

**A SATELLITE ASSISTED-TRACKING SYSTEM WITH REAL-TIME ACCOMODATION
FOR MAXIMAL POINTING ACCURACY**

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ABSTRACT

An operational difficulty of ground receiving stations is to reacquire a satellite in high elevation after a loss due to a zenithal pass (when employing an El-over-Az antenna), a receiving chain malfunction or another cause that breaks reception. Traditional recovery schemes employ rate memory or precalculated pointing data (programmed tracking) to command the antenna movement after a tracking loss. The system described in this paper has been implemented at the Brazilian Landsat receiving station. It does not require a fast computer and takes very little memory, yet has proven extremely effective, with significant advantages over previously available systems. Extensions to the method, to be employed for the upcoming Brazilian satellites, are discussed.

SUMMARY

1. INTRODUCTION
 - 1.1 Initial Motivation: the Zenith Pass Problem
 - 1.2 New Motivation: The "Silence Zones"
2. THE 1982 IMPLEMENTATION
 - 2.1 Characteristics of the Antenna Control Unit (ACU)
 - 2.2 Characteristics of the Computer
 - 2.3 The Calculation Algorithm
 - 2.4 The Simulations Carried
 - 2.5 The Real-Time Structure
 - 2.6 The Real-Life Constraints
 - 2.7 Integration and Checkout
3. EXTENSIONS FOR THE BRAZILIAN SATELLITES
 - 3.1 The New ACU and Antenna System
 - 3.2 The New Station Computer
 - 3.3 Changes in the Calculation Algorithm
 - 3.4 Changes in the Real-Time Logic
4. CONCLUSION

1. INTRODUCTION

1.1 Initial Motivation for Development: the Zenith Pass Problem

Every Remote Sensing Specialist is familiar to some extent with the need for tracking low-orbit remote sensing satellites with parabolic antennas in order to receive and utilize the data they transmit down to Earth.

Most antennas employed for this purpose have automatic tracking capabilities, i.e., they can "follow" automatically a passing satellite since the moment it is "found" on the sky. However, most such antennas in operation employ Elevation-over-Azimuth pedestals, which have a serious limitation for near-zenith passes.

Figures 1.1 and 1.2 show typical azimuth speed and acceleration patterns in EI-over-AZ antennas for high elevation passes as a function of time near the overhead. With the existing systems, limited at about 20 degrees/sec maximum turning speed and about 10 degrees/sec² maximum acceleration, we can see that 89 degree elevation is a practical limit.

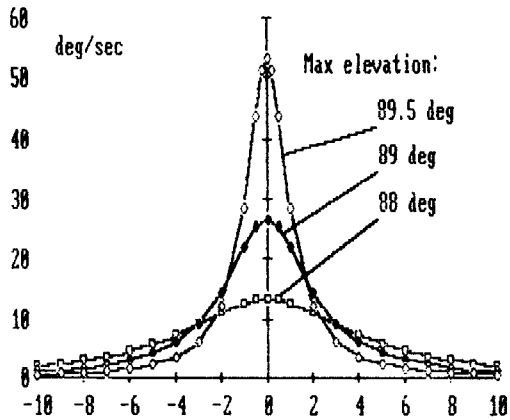


Fig. 1.1: Azimuth Speed vs. Time (seconds) Around Highest Elevation

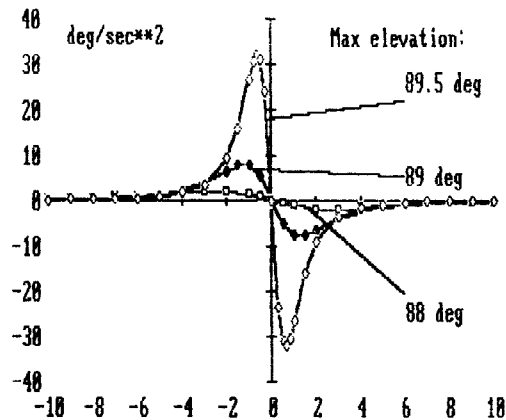


Fig. 1.2: Azimuth Acceleration vs. Time (seconds) Around Highest Elevation

Although apparently a low-probability event, this may turn out to be a serious problem for ground stations that happen to lie too near to one of the repetitive ground tracks of satellites such as the Landsats.

This condition determined the initial motivation for the development of the assisted-tracking system described herein. The first Brazilian Landsat Station, installed in 1973 at Cuiabá, just 17 Km west of Landsat-1 WRS Path 243, spent several months without being able to acquire images south of its location, because it systematically lost the satellite, coming from the North, at 88.8 degrees elevation. Only after the motor power drives were modified to allow a little more current, raising the maximum turning speed to about 22 degrees per second, the problem was settled. However, if Path 243 was just a little closer to the Station the overhead loss could not be avoided.

The devised assisted-tracking system, in opposition to programmed tracking, took into account the antenna elevation and azimuth readings while locked on the satellite to compute its position in the immediate future, achieving much higher accuracy than an analytical predictor could do based on mean orbital elements two or more days old. This would allow, even after an unavoidable overhead loss, to recover after a few seconds instead of minutes, which was the case when available precalculated pointing data were not accurate enough to allow catching up still in high elevation.

The implementation was carried in 1982, when Brazil was preparing for the Thematic Mapper era and a new antenna system was being purchased to receive Landsat 4 in X-band at the Cuiabá Station. This implementation is described in Chapter 2 of this paper.

1.2 New Motivation: the "Silence Zones" of the First Brazilian Satellites

Although present antenna systems have already overcome or minimized the zenith pass problem with either motorized tilt pedestals or servocontrolled subreflectors, a new motivation for an assisted-tracking system arose with the characteristics of the first Brazilian satellites, which may start flying in 1989. A third antenna system is being purchased for installation at Cuiabá for the tracking and command of these satellites.

The two first satellites, devoted to platform data collection, will be near-equatorial rather than near-polar orbiters, while motorized tilt mechanisms like the one to be employed in the purchased antenna system are normally mounted to work in the east-west direction. This will limit the efficacy of such device and assisted tracking may still be necessary near the zenith.

However, the most important service that an assisted-tracking system can provide to the early Brazilian satellite program relates to the absence of active attitude control on the satellites (except for an initial spin-stabilization). This means that at certain periods the satellite orientation can be such that during a pass the Receiving Station will enter the "silence zone" of the satellite irradiation pattern. The resulting signal loss can take from several seconds up to a few minutes.

The initial idea to reacquire the satellite after a silence zone was to move the antenna to the predicted reacquisition position and wait there for the satellite. This approach was abandoned after two problems were pointed out: first, the predicted recovery could be inaccurate, since prediction errors can affect not only the coordinates but also the RF downlink calculation; and second, if reacquisition should occur in high elevation the antenna acceleration capability would certainly not be big enough to suddenly start following the satellite, even if it passed in front the antenna main lobe with signal strength above the required level.

Thus, an assisted-tracking scheme may be employed to command the antenna, keeping it pointed to the satellite during the whole loss period, guaranteeing the earliest reacquisition. Chapter 3 of this document presents possible modifications that can be made onto the present design for the Brazilian mission.

2. The Implementation Carried for Landsat-4 in 1982

2.1 Characteristics of the Antenna Control Unit (ACU)

The ACU to be delivered with the Brazilian Thematic Mapper subsystem was a Scientific-Atlanta model 3842. It had, of course, autotrack capability,

which was the primary mode of operation, and a backup mode selectable among rate memory, position memory and remote command. For this last mode it included a computer interface to allow reading out pedestal angles and commanding antenna positions from an external computer.

The ACU was designed to work in autotrack mode and switch automatically to the selected backup mode in the event of a signal loss. The acquisition/loss status was also available to the external computer through the interface. While in autotrack mode, the ACU would ignore any remote command received. Due to its internal processor constraints, the maximum remote command rate was about 10 times a second, or a command issued every 100 milliseconds.

2.2 Characteristics of the Station Computer

The Receiving Station did not have a computer on site before the Thematic Mapper subsystem was delivered. The one then bought, chosen to be software- and hardware-compatible with the Processing Station, installed in another facility, was a DEC PDP-11/34 minicomputer and its initial role was just to allow local computation of the antenna pointing data.

Taking into account its limited speed (about 0.2 Mips and no floating point hardware) and internal memory (56 Kbytes), a numerical integrator was out of consideration. Therefore, the pass calculation would have to keep being analytical and based only on the Brouwer Mean Elements then sent via telex by NASA's Goddard Space Flight Center 3 or 4 times a week. For the same reasons, any assisted-tracking software would have to be simple and efficient enough to perform the calculations in real time and still keep ahead of the satellite, i.e., produce predicted Elevation and Azimuth values faster than they might be needed in case of a satellite loss.

2.3 The Calculation Algorithm Employed

If you have a set of orbital elements (which are six for the general case) for a satellite at a given instant, you can use them to compute its position along time and therefore, knowing an antenna location, derive the corresponding pointing angles. In the case of Brouwer Mean Elements, some of them (semi-major axis a , eccentricity e and inclination i) are almost constant

in the course of a few days and could therefore be used as operator inputs. Our problem was to derive or adjust the other three (longitude of the ascending node, argument of the perigee and mean anomaly) based on observations of Elevation and Azimuth during a pass.

To simplify as much as possible the computation, the basic idea was to use a *circular* rather than *elliptical* model for the satellite orbit, assuming that its eccentricity (typical value 0.0002) was small enough to be disregarded for a very short term prediction. With this approach the orbital elements would be reduced to five, since there would no longer be a "perigee". Therefore, a single observation of E/AZ would allow resolving the two remaining elements. The sequence of calculus would be:

- 1 - find the satellite position at the intersection of the antenna pointing direction with a sphere of radius a , concentric with the Earth ellipsoid;
- 2 - use this position to derive the longitude of the ascending node and the mean anomaly M (which would coincide, since $e=0$, with the true anomaly u);
- 3 - use the derived elements, together with a and r , to compute the satellite positions for a time series of N seconds in the immediate future;
- 4 - calculate and store the pointing angles for this time-series.

Presenting the full mathematical derivation for the above mentioned procedure is outside the scope of this paper since it involves only well-known equations and formulas of trigonometry, coordinate transforms and orbital calculus. As reference, the interested reader can see Brouwer [1] and Escobal [2], chapters 1 thru 4.

2.4 The Simulations Carried to Check the Model Performances

The model was implemented firstly as a simulation program on the Processing Station's PDP-11/34, identical to the one to be installed at the Receiving Station, in order to validate the intended approach against the performance requirements.

2.4.1 Accuracy (Requirement: less than 0.1 degrees of pointing error for at least 10 seconds to allow

reacquisition in Band X after an overhead loss.) — To verify the delivered accuracy, the model was checked against different Elevation/Azimuth time series, produced by a full model numerical integrator running on a mainframe computer, for high and low elevation passes. Several experiments involving different loss conditions were conducted.

It was found that the worst case conditions for the model, i.e. where the prediction deviated fastest from reality, happened near the zenith. However, even in the worst case the pointing error took at least 2 minutes of loss to exceed 0.1 degrees. Across a full pass (simulating a loss just after the satellite was acquired), the error never exceeded 0.7 degrees (see Figure 2.1), which is enough for a reacquisition in Band S. The maximum error observed near the zenith presented an interesting behavior as a function of the elevation at which the loss was simulated (see Figure 2.2).

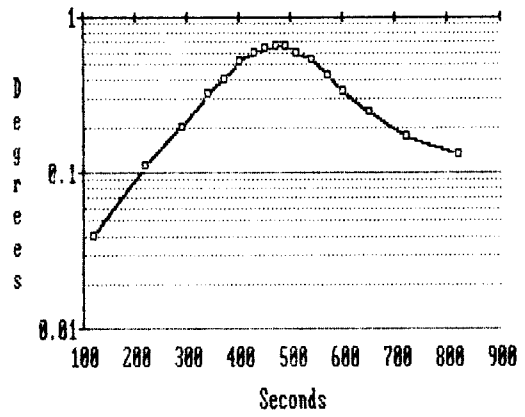


Fig. 2.1: Worst Case Pointing Error vs. Time After Loss

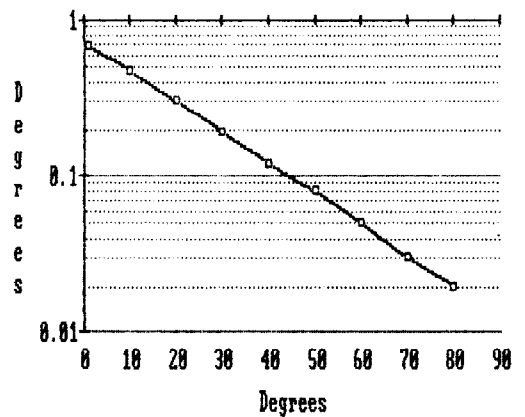


Fig. 2.2: Maximum Pointing Error vs. Elevation at Loss

2.4.2 *Speed* (Requirement: less than 100 msec computing time per EI/Az pair to allow commanding the antenna at the maximum ACU rate.) — The computing times were measured and the results showed 1) less than 7 milliseconds for deriving the desired orbital parameters from an observed EI/Az pair, and 2) less than 27 milliseconds to compute a pair of predicted pointing coordinates.

2.4.3 *Sensitivity to Input Parameter Inaccuracy* (Requirement: no degradation of accuracy beyond specification for unaccounted-for typical time drifts in the operator-introduced parameters.) — The operator input parameters (orbit inclination i and semi-major axis a , which would have to be taken from sources 2 or more days old) were changed with respect to those used to produce the time series. The model was found to be practically insensitive to errors up to a hundred times greater than the typical day-to-day change figures, which are about 0.05 Km for the semi-major axis and around 0.001 degrees for the orbit inclination.

The above performances were considered far more than enough to satisfy all the requirements of the devised assisted tracking system. Therefore, a green light was set for the implementation.

2.5 The Real-Time Structure

Considering that in real life conditions the computer would have not only to calculate and store the orbit extrapolation data but also to handle all the traffic of data and statuses between itself and the ACU, the software was designed with a background/foreground architecture.

The synchronous part of the program (background) would take the last available EI/Az observation to derive the corresponding orbital elements and then compute and store N_1 seconds of future pointing data. After that it would sit in a wait loop, going back when either a loss was detected or less than N_2 seconds of predicted pointing data remained in the buffers with the satellite still being acquired. N_1 and N_2 are parameter variables set respectively to 90 and 30 based on the simulation behavior.

The asynchronous part of the program (foreground) would read the

acquisition status under the pace of an external clock and then, depending if in autotrack or not, either read and store the antenna elevation and azimuth positions or command them from the prediction buffers filled by the background part.

The two parts would communicate through a common area in memory where all flags, pointers and buffers would reside.

The real-time logic was tested by attaching the external clock interrupt routine to the computer real-time clock and implementing a dummy ACU driver to take the EI/Az "readings" from the stored time series and take the acquisition "status" from a flag changed asynchronously at another interrupt routine attached to the terminal keyboard.

2.6 The Real-Life Constraints

Certain real-life constraints determined some modifications to the logic used in the simulations:

a) although EI/Az during acquisition state could keep being read once a second, to obtain as smooth an antenna movement as possible a decision was taken to command it at 10 Hz instead of once a second as in the simulations. The external clock pace must be then 10 Hz instead of 1 Hz and the interrupt routine in the foreground software and the prediction interval in the background were adapted accordingly.

b) due to the ACU characteristics it was important, during normal acquisition, to keep its remote EI/Az command registers updated consistently with the current antenna position. Otherwise, when falling automatically to the remote command backup mode at a signal loss, the ACU would find and use dummy EI/Az values to command the antenna before the first predicted values were sent in by the computer, which could impose unnecessary strain to the antenna drives. The decision was to keep the command logic active at all times, loading the ACU command registers with predicted values which would be ignored by the ACU logic during acquisition but would be immediately available when needed.

c) to reduce the effect of the small potential antenna jitter around the satellite position while tracking it, steps 1 and 2 of the calculations (see Section 2.3) should be repeated a few (3 to 8) times for consecutive EI/AZ readings, so that the derived elements could be averaged.

d) to avoid that potentially inaccurate readings made during high antenna acceleration periods impacted the calculations, the software was built not to take into account EI/AZ pairs above a given elevation, which was initially set to 80 degrees. This value could be certainly higher but its maximum could not be determined by simulation without modelling into it the antenna inertia and servo response. Since satellites at altitudes below 1000 Km cannot spend more than about 45 seconds above 80 degrees elevation for a given station and our assisted tracking was safe for at least 2 minutes, the cost/benefit ratio of this investigation did not justify it.

2.7 Integration and Checkout

The Thematic Mapper subsystem was installed at Curitiba in August, 1982 and the developed simulation program was then adapted to work in real life environment.

As, by chance, the Landsat-4 WRS coverage pattern did not have a ground track close enough to the Receiving Station, there were no near-zenith passes and therefore losses had to be simulated by disconnecting the tracking receiver during a pass. This had advantages over a real loss; first, of course, because no data was lost; and second, because the signal level at the data receiver could be monitored while the assisted tracking was in command.

RESULTS OBSERVED:

It could be checked that there was not a single dB of fading for more than one minute in that condition. For comparison, the ACU Rate Memory backup mode would lose the satellite in less than 15 seconds for a loss around 30 degrees of elevation, or 5 seconds above 80 degrees.

3. Extensions of the System for the Brazilian Data Collection Satellites

3.1 The New ACU and Antenna System

The receiving system purchased for the Brazilian missions includes an ACU of the same manufacturer and model as the one with which the assisted tracking was implemented, although of a more recent design. Its operation will be basically the same, with the addition of a motorized tilt mechanism for the antenna pedestal. Therefore, the basic characteristics of our assisted tracking system can be maintained. Its usefulness, as mentioned in the Introduction, will be in helping the antenna across the "silence zones" and perhaps also across overhead passes if the tilt axis must be mounted North-South.

3.2 The new Station Computer

The new Station computer will be a DEC MicroVAX II, more than 10 times faster than the existing PDP-11/34, although with a heavy multitask role of monitoring and recording statuses of all station and satellite subsystems, supporting on-line data communications with the Control Center and sending preprogrammed or emergency commands to the satellite during each pass. Nevertheless, in a signal loss situation, which is when assisted tracking will have to take over, this task is expected to be highly alleviated.

3.3 Changes in the Calculation Algorithm

It is expected that the first Brazilian satellites have an orbit eccentricity well above Landsat's, reaching perhaps 0.05 or a little more. Therefore, the algorithm described at Section 2.3 may not be able to disregard eccentricity. On the other hand, the argument of the perigee will be better defined and can be used as an additional operator input, keeping still at 2 the number of "missing" elements.

As the intersection of the antenna pointing direction with an ellipsoid not concentric with the Earth cannot be analytically explicit, a rigorous solution to find the distance r from the satellite to the Earth center would require numerical methods. However, utilizing steps 1 and 2 of the mentioned algorithm using the semi-major axis a as a first approximation

to r , the obtained true anomaly u would allow a new value for r through the equation

$$r = a (1 - e \cos E),$$

where

$$E = 2 \operatorname{atan}(\operatorname{tg}(u/2) \operatorname{sqrt}((1-e)/(1+e)))$$

is the eccentric anomaly. This makes out a quickly converging series to yield reliably updated values for the desired orbital elements.

From there on, steps 3 and 4 would be exactly the same.

3.4 Changes in the Real-Time Logic

To minimize CPU demand during normal acquisition periods, the real-time logic of the assisted-tracking model can be modified to perform just the orbital element updates, at specified intervals. In a loss event, predicted EI/AZ pairs will start being needed at a 10 Hz rate, which is something the MicroVAX can compute and command with plenty of margin, based on the last adjusted orbital elements. In fact, since it is unlikely that the condition that caused the loss will disappear before at least some seconds, even the orbital elements adjustment, taking into account the last EI/AZ readings while still in "lock" state, could be performed right after the loss without delaying recovery.

In any case, as mentioned in Section 2.6.b, it will be necessary, during normal acquisition, to keep the ACU remote EI/AZ command registers updated, for instance with a copy of the EI/AZ readings.

4. Conclusion

Although not having been effectively needed after its first implementation, the assisted tracking system described herein was certified for effectiveness and efficiency. The authors are confident that, although representing a very minor part of the system being developed for the Brazilian satellite program, the concepts presented herein can give an important contribution for the successful operation of the first Brazilian satellites and perhaps to other countries' ground systems that might face similar problems.

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