# *Implementing a Digital Tracker for Monopulse Radar Using the TMS320C40 DSP*

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## Abstract

This project AXIR_B (Digital Tracker) corresponds to a PCB that performs the following main tasks.

- ❑ Deviation calculus and coordinates transformations.
- ❑ Tracking and smoothing the rectangular (X, Y, Z) coordinates.
- ❑ Interfacing with the pedestal and the Radar Manager.

The Digital Tracker operates different algorithms during the three modes of the AXIR. The three modes of the AXIR radar are acquisition process, tentative tracking, and confirmed tracking.

The Digital Tracker communicates through dual access memory with AXIR_A (Doppler processing) and AXIR_C (Radar Manager) projects.

The input data used by the Digital Tracker corresponds to four beams, 16 ranges bins, and three Doppler filters. From this data the Digital Tracker calculates the deviations in elevation, azimuth, and range and transforms them into rectangular errors. Three Alpha-Beta filters are used to smooth the coordinates and to calculate the derivatives (predicted X, Y, Z, dX/dt, dY/dt, dZ/dt).

From this trajectory data, the loops are completed via the reverse matrix conversion calculating the azimuth and elevation voltages to the benefit of the pedestal motors. The predicted range is used to generate the early and late range gates.

The Radar Manager is responsible for updating the Alpha-Beta coefficents.

This project is based on a PCB using one Texas Instruments (TI™) TMS320C40 digital signal processor(DSP).

This document was an entry in the 1995 DSP Solutions Challenge, an annual contest organized by TI to encourage students from around the world to find innovative ways to use DSPs. For more information on the TI DSP Solutions Challenge, see TI's World Wide Web site at www.ti.com.

The submission package for the TI DSP Solutions Challenge included:

- ☐ This current paper.
- ☐ A disk containing the C sources and assembler programs.
- ☐ The AXIR demonstration program.

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# Introduction

AXIR is a concept of low-cost Automatic Xband Instrumentation Radar especially designed for the TI DSP Solutions Challenge. This concept is based around four projects. The idea was to demonstrate that is possible to quickly design a small intelligent radar, including expert and adaptive digital signal processing, made up of less than 8 TMS320C4x/TMS320C5x chips.

The objective cost is under 80,000 $ for the entire radar. This includes the pedestal, antenna, transmitter, RF front-end, signal processing, and display. The AXIR is basically a monopulse Doppler ground base radar. Numerous AXIR civilian applications include:

- ☐ Tracking of meteo-sounders,
- ☐ Cloud doppler analysis for meteo purposes,
- ☐ Short range air control radar for parallel runways or difficult access airports,
- ☐ Detecting wind-shear and bursts,
- ☐ Trajectory control for piloting schools, aerobatics sporting events, and aero clubs,
- ☐ General low-cost instrumentation radar (radar cross section evaluation, tutorial radar for universities, and private air tracking).

The digital signal processor is composed of four printed circuit boards, corresponding to one of four separate projects submitted to the TI DSP Solutions Challenge by four distinct teams from the same university sharing the same advising professor. The four projects are named:

a) Front-end/Doppler Processing
b) Digital Tracker (AXIR B)
c) Adaptive Radar Manager
d) Test Simulator/Display Control.

AXIR features modern technology for the other subsystems. The antenna is planar monopulse, printed on three layers. The transmitter, the Stalo, and the RF homodyne front-end are 100% solid-state. All the circuits and the processor are located at the back of the planar array antenna.

The pedestal uses low-cost modern technology developed for robotic applications. The flat antenna is free to rotate 360° both in azimuth and elevation, which is not common. A standard PC, running Microsoft Windows/MS-DOS, was used for the operator remote control, graphics display, monitoring, and recording. A radio link was managed between the sensor and the operator desk.

This project was developed by three undergraduate students in preparation for a radar course. It has been a practical exemplify of their signal processing course.

# Overall Description

## Operating Modes

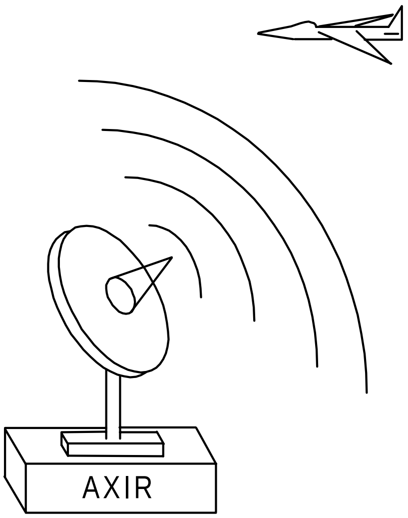
AXIR, the tracking radar, operates sequentially in the following three modes:

- ☐ Acquisition
- ☐ Tentative Tracking
- ☐ Confirmed Tracking

### Step One: Acquisition

Once a target is spotted by the radar's operator, the radar searches to acquire it (see Figure 1). The magnitudes of the upper, lower, right and left four squinted beams are accumulated individually for the three Doppler filters and for the sixteen range gates. Each channel is compared to a threshold. If one result is trespassing this level, the target is declared present in the cell providing the largest number.

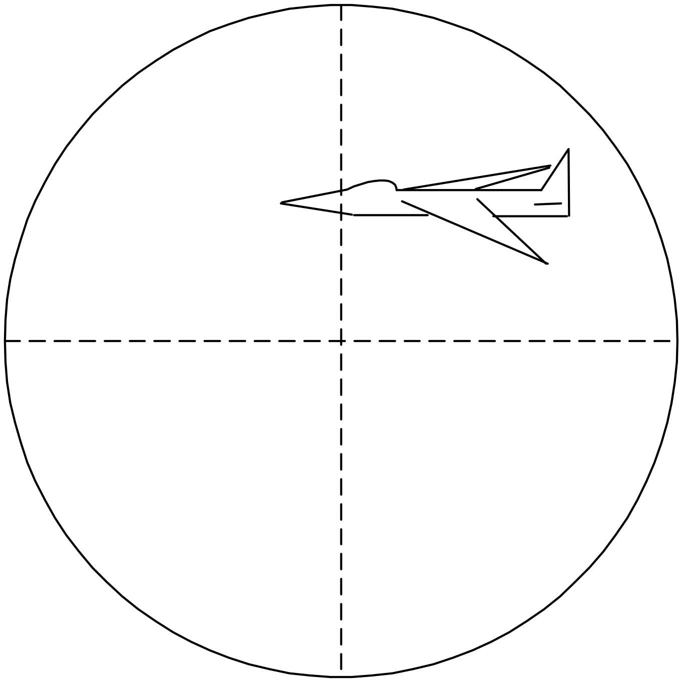
*Figure 1. Acquisition Mode*



## Step Two: Tentative Tracking

Several Doppler measurements (coherent bursts) are operated with at least 3 different Pulse Repetition Intervals (PRI) in order to solve the range-Doppler ambiguities (see Figure 2). The objective of this step is to evaluate the coherence of the unfolded range measurements and Doppler frequencies. During this mode, the angular deviations are computed and are used by the Alpha-Beta filters with a short time constant.

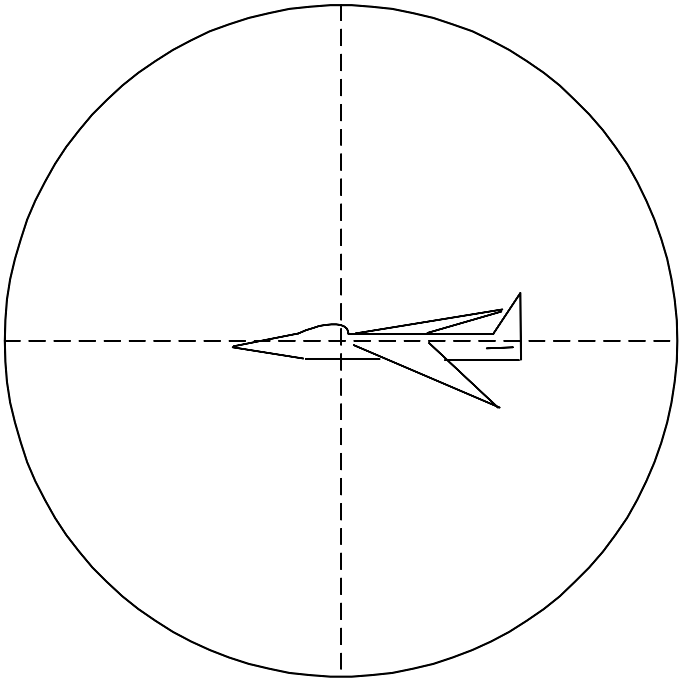
*Figure 2. Tentative Tracking Mode*



## Step Three: Confirmed Tracking

In this mode, the target is completely acquired (see Figure 3). The bandwidths of the servo-loops are progressively reduced up to a certain limit. As the trajectory is perfectly smoothed, the Doppler frequency is calculated by the Radar Manager and only the central Doppler filter is used for the calculus of the deviations.

*Figure 3. Confirmed Tracking Mode*



## Deviation Computation

### Acquisition Mode

The Digital Tracker calculates the sums of the four beams individually for the 16 range bins and for the 3 Doppler filters.

$$SUM(R, f) = \|B1(R, f)\| + \|B2(R, f)\| + \|B3(R, f)\| + \|B4(R, f)\| \quad (1)$$

where R is the range bin index (1 to 16), f is the Doppler index (1 to 3), B1, B2, B3, and B4 are respectively the upper, right, lower, and left receiving antenna channels. The two dimensions array SUM( ) is transmitted to the Radar Manager for thresholding (Th1).

## Tentative Tracking Mode

The Digital Tracker evaluates the same array SUM( ) according to formula 1. The Radar Manager governs successive coherent measurements changing the Pulse Repetition Frequency (PRF). The "target present" booean is determined by the central range gates and the threshold (Th2). Side range bins are accumulated to give the ambient noise level used to determine Th2. Concerning the angular and range deviations, the principles are used to compute ratios DIF (difference) over SUM.

In this mode, the feed back loops are closed and the Alpha-Beta coefficients are upgraded by the Radar Manager. It is also necessary to supply the radar with great precision in the calculus of the different deviations. It must work on the four beams of the radar with three IIR Doppler filters and three range bins. The 6, 7 and 8 range bins are also centered precisely in the range gate windows by the Radar Manager. The calculus of deviation in azimuth, elevation, and range are given by the following equations:

Ecart Azimuth

$$EAz = \frac{\sum_{f=0}^{2}\sum_{R=6}^{8} B4\ (R,f) - \sum_{f=0}^{2}\sum_{R=6}^{8} B2\ (R,f)}{\sum_{f=0}^{2}\sum_{R=6}^{8} B4\ (R,f) + \sum_{f=0}^{2}\sum_{R=6}^{8} B2\ (R,f)}$$

Ecart Elevation

$$EEI = \frac{\sum_{f=0}^{2}\sum_{R=6}^{8} B1\ (R,f) - \sum_{f=0}^{2}\sum_{R=6}^{8} B3\ (R,f)}{\sum_{f=0}^{2}\sum_{R=6}^{8} B1\ (R,f) + \sum_{f=0}^{2}\sum_{R=6}^{8} B3\ (R,f)}$$

Range

$$N = \frac{\left(B2(0,6) + B4(0,6)\right)\cdot(-1) + \left(B2(0,7) + B4(0,7)\right)\cdot(0) + \left(B2(0,8) + B4(0,8)\right)\cdot(+1)}{\sum_{R=6}^{8} B2(0,R) + B4(0,R)}$$

The new value for R is R = Ro + N * 75 meters. It is the Radar Manager which calculates this value and sends it back to the Digital Tracker. It is still needful to provide the calculus with the three IIR Doppler filters. These three filters will help the radar locate the exact position of the target and to compensate for the Doppler effect.

If the tentative tracking mode is conclusive, the radar will pass to the next step, the confirmed tracking mode.

## Confirmed Tracking Mode

Indeed, like the position of the target is well-known in the tentative tracking mode, it could be sure that the Doppler effect will not work this time. It isn't necessary to check it any more. The equations are:

Ecart Azimuth

$$EA = \frac{\sum_{r=7}^{8} B4(0,r) - \sum_{r=7}^{8} B2(0,r)}{\sum_{r=7}^{8} B4(0,r) + \sum_{r=7}^{8} B2(0,r)}$$

Ecart Elevation

$$EA = \frac{\sum_{r=7}^{8} B1(0,r) - \sum_{r=7}^{8} B3(0,r)}{\sum_{r=7}^{8} B1(0,r) + \sum_{r=7}^{8} B3(0,r)}$$

Range

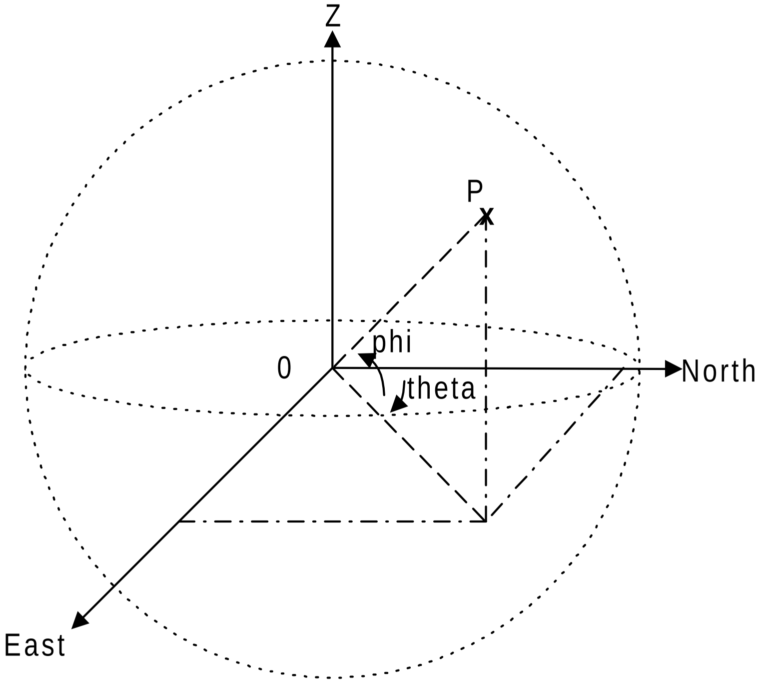
$$N = \frac{\left(B2(0,7) + B4(0,7)\right) \cdot (-1) + \left(B2(0,8) + B4(0,8)\right) \cdot (+1)}{\sum_{r=7}^{8} B2(0,r) + B4(0,r)}$$

## Matrix Conversion

Notation

θ = Azimuth

φ = Elevation



## Spherical to Cartesian

### Spherical to Cartesian Conversion (Total Difference)

The dXm, dYm, and dZm coordinates are obtained with the following equations:

$$dX = \cos\varphi.\sin\theta.d\rho - \rho.\sin\theta.\sin\varphi.d\varphi + \rho.\cos\varphi.\cos\theta.d\theta$$
$$dY = \cos\varphi.\cos\theta.d\rho - \rho.\cos\theta.\sin\varphi.d\varphi - \rho.\cos\varphi.\cos\theta.d\theta$$
$$dZ = \sin\varphi.d\rho + \rho.\cos\varphi.d\varphi$$

Where:

$d\theta = dAz = dLat/(\cos(El))$ is the azimuth deviation.

$d\rho = dR$ is the range deviation.

### Spherical to Cartesian Conversion (in Position)

$$\begin{aligned} X &= \rho.\cos\varphi.\sin\theta \quad (East) \\ Y &= \rho.\cos\varphi.\cos\theta \quad (North) \\ Z &= \rho.\sin\varphi \quad (Altitude) \end{aligned}$$

By using these two algorithms it is possible to settle the Xm, Ym, and Zm coordinates; using the following algorithm:

```
dAz = dLat/cos(El);
Convert_Polar_To_Cartesian_Diff ( dAz, dEl, dR, &dXm, &dym,
&dZm);
Convert_Polar_To_Cartesian_Pos ( AZ, El, R, &Xa, &Ya, &Za);
Xm = Xa + dXm;
Ym = Ya + dYm;
Zm = Za + dZm;
```

## Cartesian to Spherical Conversion

### Cartesian to Spherical Conversion (Total Difference)

This function is used to send filtered deviations from the Alpha-Beta filters to the pedestal encoders.

$$d\theta = \frac{y.dx - x.dy}{x^2 + y^2}$$

$$d\varphi = \frac{(x^2 + y^2).dz - z.(x.dx + y.dy)}{(x^2 + y^2 + z^2).\ \sqrt{x^2 + y^2}}$$

$$d\rho = \frac{x.dx + y.dy + z.dz}{\sqrt{x^2 + y^2 + z^2}}$$

### *Cartesian to Polar Conversion (Position)*

This function is used to send the El, AZ and R coordinates to the Radar Manager (AXIR_C).

$$\rho = \sqrt{x^2 + y^2 + z^2} \quad (Radar\ Range)$$
$$\varphi = arc\sin(Z / \rho) \quad (Elevation)$$
$$\theta = arc\tan(X / Y) \quad (Azimuth)$$

# Alpha-Beta Filters

## Smoothing the Cartesian Coordinates

The X, Y, and Z signals of the trajectory target are used to control the engines of the radar. First, the coordinates must be smoothed to remove noise in order to accurately compute the targets trajectory. There is an Alpha-Beta target tracker filter for each of the three coordinates. The DSP implements these filters with a simple recursive procedure. The recursive procedure can estimate the position and velocity of a two state, one dimensional motion based on position measurements.

The structure of Alpha-Beta target tracker is well known. It is based on the error estimation of a position vector measurement. For example, if we suppose that the velocity of the X variable is constant, we can predict the position at time sample k+ 1.

Prediction: $Xp(k+1) = X(k) + T.V(k)$

However, if the target manoeuverability is not null we can update this prediction by adding a pourcentage of the error.

Update: $X(k+1) = Xp(k+1) + Alpha.[z(k+1) - Xp(k+1)]$

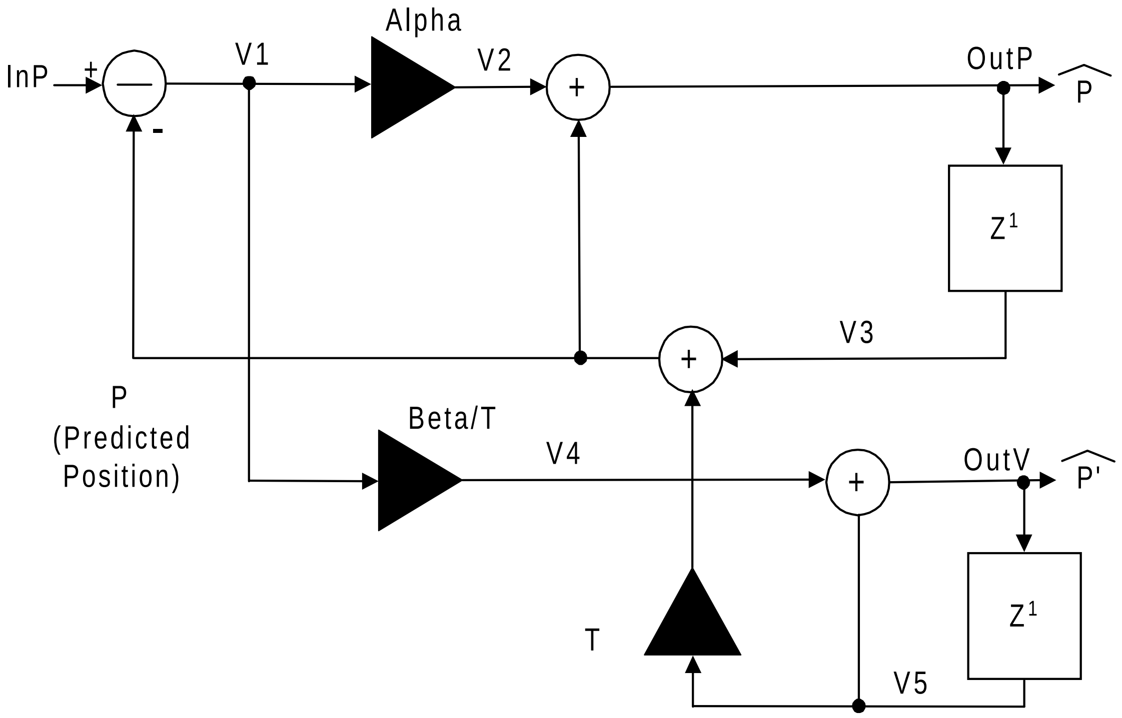
where, z(k+1) is the position measurement and Alpha is the first tracking parameter.

The same principle is used to attenuate the velocity noise.We have just to divide the error by the sampling periode.

$$V(k+1) = V(k) + (Beta / T).[z(k+1) - Xp(k+1)]$$

These equations can be represented by the schematic shown in Figure 4.

*Figure 4. Alpha-Beta Filter Schematic*



The predict position is V1 = In – P, it is multiplying by the Alpha coefficent to give V2 and by Beta to give V4. The output OutP is the filtered position which is equal to the true position P plus the Error V2:

$$OutP = P + V2$$

The same principle is used for the filtered velocity:

$$OutV = V4 + V5$$

Where V4 is the velocity error and V5 is the velocity at the time; T-1.

We can also deduce the Z transformed formulas:

$$\frac{OutP}{In} = \frac{Alpha-(Alpha-Beta).Z^{-1}}{1-(2-Alpha-Beta).Z^{-1}-(Alpha-1)Z^{-2}}$$

and,

$$\frac{OutV}{In} = \frac{Beta.(1-Z^{-1})}{1-(2-Alpha-Beta).Z^{-1}-(Alpha-1)Z^{-2}}$$

Now, the algorithm for implementation in the DSP can be deduced.

*Beginning period*

P = V3 + V5
V1 = In - P
V2 = Alpha V1
V4 = Beta V1
OutP = P + V2
OutV = V4+ V5
V3 = OutP
V5 = OutV

*Next period*

## Optimal Target Tracking

*How to choose the parameters Alpha and Beta?*

The main object of this target tracking device is to use the possibility to change Alpha and Beta during confirmed tracking. Thus, the unknown target manuvers must influence the Alpha-Beta parameters by increasing swiftness or stability according as the target is accelerating or not. The solution of the target tracking is given by the tracking index, which characterizes the generalized tracking solution. The tracking index is proportional to the ratio of position uncertainty due to the target maneuverability and the sensor measurement. A simple solution to increase the speed of the filter in the acquisition mode is to use the evolutive coefficients Alpha (n) and Beta(n).

Evolutive coefficients with time index ( n = 1, 2, 3...)

Example: $Alpha(n) = 2(2n-1)/(n(n+1))$
$Beta(n) = 6/(n(n+1))$

The predict position is V1 = In - P; it is multiplying by the Alpha coefficient to give V2 and by Beta to give V4. The output OutP is the filtered position, which is equal to the true position P, plus the Error V2.

# Algorithms and Hardware

## General Algorithm for Tracking

If target parameters correspond to the fixed threshold, track is maintained and smoothed. Moreover, waveform ( DCP, PRI ) are continuously optimized. The project_C (Radar Manager) optimized the Alpha-Beta parameters according to trajectory variations. The goal of this project is to supply project_C with the trajectory filtered elevation, azimuth and range coordinates. These coordinates are calculated by addition of the sidesteps dXm, dYm and dZm with the position coordinates Xm, Ym and Zm, which are received from the pedestal.

As a result of the Cartesian variation of a plane being generally lower than the polar variation, the tracking stage is calculated in rectangular coordinates. This enables the filters to smooth more regularly.

If (Mode is Confirmed):

{

1) Read the values of 6 and 7 range squares in the Dual Access RAM.

2) Calculate the azimuth and lateral deviation.

3) Convert these spherical deviations into the Cartesian differentials dXm, dYm, dZm.

4) Read the values of pedestal spherical coordinates from the ADC interface circuits.

5) Converts the elevation, azimuth and range into Xa, Ya, Za coordinates.

6) Add the total differentials dXm, dYm and dZm to the position Xa, Ya, Za.

7) Filter the resulting coordinates Xm, Ym and Zm.

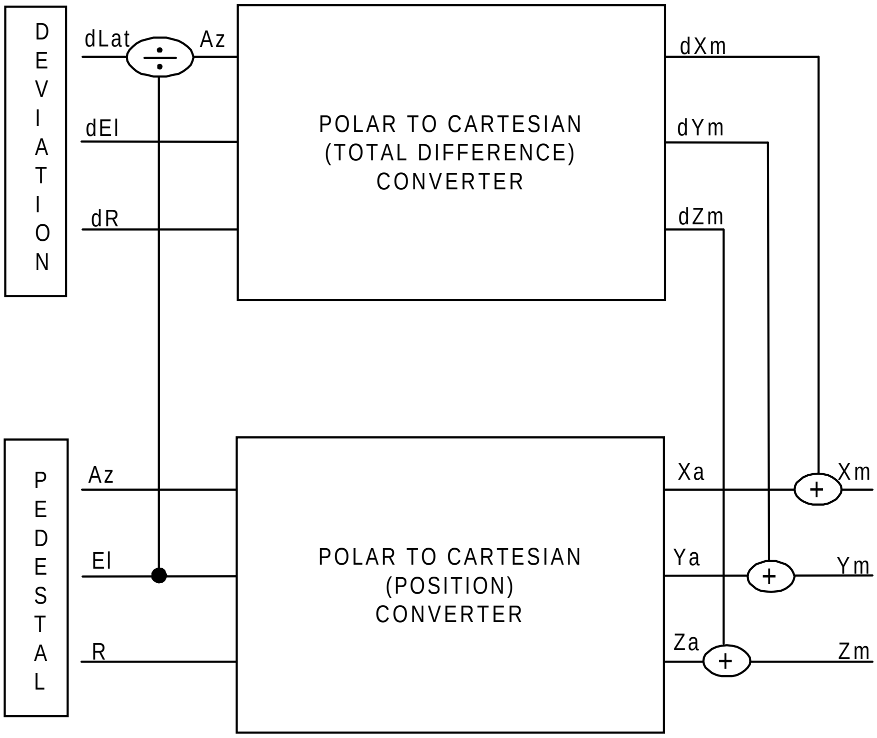
8) Convert the smoothed velocity, which is received from the Alpha-Beta filter, into spherical deviations and send the results to the pedestal’s azimuth and elevation encoders.

9) Convert the X, Y, and Z filtered coordinates and send the results (El, Az, and R) to the Radar Manager.

}

All of these functions are represented in Figure 5.

*Figure 5. Tracking Algorithm Block Diagram*



# Hardware Specifications

## Pedestal

The pedestal serves as a low cost stand for the antenna. The pedestal can rotate 360° in azimuth and in elevation. Pedestal angles are available at each period of the PRI. Double potentiometers provide a voltage that is proportional to the angle, for example 1 V/degree. Using double potentiometers eliminated (see Figure 6) a discontinuity, when the angle passes from 360° to 0°, that was encountered with a single potentiometer. This ambiguity was suppressed by adding the second potentiometer (see Figure 7), which is calibrated to 0° when the first potentiometer passed 360°. Thus, suppressing the shift forward.

*Figure 6. One Potentiometer Device*

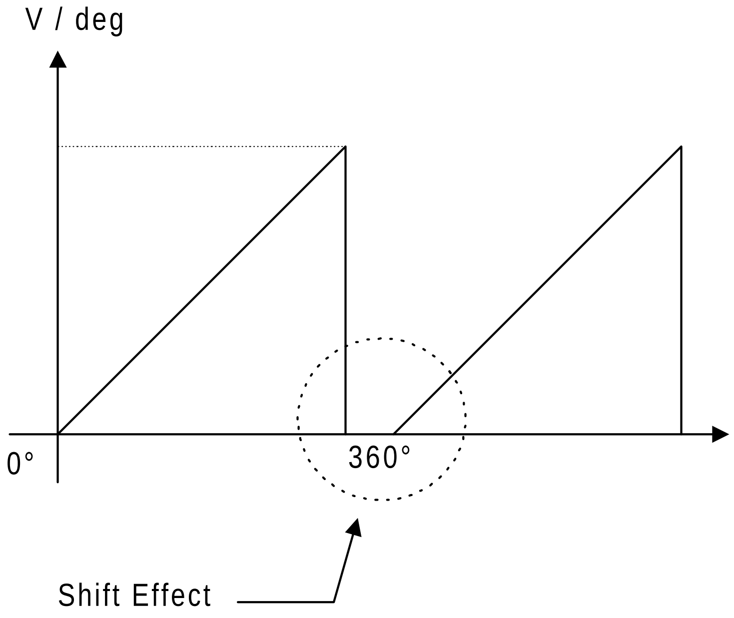
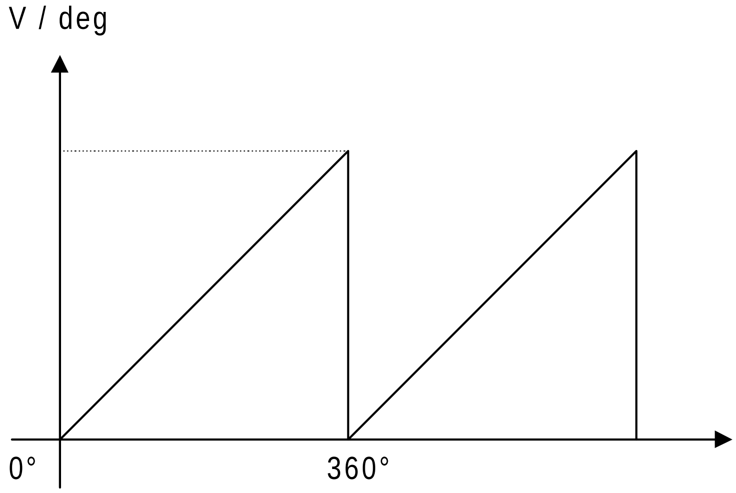


*Figure 7. Two Potentiometer Device*



## DMA Memories

The DMA 0 was used for transferring data from project 1 to project 2. The DMA0 constant word can also be defined.

DMA0: 0010 00A0 Hex

Data transfer between project 2 and project will be made with the TRANSFER MODE 00. Thus, the ICRDY signal is used to synchronize DMA channel transfers. When DSP 2 sends data, the ICRDY interrupt allows DSP 3 to write from the DMA to internal memory. For using this mode, several bits of the DMA Channel Control must be configured. The two bits of DMA SYNC MODE must be set to 01 value. So, a read will not be performed until the ICRDY interrupt will occur.

The DMA Channel Control variable can also be fixed as:

CONTROL : 00C0 0040 Hex

The communication port 0 will be used as the source address. The constant used to address this port will be:

SOURCE : 0010 0040 Hex

Because only one word will be transferred at each interrupt, the source index register will be set to 0. The destination index will be set to 1 for incrementing the destination address after each transfer.

# Conclusion

The accomplishment of such as device requires the use if a fast processor because the calculus of the three deviations and all the tracking algorithms including the Alpha-Beta filters must be brought up up to date during a period lower than the Pulse Repetition Impulsion.

The DSP toolkit pack allows to compile, link, optimize, and to test the whole C code implemented for these algorithms. The AXIR program contains a simulation of all the parts of the radar.

This TI DSP Solutions Challenge allows to the three undergraduate students to find out a concrete aspect of their digital processing course. All the DSP facilities such as the direct memory access concept and pipe line programation can accelerate the process and also increment the resolution of the radar.

The main advantages of the AXIR radar are:

☐ Its very high Doppler quality.

☐ Its auto-adaptive digital pulse compression.

☐ Its intelligent automatic trajectory smoothing.