Interactive Satellite Navigation for the Naval Environmental Operational Nowcasting System

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Foreword

The earth location of satellite information has improved dramatically over the last 5 years; however, under certain conditions, the positioning of the satellite image must be fine tuned. This is particularly true for ships at sea where time accuracy is to the nearest millisecond instead of the needed microsecond or when the orbital elements have become outdated. When this happens, noticeable discrepancies occur where the computer-drawn land boundaries do not match those visible in the satellite image. To correct for this, the Tactical Environmental Support System (TESS (3)) Program Office, Space and Naval Warfare Systems Command (PMW-165), requested that the Naval Oceanographic and Atmospheric Research Laboratory (NOARL) develop computer software that would allow the TESS(3) operators to interactively shift the computer-drawn geographic boundaries until they matched the image. This report discusses the development and performance of the interactive satellite navigation developed for TESS(3).

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Executive Summary

The capability of the Tactical Environmental Support System (TESS(3)) to acquire real-time satellite data led to a requirement to earth-locate the satellite data with a high degree of accuracy. After ingesting satellite data, the TESS(3) earth locates the data using an orbital prediction model, orbital elements, and an accurate time source. Because of limitations in the model, age of the elements, and time errors as large as 0.5 second, an interactive method was developed to correct navigated images with detectable errors.

After reviewing existing methods, an interactive method was designed and developed for the user interface and computer hardware of TESS(3). The method incorporates a geographic data base, satellite imagery, an operator, and a mouse or trackball. The one rule for this method is that some visible land features occur in the image. By using a trackball, the operator can position the geographic overlay onto features discernible on the image. The change in the geographic overlay is then used to correct the satellite navigation data so the current and subsequent retrievals can be extracted with the updated information.

The procedure developed satisfies the Navy's requirement for accurate satellite navigation, and it is being implemented into the operational system. Newer procedures are planned that will eliminate most of the need for an operator by contrast processing the satellite image and then matching the image with a geographic data base.

Acknowledgment

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The mention of commercial products or the use of company names does not in any way imply endorsement by the U.S. Navy or NOARL.

Contents

Interactive Satellite Navigation for the Naval Environmental Operational Nowcasting System

1.0 An Overview of Interactive Satellite Navigation

Satellite navigation, or earth location, is the process in which the data received by satellite sensors are tagged with latitude and longitude values. This process is fairly automated. With the use of precise orbital prediction models and an accurate clock, the automated satellite navigation process could accurately earth-locate the satellite data to within one picture element (pixel) of the satellite data.

However, the limitations in the orbital prediction models and the drift in clock time combine to produce earth locations of satellite data with accuracies worse than one pixel of the satellite data. The results of this discrepancy are realized in the display and assimilation of the satellite data with other data. An obvious example of this error in earth location is the display of the satellite data with geographic boundaries. The computer-drawn boundaries may appear translated or rotated from the geography boundaries visible in the image.

Since all subsequent assimilation of the satellite data is done using these latitude and longitude values, the earth locations need to be corrected when their errors are larger than one pixel. Some commercial software programs, e.g., TeraScan and RSMAS, allow a user to interactively navigate an image, but commercial software licenses make them difficult to use in secure operational environments. This report describes the method developed to correct the latitude and longitude values tagged to the satellite data when they are in error.

Interactive satellite navigation (ISN) is a software routine developed on the Naval Environmental Operational Nowcasting System (NEONS) in response to a Navy operational requirement to earth-locate satellite data to within a pixel of the sensor. The initial earth location of the satellite data is accomplished using an orbit prediction model described in section 2.2.

ISN allows the user to fix errors in the orbit predictions through interactive positioning of the satellite image to land boundaries. Although this software was developed on the NEONS system, Hewlett-Packard (HP) 835 TURBO SRX, it was developed for the Tactical Environmental Support System, or TESS(3). TESS(3) is currently on a Masscomp 6605 computer. Both the HP and the Masscomp have UNIX operating systems.

ISN functions on visible and infrared data sensed by both the Advanced Very High Resolution Radiometer (AVHRR) aboard the National Oceanic and Atmospheric Administration (NOAA) satellite and the Operational Linescan System (OLS) on the Defense Meteorological Satellite Program (DMSP) satellite. Characteristics of these polar-orbiting satellites are given in the next section.

Once the satellite data are retrieved and earth located using the orbit prediction model, the imagery is displayed with geographical boundaries.

The ISN can then be employed on a full-resolution image, a subset of the entire pass. The ISN user renavigates the satellite data by shifting the geography outlines to match those visible on the image. The program then calculates the corrections to the orbital elements and places them in the data base. The updated orbital elements can then be used for other images in the satellite pass.

2.0 Polar-Orbiting Satellites

2.1 Satellite Characteristics

The polar-orbiting satellites, DMSP and NOAA, orbit the earth in a track that provides total coverage of the globe, including both poles. The characteristics of the DMSP and NOAA satellites are given in Table 1 for the sensors relevant to ISN.

The most important similarity between the OLS and AVHRR sensors is that they are sensitive to both the visible and infrared portions of the electromagnetic spectrum. The OLS observes in the visible and infrared spectrums using fine and smooth resolutions. The visible channel responds to the range 0.4–1.1 μm band and the infrared or thermal channel responds to the 10.8–12.5 μm band. Although the along-track spatial resolution is the same for both fine and smooth data (approximately 0.56 km), the across-track spatial resolution is 0.56 km for fine data and 2.78 km for smooth.

The OLS sensor scans with a pendulum motion and produces a swath of approximately 2961 km. Sophisticated electronics in the sensor maintain constant spatial resolution across the track. This means that no distortion occurs at the edges or the end of the scan lines. The OLS also has an automatic gain control that allows the sensor to correct slowly to abrupt changes in reflectivity.

The AVHRR sensor differs from the OLS in sensor motion and spectral and spatial resolutions. The AVHRR sensor is sensitive to five bands in the electromagnetic spectrum. Table 2 shows each channel and its respective bandwidth for the AVHRR sensor.

The AVHRR sensor is a circulating sensor, and the spatial resolution changes along the scan line. The spatial resolution varies from 1.1 km^2 at nadir to approximately 4 km^2 at the edge of the scan line.

2.2 Satellite Tracking

The environmental satellites that monitor the earth are either polar-orbiting or geostationary satellites. The U.S. Air Force tracks the location of these satellites, as well as others. The satellite tracking is needed to plan new satellite orbits and to ensure that the satellite information is properly received and navigated.

Table 1. Satellite characteristics.

CHARACTERISTIC	NOAA	DMSP
Sun Synchronous	Yes	Yes
Inclination	~98.9°	~98.8°
Altitude	860 km	860 km
Period (minutes)	~101.92	~101.4
Orbits/Day	14.1	14.2
Sensors	AVHRR	OLS

Table 2. Channels and bandwidths for the AVHRR sensor.

CHANNEL #	λ(μm)
1	0.6–0.8
2	0.8–1.1
3	3.55–3.93
4	10.5–11.0
5	11.0–12.5

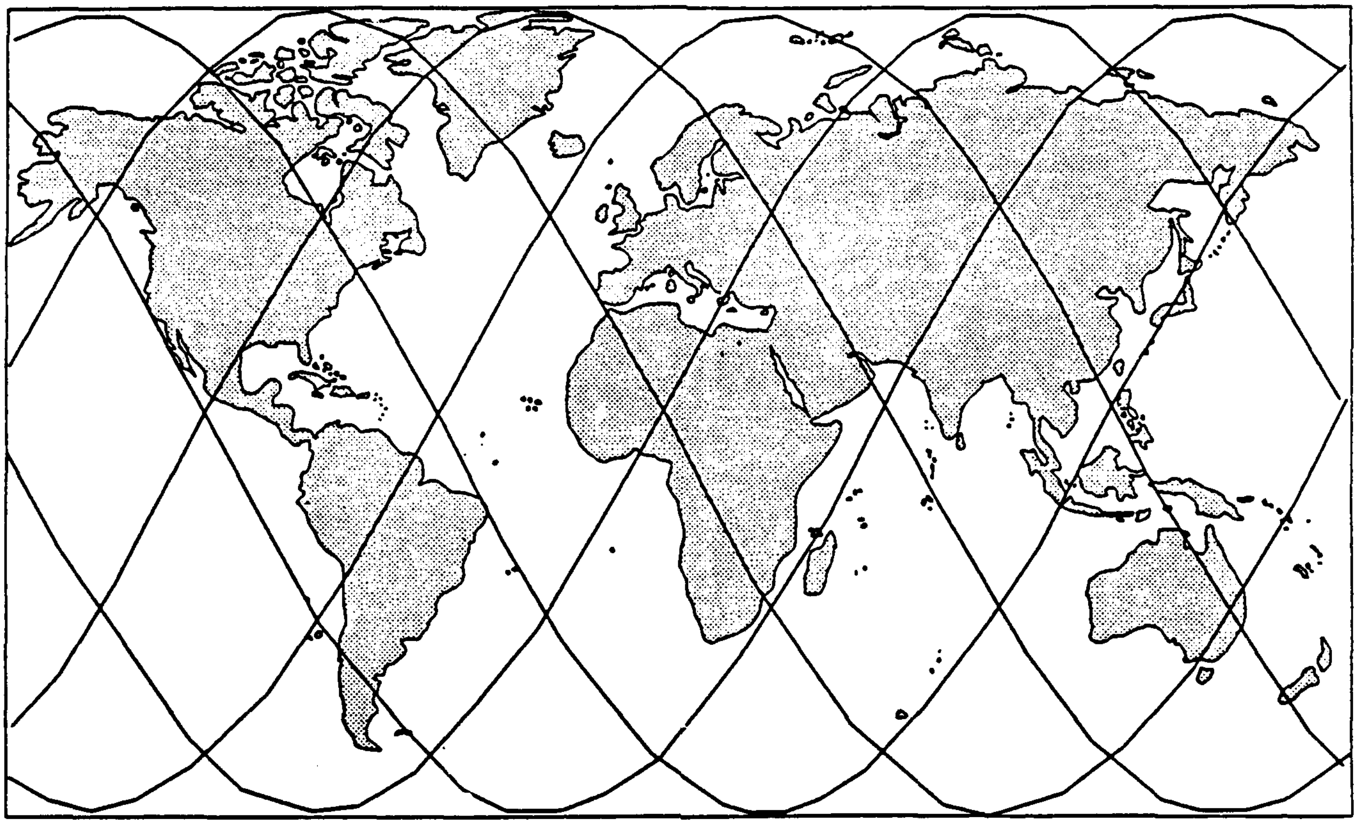

Figure 1. Track representing an orbit from a polar-orbiting satellite.

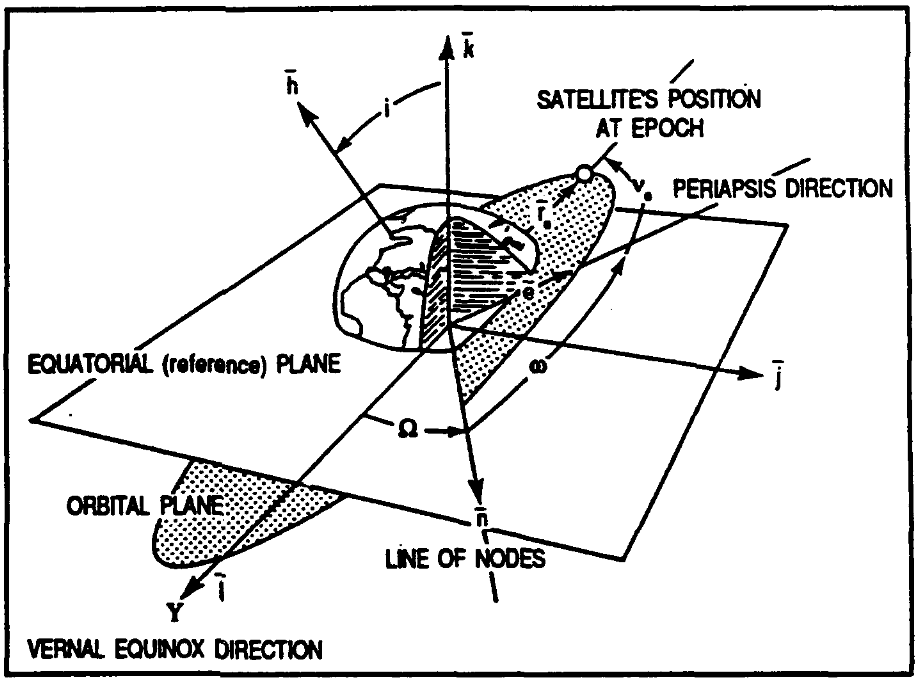

Figure 2. Orbital elements (taken from Bate) et al., 1971).

An example of three tracks, or orbits, from a polar-orbiting satellite is shown in Figure 1. The vector $\bar{r}_0$ is the radius vector to the satellite. Six parameters, orbital elements, and an epoch time are needed to track a satellite; these elements are defined below and shown in Figure 2.

Orbital Element	Description
Eccentricity ($\bar{e}$)	A vector from the center of the earth (focus of the orbit) toward the perigee with a magnitude exactly equal to the eccentricity of the orbit.
Semi-major axis (a)	Half the distance of the major axis of an ellipse.
Inclination (i)	Angle the orbital plane makes with the reference plane.
Longitude of the ascending node (Ω)	Angle that describes the rotation of the orbital plane from a line within the reference plane, which points toward an inertially fixed direction (in the direction of the vernal equinox) to the line formed by the intersection of the reference and orbital planes (line of nodes) on the side where the orbital motion is from south to north.
Line of nodes ($\bar{n}$)	The intersection of the ascending orbit with the equatorial plane.
Argument of perigee (ω)	The orientation of the orbit within the orbital plane. This is measured as the angle between the line of nodes and perigee of the orbit.
True anomaly (v_o)	The actual position of the orbiting body at any particular location within the orbit.

These elements are used in ephemeris prediction models to locate satellites to schedule reception and to earth locate the received satellite data. TESS(3) uses three different kinds of orbital elements in three different orbit models. Examples of these three orbital sets are C-elements, the TBUS, and the NORAD 2-card and are given in Appendix A.

ISN uses the PPT2 orbit model, which is the Naval Space Surveillance Center's (NAVSPASUR) satellite motion model (Solomon, 1991). PPT2 was developed in the late 1960s and early 1970s and has a satellite position accuracy of several hundred meters. The position prediction degrades with time due to several factors, one of which is drag.

PPT2 is based on Brouwer-Lyddane theory, which is more involved than the Kepler elliptical model. Lyddane addresses the singularities present in Brouwer's model, specifically zero inclination and zero eccentricity. PPT2 addresses the singularity at the critical inclination of 63.4°. PPT2 also has two parameters that handle the atmospheric drag and the epoch of the elements. The source code and other details can be found in Solomon (1991).

3.0 ISN Software

The ISN software gives the user fine-tuning capability to the earth location computed with an orbit model, such as PPT2. Errors can occur at least three ways when such orbit prediction models as PPT2 are used: outdated orbital elements, inaccuracies in the prediction model, and errors in time labeling. The more outdated the orbital elements become, the more likely there will be errors in the navigated data. The orbital elements are calibrated by NAVSPASUR and transmitted to users as often as daily. The orbital model makes approximations that may directly impact errors in the calculations of the satellite's velocity and position. This can occur even with updated orbital elements. Time errors, however, account for most of the error in orbit models. Aboard the NOAA spacecraft, the satellite clock can be off by 0.5 second before it is reset. The clock error alone can cause an along-track location error of approximately 3 km.

The along-track errors are adjusted by a vertical translation of the geography overlay, and across-track errors are corrected with a horizontal translation of the overlay. These X and Y translations are used to correct the satellite attitude for roll and pitch, respectively. The field of view of an AVHRR pixel is 1.3 mrad. The shift of geography, translated vertically, is multiplied by 0.073125°, and that value is the pitch correction. The horizontal shift is multiplied by 0.054° to determine the roll correction.

Should the overlay appear rotated from the image boundaries, a rotation correction is applied and the satellite attitude is adjusted for yaw. The minimum size rotation or yaw correction is currently at 1.0°. The roll, pitch, and yaw corrections are then passed to the data base.

The ISN software performs the translation and rotation functions with the following two assumptions: that a Cartesian plane can approximate a spherical surface, and that the corrections made in the navigation are based on shifts in screen coordinates. For the surface area covered by a 14-minute satellite pass, the first assumption is good. The second assumption limits the corrections for time to an accuracy of 0.16 second. This is an along-track correction to within 1 km.

The ISN software gives the user the opportunity to overcome such errors as those described. Since the procedure uses land boundaries discernible in the image to relocate the data, it is not useful in the absence of land or complete cloud obscuration. The functionality of ISN is discussed in the next section.

3.1 Capabilities

ISN's implementation on NEONS HP-835 requires use of the alphanumeric and graphics terminals. The program is initiated from the alphanumeric screen, and the interactive communication is done on the graphics terminal with a mouse or a trackball.

The program prompts the user for the satellite identification number, which it uses to interface to the NEONS data base. The program then asks for line and element number of the pass, which is essentially the subset of the pass to be used in navigation. Finally, the program needs to know whether the pass is ascending or descending.

After all of the data are input, the program queries the data base for the data, and the graphics terminal displays a thermal image at full resolution. The geographic boundaries and a main menu are overlaid on the image. The menu options are described below.

3.1.1 Main Menu

The Main Menu (Fig. 3) displays the options available. The arrow selections in the first two rows translate the coastline in the vertical and the horizontal. The selection marked YAW creates a new menu and displays a whole subsampled pass with its corresponding overlay of geography. This selection is discussed further in the Yaw Menu section below.

The UNDO selection erases all of the corrections and restores the coastline to its original location. The HELP selection produces online help as shown in Figure 4. This menu describes each function of the Main Menu. A click of mouse button 1 clears the HELP menu and restores the Main Menu.

The MOVE MENU option places the menu in one of four different locations on the screen. This option is necessary to avoid covering areas of interest.

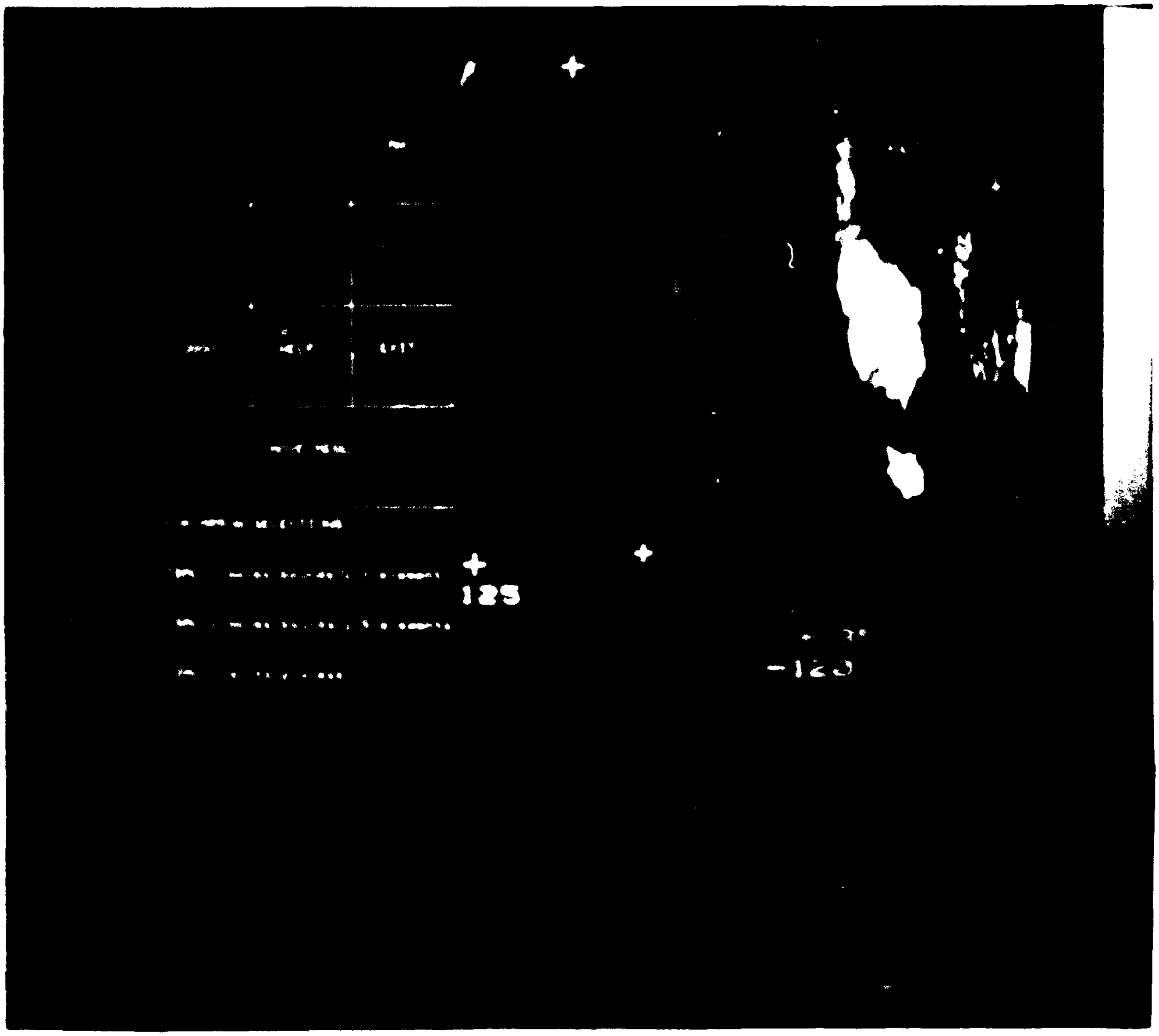

Figure 3. ISN's main menu.

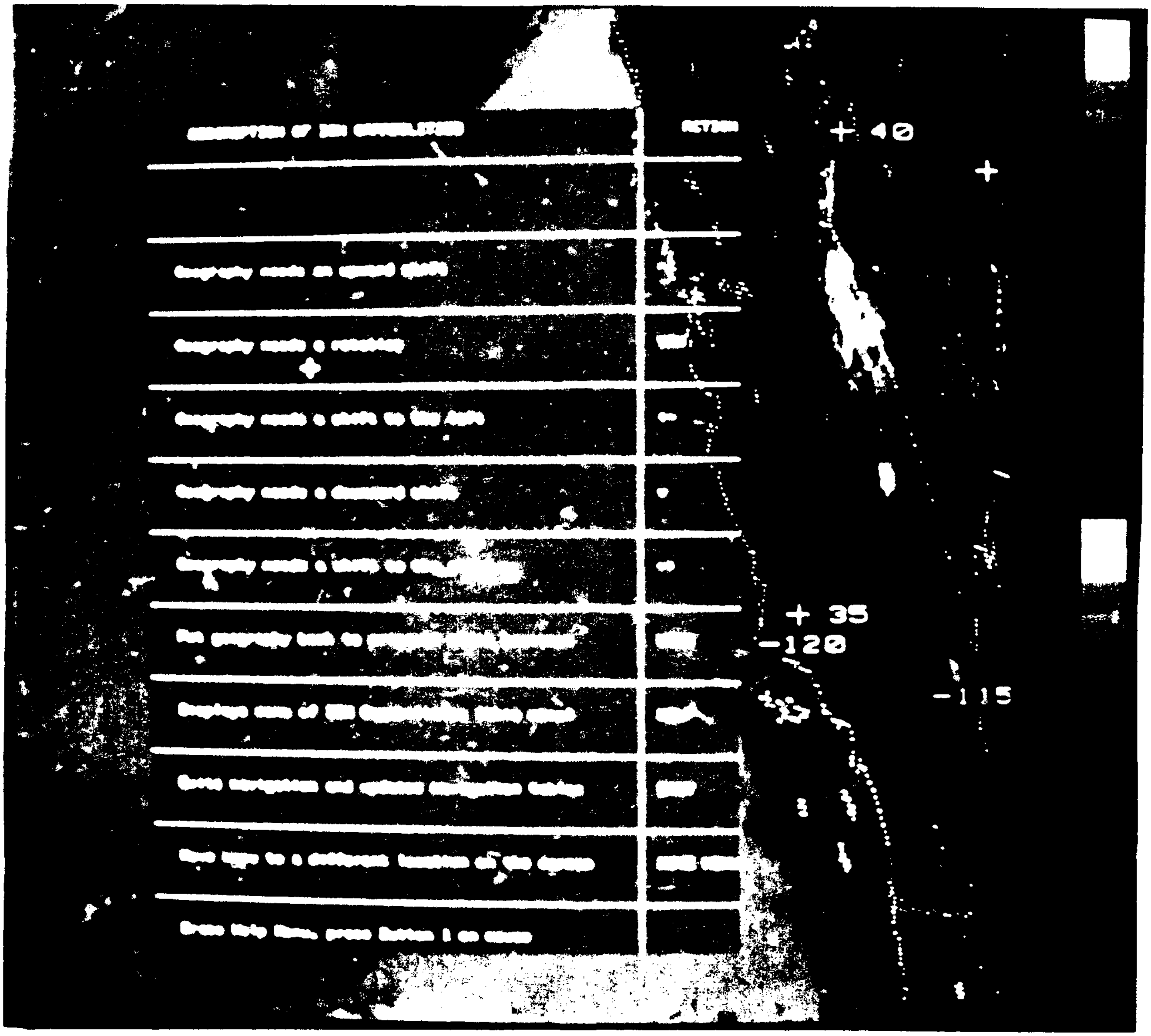

Figure 4. ISN's help menu

The EXIT selection updates the data base, closes the devices, and stops the software.

Several lines of text beneath the option boxes describe the response of the various selections. Positioning the mouse's cursor in one of the translation boxes moves the coastline one pixel at the click of button 1 and five pixels at the click of button 2. Clicking button 3 closes the translation option.

3.1.2 YAW Menu

The YAW Menu is similar to the Main Menu and provides the UNDO, HELP, and EXIT options plus rotation options as shown in Figure 5. The YAW selection corrects for the rotation or twist of the satellite about the vertical axis. But since only about 5 passes of 100 passes require rotation for correction, having the YAW menu separate from the Main Menu should not be a problem.

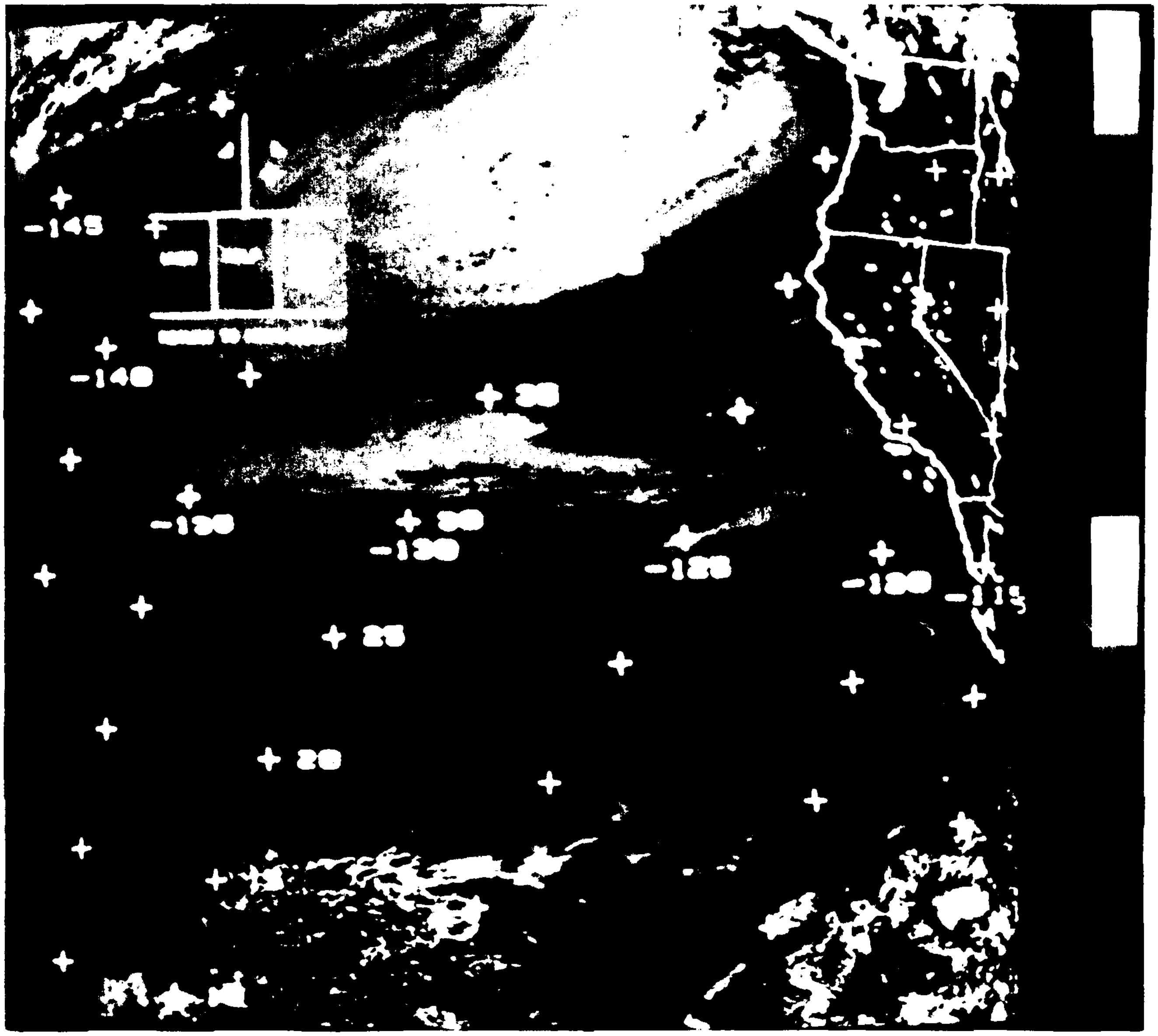

Figure 5. ISN's YAW menu.

The YAW correction requires mathematics using the entire image versus a subset of the pass. The YAW option corrects rotation to within 1°.

3.2 Data Base Updates

The data base is structured into three different realms: descriptive, associative, and primary. The descriptive realm holds the static information. The associative data refers to the specifics of the data, e.g., day, time group. The primary data are the actual data values.

After the corrections are calculated — before and after the YAW correction, as well as after the EXIT from the program — the associative data in the data base are updated. This calculation ensures that subsequent retrievals of satellite data will be navigated with the updated information. The module **updt_db** as listed in Appendix B is used to update the associative information in the database.

4.0 Future Directions

4.1 Incorporation of ISN into TESS(3)

ISN was designed to be hardware dependent, since it uses HP Starbase Graphics. ISN's starting point, a displayed satellite thermal image and overlaid geography, uses resident routines, get_image, and Polnavs. The HP design is different from the original design for TESS(3), as highlighted in the following text.

Three general areas must be addressed to integrate ISN into TESS(3). The first is the user interface (pop-up, pull-down menus). The second is the input/output of the satellite data (including display of geographic boundaries), and the third is the calculations and data base update. The last area is the most straightforward of the three.

Since the TESS(3) user interface already provides most of the menu structure, the modification and creation of menus should be sufficient to integrate ISN. The input/output of the satellite data will require the addition of at least one new menu.

The display of satellite data in natural coordinates will require a routine that produces an image overlay. Currently, the TESS(3) software does not place geography on natural satellite coordinate data. To do so requires a search through a megabyte of pixels to identify matches with the geography. The NEONS bit map of the TESS(3) world data base is best for this, and may have to be implemented with ISN.

The calculations and updates to the data base are valid for the NOAA satellites. Since real-time DMSP data are not available on the HP, DMSP specific code and calculations must still be developed.

4.2 A New Version of Satellite Navigation

Although automated procedures that match land boundaries from satellite images with computerized maps of the world would be ideal for TESS(3), more development is required to make them reliable. The next version of the interactive satellite navigation will utilize these newer procedures so that the operator will have much less to do.

5.0 References

Bate, Roger R., Donald D. Mueller, and Jerry E. White (1971). *Fundamentals of Astrodynamics*. Dover Publications, Inc., p. 59.

Solomon, Daniel (1991). The NAVSPASUR satellite motion model. Draft document for the Naval Research Laboratory, Naval Center for Space Technology, Space Systems Engineering Department, Space Applications Branch, Contract N00014-87-C-2547, August, p. 54.

Appendix A

Orbital Elements Examples

Example of C-Element Message with Associated Format

```
SAT.NO*MN.ANA.*MN.MOT.*DECAY*ECCEN.*ARG.PG.*LG.NODE*INCLIN.*EPOCH*
XXXXX.XXXXXXX.XXXXXXX.XXXXX.XXXXXXX.XXXXXXX.XXXXXXX.XXXXXXXYRMODY
11416.7329058.8356045.00061.0012200.1768671.8161393.2739485821003
```

SAT.NO	=	Satellite Number
MN.ANA	=	Mean Anomaly
MN.MOT	=	Mean Motion
DECAY	=	Decay
ECCEN	=	Eccentricity
ARG.PG	=	Argument of Perigee
LG.NODE	=	Longitude of Ascending Node
INCLIN	=	Inclination
EPOCH	=	Epoch (Year, Month, Day)

NORAD 2 Card Elements and Associated Format

```
1 10061U 77048  A 89297.41250243  .00000000  00000-0  00000-0 0 03208
2 10061 007.4194 066.8342 0006440 165.0516 194.9734 01.00269842006670
```

Format

```
A BBBBBC DDDDDDDD EEEEE.EEEEEEEE  .FFFFFFFF  GGGGG-G  HHHHH-H H IIIII
A BBBBB JJJ.JJJJ KKK.KKKK LLLLLLL MMM.MMMM NNN.NNNN OO.OOOOOOOOPPPPP
```

A	Line Number
BBBBB	Satellite Number
C	Class
DDDDDDDD	Intl. Design
EEEEE.EEEEEEEE	Epoch
.FFFFFFFF	First Decay Term
GGGGG-G	Second Decay Term
HHHHH-H H	BSTAR - Drag Term
IIIII	Set Number
JJJ.JJJJ	Inclination
KKK.KKKK	Right Ascension
LLLLLLL	Eccentricity
MMM.MMMM	Argument of Perigee
NNN.NNNN	Mean Anomaly
OO.OOOOOOOOO	Rev/Day
PPPPP	Rev Number

Example of TBUS Message with Associated Format

```
PART IV
1988 089A 03069 120054123264 890430011756250 2374540
01020586 01021144 00125839 01075838 06430657 09893654
34939288 07231416 P031338273 P065135047 P000000000
P01035468 M00509102 P07342118 001369821 170208023 9449
0000499999 M00277691 F00099451 P00507944 SPARESPARE
APT 137.62 MHZ, HRPT 1707.0 MHZ, PCN DSP 137.77 MHZ.
APT DAY/NIGHT 2,4/3,4. VIS CH. 2 /0.725 TO 1.0/ AND
IR CH. 4 /10.5 TO 11.5/ WILL BE XMTD DURING S/C DAY.
IR CH. 3 /3.55 TO 3.93/ AND CH. 4 /10.5 TO 11.5/ WILL
BE XMTD DURING S/C NIGHT. DCS CLK DAY/TIME 295 83690.03.
295 83690.03. LAST TIP CLK CORR 04/18/89. CLK ERR AFTER
CORR/SEC/MINUS 1.2 SEC. CLK ERR/SEC AS OF 04/24 MINUS
1.1.    ERR  RATE/MSEC DAY/AS OF 04/24/89 PLUS  9.
```

```
Format  (dp = decimal places)
AAAAAAAAA BBBBB CCCCCCCCCCCC DDEEFFGGHHIIIII JJJJJJJ
KKKKKKKK LLLLLLLL MMMMMMMM NNNNNNNN OOOOOOOO PPPPPPPP
QQQQQQQQ RRRRRRRR SSSSSSSSSS TTTTTTTTTT UUUUUUUUUU
VVVVVVVVV WWWWWWWWW XXXXXXXXX YYYYYYYYY ZZZaaabbb cccc
dddddddddd eeeeeeeee fffffffff ggggggggg SPARESPARE
```

AAAAAAAAA	Spacecraft Identification	DD	Epoch year
BBBBB	Orbit number at epoch	EE	Epoch month
CCCCCCCCCCCC	Time of ascending node	FF	Epoch day
GG	Epoch hour	HH	Epoch minute
IIIII	Epoch second, 3 dp		
JJJJJJJ	Greenwich Hour Angle at Aries, 4 dp		
KKKKKKKK	Anomalistic period (minutes), 4 dp		
LLLLLLLL	Nodal period (minutes), 4 dp		
MMMMMMMM	Eccentricity, 8 dp		
NNNNNNNN	Argument of perigee (degrees), 5 dp		
OOOOOOOO	Right Ascension of ascending node (degrees), 5 dp		
PPPPPPPP	Inclination (degrees), 5 dp		
QQQQQQQQ	Mean anomaly (degrees), 5 dp		
RRRRRRRR	Semi-major axis (km), 3 dp		
SSSSSSSSSS	Sign and Epoch X position component (km), 4 dp		
TTTTTTTTTT	Sign and Epoch Y position component (km), 4 dp		
UUUUUUUUUU	Sign and Epoch Z position component (km), 4 dp		
VVVVVVVVV	Sign and Epoch X velocity component (km/s), 6 dp		
WWWWWWWWW	Sign and Epoch Y velocity component (km/s), 6 dp		
XXXXXXXXX	Sign and Epoch Z velocity component (km/s), 6 dp		
YYYYYYYYY	Ballistics coefficient CD-A/M (m^2/kg), 8 dp		
ZZZ	Daily solar flux value (10.7 cm) [10^{-7} watt/m^2]		
aaa	90-day running mean of solar flux [10^{-7} watt/m^2]		
bbb	Planetary magnetic index [$2x10^{-5}$ gauss]		
cccc	Drag modulation coefficient, 4 dp		
dddddddddd	Radiation pressure coefficient, 10 dp		
eeeeeeeee	Sign and perigee motion (deg/day), 5 dp		
fffffffff	Sign and motion of "OOOOOOOO", 5 dp		
ggggggggg	Sign and rate of change of "QQQQQQQQ", 2 dp		
SPARESPARE	spare		

Appendix B

Update Data Base Module

```
/***************************************************************************/
/*  Function Name: updt_db                                                 */
/*                                                                         */
/*  Purpose:  This module updates the Empress database for a particular   */
/*            pass with regards to the roll, pitch and yaw corrections    */
/*            in degrees.  This allows subsequent calls to the pass       */
/*            greater navigation accuracy.                                 */
/*                                                                         */
/*  Calling Function/s: make_selection                                     */
/*                      exit_isn                                           */
/*                                                                         */
/*  Called Function/s:  im_upd_as_sat                                      */
/*                                                                         */
/*  Inputs:  none                                                          */
/*                                                                         */
/*  Outputs:  roll_ang, pch_ang and yaw_ang into the database through     */
/*            the called function.                                         */
/*                                                                         */
/*  External Devices:                                                      */
/*                                                                         */
/*  Notes: UNIX Version (C language).                                      */
/*                                                                         */
/***************************************************************************/
/*                                                                         */
/*                                                                         */
/*                 Creator:  C. Crosiar                                    */
/*            Organization:  NOARL                                         */
/*                    Date:  26 Feb 1991                                   */
/*                                                                         */
/*          Change History:                                                */
/*                                                                         */
/***************************************************************************/
/***************************************************************************/
/*                                                                         */
#include <starbase.c.h>
#include <isn.h>
#include <isdb.h>
#include <image_exec.h>

struct geography geo;
SAT_GEOM geom;
image_disp disp_info;
image_header asoc_info;
```

```
void updt_db()

{
        int     status;
        long    im_id;

        extern void     im_upd_as_sat();

        geom.yaw_ang = geo.yaw_corr;
        geom.roll_ang = geo.roll_corr * 0.027539062;
        geom.pch_ang = geo.pitch_corr * 0.074;

        im_id = asoc_info.id;
        geom.bgn_lin_num = geo.il;
        geom.bgn_smp_num = geo.ie;
        geom.lin_int = geo.interval;
        geom.smp_int = geo.interval;

        im_upd_as_sat(&im_id,&geom,&status);
        return;

}
```

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The capability of the Tactical Environmental Support System (TESS(3)) to acquire real-time satellite data led to a requirement to earth-locate the satellite data with a high degree of accuracy. After ingesting satellite data, the TESS(3) earth locates the data using an orbital prediction model, orbital elements, and an accurate time source. Because of limitations in the model, age of the elements, and time errors as large as 0.5 second, an interactive method was developed to correct navigated images with detectable errors.

After reviewing existing methods, an interactive method was designed and developed for the user interface and computer hardware of TESS(3). The method incorporates a geographic data base, satellite imagery, an operator, and a mouse or trackball. The one rule for this method is that some visible land features occur in the image. By using a trackball, the operator can position the geographic overlay onto features discernible on the image. The change in the geographic overlay is then used to correct the satellite navigation data so the current and subsequent retrievals can be extracted with the updated information.

The procedure developed satisfies the Navy's requirement for accurate satellite navigation, and it is being implemented into the operational system. Newer procedures are planned that will eliminate most of the need for an operator by contrast processing the satellite image and then matching the image with a geographic data base.

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