Digital Monopulse Doppler Radar and DSP Teaching

Authors: P-H Dezaux, X. Gilles, S. Marques, L. Fourdan

ESIEE, Paris

September 1996
SPRA342

Texas Instruments

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CONTACT INFORMATION

US TMS320 HOTLINE	(281) 274-2320
US TMS320 FAX	(281) 274-2324
US TMS320 BBS	(281) 274-2323
US TMS320 email	dsph@ti.com

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Abstract

In 1995 several teams of EFREI students submitted a project to the Texas Instruments DSP Challenge. This paper describes the adventure of one project which passed with success the European semi-finals to go and participate to the worldwide final in May, 1996 in ATLANTA.

The winning project deals with the Digital Signal Processing (hardware and software) associated with a new class of a Digital Monopulse Doppler Radar. The study has been an interesting practical application of the Radar and DSP courses.

AXIR (Automatic X-Band Instrumentation Radar) is a very innovative design. The analog RF head is reduced to the minimum. The principal tasks are realized digitally by seven TMS 320 DSPs. Nearly all the circuits are located at the rear of the printed planar monopulse antenna.

The digital processors are organized on four PCBs (Printed Circuit Board)

1) Front-End Processor (Digital Pulse Compression and Doppler Filtering)

2) Tracker (Three Alpha-Beta evolutive filters smoothing the cartesian coordinates)

3) Radar Manager (Automatic determination of the waveform and of the coefficients)

4) Simulator and Built-In-Test-Equipment (BITE)

This low-cost tracking radar has many applications related to civil aviation, meteorological surveillance or general instrumentation.

This document was an entry in the 1996 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.

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EE students are motivated by technical contests

Some manufacturers regularly, organize contests or challenges for new design. Some technical magazines are continuously opening their columns to welcome new ideas for design, hardware or software. All these opportunities are to be recommended to students in Electrical Engineering (EE), by the professors in charge of related courses.

The students are motivated to participate in a practical project or application. Maybe the first attracting goal is to earn some money, as a student is always looking for some complementary resource. The second goal is to take benefit from this project to enhance the technical knowledge by realizing a personal and applied design.

A published communication allows a student to earn professional recognition, via some mention on the student’s resume. It demonstrates the expertise and the skills to write and to speak in front of a jury or an auditorium. A student is also proud to see and to show his name and sometimes his photograph in some publication or Proceedings.

At EFREI (Ecole Francaise d’Electronique et d’Informatique) educators have known for many years that hands-on experience, selected by the student himself, is the most effective learning method. The managerial staff strongly encourages this type of activity. The contributions can be officially incorporated at the student’s credit, replacing internal projects normally realized during one semester.

For students in EE a contest theme involving RF, analog, power circuits or DSP processors is well matched to the undergraduate or postgraduate courses. For students in Computer Engineering, a challenge limited to software or DSP applications is preferable.

This educational politics was practiced in 1995/1996 when EFREI heard of Texas Instruments DSP Solutions Challenge. The grand prize ($100,000) was extremely attractive and many students applied to participate in a team.

A Tracking Radar is a good support for DSP teaching

A typical cursus about DSP is made of the following chapters:

- Introduction to Signal Processing
- Digital Filters Analysis and Synthesis
- Spectral Analysis
- Multidimensional DSP
- DSP hardware and software review, VLSI Signal Processing

Applications are often optional. Usually they deal with Speech and Image Processing, and are more theoretical than practical. Telecommunications, Radar and Sonar are other possible applications strongly related also to DSP theory At EFREI, DSP applications are covered through an " Introduction to Radar Systems " (16 hours) and DSP applied to Radar " (12 hours of Laboratory work). Three Engineering Projects including PC simulation and student reports are associated to the laboratory work.

A tracking radar is particularly interesting to serve as a support of DSP applications. The areas are:

- Digital Beam Forming and Adaptive Antennas
- Waveform Management (Pulse Repetition Interval)
- Digital Pulse Compression (FIR filter, Inverse filtering)
- NM and Doppler Filtering (DFT, FFT, Windows, IIR, Complex coefficients filters)
- Digital Monopulse Algorithms
- Alpha-Beta filters for Smoothing and Derivatives Computation
- Kalman filters
- Digital Phase-Lock Loops (pedestal control)

These considerations, conjugated to the TI contest announcement, were good reasons to place four submissions related to the DSP design of a new class of Tracking Instrumentation Radar called AXIR One EFREI team was first selected as the winner of the Western Europe Region (UK, Belgium, Sweden, Spain, France). Then the team won the second round against Eastern Europe (Germany, Finland, Austria, Switzerland, Italy and went to Atlanta to participate at the worldwide final, organized by Texas Instruments during ICASSP 96 meeting. EFREI team won a second prize ($10,000).

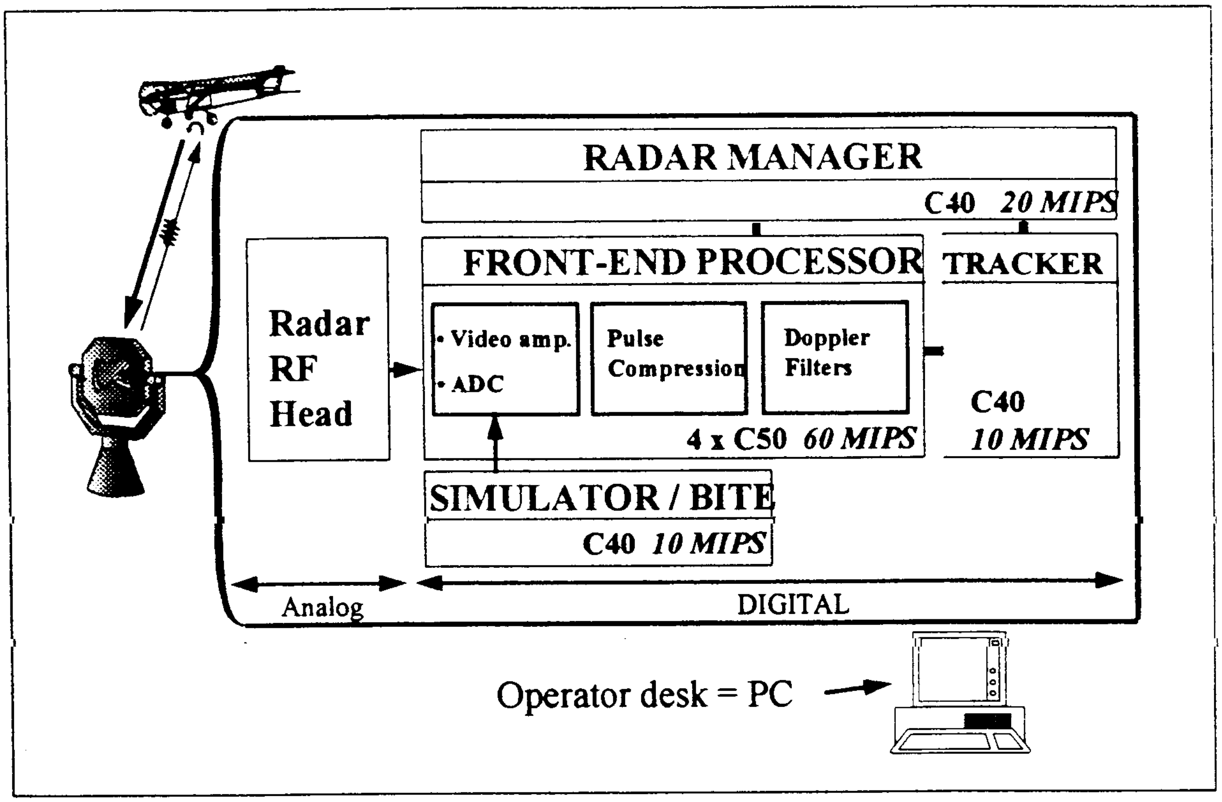
Axir = Automatic X-band Instrumentation Radar

This project is a new concept of a low-cost radar, specially designed for the Texas Instruments DSP Solutions Challenge. The idea was to use the performances of the TMS 320C5x and TMS C4x families to design a performant and intelligent radar processing.

The objective product-cost of the radar is around $80,000, including the pedestal, the antenna, the transmitter, the processors and the display, but without the optional opto-electronics that could be a classical TV-tracking. AXIR is basically a Monopulse Doppler Ground-based Radar with many civilian applications that are listed at the end of this paper.

AXIR features modem technology for all the subsystems. All the circuits are solid-state, thus providing an excellent reliability. The general architecture (figure 1) is very innovative : the antenna is a set of five printed planar fixed arrays. The RF analog circuits are reduced to the minimum by the use of Homodyne (no intermediate frequency) down converters. The Monopulse deviations are digitally computed after time sampling, binary encoding, Doppler processing and integration, without any microwave combiners as in the classical Monopulse radars. The pedestal is ultra lightweight, made principally of graphite fibers and plastics, with low-power servo-motors exactly optimized to the trajectory of civil planes when landing. The operator desk is simply a PC under WINDOWS, used for menu-mouse-driven control, graphics display, monitoring, recording and play-back.

Figure 1. General architecture of AXIR



Aerial, RF head and pedestal

The antenna comprises five printed sub-arrays fixed on a honeycomb plateau. One sub-array is used for the transmitting beam. Four sub-arrays constitute four receiving squinted beams (up, down, right and left). The reference carrier is generated by a Stable Local Oscillator (STALO), made of a small dielectric-cavity and a low-cost solid-state amplifier. AXIR is a fixed frequency radar in X-band. The frequency could be set at the factory.

The transmitter is a commercial-off-the-shelf (COTS), medium power solid-state amplifier in the range 10 to 20 watts (peak power). This apparently small power is compensated by different factors. First the received signals are coherently integrated by small bandwidth Doppler filters. Secondly the losses are reduced to the minimum, as there are no microwave rotary joints, no circulators. The transmitter is directly connected to the antenna and the same for the four low-noise amplifiers, directly connected to the four receiving arrays. All the circuits, including ADC and processors (4 DSP boards) are at the rear of the antenna in a plastic box. Only the servo-amplifiers are in the pedestal.

The pedestal is very light, constituted of a fixed basis, an azimuth-rotating yoke and an elevationrotating axis, associated with the aerial box. Power supply (220 V,50/60 Hz) is going up in the box, through slip-rings. Numerical data are going down to the fixed basis, via two optical rotary joints. Low-cost robotics circuits and motors arc used, as the servo-loops are controlled digitally. The radio or cable link interface is placed in the basis, ready to communicate with the PC. An installation could be made on a mobile van or at the top of a small house or simply on the ground with a light fixing.

All the Digital Signal Processing tasks are distributed on four Processors boards, that are:

1) the Front-End Processor,
2) the Tracker,
3) the Radar Manager and
4) the Simulator/Bite.

Front-end processor for monopulse radar (FEPMR)

This part corresponds to one PCB, developed by one EFREI team that was the TI contest European winner. It is at the frontier between the RF and the Digital Circuits. There are four identical channels, corresponding to the four squinted receiving beams Each beam channel is processed in phase (I) and in quadrature (Q). The two baseband analog signals are amplified and filtered by low-pass filters matched to the sub-pulse time duration (500 ns). Then the signals are sampled and binary encoded. As there are four beams, eight video amplifiers and eight ADCs are needed. For the prototype, eight couples Philips NE 5539 + Analog Devices AD876 were used.

The clock sampling signals are provided by the Radar Manager. The number of range cells are 16 and as the DPC code length could be up to 31, the maximum number of time-samples are 16+31 = 47. The time samples are processed beam per beam by four independent TMS320C50s. Two major algorithms are operated in cascade:

- A flexible FIR Digital Filter with complex coefficients is first applied as a Digital Pulse Compressor. The complex coefficients are computed and provided by the Radar Manager. taking into account the Doppler-shift of the objective or tracked target and the algorithm to reduce the range-side-lobes.
- The second software component implements three IIR Digital filters. using also complex coefficients, as 3 Doppler Filters. The time-rate is then the Pulse Repetition Period. The Doppler filters are adaptive, via the control of the complex poles by the Radar Manager. Doppler Filters allow the system to reject fixed echoes and to track the radial velocity.

The Front-End Processor transmits digital data to the Tracker by the way of four Dual Port Memory (one per beam or that is the same one per TMS320C50)

Tracker

The Tracker is a second PCB comprising one DSP TMS320C40. This design was studied by a second EFREI team and was submitted to the TI challenge. The software tasks of this board are:

1) to compute difference and sum channels in azimuth, elevation and range,

2) to derive angular and range deviations as quotients,

3) to transform spherical coordinates into cartesian (Xm, Ym, Zm) measured coordinates,

4) to smooth these values into predicted cartesian coordinates and derivatives via three Alpha-Beta order 2 IIR filters,

5) to calculate control voltages to the servo-amplifiers and motors by transforming cartesian data into spherical derivatives.

The Alpha-Beta coefficients are continuously updated by the Radar Manager

Radar Manager

The Radar Manager is a third PCB comprising one DSP TMS320C40. This board was studied by an other EFREI team to be submitted to the TI challenge. This design is the most intelligent part of the radar AXIR A software similar to an expert system is in charge of piloting all the important parameters of the radar.

- ❑ The class of the target is determined as a function of the Signal To Noise Ratio, the range, the altitude and the velocity along the trajectory.
- ❑ The waveform is regularly optimized, on a per burst basis. The Digital Pulse Compression transmit sequence is selected as a function of the Range and of the Radar Cross Section estimated for the target. The Pulse Compressor code is computed as a function of the Doppler velocity. The Pulse Repetition Interval is also selected in a collection of pre-defined values, via a cost-function optimization, avoiding automatically Range Doppler ambiguities.
- ❑ The Doppler complex coefficients are derived first from the 3 Doppler filters outputs, during the acquisition process and the preliminary tracking. Later during the confirmed tracking stage, the Doppler filters are associated to the smoothed trajectory radial velocity.
- ❑ The Alpha-Beta coefficients for the X, Y, Z tracker are selected as a function of the target class.
- ❑ The operational sequencing, missions and constraints defined by the operator are acting on the Radar Manager program.

Simulator and Built-In-Test-Equipment

This fourth and last PCB is made of one TMS320C40 associated with a DAC. It provides the computation of a virtual target along a virtual trajectory. A program simulates a theoretical antenna to calculate the theoretical signals received by the four beams, as seen by a theoretical radar equation. The pedestal position is taken into account. The signals are then converted into video I & Q analog signals to be superimposed to the real channels.

AXIR applications

AM is a light and low-cost Instrumentation Radar designed fix civil applications (no ECCM features). It is basically a Monopulse Doppler Tracking Radar. The design of this sensor is very innovative, using a minimum of components, affording thus a low serial production cost and an excellent reliability.

Concerning the technical performances AXIR is able to track one target up to 100 kin, while surveying other possible targets in the beam and in 14 remaining range gates. The acquisition range depends of the target RCS and of the a priori information about the trajectory and the velocity. A typical value is around 20 km.

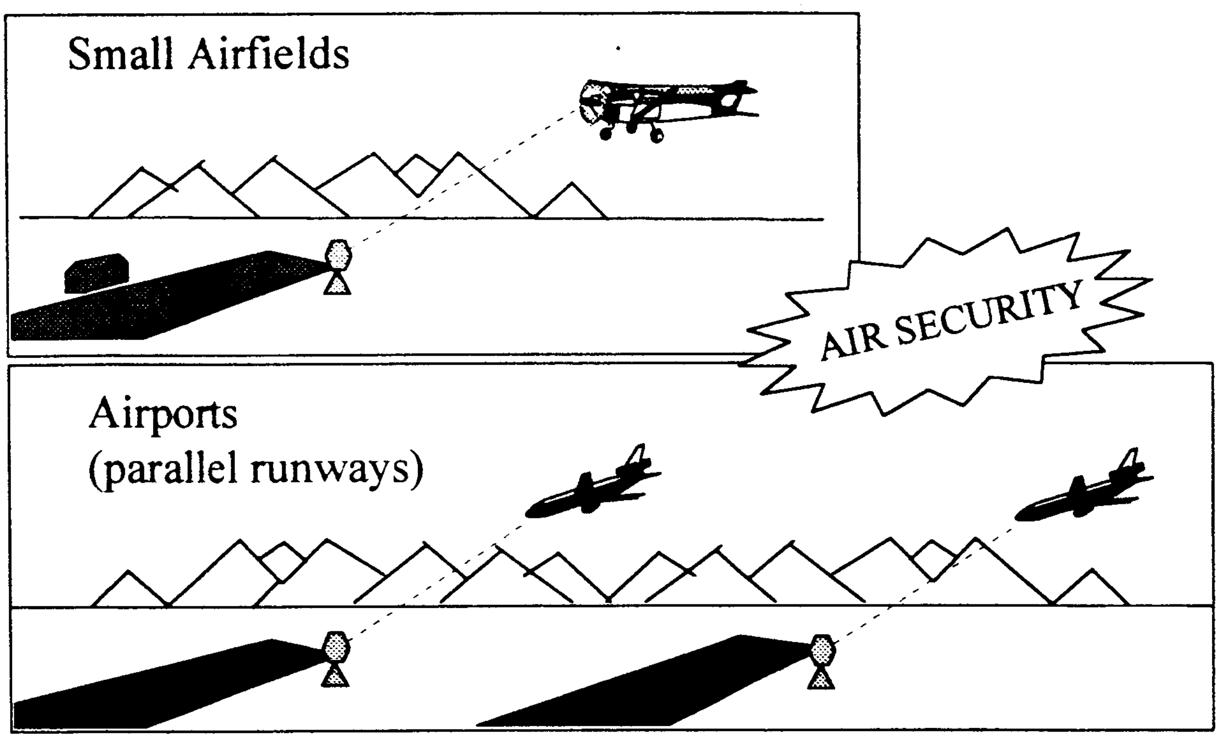
An optional Tracking TV equipment could be associated with the Radar. allowing the operator to get a look on the tracked target, depending of the range and of weather conditions. Data about the trajectory (spherical and/or Cartesian coordinates. derivatives) are available for Graphical or Text displays and for recording.

AXIR is capable of filling many jobs, principally in the area of civil aviation (figures 2 and 3) :

- Short range air-control for small airfields, air-clubs or piloting schools, public or private
- Air-security for parallel runways or difficult access airports
- Runways and taxiways ground control of one aircraft or vehicle, with warning of around intruders
- Weather hazards detection and warning (wind-shears, air gusts, tornadoes ...) while tracking a plane
- Tracking of atmospheric sounders
- Trajectory control, monitoring and recording for aerobatics sports events
- Cloud back-scattering analysis (via scanning)

- Tutorial radar for Universities and Research Centers

Figure 2. Air security



Conclusion

AXIR has been an excellent application for a total of 16 EFREI students, to realize practically hardware breadboards and software. The four Processors were simulated and tested in High Level Language. Each processor was tested independently due to the limited time of this experience. EFREI is looking for a contract to develop completely the pedestal, the RF head and to finish a global integration.

Figure 3. Weather hazards detection and warning