ , the following simple equations are used.

$$\vec{r} = \frac{\vec{r}_0}{|\vec{r}_0|} R \quad (1)$$

where

$$R = |\vec{r}_n| + \dot{r} (t - t_n) \quad (2)$$

$$\dot{r} = \frac{|\vec{r}_{n+1}| - |\vec{r}_n|}{t_{n+1} - t_n} \quad (3)$$

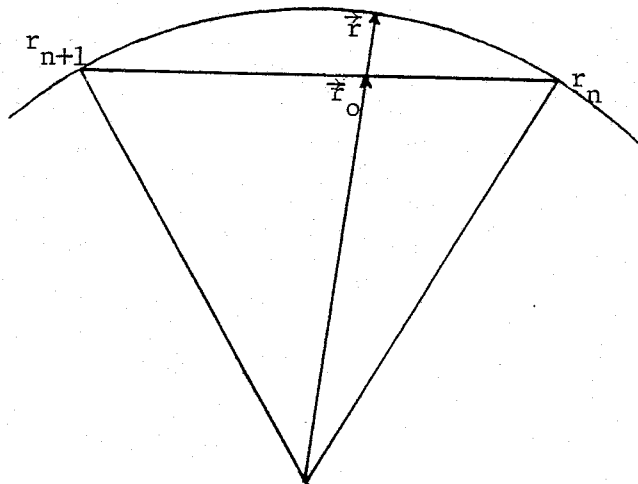
and

$$\vec{r}_o = \vec{r}_n + \vec{v}(t - t_n) \quad (4)$$

$$\vec{v} = \frac{\vec{r}_{n+1} - \vec{r}_n}{t_{n+1} - t_n} \quad (5)$$

$\dot{r}$  and  $\dot{v}$  are not recalculated unless  $t$  moves between a different pair of times.

To make the satellite ephemerides useable at all times we assume the position of the spacecraft is unknown and make the allowable error for the satellites smaller than for the spacecraft. When the spacecraft is far out, errors over 100 km are acceptable. However for the Galilean satellites the greatest error ever allowed is less than 75 km (at Callisto), and for the Uranian satellites the greatest error is around 25 km (at Oberon). These errors result from taking the points at a standard  $6^\circ$  interval in the orbits for all the satellites.



The errors are small largely because all the satellites have highly circular orbits with  $e < .01$ . The errors may be calculated as follows. First, the orbits may always be represented over a short interval by an ellipse. We will show that the difference between an ellipse with  $e = .01$ , and uniform angular and radial motion for motion between two points in space at a  $6^\circ$  interval is less than 45 km. Then we will show that the difference between uniform motion and the approximation used is less than 30 km.

For our orbits we may use the following simple approximation for true anomaly.

$$V = M + 2e \sin M + 1.25e^2 \sin 2M \quad (6)$$

where  $V$  is the true anomaly and  $M$  is the mean anomaly. At point  $n$  we have

$$V_n = M_n + 2e \sin M_n + 1.25e^2 \sin 2M_n$$

and at point  $n+1$ , letting  $M_{n+1} = M_n + \phi$  we have

$$V_{n+1} = M_n + \phi + 2e \sin(M_n + \phi) + 1.25 e^2 \sin 2(M_n + \phi)$$

Now  $\dot{V}$  changes most rapidly near  $M = 90^\circ$ , so let's look at the equations here, because we are attempting to approximate the motion with a constant  $\dot{V}$ . We have

$$V_n = \frac{\pi}{2} + 2e$$

$$V_{n+1} = \frac{\pi}{2} + \phi + 2e \cos \phi - 1.25 e^2 \sin 2\phi$$

Uniform circular motion between the points gives an angular approximation,  $\theta$ , to  $V$  of

$$\theta = V_n + \frac{V_{n+1} - V_n}{T} (t - t_n)$$

where  $T = t_{n+1} - t_n =$  time difference between points  $n+1$  and  $n$ .

Substituting, we have

$$\theta = \frac{\pi}{2} + 2e + \frac{\phi + 2e \cos \phi - 1.25e^2 \sin 2\phi - 2e}{T} (t - t_n)$$

For the true value (eq. 6)  $M$  can be expressed as

$$M = \frac{\pi}{2} + \frac{\phi}{T} (t - t_n)$$

so

$$V = \frac{\pi}{2} + \frac{\phi}{T} (t - t_n) + 2e \sin \left[ \frac{\pi}{2} + \frac{\phi}{T} (t - t_n) \right] + 1.25e^2 \sin 2 \left[ \frac{\pi}{2} + \frac{\phi}{T} (t - t_n) \right]$$

The difference between the true anomaly,  $V$ , and the approximation,  $\theta$ ,

is (let  $\frac{t - t_n}{T} = \tau$ )

$$\Delta V = V - \theta = 2e \cos(\phi\tau) - 1.25 e^2 \sin(2\phi\tau) - 2e - 2e(\cos\phi)\tau + 1.25e^2(\sin 2\phi)\tau + 2e\tau$$

Note that for  $\tau=0$  and  $\tau=1$ ,  $\Delta V = 0$ . For  $\tau = 1/2$ ,  $\phi = 6^\circ$ , and  $e = .01$  we have

$$\Delta V = .0000273 \text{ radians}$$

For the orbit of Callisto with a semimajor axis of  $1.6 \times 10^6$  km this error,  $\Delta V$ , is 44 km.

Considering now the magnitude,  $r$ , of the position vector for an ellipse, we have

$$r = \frac{a(1-e^2)}{(1+e \cos V)}$$

an approximate expression for  $r$ , call  $R$ , between the interval  $t_n$  and  $t_{n+1}$  is

$$R = r_n + \frac{r_{n+1} - r_n}{t_{n+1} - t_n} (t - t_n)$$

Now  $r$  changes most rapidly near  $V=0^\circ$ , so let  $V = 0^\circ$  at  $t_n$  and  $V = \phi$  at  $t_{n+1}$ . Then the approximate expression becomes

$$R = a(1-e) + \left[ \frac{a(1-e^2)}{(1+e \cos \phi)} - a(1-e) \right] \frac{t - t_n}{T}$$

where  $T = t_{n+1} - t_n$ .

For the exact expression we make the approximation  $V = \frac{\phi}{T} (t - t_n)$ . This is permissible as was shown above. Therefore

$$r = \frac{a(1-e^2)}{1+e \cos \left[ \frac{\phi}{T} (t - t_n) \right]}$$

If we evaluate both  $R$  and  $r$  at  $a=1$ ,  $\phi = 6^\circ$ ,  $e = .01$ , and  $t - t_n = 1/2 T$ , the result is

$$\Delta r = |R - r| = .0000134$$

Multiplying this number by the semi-major axis of Callisto yields

$$\Delta r = 21 \text{ km}$$

So we have seen that an ellipse with small eccentricity can be approximated accurately over a small interval with linear equations for  $V$  and  $r$ . Now let's compare the actual approximation used (eqs. 1-5) with this linear approximation. In both cases we are in the same plane, and  $r$  may be held fixed. This is because the variation of  $r$  with  $V$  is

$$\frac{dr}{dV} = \frac{a(1-e^2)}{(1+e \cos V)^2} e \sin V$$

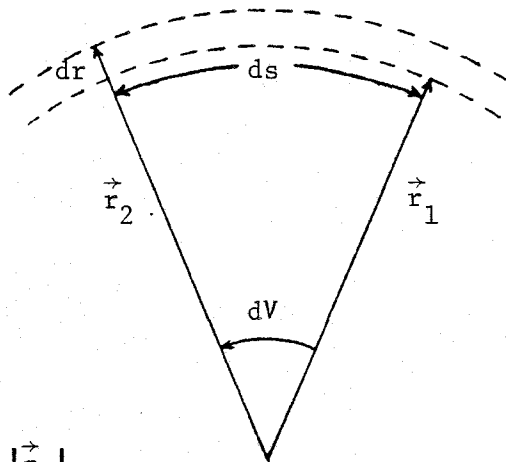
This equation is a maximum at  $V = 90^\circ$ . For  $V = 90^\circ$ ,  $a = 1.6 \times 10^6$  ( semi-major axis of Callisto), and  $e = .01$

$$dr \cong (16000)dV$$

However if an orbit were in error by an angle  $dV$ , the angular error in km,  $ds$ , would be

$$ds \cong (1600000)dV$$

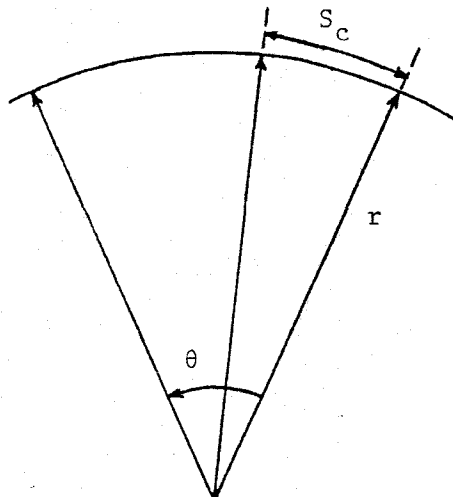
which is 100 times larger. We need therefore to only consider the angular error. See below.



$$dr = |\vec{r}_2| - |\vec{r}_1|$$

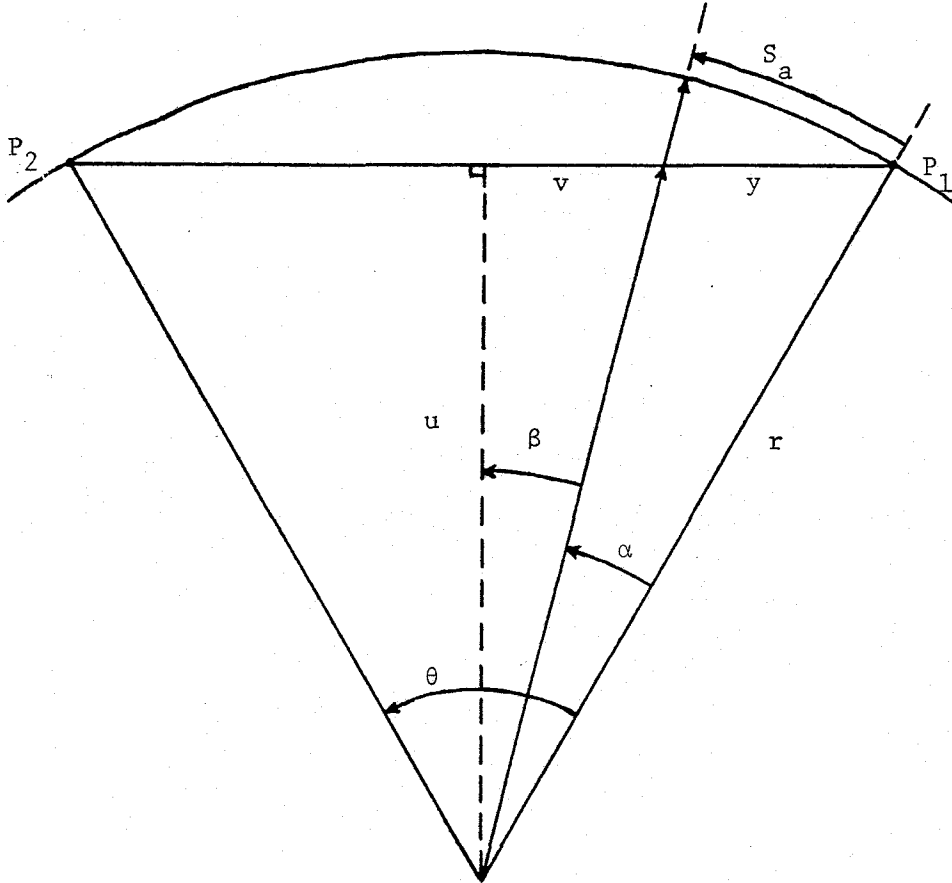
$$ds = |\vec{r}_1| dV$$

Therefore, the problem reduces to finding the maximum difference between  $S_c$  and  $S_a$ . Where  $S_c$  is the distance along the arc for uniform circular motion at time  $t$  between  $t_n$  and  $t_{n+1}$ , and  $S_a$  is the distance along the arc for uniform straight line motion projected onto the circle, also at time  $t$  between  $t_n$  and  $t_{n+1}$ .  $S_c$  is easily calculated and shown below.



$$S_c = \frac{\theta r}{T} (t - t_n) \text{ where } T = t_{n+1} - t_n$$

For  $S_a$  we have



The rate along the line between  $P_1$  and  $P_2$  is

$$\text{rate} = \frac{2r \sin\left(\frac{\theta}{2}\right)}{T}$$

The distance  $y$  is

$$y = \frac{2r \sin\left(\frac{\theta}{2}\right)}{T} (t - t_n)$$

The distance  $v$  is

$$v = r \sin\left(\frac{\theta}{2}\right) - y$$

The distance  $u$  is

$$u = r \cos\left(\frac{\theta}{2}\right)$$

Therefore the angle  $\beta$  is

$$\beta = \tan^{-1}\left(\frac{v}{u}\right)$$

and the angle  $\alpha$  is

$$\alpha = \frac{\theta}{2} - \beta$$

Finally  $S_a$  may be calculated from

$$S_a = r\alpha$$

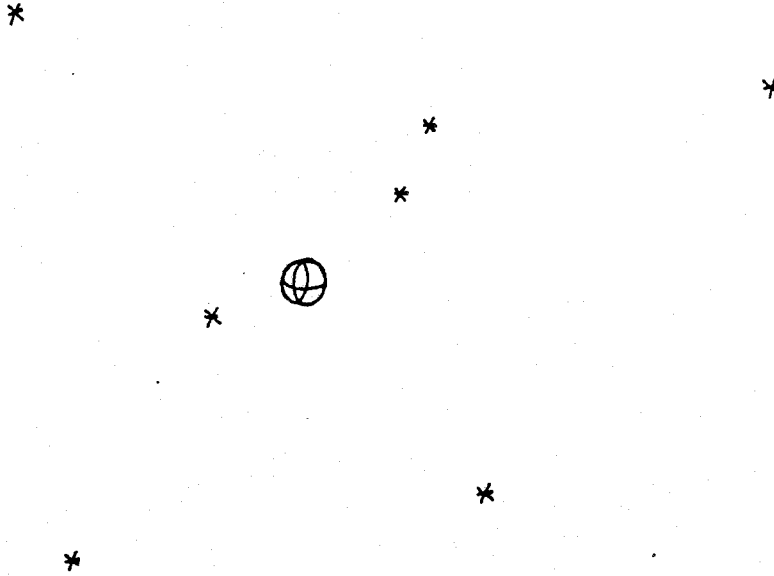
Let  $S_a - S_c = \Delta r$ . A plot of  $\Delta r$  vs.  $\frac{t-t_n}{T}$  is sinusoidal in nature, and for  $r = 1.0$ ,  $\theta = 6^\circ$  it peaks at  $\frac{t-t_n}{T} = .212$ ,  $\Delta r = 1.84 \times 10^{-5}$ .

Multiplying this  $\Delta r$  by the semi-major axis of Callisto yields an error of only 29 km, which is only .6% of the diameter of the satellite.

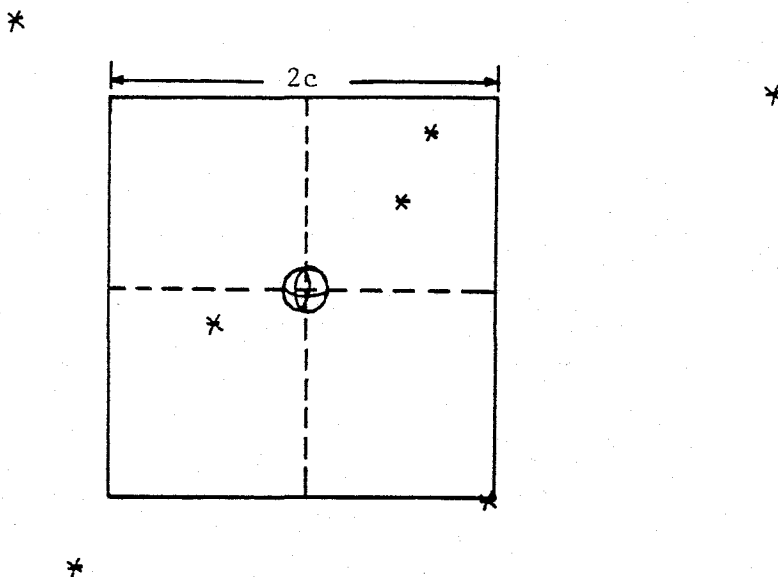
Since an orbit may be represented by only 60 positions, vip and gip can easily store in core 2 orbits per satellite all the time. An entire satellite file is 1/2 as big as an equivalent cheycheve file, and easier to work with.

One other important new theoretical method is used in vip and gip. This has to do with camera pointing optimization in order to increase stars - target body capture probabilities. Important work in this area has been done by Bob Davis (Ref. 5) and Bill Owen (Ref. 6). The problem is not easy and no 'exact' solution has been arrived at. For vip and gip the problem is further complicated by the interactive requirement. Any algorithm used in these programs must be very fast in addition to giving good results. The following simple method is fast and good, and agrees fairly well with Bob Davis' methods as implemented in SATGEOM. However it is still only a guess. The user has the option of manually adjusting the pointing with bezel key #6 and the joystick.

First, consider a satellite against a star field

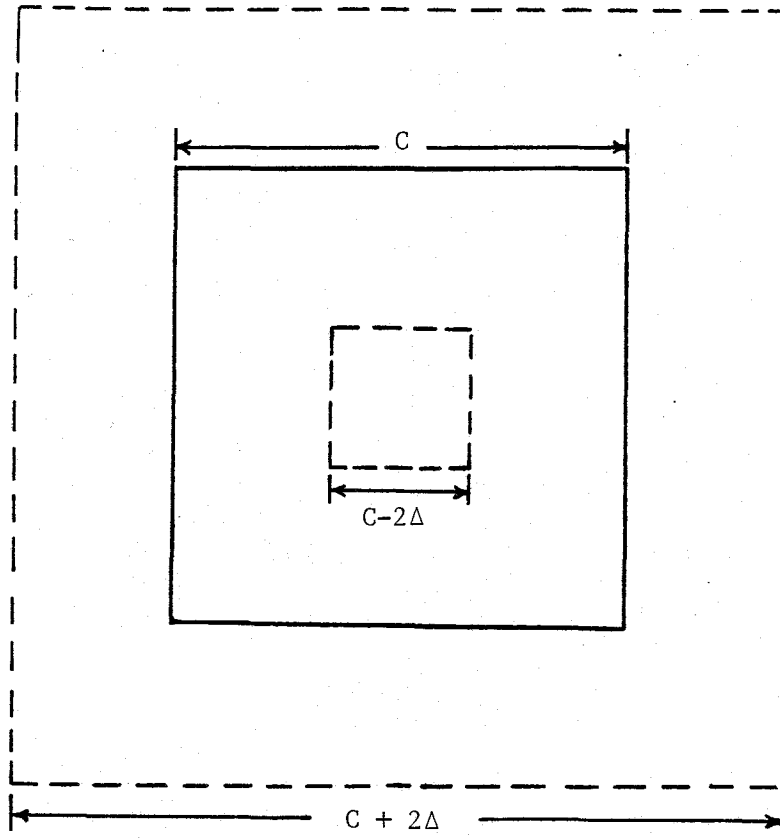


Only stars within one camera field of view of the satellite may be imaged with it. Therefore we need consider only stars within a square with satellite at center and sides  $2c$  (2 times camera field)





Now wherever the camera is told to point, there is a gaussian probability distribution associated with the actual pointing. The 3 sigma defines two boxes with probabilities of capture near 1 and 0. The boxes are shown below.



$C$  = Camera field

$\Delta$  =  $3\sigma$  Pointing error

If we individually consider each star within one  $c$  of the satellite and point the camera halfway between the star and satellite, then the probability of capturing both can be approximated by:

$$\begin{array}{ll}
 p = 1 & d \leq c - 2\Delta \\
 p = 0 & d \geq c \\
 p = -\frac{d}{2\Delta} + \frac{c}{2\Delta} & c - 2\Delta < d < c
 \end{array}$$

where

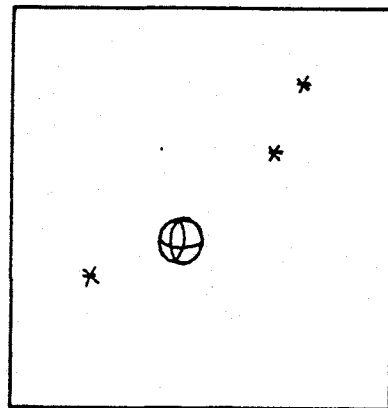
$d$  = distance between one star and the satellite  
 $p$  = probability of capturing the star and satellite if camera is pointed halfway between the two

Since we can move the camera anywhere to optimize satellite-star capture probability, it would seem reasonable to weight each star with the above probability function, and do a simple 'weighted average' or 'center of mass' to get the pointing. The satellite is included and given a weight equal to all the stars.

$$\vec{r}_1 = \frac{\sum \vec{d}_i p_i}{\sum p_i}$$

$\vec{r}_1$  is the 'first pass' optimized pointing and may look like:

\*



\*

Now it is assumed that this 'first pass' solution is close to the 'best solution'. If the pointing is close then each object should now be given a probability of capture dependent on the gaussian probability function. This function is approximated by:

$$p = 1 \quad ; \quad r \leq \frac{c}{2} - \Delta$$

$$p = e^{-4 \frac{\left(r - \frac{c}{2} + \Delta\right)^2}{4\Delta^2}} \quad ; \quad r > \frac{c}{2} - \Delta$$

where  $r$  is the distance from the 'first pass' solution. Two more 'center of mass' fits are done with each star weighted according to the above equation for  $p$ . The satellite is given a weight equal to the single most valuable star.

For both Voyager and Galileo,  $c = .424^\circ$ . For Voyager,  $\Delta = .129^\circ$ , and for Galileo,  $\Delta = .195^\circ$ .

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