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Technical memorandum NESCTM-6
Computer processing of TOS attitude data,
by J.F. Gross.

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NATIONAL ENVIRONMENTAL SATELLITE CENTER
Washington, D.C.

November 1968

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National Oceanic and Atmospheric Administration
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National Environmental Satellite Center Technical Memorandum NESCTM 6

COMPUTER PROCESSING OF TOS ATTITUDE DATA

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COMPUTER PROCESSING OF TOS ATTITUDE DATA

J. F. Gross

ABSTRACT

This memorandum describes the computer program used operationally at the National Environmental Satellite Center (NESC) to determine the attitude of a TIROS Operational Satellite (TOS). It includes background information of historical interest, specific details of the problem and its solution, and thoughts about future approaches. It is intended as a description of this part of the NESC operation and as an introduction to the more esoteric program documentation.

I. INTRODUCTION

Throughout the TIROS mission, maintenance and control of the satellites was the responsibility of the TIROS Technical Control Center (TTCC) at NASA's Goddard Space Flight Center. Though the TIROS satellites were reliable, the coverage they provided was less than complete. The cartwheel mode TOS was proposed as a solution. It was also decided that the operational responsibility for the TOS system would be in NESC, while NASA would retain the launch and checkout responsibility. To this end, TTCC became the TIROS Evaluation Center (TEC), and a new TIROS Operations Center (TOC) was established at the NESC. At TEC, past experience (1) was smoothly combined with new techniques (2), and a reliable operational system was quickly produced (3). TOC recruited a corps of experienced specialists and began to parallel the old TTCC functions. As proficiency and familiarity were gained, the dependence on NASA for support of the operation grew less and less. The NESC Programming Branch was developing computer support for TOC. The first jobs were the production of ephemerides and satellite-locating schedules. Once these tedious functions were being performed routinely by computer, emphasis shifted to other aspects of the satellite management problem which might be automated to save time and effort. One of these was the determination of the attitude of the spacecraft. The problem proved to be more involved than had been anticipated. At the outset there were lengthy discussions with the NASA personnel to get an understanding of the general approach to adapt to the specific needs and equipment at the NESC. Since then, with guidance from TOC, the attitude determination program has evolved from an interesting curiosity to a reliable work-saving tool.

II. DEFINITION OF THE PROBLEM

As far as is possible, a TOS system spacecraft is maintained in an orientation such that the plane of rotation is in the orbital plane, thereby keeping the top-to-bottom line of a picture coincident with the subsatellite track. The desired condition in the perpendicular direction is coincidence of the picture center with the subsatellite point, a condition obtained by triggering the camera shutter at the proper point in the rotation. To do this, a special

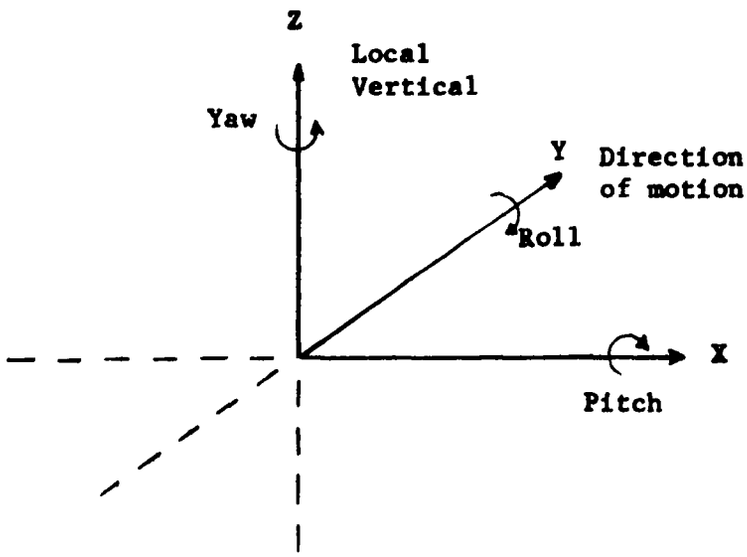


Figure 1
Definition of attitude errors

sensor is mounted in the plane of rotation so that it detects the horizon at the same time the camera is pointing straight down. Figure 1 defines the attitude errors.

The data for roll/yaw determination are provided by two bolometers (sensitive to radiation in the infrared between 8 and 18 microns) which are mounted on the perimeter of the baseplate looking out to either side at a 43-degree angle from the plane of rotation. The spinning of the satellite, therefore, causes the field-of-view of a sensor to describe a cone around the spin axis, intersecting the earth for some portion of each spin. The raw output of the bolometer as shown in Figure 2a is electronically differentiated (to avoid ambient-temperature drifts) and telemetered to the ground. An example of this signal is given in Figure 2b. It can be seen that a roll error will change the duration of the earth scans (assuming a constant height), but that the yaw will not (see Figure 3).

In order to deduce the yaw component, and to infer the conditions beyond the observable portion of an orbit, one assumes that spin axis perturbations are negligible for periods of an hour or more.

Even though the spin axis does not move, the local coordinate system does move 360 degrees in one orbit. Since roll is defined with respect to the local vertical, it, too, changes with a period of one orbit. Yaw is similarly defined and undergoes similar changes but 90 degrees out of phase with respect to the roll. Figure 4 illustrates this roll/yaw interchange and also demonstrates the curve-fitting aspects of the attitude determination method. If the instantaneous roll angle can be determined at many points in an orbit, the

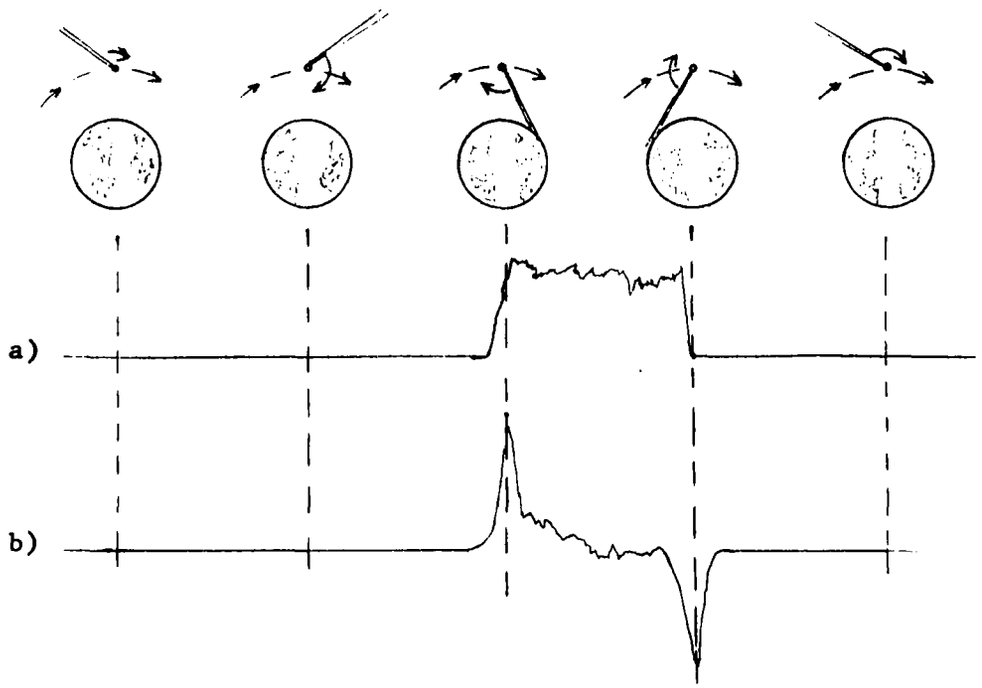


Figure 2
Raw (a) and differentiated (b) sensor output

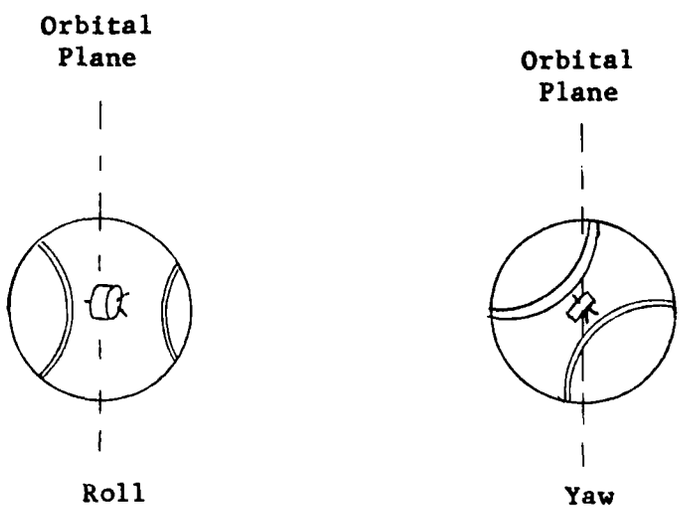


Figure 3
Effect of roll and yaw on scan duration

entire curve can be determined and described by solving simultaneous equations of the form.

$$\sin \phi_i = \sin \phi_{max} \sin (\omega_i - \lambda)$$

where ϕ_i is the instantaneous roll angle

ω_i is the instantaneous orbital phase angle

ϕ_{max} is the amplitude of the curve

λ is the phase angle at which ϕ_i is zero, going from - to +

Note that this is a sine curve only for small values of ϕ max; as ϕ max approaches 90 degrees, the curve becomes triangular. When these two descriptors, Phimax and Lambda, are known, the roll and yaw at any point in the orbit can be found. The biggest problem is determining the instantaneous roll angles from the output of the scanners.

III. PROCESSING DETAILS

As was implied in the introduction, the reduction of attitude data has been a manual procedure. The analog signal representing the differentiated output of the sensor is recorded on an oscillograph as shown in Figure 5. The ratio of the earth-viewing time to the whole-spin time can be determined for each sensor at a particular time. Two simultaneous ratios, one from each sensor, are used as entries to a nomogram to obtain the instantaneous roll. A number of roll angles are determined and plotted against orbital phase angle (from an ephemeris), and the amplitude and phase of the resultant curve (ϕ max and λ) are estimated. This manual procedure is outlined in Figure 6.

In order to allow computer processing, the data must be converted to digital form. This conversion is done at the Data Processing and Analysis Facility by an electronic complex, the Digital Formatting System (DFS) (4). The 5-volt amplitude range of the incoming signal becomes a 64-count digital range. To preserve the highest frequency information, the sampling rate is 500 samples per second. The string of digital samples, representing the original signal, is sent by the DFS to the ingest computer which writes a digital magnetic tape for further processing by a larger computer.

The actual process is fairly straightforward, since it has evolved from semi-graphic manual methods. The characteristics of the sensor response, including "meteorological noise", dictate the procedure. But even with an understanding of how to approach it, subtle problems of translating a partially subjective manual operation to computer objectivity were troublesome and the solutions were slow in emerging. The initial version of the program worked well on the initial test data, but when given signals from the real world it failed completely. Each succeeding revision worked for a longer time, only to be discarded when new troubles (or new solutions to old troubles) arose. It gradually became evident that many externally adjustable parameters would be needed to set limits for the logical decisions. Features of the signal which a

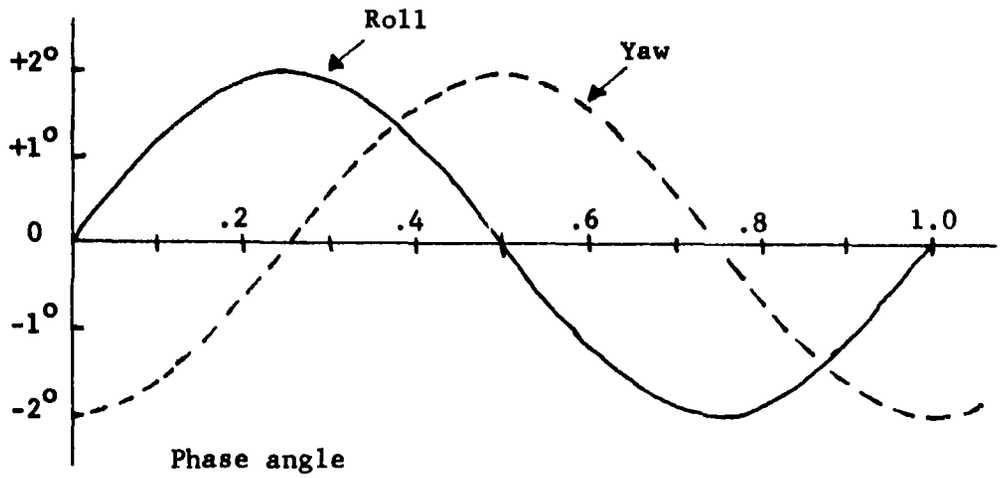


Figure 4

Roll and yaw vs. orbital phase angle

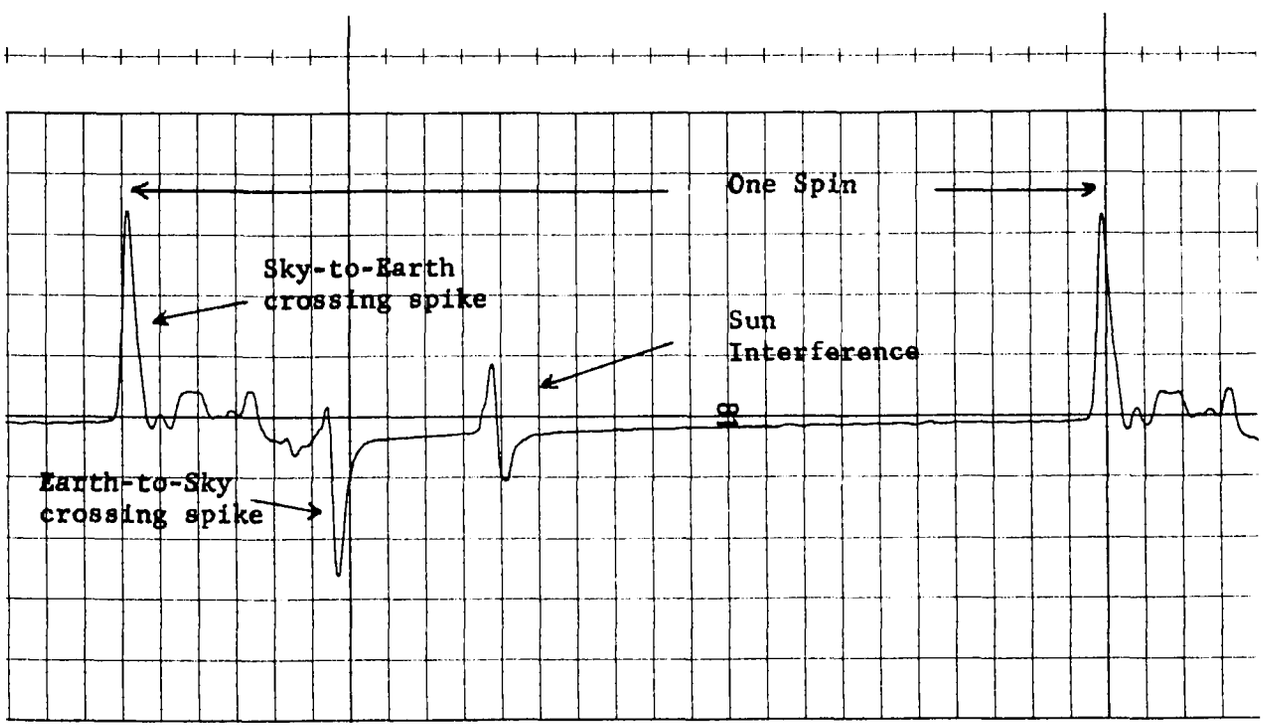
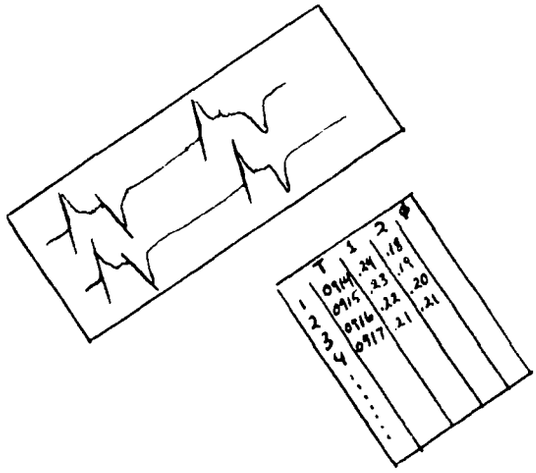
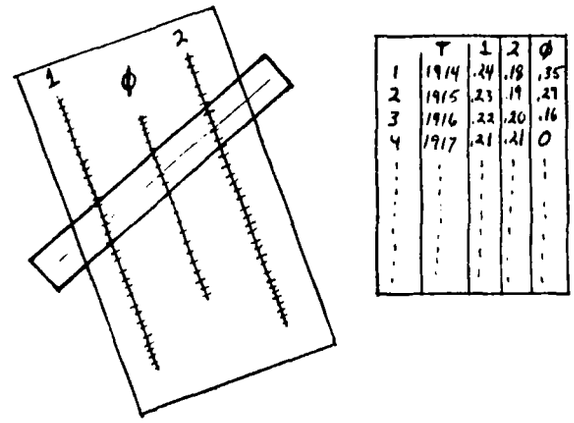


Figure 5

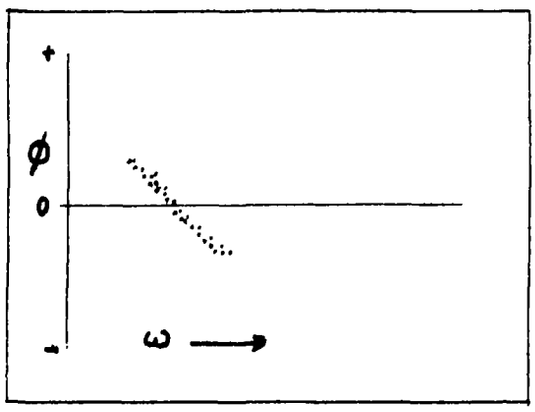
Typical oscillogram of
differentiated data as seen on the ground



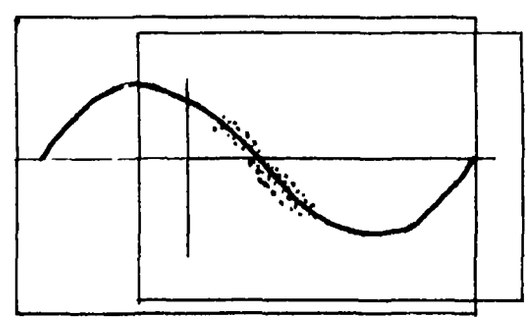
Step 1: Mark earth limits and measure ratios.



Step 2: Obtain roll angles from nomogram.



Step 3: Plot roll vs. phase angle.



Step 4: Overlay a sine curve template and estimate phase and amplitude.

Figure 6

Manual attitude reduction

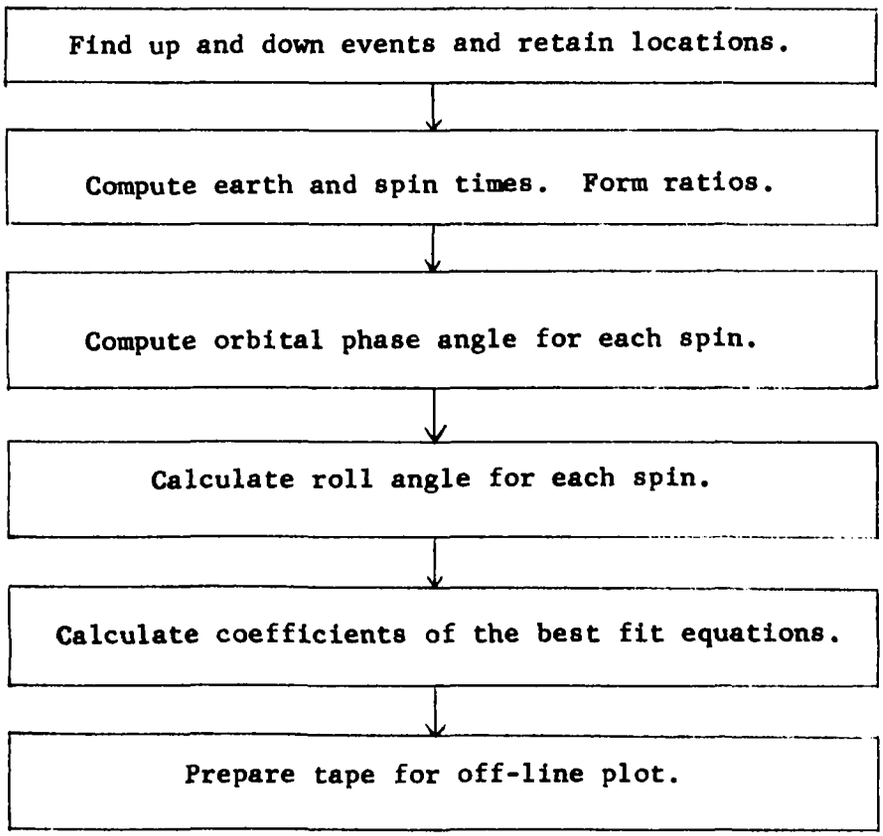


Figure 7
Program logic

technician would class as "too high", "too short" or "wrong shape" had to be changed to "value greater than L", "fewer than M samples", or "slope exceeds N", where L, M, and N might depend upon the satellite, season, or sun angle and can be changed readily as needed.

The basic program logic, shown in Figure 7, is quite similar to the manual technique. The first feature of the signal that is looked for is sky-to-earth crossing. This event appears as a rapid increase in the digital values and is detected by comparing successive sample values against a preset threshold value. When a sample is found which exceeds the threshold, its position (sample number) is retained as being the probable beginning of a sky-to-earth transition. Further checks are made to ascertain that it is indeed such an event and not communication noise or solar interference as was shown in Figure 5. The verification consists of seeing that (a) a certain number of the samples immediately following are also above the threshold, (b) the values fall below the threshold within a reasonable time, and (c) they remain below for several samples, indicating the end of the general up-spike region. Failing any of these criteria causes a reinitialization of the

search for the first value above the threshold. If, on the other hand, all tests are passed, it is quite probable that a sky-to-earth transition has been found.

The associated earth-to-sky transition, which appears as a rapid decrease in sample values, is detected in much the same way. Because of the meteorological noise in the earth-viewing region, the downspike is approached from the quiet space-viewing area. This is accomplished by skipping a specified number of samples and searching backward for a sample whose value is less than a lower threshold level. When such a sample is found, tests are made as in the upspike. If the criteria are satisfied, this downspike indicates the end of the earth-viewing portion of a spin, which is compared to a nominal earth time. If it is within tolerance, the actual horizon crossings are determined more precisely in a manner similar to the manual method. As was suggested in Figure 6, the horizon crossing is located by extending the slope of the upspike to the null level. The computer does this by calculating the slope of the straight line which gives the best statistical fit with the samples. The population for this fit includes the samples between the threshold and an upper limit which is set at 2 or 3 digital counts below the maximum.

The earth-to-sky horizon crossing is handled similarly except that the trailing edge is used for the slope fit and the resulting intercept is shifted to the left by an amount comparable to the width of an uncontaminated pulse. The meteorological phenomena near the off-going horizon were found to affect the earth times based on the leading edge, so the present adjusted trailing edge was adopted.

The positions of the sky-to-earth and earth-to-sky crossings as outlined above are retained until all data from both sensors has been processed. These tables are used in the calculation of earth times (from an upspike to its associated downspike) and spin times (from one upspike to the next). The midpoint time of each scan is also saved so that simultaneous Channel 1 and Channel 2 scans can be selected. For each scan the ratio (T_{earth}/T_{spin}) is determined and, where possible, three independent roll angles are calculated, based on sensor 1 only, sensor 2 only, or both sensors. The one of these three which is closest to some expectation is the one which is preserved for the final analysis. The expected value is derived from a historical trend. The chosen instantaneous roll angles are entered into a table and for each one the time-of-day is converted to orbital phase angle by a routine that calculates orbital position versus time from the orbital elements. Having the final table of values of roll angle versus orbital phase angle, the equation of the curve (and therefore the amplitude and phase) can be calculated. Finally, a tape for off-line display is prepared, and graphic plots of roll angle versus orbital phase angle as shown in Figure 8 are produced. These are used to verify the answer and to judge the quality of the determination. In cases where plots are ragged or results seem bad, the oscillogram of the incoming signal is examined to determine the probable cause. In most instances, excluding equipment error, the problem can be eliminated by changing the control parameters.

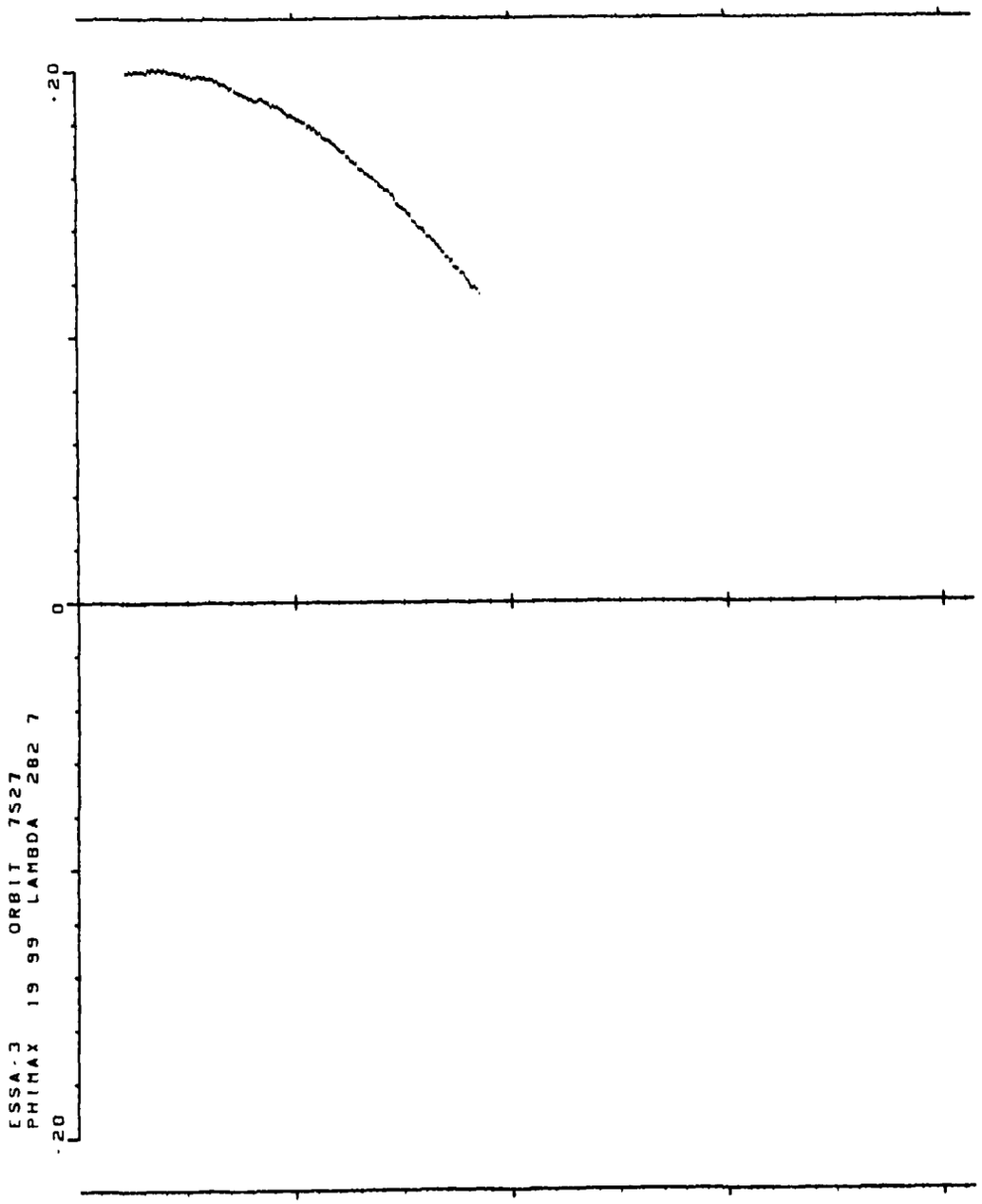


Figure 8

Actual roll vs. phase angle plot

The preceding describes the current operational attitude determination system used at the NESC. It produces consistent results with an accuracy approaching the limit of the TOS-type sensor and equipment. Fortunately, it is also adequate for earth-locating the relatively low-resolution video data.

IV. PLANS

Even as the TOS series continues, the first of the Improved TIROS Operational Satellite (ITOS) series is being built. Its primary sensor complement includes a scanning radiometer which may well be the source of attitude data also. It is designed for meteorological application and is a much more sensitive device than the TOS attitude bolometer. A further advantage is that it scans perpendicular to the direction of motion (and therefore about the roll axis). The angle between the scan angle index pulse and the horizon is very directly related to the roll angle. The use of scanning radiometer data for attitude determination is shown in Figure 9.

Another device being considered for future use is the Scanning Celestial Attitude Determination System (SCADS) (5). It consists principally of a telescope and rotating slit in front of a photomultiplier tube. As the slit rotates, different stars will illuminate the tube and generate pulses. Comparing the time-series of star pulses with a star map will yield a unique direction for the axis of the telescope. This system is an order of magnitude more precise than the present one. A simplified SCADS is shown in Figure 10.

The trend toward more quantitative treatment of imaging sensor data with higher spatial resolution indicates a continuing need for more precise attitude determination. The experience gained in the TOS mission will be a definite asset in meeting that need.

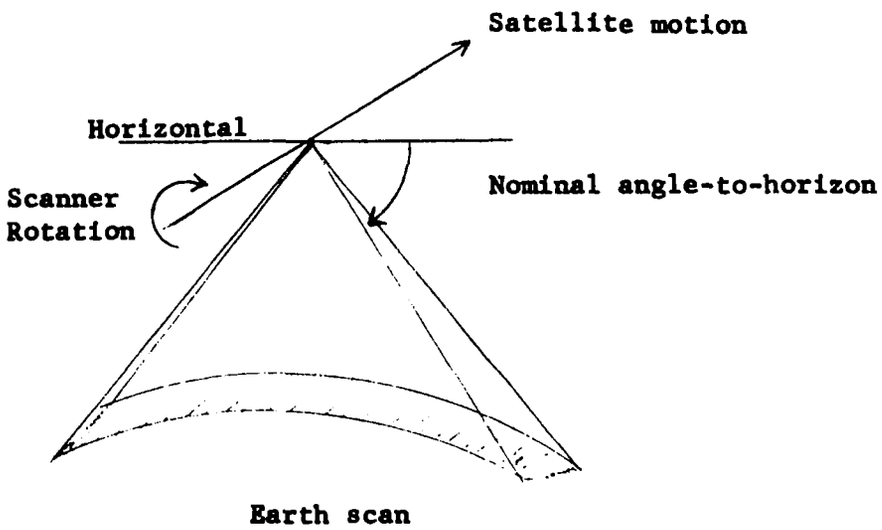


Figure 9

Scanning Radiometer

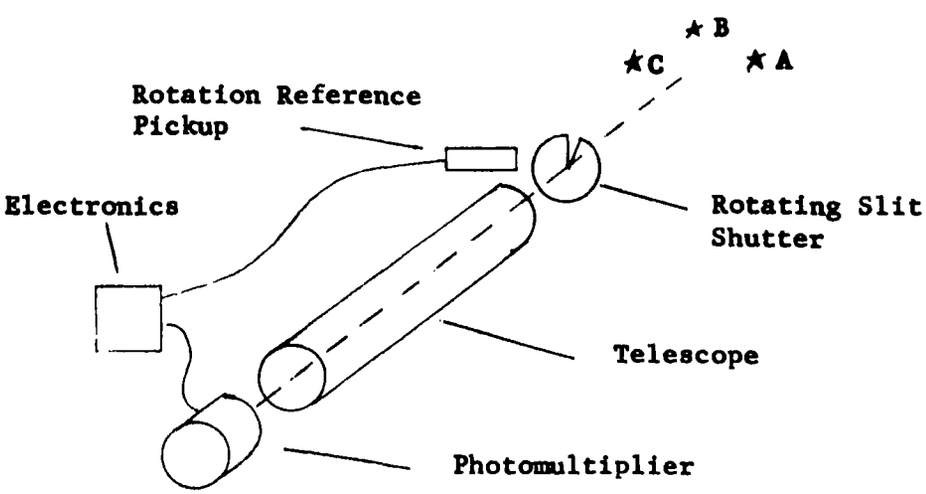


Figure 10

Scanning celestial attitude
determination system

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