

# **A MORE EFFICIENT TRACKING SYSTEM FOR THE SANTIAGO SATELLITE TRACKING STATION**

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## **ABSTRACT**

A digital antenna control system has been designed and installed on a pedestal that was formerly used to drive a VHF array and that has now been replaced with an 11 meter S-Band parabolic reflector.

In this Paper, the former analog tracking system will be described, showing all the drawbacks that made it unusable for S-Band. Subsequently, the development and implementation of the digital S-Band tracking system, using Labview, C++ & digital control theory will be discussed. Finally, there will be a comparison between the digital and analog system, to .

## **KEYWORDS**

Pointing accuracy, antenna control system, tracking systems, control algorithms, servo controllers.

## **INTRODUCTION**

During the 70's and 80s, the SATAN antenna (acronym that stands for Satellite Automatic Tracking Antenna) was used for supporting many satellites in the VHF band; currently, however, mission support at the site occurs mainly in the L & S bands (1.5 GHz- 2.5 GHz), so that it became necessary to modify the SATAN antenna to replace its VHF array with an 11 meter parabolic reflector and associated RF gear. When doing this, an antenna control system had to be developed in order to meet the more stringent S-Band tracking accuracy requirements.

The hydraulic equipment of the antenna is mainly comprised by: a low pressure pump to circulate the oil and keep it within the adequate temperature range, a high pressure pump to power the actuators, and the actuator circuit (servo-valves, manifold and actuator).

With regard to the control system, the antenna had an analog servo composed of two feedback loops. The position feedback loop, which came from the angular readings of the synchros, and the velocity loop, from the tachometers in each axis. To drive the antenna, the position loop was created as a result of the comparison between the synchro transmitter (located in the antenna axis) and the synchro receiver (driven by the antenna operator). The velocity loop function is to reduce the overshoots of the antenna.

The system provided a very unstable and inaccurate control in the new S-band front end configuration due to the fact that the analog servo was designed for operating with VHF satellites where a 12 degree beam width is used, instead of the 0.82 deg. beam width of the 11 meter dish in S band. Besides, synchros provided a very poor feedback loop resolution, of about 0.1 degrees.

### **UPGRADES FOR THE NEW SYSTEM**

A parabolic, locally designed and manufactured 11.32m dish with an S-band feed (freq:1.6-2.4 Ghz) was mounted on the SATAN pedestal. As it can be seen in Figure 1, the antenna has an X-Y type mount.



Figure 1 SATAN antenna & its X-Y mount (front & rear view).

To design a better control system, new data acquisition boards (DAQ) were installed in a PC. The main features of these boards are: 48 digital inputs/outputs and 2 analog outputs (12 bits of resolution). Besides, the synchros in the angular measurement system were replaced with absolute optical encoders, which give a resolution of 0.005 degrees. These optical encoders communicate with the PC through an encoder interface. The task of this interface is to interrogate the encoders and receive the angle via RS422 and then send the angle data (parallel output) to the tracking PC.

Once the “tracking computer” was assembled, the next step was programming a digital control algorithm. This algorithm would be in charge of the control and pointing of the antenna. This control algorithm was tuned according to the transfer functions of both axes of the antenna.

### **CONTROL STRATEGIES AND COMPUTER ALGORITHM.**

After determining the transfer functions of the antenna, different control strategies can be applied. The absolute optical encoders were used to create the feedback loop. The two servo valves (one for each axis) will continue being used to drive the antenna to different positions.

With regard to the control loop, a PID controller (proportional+integral+derivative) was used in conjunction with velocity and position feedforwards. All these calculations are performed every 100 milliseconds.

The software has two positioning modes, Manual or Automatic. In the Manual mode, the system follows an angular position driven by the operator. In the Automatic mode, the system calculates the orbital position of the satellite every 100 milliseconds, using Two-line elements (TLE) as an input.

Feedforward velocities and accelerations are calculated using the values of the predicted positions. These feedforward loops are called velocity and acceleration profiles. Such profiles (based on Motion Control Theory) were added to the PID controller. As a result, there was an improvement in the controller's response because the feedforward loops have a predictive action and the PID algorithm reacts to the difference between the actual and predicted position. In other words, feedback deals with deviations from the desired behavior in the past and feedforwards are predictive elements that drive the system to exhibit a desired behavior. This control strategy is shown in Figure 2.

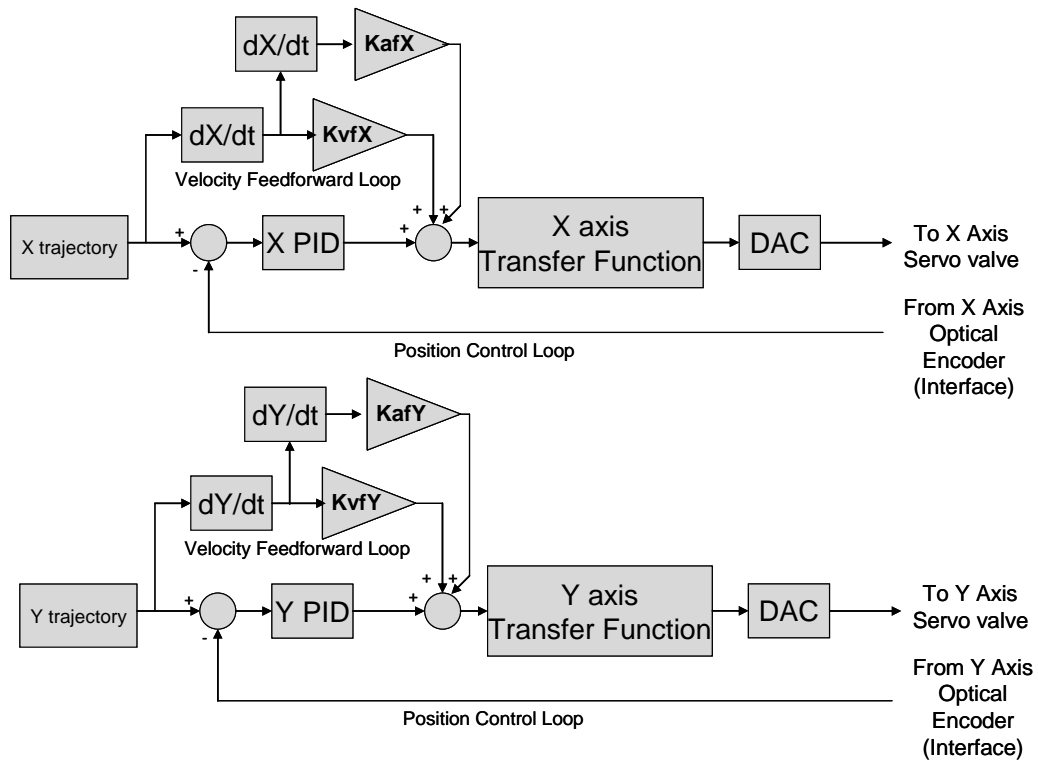


Figure 2 Diagram of the Antenna Control Loop that incorporates PID plus velocity and acceleration feedforwards.

### CONTROL SOFTWARE

LabView 6 RT was used to develop the software, due to its mathematical processing capability, GUI & stability. On the other hand, C++ was used for the implementation of the control formulas and orbital calculations.

The angular data is digitally read by the PC through a 16 bit parallel signal coming from the encoder interface. Besides, the systems uses a 10 pulse per second (PPS) signal to synchronize the encoders' readings, the time readings and the antenna control loops. The time & angular data readings are input to the PC using two 48 bit digital input/output (DIO) DAQ boards. .

Once the antenna angles are read, the predicted and actual positions are compared and subtracted. The position errors are processed by a digital PID controller, which sends its output to an analog output PC board (2 channels/12 bits of resolution). Figure 3 shows a diagram of the system.

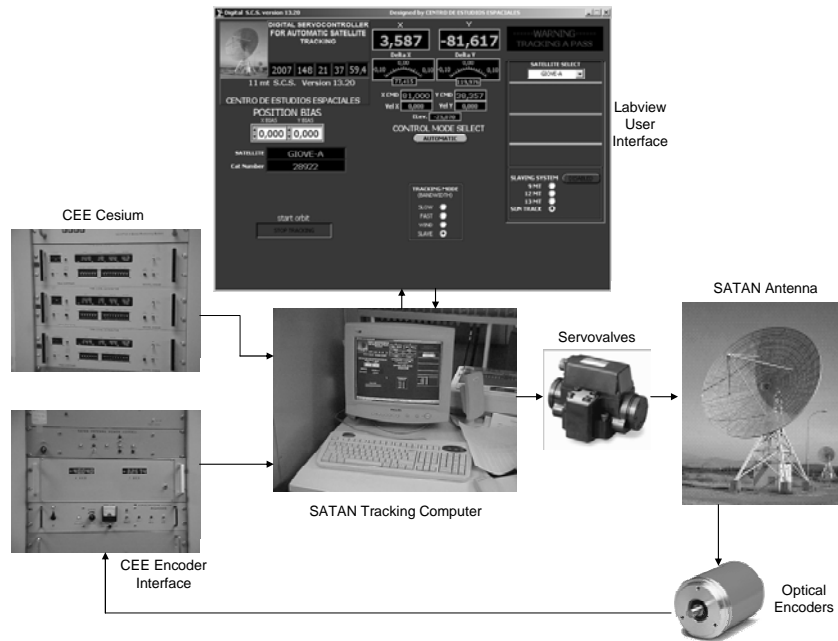


Figure 3: General Diagram of SATAN antenna control system.

### EXPLANATION AND IMPLEMENTATION OF THE DIGITAL PID CONTROLLER

In the PID controller, the position setpoint, which varies every 100 milliseconds, is compared to the process variable (actual angle) to obtain the angular error “e”:

$$e = SP - PV \quad (1)$$

Where e=position error

SP=Set Point position or predicted angle of a certain orbit

PV=Process variable or actual read angle

Thus calculating the controller action as:

$$u(t) = K_c * \left( e + \frac{1}{T_i} \int_0^t e dt + T_d \frac{de}{dt} \right) \quad (2)$$

where  $K_c$ =controller gain.

$T_i$  is the integral time (also called reset time), and  $T_d$  is the derivative time (also called rate). The proportional action **Up** is :

$$u_p(t) = K_c * e \quad (3)$$

The integral action **Ui** is

$$u_i(t) = \frac{K_c}{T_i} \int_0^t e dt \quad (4)$$

And the derivative action **Ud** is

$$u_d(t) = K_c * T_d * \frac{de}{dt} \quad (5)$$

Thus, the implemented program contains the positional PID algorithm that will be described in the following steps:

A digital filter of the process variable is applied to the algorithm to avoid any possible noise in the angular data readings. The filter is as follows:

$$PV_f = 0.5PV + 0.25PV(k-1) + 0.175PV(k-2) + 0.075PV(k-3) \quad (6)$$

Where  $PV_f$  = filtered process variable

The error used to calculate the derivative action and integral action is

$$e(k) = (SP - PV_f) * (L + (1-L) * \frac{|SP - PV_f|}{SP_{rng}}) \quad (7)$$

The error used to calculate the proportional action is

$$eb(k) = (\beta * SP - PV_f)(L + (1-L) * \frac{|\beta SP - PV_f|}{SP_{rng}}) \quad (8)$$

where  $PV_f$  is the filtered process variable, and  $PV$  is the process variable without filtering,  $SP$  is the position set point from the PC,  $SP_{rng}$  is the setpoint range,  $\beta$  (beta) is the setpoint factor (for the two degree of freedom PID algorithm described under proportional action), and  $L$  is the linearity factor that produces a non-linear gain term, in which the controller gain increases with the magnitude of the error. Thus, if  $L = 1$ , the controller is linear. A value of 0.1 makes a minimum gain of the controller (10%  $K_c$ ).

Related to the proportional action, in some cases the setpoint changes are normally greater and faster than load-perturbations, while load disturbances appear as a slow deviation of the controlled variable from the setpoint. Tuning the controller for a good response to load-perturbations means setpoint-responses with great oscillations. On the other hand, a good setpoint-response results in very slow responses to load-perturbations. As shown in equation (8), when  $\beta$  is less than 1, this factor reduces the setpoint-response overshoot without affecting the load-disturbance response. This is referred to as a Two Degree of Freedom PID algorithm. In other words,  $\beta$  is an index of the setpoint response importance, from 0 to 1. For instance, if load-response is considered the most important variable for the loop performance, then  $\beta=0$ . Otherwise, if the process variable needs to quickly follow the setpoint changes, then  $\beta=1$ .

Finally,

$$u_p(k) = K_c * eb(k) \quad (9)$$

In the integral action, the trapezoidal integral action is used to avoid abrupt changes when there is a change in the SP or PV; the nonlinear adjustment of the integral action neutralizes the overshoots. The larger the error, the smaller the integral action, as shown in equation (10) and Figure 4 .

$$u_i(k) = \frac{K_c}{T_i} \left[ \frac{e(i) + e(i-1)}{2} \right] \Delta t \left[ \frac{1}{1 + \frac{10 * e(i)^2}{SP_{mg}^2}} \right] \quad (10)$$

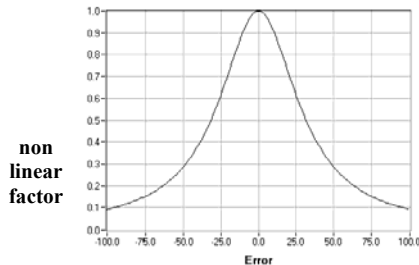


Figure 5 Nonlinear multiple for integral action (SP range = 100).

Because of the abrupt changes in the setpoint SP, the derivative action was only applied to the process variable PV<sub>f</sub> (not to the error) to avoid derivative kick.

$$u_D(k) = -K_c \frac{T_d}{\Delta_t} (PV_f(k) - PV_f(k-1)) \quad (11)$$

The controller output U(k) is the addition between proportional, integral and derivative actions.

$$u(k) = u_p(k) + u_i(k) + u_D(k) \quad (12)$$

Finally, the formula of the implemented PID model was:

$$u(t) = K_c \left[ (\beta SP - PV_f) + \frac{1}{T_i} \int_0^t (SP - PV_f) dt - T_d \frac{dPV_f}{dt} \right] \quad (13)$$

## COMPUTER SIMULATION OF THE SYSTEM

A step input voltage was applied to the servovalves, to calculate the antenna transfer function. Then, its response was approached to a Second Order plus Dead Time System. The antenna response (antenna angles versus time) is shown in figure 5. Using Excel Solver, the antenna response was approached to the model proposed in equation (14).

Figure 5-a shows the antenna step response and Figure 5-b shows the simulated response using Simulink with the model proposed in equation (14):

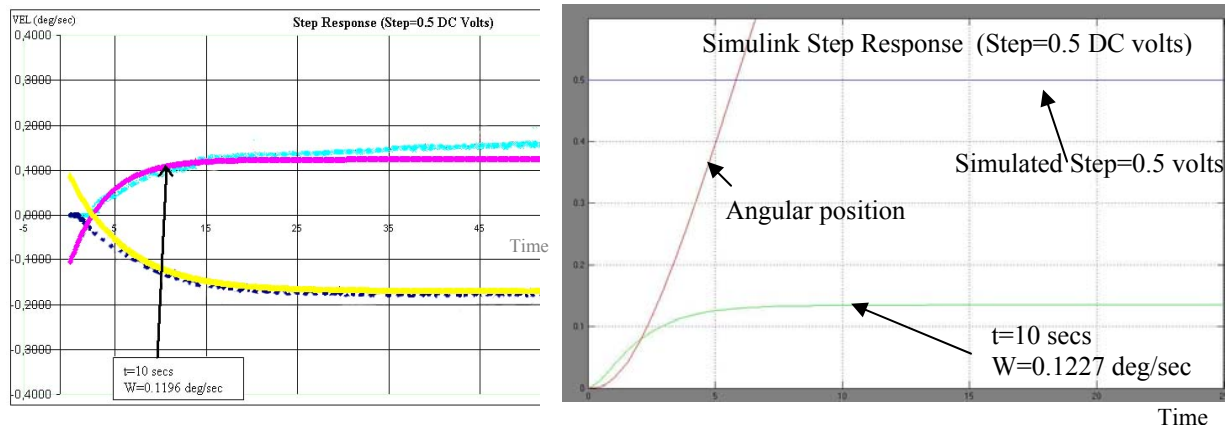


Figure 5: Step Response in real(6-a) & simulated(6-b) models

Using Solver along with the theoretical model, the following parameters were calculated:

<u>X axis</u>	<u>Y axis</u>
K=0.2694 (rad/sec)/volt	K=0.3934 (rad/sec)/volt
T1=0.5128 sec	T1=0.6453 sec
T2=1.67 sec	T2=2.387 sec

The model to be used is:

$$G_m(s) = \frac{K \cdot e^{-\theta \cdot s}}{(\tau_1 s + 1)(\tau_2 s + 1)} \quad (14)$$

Where  $K$  = gain of the model  
 $\theta$  = dead time  
 $\tau_1, \tau_2$  = time constants of the model

### OVERVIEW OF THE SOFTWARE

The software was implemented in Labview and C++. Three DAQ boards were used to drive the antenna, receive data from the encoders and receive time from a Time code reader. Figure 8 shows a general view of the antenna control software screens. The satellite can be selected in the upper right hand corner of the screen.



Figure 8: General View of the program

The UTC time is displayed in the upper left hand corner of the screen. This signal comes from a Time Code Reader. The actual angles of the antenna (for both axes) are displayed in the top middle of the screen. Besides, there are two indicators labeled X CMD and Y CMD, which show the predicted positions of the satellite that is being tracked.

In the middle left hand of the screen, there is an indicator showing the satellite that is being tracked by the system (See figure 9). The system starts to move the antenna and calculate the orbit by pressing the button labeled “Start Tracking” (located in the lower left hand corner of the screen). Once pressed this button, the system indicates that it is tracking a satellite.

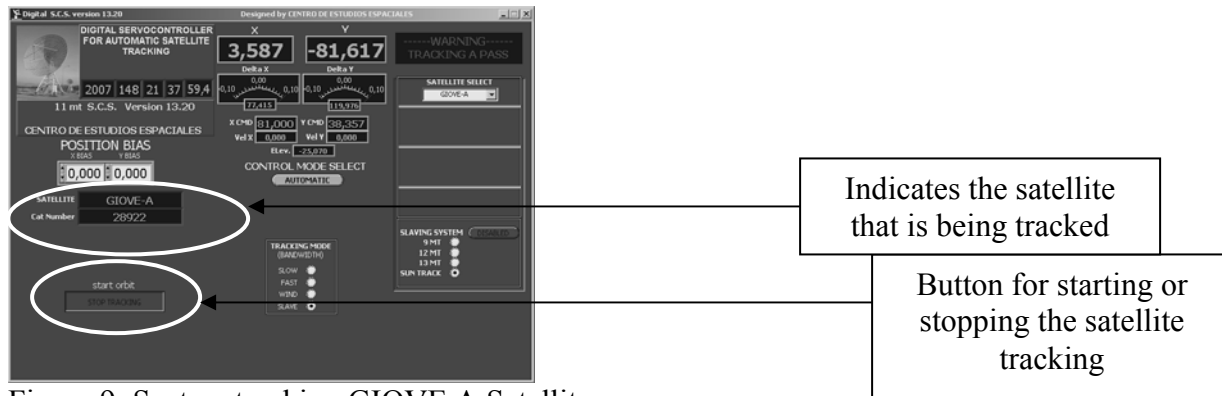


Figure 9: System tracking GIOVE A Satellite.

Besides, the system can be used in slave mode. At this mode, the system is capable of receiving or following the angles of other antennas as an input. Thus, the antenna can track the same satellite that other antennas are tracking, without using orbital predictions.

Finally, the system can be moved at any other position desired by the operator. Such Control mode can be selected by clicking on “Control Mode Select” button. When this mode is selected, four option buttons (Angles By User, Central Coll Tower, 12 MT Coll Tower y Parking Position) are displayed, as shown in figure 10.

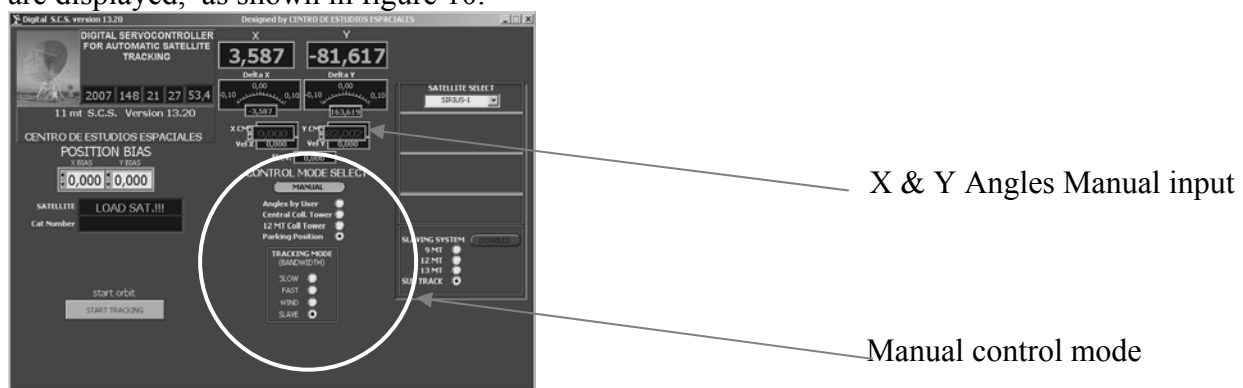


Figure 10: System in Manual Control Mode

## COMPARISON BETWEEN THE OLD AND NEW SYSTEMS

Comparing the old and new systems requires an analysis of the responses of both axes, and the best way to do this is by using charts that represent the angles of the antenna versus time. This is shown in figures 11 a, b, c and d. Figures 11-a and 11-c show the antenna response driven by the Analog Servo. On the other hand, Figures 11-b and 11-d display the response given by the digital servo. As it can be seen in Figures 11-a and 11-b, there was a substantial improvement in the settling time. Analyzing the step response from 0 to 45 degrees, the settling time for the digital servo was around 24 seconds for the X axis and 38 seconds for the Y axis, whereas in the analog servo the settling times were 44 and 64 seconds for X and Y axis, respectively. The same results can be obtained when analyzing Figures 11-c and 11-d.

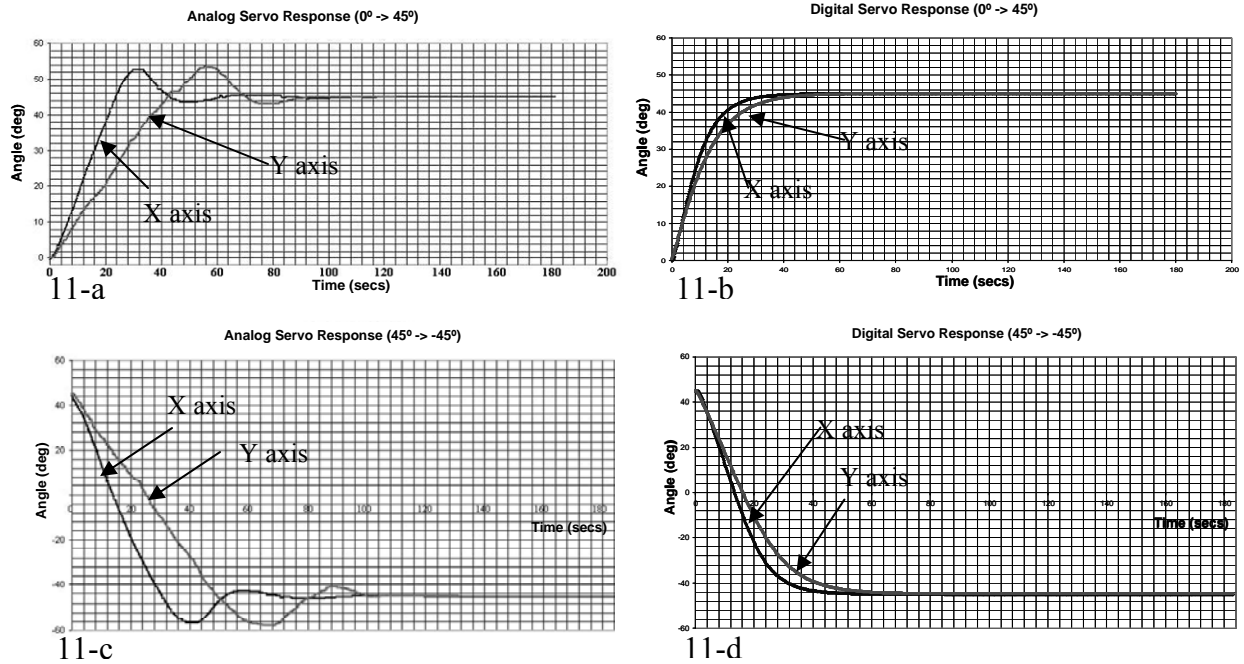


Figure 11: Step Responses for analog (11-a & 11-c) and digital servos (11-b & 11-d).

## CONCLUSIONS

As a result of this engineering modification to the SATAN antenna control system, a substantially better accuracy has been achieved, fulfilling the demands that S-band spacecraft tracking represents. Also, the new system's software makes the antenna operation easier because it has been designed to satisfy the operator's requirements.

Multiple hours of support provided by the Santiago station using the modified SATAN antenna show that that all design objectives have been met.

With regard to the programming, Labview & C++ showed a great stability. The reason for using C++ was because the control system takes less time in doing the calculations related to orbits, angular readings and control, whereas Labview has a lot of features that are very helpful in creating an easy to use GUI.

Finally, and as it could be expected, the use of digital control systems in replacement of the former analog counterparts has shown many advantages and performance improvements that we at the Santiago site plan to take advantage of when modifying or designing station tracking systems.

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