Eindhoven University of Technology

MASTER

Digital beacon receiver for propagation experiments: optimization and testing of a Digital Frequency-Locked Loop/Phase-Locked Loop

Aalberts, D.J.

Award date:
1995

Disclaimer
This document contains a student thesis (bachelor's or master's), as authored by a student at Eindhoven University of Technology. Student theses are made available in the TU/e repository upon obtaining the required degree. The grade received is not published on the document as presented in the repository. The required complexity or quality of research of student theses may vary by program, and the required minimum study period may vary in duration.

General rights
Copyright and moral rights for the publications made accessible in the public portal are retained by the authors and/or other copyright owners and it is a condition of accessing publications that users recognise and abide by the legal requirements associated with these rights.

- Users may download and print one copy of any publication from the public portal for the purpose of private study or research.
- You may not further distribute the material or use it for any profit-making activity or commercial gain

Take down policy
If you believe that this document breaches copyright please contact us providing details, and we will remove access to the work immediately and investigate your claim.
Report of graduation work:

Digital Beacon Receiver  
for propagation experiments

Optimization and testing of a Digital  
Frequency-Locked Loop/  
Phase-Locked Loop

by D.J. Aalberts

Coach : Ir. J. Dijk  
Supervisor : Prof. Dr. Ir. G. Brussaard  
Period : February 1995 - December 1995

The Faculty of Electrical Engineering of Eindhoven University of Technology does not accept any responsibility regarding the contents of graduation reports.
Summary

Propagation experiments at Eindhoven University are carried out using beacon signals of satellites. The equipment used to receive the beacon signals consists of an analog PLL and a digital detector, based on a Z80 microprocessor. The processing power of this processor is poor. Therefore the telecommunications division started the development of a digital receiver, based on a Digital Signal Processor (DSP). The receiver consists of a digital Frequency-Locked Loop / Phase-Locked Loop and a Decimator/Detector.

The digital Frequency-Locked Loop / Phase-Locked Loop (FLL/PLL) was already built in a previous project but this design was reconsidered. The hardware is designed using a Texas Instruments TMS 320C25 DSP. The digital FLL is used to realize that the incoming analog signals are mixed to a fixed intermediate frequency. At this intermediate frequency, subsampling of the signal is performed and the All Digital PLL is used to generate coherent in-phase and quadrature components derived from of the received harmonic beacon signals. This is necessary to perform coherent detection of the received signals.

Unfortunately, the first prototype receiver did not function very well. The main problems encountered in the software of the FLL/PLL.

The purpose of this study for graduation is to optimize and measure the characteristics of the FLL/PLL. All parts of the software were studied and tested. The general setup of the software proved to be good. However, several bugs were found and debugged in the implementation.

For characterization of the FLL/PLL several measurements have been executed. The FLL is tested and proved to be able to track a beacon signal of the "ITALSAT" satellite with a C/N ratio at the input of the FLL/PLL of at least -16.5 dB. The PLL is tested and will lock on a received beacon signal with a C/N ratio at the input of at least -14.5 dB. These figures compare very good with respect to measured figures of analog Phase-Locked Loops of proven design.
# Contents

Summary .................................................................................. i

Contents .................................................................................. ii

Symbols ................................................................................... iv

Abbreviations .............................................................................. vi

1 Introduction .............................................................................. 1
   1.1 Propagation research at Eindhoven University of Technology .......... 1
   1.2 The problem definition .......................................................... 3

2 The Frequency-Locked Loop/Phase-Locked Loop ......................... 4
   2.1 The Frequency-Locked Loop ................................................. 5
   2.2 The Phase-Locked Loop ...................................................... 5
   2.3 The coherent detection of the signals to be measured ................. 6
   2.4 Communication between the different devices ......................... 8

3 Hardware for the digital FLL/PLL ........................................... 10
   3.1 The Digital Signal Processor ............................................... 10
   3.2 Memory ............................................................................ 11
   3.3 The waitstate generator ..................................................... 12
   3.4 The I/O section ................................................................. 12

4 Frequency Tracking with the FLL ............................................ 14
   4.1 The Fourier Transform ..................................................... 14
   4.2 The Fast Fourier Transform .............................................. 15
   4.3 Window functions to be used ............................................ 16
   4.4 Choosing the number of samples for the FFT ....................... 18

5 Digital Phase-Locked Loops .................................................. 20
   5.1 A conventional analog PLL .............................................. 20
   5.2 The All Digital Phase-Locked Loop .................................... 21
   5.3 Measurement results of the ADPLL .................................... 24

D.J. Aalberts
<table>
<thead>
<tr>
<th>Symbol</th>
<th>Description</th>
<th>Unit</th>
</tr>
</thead>
<tbody>
<tr>
<td>Δf</td>
<td>bin size</td>
<td>[Hz]</td>
</tr>
<tr>
<td>εst</td>
<td>Steady state error</td>
<td>-</td>
</tr>
<tr>
<td>θ</td>
<td>angle between 0° and 90°</td>
<td>[degrees]</td>
</tr>
<tr>
<td>θco, x</td>
<td>angle between xco and x</td>
<td>[degrees]</td>
</tr>
<tr>
<td>θd</td>
<td>detection angle</td>
<td>[degrees]</td>
</tr>
<tr>
<td>ξ</td>
<td>damping ratio of the PLL-filter</td>
<td>-</td>
</tr>
<tr>
<td>φ</td>
<td>Angle</td>
<td>[degrees]</td>
</tr>
<tr>
<td>φd</td>
<td>phase angle difference</td>
<td>[rad]</td>
</tr>
<tr>
<td>φi</td>
<td>Input phase angle</td>
<td>[rad]</td>
</tr>
<tr>
<td>φo</td>
<td>Output phase angle</td>
<td>[rad]</td>
</tr>
<tr>
<td>ω</td>
<td>Angular frequency</td>
<td>[rad/s]</td>
</tr>
<tr>
<td>Ω</td>
<td>Harmonic angular frequency</td>
<td>[rad/s]</td>
</tr>
<tr>
<td>ωo</td>
<td>Angular centre frequency at the output</td>
<td>[rad/s]</td>
</tr>
<tr>
<td>ωi</td>
<td>Angular centre frequency at the input</td>
<td>[rad/s]</td>
</tr>
<tr>
<td>ωn</td>
<td>Natural angular frequency of the PLL loopfilter</td>
<td>[rad/s]</td>
</tr>
<tr>
<td>Aco, Ax</td>
<td>co-polar amplitude, cross-polar amplitude</td>
<td>-</td>
</tr>
<tr>
<td>B0, B1, B2</td>
<td>Beacon Signals of 12.5, 20 and 30 GHz</td>
<td>-</td>
</tr>
<tr>
<td>BW</td>
<td>Bandwidth</td>
<td>[Hz]</td>
</tr>
<tr>
<td>C0</td>
<td>DVCO Constant (free running angular frequency)</td>
<td>-</td>
</tr>
<tr>
<td>C1</td>
<td>Constant used in the ADPLL</td>
<td>-</td>
</tr>
<tr>
<td>C2</td>
<td>Constant used in the ADPLL</td>
<td>[rad²/s⁴]</td>
</tr>
<tr>
<td>f</td>
<td>Oscillator frequency</td>
<td>[Hz]</td>
</tr>
<tr>
<td>f₁</td>
<td>Sample frequency</td>
<td>[Hz]</td>
</tr>
<tr>
<td>G</td>
<td>Gain</td>
<td>-</td>
</tr>
<tr>
<td>h(n)</td>
<td>discrete impulse response</td>
<td>-</td>
</tr>
<tr>
<td>HCL</td>
<td>Closed Loop Transfer function</td>
<td>-</td>
</tr>
<tr>
<td>Hol</td>
<td>Open Loop Transfer function</td>
<td>-</td>
</tr>
<tr>
<td>Ico, Ix</td>
<td>In phase, co-polar and x-polar</td>
<td>-</td>
</tr>
<tr>
<td>k</td>
<td>Sample counter</td>
<td>-</td>
</tr>
<tr>
<td>M</td>
<td>²log N</td>
<td>-</td>
</tr>
<tr>
<td>N</td>
<td>Number of FFT inputs</td>
<td>-</td>
</tr>
<tr>
<td>nco, nx</td>
<td>Noise amplitude</td>
<td>-</td>
</tr>
<tr>
<td>Qco, Ico</td>
<td>Quadrature, co-polar and x-polar</td>
<td>-</td>
</tr>
<tr>
<td>s</td>
<td>Laplace Transform variable</td>
<td>-</td>
</tr>
<tr>
<td>t</td>
<td>Time</td>
<td>[s]</td>
</tr>
<tr>
<td>T</td>
<td>time between samples</td>
<td>[s]</td>
</tr>
<tr>
<td>t₀</td>
<td>Clock signal low-time</td>
<td>[sec]</td>
</tr>
</tbody>
</table>

D.J. Aalberts
<table>
<thead>
<tr>
<th>Symbol</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>$W_N$</td>
<td>Twiddle Factor</td>
</tr>
<tr>
<td>$X(\omega)$</td>
<td>Fourier transformed input signal</td>
</tr>
<tr>
<td>$X(k), X_1(k), X_{11}(k), X_{12}(k)$</td>
<td>Discrete Fourier transform of $x(t)$</td>
</tr>
<tr>
<td>$x(nt)$</td>
<td>Sampled signal</td>
</tr>
<tr>
<td>$x(t)$</td>
<td>Analog signal</td>
</tr>
<tr>
<td>$x_{co}, x_x$</td>
<td>co-polar input signal</td>
</tr>
<tr>
<td>$X_i(k)$</td>
<td>Delayed input signal</td>
</tr>
<tr>
<td>$x_i(t)$</td>
<td>Input signal</td>
</tr>
<tr>
<td>$x_o(t)$</td>
<td>Output signal</td>
</tr>
<tr>
<td>$Y_i(k)$</td>
<td>Hilbert transformed input signal</td>
</tr>
<tr>
<td>$z$</td>
<td>$z$-transform variable</td>
</tr>
</tbody>
</table>
# Abbreviations

<table>
<thead>
<tr>
<th>Abbreviation</th>
<th>Full Form</th>
</tr>
</thead>
<tbody>
<tr>
<td>A/D, D/A</td>
<td>Analog/Digital, Digital/Analog</td>
</tr>
<tr>
<td>BW</td>
<td>Bandwidth</td>
</tr>
<tr>
<td>C/N</td>
<td>Carrier to Noise ratio</td>
</tr>
<tr>
<td>CL</td>
<td>Closed Loop</td>
</tr>
<tr>
<td>Co,X</td>
<td>Co-polar, Cross-polar</td>
</tr>
<tr>
<td>CRC</td>
<td>Cyclic Redundancy Check</td>
</tr>
<tr>
<td>DC</td>
<td>Direct Current</td>
</tr>
<tr>
<td>DFT</td>
<td>Discrete Fourier Transform</td>
</tr>
<tr>
<td>DPLL, ADPLL</td>
<td>(All) Digital Phase-Locked Loop</td>
</tr>
<tr>
<td>DSP</td>
<td>Digital Signal Processor</td>
</tr>
<tr>
<td>DUT</td>
<td>Delft University of Technology</td>
</tr>
<tr>
<td>DVCO</td>
<td>Digital Voltage Controlled Oscillator</td>
</tr>
<tr>
<td>EOT</td>
<td>End Of Transmission</td>
</tr>
<tr>
<td>EEPROM</td>
<td>Electrically Erasable Programmable ROM</td>
</tr>
<tr>
<td>EUT</td>
<td>Eindhoven University of Technology</td>
</tr>
<tr>
<td>FFT</td>
<td>Fast Fourier Transform</td>
</tr>
<tr>
<td>FIFO</td>
<td>First In, First Out</td>
</tr>
<tr>
<td>FLL</td>
<td>Frequency-Locked Loop</td>
</tr>
<tr>
<td>I/Q</td>
<td>In Phase/Quadrature</td>
</tr>
<tr>
<td>IC</td>
<td>Integrated Circuit</td>
</tr>
<tr>
<td>IF</td>
<td>Intermediate Frequency</td>
</tr>
<tr>
<td>I/O</td>
<td>Input Output</td>
</tr>
<tr>
<td>IRQ</td>
<td>Interrupt ReQuest</td>
</tr>
<tr>
<td>L-ADPLL</td>
<td>Linear All Digital Phase-Locked Loop</td>
</tr>
<tr>
<td>LEN</td>
<td>Length</td>
</tr>
<tr>
<td>LF</td>
<td>Loop Filter</td>
</tr>
<tr>
<td>LNB</td>
<td>Low Noise Block converter</td>
</tr>
<tr>
<td>LO</td>
<td>Local Oscillator</td>
</tr>
<tr>
<td>OL</td>
<td>Open Loop</td>
</tr>
<tr>
<td>OTS</td>
<td>Orbital Test Satellite</td>
</tr>
<tr>
<td>PC</td>
<td>Personal Computer</td>
</tr>
<tr>
<td>PD</td>
<td>Phase Detector</td>
</tr>
<tr>
<td>PLL</td>
<td>Phase-Locked Loop</td>
</tr>
<tr>
<td>RAM</td>
<td>Random Access Memory</td>
</tr>
<tr>
<td>RMS</td>
<td>Root Mean Square</td>
</tr>
<tr>
<td>ROM</td>
<td>Read Only Memory</td>
</tr>
<tr>
<td>SOH</td>
<td>Start of Header</td>
</tr>
<tr>
<td>VCO</td>
<td>Voltage Controlled Oscillator</td>
</tr>
</tbody>
</table>
1

Introduction

1.1 Propagation research at Eindhoven University of Technology

Research on radiowave propagation forms an important contribution to the design of telecommunications applications. Eindhoven University of Technology (EUT) and PTT Research started propagation experiments with the Orbital Test Satellite (OTS), which carries a propagation beacon and transponder. Extensive tests were carried out at 11 and 14 GHz. The Olympus satellite, which carries three beacon transmitters operating at 12.5, 20 and 30 GHz, was launched and commissioned in 1989. This provides the opportunity to characterize the atmospheric transmission channel. EUT carries out the complete set of measurements possible with the Olympus beacons. Radiometers at all three frequencies and meteorological instruments are used at the earth station. The comparison of the 12.5 GHz, 20 and 30 GHz results will give insight in the frequency dependence of the propagation effects. These results will be applied to the prediction of signal impairments on satellite earth links [10].

The beacon receiver is divided into five different functional parts as shown in Figure 1.1. The first stage is the antenna which is capable of receiving three beacon signals simultaneously. The Co- and Cross-polar components of these three frequencies are provided at six separate antenna ports.
The Low Noise Block (LNB) downconverts the received signals to 10 MHz. The converted signals are band filtered and amplified. The Phase-Locked Loop (PLL) will maintain the input frequency at a stable 125 kHz by measuring the Phase Difference in a Phase Detector (PD). The signal representing the phase difference controls a Voltage Controlled Oscillator (VCO), which is used for mixing to the 10 MHz signal. With the stable 125 kHz signal the digital detector determines the amplitude of the Co- and Cross-polar signals and phasedifference between them.

![Block diagram of the receiver](image)

*Figure 1.1 Block diagram of the receiver*

Currently, analog receivers and digital detectors are used to process the converted signals. The analog receiver splits the incoming co- and cross-polar signals to in-phase and quadrature components. The digital detector, developed by PTT Research, determines the amplitude and the phase of the incoming satellite signals. The detector was built using a Z80 microprocessor. Unfortunately, this processor does not have enough processing power to process complicated algorithms; consequently, the algorithms have been simplified.

The Telecommunications Division started to design a new detector, using the TMS320C25 Digital Signal Processor (DSP). This processor has more processing power; therefore, and filter characteristics and communication possibilities were improved. In 1991 this resulted in a dual channel digital detector with a serial communications link to a PC [11].

The next step was the design of a digital Phase-Locked Loop (PLL), combined with a frequency tracking facility, indicated as the Frequency-Locked Loop (FLL). The detector is improved by adding a decimator, which reduces the input data. The whole path from receiver to data acquisition is digital in this setup. In this way the main disadvantage of analog receivers, i.e. the non-constant behaviour in time, will be avoided.

The FLL/PLL was implemented using the same DSP. However, a new board was designed for both the FLL/PLL and the Decimator/Detector. The two boards are based on the same architecture. Some differences exist in the number of A/D and D/A converters, communication possibilities etc.
1.2 The problem definition

The software for the FLL/PLL was designed and implemented by Op den Camp [1]. Strik [2] implemented the software for the Decimator/Detector. Together they wrote several parts of the programs. Unfortunately the software for the FLL/PLL did not function very well. Franken [9] has improved the FLL/PLL-software. However, this software still did not function satisfactorily when Franken graduated.

The purpose of this study for graduation is to optimize and characterize the FLL/PLL. All parts of the software were studied and tested. The general design of the software proved to be good. However, several bugs were found. For characterization of the FLL/PLL several measurements have been done.

This report describes the FLL/PLL hard- and software, the improvements made and the measurements done. Chapter 2 describes the functional configuration of the FLL/PLL. In Chapter 3 the FLL/PLL hardware is described. Chapter 4 deals with algorithms used for frequency tracking. In Chapter 5 the PLL is described. The configuration and algorithms used for the communication are described in Chapter 6. In Chapter 7 general configuration problems, programming problems etc. are described. Finally, conclusions and some recommendations are presented in Chapter 8.
The Frequency-Locked Loop and Phase-Locked Loop

The FLL/PLL software developed at the Telecommunications Division of EUT consists of four functional blocks [1] as shown in Figure 2.1:

- The Frequency-Locked Loop, which determines the carrier frequency of the co-polar signal;
- the Phase-Locked Loop, which has the possibility to recover the carrier of the co-polar signal with a poor Signal to Noise ratio;
- the coherent detector, which resolves the in-phase and quadrature components from the co- and crosspolar input signals with the use of the recovered carrier;
- a communications module, which is able to send data to the Decimator/Detector and to the data logger PC.

Figure 2.1 Block diagram of the EUT digital FLL/PLL satellite receiver
2.1 The Frequency-Locked Loop

The Frequency-Locked Loop maintains the frequency of the input signal constant by determining the frequency of the carrier, calculating the error between the frequency of the input signal and the frequency of the output signal and correcting the difference in frequency with a Voltage Controlled Oscillator (VCO).

![Diagram of Frequency-Locked Loop](image)

**Figure 2.2 The Frequency Locked Loop**

The carrier frequency is found by calculating the discrete frequency spectrum of the input signal. The frequency bin with the highest signal power should be the carrier frequency. Calculating the difference between the desired frequency and the measured frequency will result in an error signal. The error signal controls the Voltage Controlled Oscillator (VCO). The signal generated by the VCO is mixed with the input signal.

Op den Camp [1] has formulated several constraints for the FLL:
- maintain a carrier frequency of 124.516 kHz with the use of a VCO;
- output voltage of -5V to 5V to control VCO;
- possibility to transmit the data that represents the frequency spectrum to the PC;
- possibility to transmit the FLL-status to the Decimator/Detector.

2.2 The Phase-Locked Loop

The function of a Phase-Locked Loop is to recover the carrier from a signal with a poor Carrier/Noise (C/N) ratio. In this application the PLL is implemented using a Digital Signal Processor. The implemented algorithm is the digital representation of the analog version. The algorithm is described in Chapter 4.
Op den Camp [1] has formulated several constraints for the PLL:
- An optimum natural frequency of 17 Hz, which equals a noise bandwidth of 56 Hz. This results in an input Signal to Noise ratio that may reduce to 25 dB/Hz before loss of lock occurs;
- Constant loop bandwidth because an adaptively controlled loop bandwidth results in additional software complexity;
- Possibility to transmit the Lock-Status to the Decimator/Detector.

2.3 Coherent detection of the signals to be measured

Coherent detection is used to determine the in-phase and quadrature component of the co- and crosspolar signals. Detection is achieved by mixing the input signal with the recovered carrier, which is the VCO output signal, shifted 90° in phase [1].

The Co-polar signal $x_{co}$ is represented by:

$$x_{co}(t) = A_{co} \cos(\omega t + \theta_{osx}(t)) + n_{co}(t) \cos(\omega t) - n_{co}(t) \sin(\omega t) \quad (2.1)$$

The Cross-polar signal $x_x$ is represented by:

$$x_x(t) = [A_x + n_{x}(t)] \cos(\omega t + \theta_{co-x}) - n_{x}(t) \sin(\omega t + \theta_{co-x}) \quad (2.2)$$
The signal received at the co-polar input is given in (2.1). Assuming that the satellite and ground station local oscillator are ideal, the co-polar input signal is represented by [1]:

\[ x_{co}(t) = [A_{co} + n_{co,c}(t)]\cos(\omega_i t) - n_{co,s}(t)\sin(\omega_i t) \]  

(2.3)

Applying coherent detection to equation 2.3 and removing the high frequency components will result in an in-phase and quadrature-component.

\[ I_{co}(t) = [I_{co} + n_{co,c}(t)]\cos(\omega_i t) - n_{co,s}(t)\sin(\omega_i t)]2\cos(\omega_i t + \theta_0(t)) \]

\[ Q_{co}(t) = [I_{co} + n_{co,c}(t)]\cos(\omega_i t) - n_{co,s}(t)\sin(\omega_i t)] - 2\sin(\omega_i t + \theta_0(t)) \]

(2.4)

In case of ideal detection, \( \theta_0(t) = 0 \), equation 2.4 will reduce to:

\[ I_{co}(t) = A_{co} + n_{co,c}(t) \]

\[ Q_{co}(t) = n_{co,s}(t) \]

(2.5)

Averaging equation 2.5 will result in:

\[ <I_{co}(t)> = A_{co} \]

(2.6)

\[ <Q_{co}(t)> = 0 \]

Demodulation of the co-polar signal results in an in-phase and quadrature component. The in-phase component will be equal to the amplitude of the co-polar input signal.

Assuming the satellite and ground station local oscillator are ideal, the crosspolar signal (2.2) can also be demodulated using coherent detection, which results in:

\[ I_{x}(t) = [I_{x} + n_{x,c}(t)]\cos(\omega_i t + \theta_{co-x}) - n_{x,s}(t)\sin(\omega_i t + \theta_{co-x})]\cdot 2\cos(\omega_i t + \theta_0(t)) \]

\[ Q_{x}(t) = [I_{x} + n_{x,c}(t)]\cos(\omega_i t + \theta_{co-x}) - n_{x,s}(t)\sin(\omega_i t + \theta_{co-x})]\cdot 2\sin(\omega_i t + \theta_0(t)) \]

(2.7)

In case of ideal detection, \( \theta_0(t) = 0 \), (2.7) will reduce to:

\[ I_{x}(t) = [I_{x} + n_{x,c}(t)]\cos(\theta_{co-x}) - n_{x,s}(t)\sin(\theta_{co-x}) \]

\[ Q_{x}(t) = [I_{x} + n_{x,c}(t)]\sin(\theta_{co-x}) + n_{x,s}(t)\cos(\theta_{co-x}) \]

(2.8)

Averaging Equation 2.8 will result in:

\[ <I_{x}(t)> = A_{x}\cos(\theta_{co-x}) \]

(2.9)

\[ <Q_{x}(t)> = A_{x}\sin(\theta_{co-x}) \]

Both signals are a measure of the phase difference between the co- and cross-polar.

The phase difference can be determined by:
\[ \theta_{co-x} = \arctan \frac{Q_x}{I_x} = \arctan \frac{A_x \sin \theta_{co-x}}{A_x \cos \theta_{co-x}} \]  \hspace{1cm} (2.10)

Moreover, it is possible to calculate \( A_x \) from the detected co- and cross-polar by true envelope detection:

\[ A_x = \sqrt{(I_x(t))^2 + (Q_x(t))^2} = A_x [\sin^2 \theta_{co-x} + \cos^2 \theta_{co-x}] \]  \hspace{1cm} (2.11)

2.4 Communication between the different devices

There must be a communication link between the FLL/PLL detector and the decimator/detector board. Data which have to be transmitted consists of the in-phase and quadrature components. The communication link is based on a First In, First Out (FIFO) principle. All data are sent to the other board without handshaking or error correction. This is done because the transfer rate must be high.

Additional data have to be sent to a PC via a parallel data link. Data to be transmitted are the frequency spectrum calculated by the FLL and the status of the FLL. The PC-link is based on a Centronics interface. The redefined Centronics interface operates in a master slave configuration where the PC is the master. It is possible to connect 8 slaves.

The principles of the communication between the different devices will be extensively discussed in Chapter 6.
3 Hardware for the digital FLL/PLL

The hardware of the FLL/PLL is designed by Op den Camp [1] and Strik [2]. The global design consists of a Digital Signal Processor (DSP), memory, a waitstate generator, an I/O-section and a reset and oscillator circuit. A block diagram is shown in Figure 3.1.

![Figure 3.1 Hardware block diagram of the FLL/PLL](image)

3.1 The Digital Signal Processor

The used DSP is a Texas Instruments TMS320C25-50. This DSP has the following characteristics:
- 50 MHz clock frequency,
- 544 words of internal RAM,
- 64k words addressable RAM and 64k words addressable ROM,
- 16 bit address and data bus,
- 16 bit address and data bus,
- 3 external interrupts,
- 40 MIPS.

### 3.2 Memory

The total memory space of a TMS320C25 DSP is divided into 64 k words program memory and 64 k words data memory. The program memory contains the software, the data memory contains the variables.

In this hardware design the program memory is divided into 32 k words EEPROM for code storage and 32 k words of RAM to hold the program code while executing. The program code copies itself into RAM where program execution is continued at triple speed. The data memory is divided into on-chip and external RAM. The address space of the on-chip RAM is 1024 words of which 544 words are available for data memory, divided into 3 blocks B0, B1 and B2. The other words are for internal use and not available for the user.

![Program and Data memory configuration](image)

**Figure 3.2 Program and Data memory configuration**

The memory configuration used is shown in Figure 3.2. To address and select the different chips, an address decoder is used which uses the signals *PS*(Program Memory Select), *DS* (Data Memory Select) and A15 (address line 15). *PS* is low when program memory is selected and *DS* is low when Data memory is selected. The truth table of the address decoder is shown in Table 3.1.

---

1. *X should be implemented as NOT(X), where X is the variable mentioned after the asterisk.
Table 3.1 The truth table of the address decoder

<table>
<thead>
<tr>
<th>A15</th>
<th>DS</th>
<th>PS</th>
<th>active output</th>
<th>selected memory</th>
</tr>
</thead>
<tbody>
<tr>
<td>L</td>
<td>L</td>
<td>L</td>
<td>Y0</td>
<td>none</td>
</tr>
<tr>
<td>L</td>
<td>L</td>
<td>H</td>
<td>Y1</td>
<td>none</td>
</tr>
<tr>
<td>L</td>
<td>H</td>
<td>L</td>
<td>Y2</td>
<td>EPROM</td>
</tr>
<tr>
<td>L</td>
<td>H</td>
<td>H</td>
<td>Y3</td>
<td>none</td>
</tr>
<tr>
<td>H</td>
<td>L</td>
<td>L</td>
<td>Y4</td>
<td>none</td>
</tr>
<tr>
<td>H</td>
<td>L</td>
<td>H</td>
<td>Y5</td>
<td>Data RAM</td>
</tr>
<tr>
<td>H</td>
<td>H</td>
<td>L</td>
<td>Y6</td>
<td>Program RAM</td>
</tr>
<tr>
<td>H</td>
<td>H</td>
<td>H</td>
<td>Y7</td>
<td>none</td>
</tr>
</tbody>
</table>

3.3 The waitstate generator

The waitstate generator controls the instruction cycle length. If a device (memory, I/O) is acting slow, the processor is halted for one or two clock cycles. In this way the slower acting device is able to finish the task that is being processed. All I/O operations and EPROM reads are implemented with two waitstates, RAM access is performed without waitstates. The waitstate generator is implemented using two J-K flip-flops. Whenever EEPROM Select or I/O is chosen, two extra clock cycles are needed before READY goes high and the processor is able to continue its task.

3.4 The Input/Output-section

The Input/Output-section (I/O) consists of a selector, two A/D-converters, a D/A converter, a micro switch block and several I/O buses for the parallel and the FIFO communication. The selector selects 1 of the 7 I/O sections. The signals used are A0, A1, Read/*Write, *I/O Space and *STROBE. The first three signals are used to select a device. The other signals are used for timing. The selected devices are shown in Table 3.2.

Table 3.2 The selected devices

<table>
<thead>
<tr>
<th>Port address</th>
<th>IN-operation</th>
<th>OUT-operation</th>
</tr>
</thead>
<tbody>
<tr>
<td>0</td>
<td>Read A/D converter 1</td>
<td>Send to FIFO</td>
</tr>
<tr>
<td>1</td>
<td>Read A/D converter 2</td>
<td>Send to parallel port</td>
</tr>
<tr>
<td>2</td>
<td>Read parallel port</td>
<td>Write to D/A converter</td>
</tr>
<tr>
<td>3</td>
<td>Read data from dip-switches</td>
<td>-</td>
</tr>
</tbody>
</table>

The A/D Converter

A/D-converters are used to convert an analog input signal to a digital value, suitable for further processing by the DSP. In this application two AD779 A/D converters are used.
The specifications of these converters configured for this application are:
- Output: 14 bit, 2's complement
- Input: -5V to +5V, sample and hold
- Conversion time: 100k conversions per second
No extra chips are needed to apply this device in a DSP-board because all necessary hardware like voltage references, amplifiers etc. are implemented on chip. A high pass filter ($\tau = 340$ Hz) is implemented to filter the input signal.

**The D/A Converter**

D/A converters are used to transform digital signals into analog signals. One D/A converter (AD569) is implemented on the board. The specifications of the converter configured for this application are:
- Input: 16 bit
- Output: -5V to +5V
- Settling time: 3μs
Latches etc. are built in the chip. The only extra device needed is an external voltage reference. In this application an AD588 is used. A second order low pass filter is designed on the printed circuit board. This filter has not been implemented.

**The First In, First Out buffer**

For communication with the Decimator/Detector board a FIFO communication bus is used. The data is sent to the other board and stored in a buffer, waiting for further processing. The FIFO communication is discussed in Chapter 6.

**Dip switches**

The FLL/PLL board is equipped with a block of 8 dip switches. The board has a communication bus address specified by the setting of 3 dip switches. One extra dip switch is used to enable or disable the communication with the acquisition computer. Four dip switches are for future use. The use of the switches is shown in Table 3.3:

<table>
<thead>
<tr>
<th>Switch</th>
<th>Function</th>
<th>default</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>Parallel address</td>
<td>0</td>
</tr>
<tr>
<td>2</td>
<td>Parallel address</td>
<td>1</td>
</tr>
<tr>
<td>3</td>
<td>Parallel address</td>
<td>0</td>
</tr>
<tr>
<td>4</td>
<td>Parallel I/O enable</td>
<td>1</td>
</tr>
</tbody>
</table>

To avoid unnecessary interrupts of the running program, addressing of the device is checked by hardware. The address specified by the acquisition computer and the FLL/PLL board, specified by switches 1, 2, and 3, are compared with hardware. If both addresses are found to be equal, an interrupt will be generated.
Frequency Tracking with the FLL

The frequency of the carrier will change in time because of Doppler shift, frequency drift and oscillator phase noise. Keeping track on the carrier frequency is important as the whole system is tuned for one carrier frequency. Tracking is done by calculating the frequency spectrum with a Discrete Fourier Transform. The frequency bin with the highest signal power should be the carrier frequency. The difference between the desired frequency and the measured carrier frequency is used to control the voltage controlled oscillator (VCO).

4.1 The Fourier Transform

The Fourier transform converts information between the time domain and the frequency domain. The Fourier transform of an analog signal \( x(t) \) is defined as:

\[
X(\omega) = \int_{-\infty}^{+\infty} x(t) e^{-j\omega t} dt
\]

where \( X(\omega) \) is a complex function. The integral exists if \( x(t) \) is piece wise continuous and if the absolute value of \( x(t) \) can be integrated.

In practice the analog signal \( x(t) \) is sampled at regular time intervals. For \( N \) samples \( x(t) \) is represented by \( x(nT) \), where \( n \) is the sample number and \( T \) is the sample period.

By assuming \( x(t)=0 \) for \( t<0 \) and for \( t>(N-1)T \) and by replacing \( x(t) \) by \( x(nT) \), \( \omega \) by \( k\Omega \) \((0<k<N) \) and \( t \) by \( nT \), Formula 4.1 becomes

\[
X(k) = \sum_{n=0}^{N-1} x(nT)e^{-j\Omega nT}
\]

where \( \Omega=2\pi/NT \) is the fundamental frequency and \( X(k) \) is understood to represent \( X(k\Omega) \).

Equation (4.2) is generally known as the Discrete Fourier Transform (DFT). Rewriting equation (4.2) gives:

\[
X(k) = \sum_{n=0}^{N-1} x(n)e^{-j2\pi nk/N} = \sum_{n=0}^{N-1} x(n)W_N^{nk}
\]

where \( W_N = e^{-j2\pi/N} \) is the complex root of unity.
$W_N = \exp(-j2\pi/N)$ is known as the twiddle factor. It can be seen as a $N$-th part of the unity circle in the complex plane.

### 4.2 The Fast Fourier Transform

Equation 4.3 is an $N$-point Discrete Fourier Transform (DFT). Because of the large quantity of multiplications and additions (Order $N^2$), this method is not generally used. If $N$ is a power of 2, a more sophisticated way of calculating a Fourier transform can be performed by decomposing equation 4.3 into two DFTs of length $N/2$ by splitting the input samples into even and odd samples.

\[
X(k) = \sum_{n=0}^{N-1} x(n)W_N^{nk} = \sum_{n=0}^{N/2-1} x(2n)W_N^{2nk} + \sum_{n=0}^{N/2-1} x(2n+1)W_N^{(2n+1)k}
\]

Identifying the even samples $x_1(m)$ and the odd samples $x_2(m)$, results in

\[
X(k) = \sum_{m=0}^{N/2-1} x_1(m)W_{N/2}^{mk} + W_{N/2}^k \sum_{m=0}^{N/2-1} x_2(m)W_{N/2}^{mk}
\]

where $W_N = W_{N/2}^a$. Equation 4.5 may be written as follows:

\[
X_1(k) = X_{11}(k) + W_N^kX_{12}(k)
\]

By comparing equation 4.6 with equation 4.4 it is seen that $X_{11}$ and $X_{12}$ are reduced to $N/2$-point DFTs. Repeating this rewriting, eventually results in $N/2$ 2-point DFTs. The 2-point DFT is a basic operation, called butterfly because of its shape in graphical representation (Figure 4.3).

![Figure 4.3](image.png)

**Figure 4.3** Representation of the Decimation in Time (DIT) radix 2 butterfly.

The formulas to perform a 2-point DFT are:

\[
X(k) = X_1(k) + W_N^kX_2(k)
\]

\[
X(k+N/2) = X_1(k) + W_N^{k+N/2}X_2(k)
\]

\[
X(k) = X_1(k) - W_N^kX_2(k)
\]

This butterfly can be used to recompose the Fourier Transform of $N$ discrete signals. A decomposition is called a stage, and the total numbers of stages is given by $M = \log_2 N$. 
Calculating a FFT results in \( N \) values which represent the power of the signal \( x(t) \) in a frequency interval which is called a bin. The size of one bin is:

\[
\Delta f = \frac{1}{NT} = \frac{f_s}{N} \quad (4.8)
\]

The spectrum will cover a frequency interval of \( \Delta f.N = f_s \) Hz.

The input data in Figure 4.4 are placed in bit reversed order, e.g. the sample \( x(1) \) is placed on the location of sample \( x(4) \) because 4 (binary representation: 100) is the bit reversed number of 1 (binary representation: 001).

### 4.3 Window functions to be used

A run of \( N \) samples is used for a FFT. When this run is not adapted at the beginning and at the end, the sharp edges in the time domain will return as high frequency components in the frequency domain. Sharp edges are the result of multiplying an infinite run of samples by a square window function in time. The high frequency components will result in leakage of information to other bins in the frequency domain. For this reason sharp edges in the window function should be avoided.

One of the most common solutions to solve the problem of sharp edges is the Hamming window:

\[
h(n) = 0.54 - 0.46 \cos(2\pi/N), \quad n=0,1,2,\ldots,N-1
\]

Almost the same result can be obtained by using the Hanning window:

\[
h(n) = 0.5 - 0.5 \cos(2\pi n / N), \quad n=0,1,2,\ldots,N-1
\]

The time and frequency response of the Hamming, Hanning and square-shaped windows are shown in Figure 4.5 - 4.10.
In these figures can be seen that a square window has worse characteristics than a Hanning
or Hamming window. A Hanning window has lower first lobes, but these remain at the same level. This window is chosen because the side lobes of the Hamming window decrease with increasing frequency distance from the center frequency.

4.4 Choosing the number of samples for the FFT.

Choosing a number of samples for the FFT is done by trading off different contributions to the carrier phase drift. Choosing a large N will implement a large sample acquisition time and a larger calculation time. Moreover, the Doppler shift may eventually cause the carrier to shift through several bins. However, the frequency bins will be smaller. An optimum N must be determined, taking these factors into consideration. Table 4.5 shows the various contributions to the carrier frequency drift for the different beacons.

Table 4.5 Contributions to carrier frequency drift

<table>
<thead>
<tr>
<th>Beacon</th>
<th>$B_0$</th>
<th>$B_1$</th>
<th>$B_2$</th>
</tr>
</thead>
<tbody>
<tr>
<td>Doppler Shift</td>
<td>0.0013</td>
<td>0.0022</td>
<td>0.0031</td>
</tr>
<tr>
<td>Satellite &amp; LO frequency drift</td>
<td>0.17</td>
<td>0.29</td>
<td>0.44</td>
</tr>
<tr>
<td></td>
<td>Hz/sec</td>
<td>Hz/sec</td>
<td>Hz/sec</td>
</tr>
</tbody>
</table>

Using a sample rate of 12.288 kHz and different number of samples the Table 4.6 can be drawn up for beacon $B_0$.

Table 4.6 Effect of the number of samples to the acquisition time and frequency drift

<table>
<thead>
<tr>
<th>Bin size</th>
<th>12</th>
<th>6</th>
<th>3</th>
<th>1.5</th>
<th>Hz</th>
</tr>
</thead>
<tbody>
<tr>
<td>Sample acquisition time</td>
<td>83</td>
<td>166</td>
<td>333</td>
<td>670</td>
<td>ms</td>
</tr>
<tr>
<td>Total drift over acquisition time</td>
<td>0.014</td>
<td>0.028</td>
<td>0.057</td>
<td>0.114</td>
<td>Hz</td>
</tr>
</tbody>
</table>

The frequency drift of the signal is small compared to the bin size. The bin size is important, because a stable input frequency will result in a better performance of the PLL. The smallest possible bin size should be the best. However, at a sample rate of 12.288 kHz, this would result in 8192 samples, leading to a huge number of multiplications and high memory usage. Changing the sample rate to 6144 Hz will result in 4096 samples. By reducing the sample rate, the covered part of the spectrum will decrease. Using a bin size of 3 Hz and a sample rate of 6144 Hz will result in an equilibrium between calculation time and accuracy of the FLL.

While testing the programs with the development system, the available memory is limited to 4000h. This results in a maximum number of samples of 1024.
5.1 A conventional analog PLL

A Phase-Locked Loop (PLL) is a special kind of feedback control system that keeps the phase difference between the input and output signal as small as possible. A basic analog PLL looks like Figure 5.1. It consists of a phase detector (PD), a loop filter (LF) and a voltage controlled oscillator (VCO).

The analog phase detector compares the phase $\theta_i(t)$ of a periodic input signal with the phase $\theta_o(t)$ of the VCO output signal $x_o(t)$. The output of the phase detector is a signal which is proportional to the phase difference between the two phase detector input harmonic signals. The output of the PD is filtered by the loop filter. The loop filter output signal will adjust the frequency of the VCO in a direction that reduces the phase difference between the input signal and the VCO output signal. The basic principles of a PLL have been extensively discussed in Gardner [5] and in Op Den Camp [1].

The advantage of a digital PLL (DPLL) are the parameters that can easily be controlled. Basically DPLLs can be divided into two categories:

* Those which are built with gates, counters, registers etc. These are available in IC's such as 4046 and LM565.
* Those which uses an A/D converter and an algorithm running on a microprocessor.

To implement a PLL on a DSP it has to be implemented in software. Two different algorithms are discussed in Op Den Camp [1]. Concluded is that the best PLL for this application is a Linear All Digital Phase-Locked Loop. This PLL is the
digital equivalent of the model of the analog Phase-Locked Loop.

5.2 The All Digital Phase-Locked Loop

At first, Digital Phase-Locked Loops were derived from analog PLL by replacing the different components by their digital equivalent. In this way some disadvantages of the analog PLL remained present. The most important disadvantages are:

- Generation of high order frequency components by the phase detector
- non-linear behaviour
- time-variant behaviour

Hagiwara [3] proposed a Linear All Digital Phase-Locked Loop (L-ADPLL), based on a zero-order loop filter which results in a first-order PLL. In 1989 Shayan and Le-Ngoc [4] proposed a second-order L-ADPLL, shown in Figure 5.2. The implemented loop filter is a first-order filter which results in a second-order PLL. A second-order PLL has better characteristics.

![Figure 5.2 L-ADPLL proposed by Shayan [4]](image)

The digitized input signal is split and one part transformed by a Hilbert transform ($H(z)$), which shifts all frequencies 90°. Because a Hilbert transform takes some time, the other part has to be delayed by $\Delta T$.

Assume $x_i(t)$ is defined as:

$$x_i(t)=A_i\sin(\omega_i t+\theta_i(t))$$  \hspace{1cm} (5.1)

The sampled (and delayed) signal $X_i(k)$ will be:

$$X_i(k) = A_i\sin[\omega_i kT+\theta_i(kT)]$$  \hspace{1cm} (5.2)

and the Hilbert transformed signal $Y_i(k)$ will be

$$Y_i(k) = A_i\cos[\omega_i kT+\theta_i(kT)]$$  \hspace{1cm} (5.3)

From (5.1) and (5.2) the input signal argument $\phi_i(k)$ can be calculated:

$$\phi_i(k) = \tan^{-1}\frac{X_i(k)}{Y_i(k)} = [\omega_i kT+\theta_i(kT)]\mod 2\pi$$  \hspace{1cm} (5.4)

The phase detector subtracts $\phi_o(k)$ from $\phi_i(k)$. The Difference is called $\phi_d(k)$. Since $\phi_i(k)$
and $\phi_i(k)$ are periodic functions, the substraction does not always produce the right phase difference. Correction is performed by the mod $[-\pi, \pi]$ block.

Figure 5.3 shows two situations, a phase lead (situation I) and a phase lag (situation II).

\[ \phi_i \]

\[ \phi_o \]

\[ \phi_e \]

\[ \phi_o \]

\[ \phi_e \]

\[ \phi_i \]

\[ \phi_o \]

\[ \phi_e \]

\[ \phi_i \]

\[ \phi_o \]

\[ \phi_e \]

Figure 5.3 Behaviour of the mod$[-\pi, \pi]$ circuit.

The transfer function of the first-order loop filter is:

\[ H_{LF}(z) = \frac{C_1}{z-1} + C_2 \]  (5.5)

The transfer function of the DVCO is:

\[ H_{DVCO}(z) = \frac{1}{z-1} \]  (5.6)

The open loop transfer function is:

\[ H_{OL}(z) = H_{LF}(z) \cdot H_{DVCO}(z) = \frac{C_2(z-1) + C_1}{(z-1)^2} \]  (5.7)

Thus the Closed loop transfer function $H(z)$ is:

\[ H(z) = \frac{\phi_o}{\phi_i} = \frac{H_{OL}(z)}{1 + H_{OL}(z)} - \frac{C_2(z-1) + C_1}{(z-1)^2 + C_2(z-1) + C_1} \]  (5.8)

This is a second order transfer function of the Linear A-DPLL.

Using the forward difference method $(z-1)$ can be replaced by $sT$ [12]. Using this method Equation 5.8 can be transformed to the transfer function of an analog second order PLL:
\[ H(s) = \frac{2\xi \omega_n s + \omega_n^2}{s^2 + 2\xi \omega_n s + \omega_n^2} \quad (5.9) \]

If \( f_n \ll f_s \), \( C_1 \) and \( C_2 \) can be calculated from 5.8 and 5.9:

\[ C_1 = 2\xi \omega_n T \]
\[ C_2 = \omega_n^2 T^2 \quad (5.10) \]

The steady state error for different inputs can be calculated using the final value theorem [12]:

\[ e_{ss} = \lim_{z \to 1} (1-z) (1-H(z)) \phi_i(z) \quad (5.11) \]

The \( z \)-transforms of the different inputs are:

\[ \phi_i(z) = \frac{z}{z-1} \Delta_i \quad \text{Phase step of } \Delta_i \text{ rad} \]

\[ \phi_i(z) = \frac{zT}{(z-1)^2} \Delta_2 \quad \text{Phase ramp of } \Delta_2 \text{ rad/s} \]

\[ \phi_i(z) = \frac{zT^2}{(z-1)^3} \Delta_3 \quad \text{Phase acceleration of } \Delta_3 \text{ rad/s}^2 \]

Using equation 5.11 to calculate the steady state error gives respectively:

\[ e_{ss} = 0 \quad \text{Phase step of } \Delta_i \text{ rad} \]

\[ e_{ss} = 0 \quad \text{Phase ramp of } \Delta_2 \text{ rad/s} \]

\[ e_{ss} = \frac{\Delta_3}{\omega_n^2} \quad \text{Phase acceleration of } \Delta_3 \text{ rad/s}^2 \]

These results corresponds to the steady state errors of an analog second order PLL.

Because the steady state error of a phase ramp (frequency step) is 0, the hold-in-range of the PLL will be large. This can be verified by calculating the DC Loop gain:

\[ G_{DC\text{loop}} = \lim_{z \to 1} H_{OL}(z) = \lim_{z \to 1} \frac{C_2(z-1) + C_1}{(z-1)^2} \to \infty \quad (5.12) \]

For a linear phase detector the hold-in-range is proportional to the DC Loop Gain.
Stability can be reached by placing the poles of the closed loop inside the unit circle in the z-plane. The poles of $H_{CL}$ are:

$$z_{1,2} = \frac{2-C_2 \pm \sqrt{(C_2-2)^2-4(C_1-C_2+1)}}{2}$$  \hspace{1cm} (5.13)

Positioning of $z_{1,2}$ inside the unit circle gives:

$$2C_2 - 4 < C_1 < C_2, \quad C_1 > 0$$  \hspace{1cm} (5.14)

These constants can be calculated with Formula 5.10. Using $\zeta=0.707$ and $\omega_n=17.2 \pi$ rad/s (17 Hz) will result in $C_1=75.56 \cdot 10^{-6}$ and $C_2=12.29 \cdot 10^{-3}$. These values appear to meet the constraints from 5.14.

The free-running frequency should be 124.952 kHz. Using the subsampling theorem, this results in a free running frequency of 1536 Hz. This frequency is represented by $C_0$ and is determined by the number of samples per period (8 samples/period).

$$C_0 = \frac{2^{16}}{f_s/1536}$$  \hspace{1cm} (5.15)

### 5.3 Measurement results of the ADPLL

Several characteristics of the ADPLL are measured using the HP-3325A oscillator. Measurements with noisy signals are carried out using the satellite signals of the beacon receiver at 40 GHz.

**Measurements without noise**

The response of the phase error $\phi_e$ is simulated with MatLab. Using an input step of 100Hz resulted in Figure 5.4. The phase error is reduced to zero in 13 $\mu$s. The maximum phase error is 31 degrees. The step response is measured and matches the simulated step.

![Figure 5.4 Phase error $\phi_e$ as a result of a frequency step of 100 Hz, using $\zeta=0.707$ and $f_n=100$ Hz](image)
response. Assuming the PLL is locked, coherent detection is performed correctly. The data shown in Figure 5.5 is measured by varying the amplitude of the co-polar input signal. As shown in Equation 2.6, $I_c$ should be proportional to the amplitude of the co-polar input signal, $Q_c$ should equal 0. The high frequency components, which are the result of the multiplications in the coherent detection procedures, are not removed in the FLL/PLL software because a digital filter is not implemented. A Low-Pass RC filter ($\tau = 550$Hz) will remove the high frequency components after the D/A-converter has converted the digital output to an analog signal.

![Figure 5.5 Ic and Qc as a function of the amplitude of the Co-polar input signal](image)

As shown in Figure 5.5, $I_c$ is linear with the co-polar input signal.

Varying the phase angle between the co- and cross-polar input signal results in varying $I_x$ and $Q_x$ signals. The phase angle between the co- and crosspolar is determined (formula 2.8 and 2.9) by the calculation of the arctangent of the quotient of the $I$ and $Q$ signals. The result is shown in Figure 5.6.
As shown in Figure 5.6, the phase angle equals the input phase difference. The output range is limited by the arctangent circuit to $[-90^\circ, 90^\circ]$.

**Measurements with noise**

For measurements with noise the ITALSAT-satellite beacon signal received at 40 GHz is used because the noisy signal is difficult to simulate. The S/N ratio is dependent on rain attenuation etc. It is also possible to change the S/N ratio manually by using an attenuator in the waveguide.

Attention should be payed to unwanted noise in the system. Unwanted noise in the digital FLL/PLL is added by the digital part to the analog part. Moreover, the FLL/PLL and the PC-clock signal add noise at a high level to the analog PLL receivers. Keeping a distance of about 3 meter is a solution to the last problem. The first problem might be solved by redesigning the digital FLL/PLL printed circuit board.
The 40 GHz signal is down converted to 10 MHz. This signal is used as input for the analog PLL, which down converts the co-polar to 125 kHz. The analog PLL is used because a VCO for use with the FLL was not available.

Kamperman [13] added an amplifier and a bandpass filter to the analog PLL. The amplifier adapts the 125 kHz signal amplitude to the input range (-5V/5V) of the A/D converter. The bandpass filter prevents aliasing. The transfer characteristic of the amplifier/bandpass filter in the down converter is shown in Figure 5.8.

![Amplifier/Bandpass Characteristic](image)

**Figure 5.8** The amplitude transfer-characteristic of the amplifier / bandpass filter section

The power spectrum of the 10 MHz signal with noise looks like Figure 5.9. The mainlobe is the noise which is mainly generated by the amplifiers and local oscillators. The smaller lobe on top of the main lobe is the received satellite signal. Whenever the satellite signal is attenuated by rain etc., the small lobe will shrink. The main lobe will remain the same because this lobe is the result of noise generated by the receiversystem.

![Power Spectrum](image)

**Figure 5.9** An impression of the shape of the powerspectrum at 10 MHz of a satellite signal

The C/N ratio of the signal at 10 MHz is determined using a power meter. The power meter is able to determine the signal power with noise of the powerspectrum shown in

D.J. Aalberts
Figure 5.9. When the satellite signal is removed using a piece of absorbing material mounted on the antenna, only the noise will remain.

<table>
<thead>
<tr>
<th>Table 5.1 The measured power densities</th>
</tr>
</thead>
<tbody>
<tr>
<td>Signal</td>
</tr>
<tr>
<td>(S+N)</td>
</tr>
<tr>
<td>(N)</td>
</tr>
</tbody>
</table>

This will result in a C/N ratio of:

\[
\frac{C}{N} = \frac{(S+N) - (N)}{(N)} = 0.5 \approx -3\,dB
\]  

(5.16)

The C/kT, which is constant in the whole system, is determined using the noise bandwidth of the noise signal at 10 MHz. The noise bandwidth by the bandpass filter in the 10 MHz IF-strip. The amplitude-transfer function of the filter is shown in Figure 5.10.

![Figure 5.10 The amplitude-transfer characteristic of the bandpass filter in the 10 MHz IF-strip](image)

The noise bandwidth of the bandpass filter is calculated using the following Formula [13]:

\[
B_N = \int_{0}^{\infty} |H(f)|^2 \, df
\]

(5.17)

Unfortunately only the transfer characteristic is known, so Formula 5.17 has to be evaluated numerically, which results in a noise bandwidth of 44.3 kHz.
Using this bandwidth the C/kT can be calculated:

\[
\frac{C}{kT} = \frac{C}{N} \cdot B_N = 0.5 \cdot 44.3 \text{ kHz} = 43.5 \text{ dBHz}
\]  

(5.18)

The noise bandwidth of the bandpass filter/attenuator is also evaluated numerically. The
noise bandwidth of this filter is 1530 Hz. Using the C/kT and the noise bandwidth of the
bandpass filter/attenuator, the C/N at the input of the digital FLL/PLL can be calculated:

\[
\frac{C}{N} = \frac{C}{kT} \cdot \frac{1}{B_N} = 43.5 \text{ dBHz} - 10 \cdot \log(1530) = 11.6 \text{ dB}
\]

The analog PLL satellite receiver, which is currently used for the propagation experiments,
will be used as a reference. The output of these receivers is registrated on a chart.
Calibration is done using a HP-synthesizer which generates a 10 MHz signal. This signal
from the synthesizer is added to the 10 MHz signal as shown in Figure 5.11. In this way
the synthesizer is able to simulate the satellite carrier, assuming that the noise is only
added by the circuits after the attenuator in the wave guide. The received satellite signals
with the dish antenna are removed with a piece of absorbing material.

![Figure 5.11 The setup of the receiver for calibration experiments](image)

The chart can be calibrated by changing the amplitude of the simulated satellite signal with
the synthesizer.

The dynamic inputrange of the DPLL is calculated using the resolution of the A/D
converter:

\[
\text{Dynamic inputrange} = 10 \cdot \log(2^{14}) = 42.1 \text{ dB}
\]  

(5.20)

Due to crosstalk and non-linearity, the resolution of the A/D converter is smaller.
The linearity is determined using the output of the analog PLL as a reference. This resulted
in the following characteristic.

From Figure 5.12 it is shown that the characteristic of the digital FLL/PLL remains linear
from a C/N ratio at the input of the digital FLL/PLL of 11.6 to -10.5 dB. At lower C/N
ratios the analog PLL compresses the signal.

If the input frequency is varied without changing the input level, the detected Ie will
change. This should not happen as shown in equation (2.4) and (2.5). An explanation is the
non-ideal transfer function of the amplifier/bandpass filter in the 10 MHz IF-strip.
non-ideal transfer function of the amplifier/bandpass filter in the 10 MHz IF-strip.

Figure 5.12 The linearity of the FLL/PLL calibrated using the analog PLL

The noise behaviour of the ADPLL is determined by measuring the phase error after the loopfilter as a function of the C/N ratio at the input of the digital FLL/PLL. For simulating a worse signal to noise ratio, an attenuator in the waveguide is used.

Figure 5.13 Phase angle $\phi_e$ as function of the input C/N ratio

The phase error is an indication for the lock status. A phase error of 9 degrees is an indication the loop might be out of lock. Using this criterion, the loop falls out of lock when the C/N is about -15 dB. The analog PLL goes out of lock at -12 dB.
The FLL/PLL is able to communicate with a Personal Computer and with the decimator/detector. For communication with the PC, a modified Centronics interface is used. Transmitting data to the Decimator/detector is done with a single direction communication buffer.

6.1 The communication between the FLL/PLL and the PC

The parallel communication is based on a standard Centronics parallel interface. This interface is a standard device on every personal computer. The Centronics interface consists of 12 digital outputs and 5 digital inputs. The Centronics interface on a PC has a 25 pin female sub-D connector. The pinning shown in Figure 6.1

Table 6.1 Standard pin-out of a Centronics interface

<table>
<thead>
<tr>
<th>pin</th>
<th>I/O</th>
<th>original function</th>
<th>pin</th>
<th>I/O</th>
<th>original function</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>O</td>
<td>Strobe</td>
<td>10</td>
<td>I</td>
<td>Acknowledge</td>
</tr>
<tr>
<td>2</td>
<td>O</td>
<td>Data 0</td>
<td>11</td>
<td>I</td>
<td>Busy</td>
</tr>
<tr>
<td>3</td>
<td>O</td>
<td>Data 1</td>
<td>12</td>
<td>I</td>
<td>Out of paper</td>
</tr>
<tr>
<td>4</td>
<td>O</td>
<td>Data 2</td>
<td>13</td>
<td>I</td>
<td>Select</td>
</tr>
<tr>
<td>5</td>
<td>O</td>
<td>Data 3</td>
<td>14</td>
<td>O</td>
<td>Auto Feed</td>
</tr>
<tr>
<td>6</td>
<td>O</td>
<td>Data 4</td>
<td>15</td>
<td>I</td>
<td>Error</td>
</tr>
<tr>
<td>7</td>
<td>O</td>
<td>Data 5</td>
<td>16</td>
<td>O</td>
<td>Reset</td>
</tr>
<tr>
<td>8</td>
<td>O</td>
<td>Data 6</td>
<td>17</td>
<td>O</td>
<td>Select</td>
</tr>
<tr>
<td>9</td>
<td>O</td>
<td>Data 7</td>
<td>18-25</td>
<td></td>
<td>Ground</td>
</tr>
</tbody>
</table>

The 12 available output lines are used for communication from the PC to the device. Three lines are used to select a device. One line is used to generate an interrupt for the device and eight lines are used to transmit data. The five available input lines are used to receive...
and eight lines are used to transmit data. The five available input lines are used to receive data from the device. One line is used to get an interrupt from the device, the other 4 lines are used to receive data. The redefined Centronics port is shown in Figure 6.2. Redefining the Centronics interface in this way will create the possibility for the master (the PC) to communicate with 8 different slaves.

Table 6.2 Pinout of the redefined Centronics interface.

<table>
<thead>
<tr>
<th>pin</th>
<th>I/O</th>
<th>function</th>
<th>pin</th>
<th>I/O</th>
<th>function</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>O</td>
<td>IRQ on device</td>
<td>10</td>
<td>I</td>
<td>IRQ on PC</td>
</tr>
<tr>
<td>2</td>
<td>O</td>
<td>Data Out 0</td>
<td>11</td>
<td>I</td>
<td>Data In 3</td>
</tr>
<tr>
<td>3</td>
<td>O</td>
<td>Data Out 1</td>
<td>12</td>
<td>I</td>
<td>Data In 2</td>
</tr>
<tr>
<td>4</td>
<td>O</td>
<td>Data Out 2</td>
<td>13</td>
<td>I</td>
<td>Data In 1</td>
</tr>
<tr>
<td>5</td>
<td>O</td>
<td>Data Out 3</td>
<td>14</td>
<td>O</td>
<td>Device Select 0</td>
</tr>
<tr>
<td>6</td>
<td>O</td>
<td>Data Out 4</td>
<td>15</td>
<td>I</td>
<td>Data In 0</td>
</tr>
<tr>
<td>7</td>
<td>O</td>
<td>Data Out 5</td>
<td>16</td>
<td>O</td>
<td>Device Select 1</td>
</tr>
<tr>
<td>8</td>
<td>O</td>
<td>Data Out 6</td>
<td>17</td>
<td>O</td>
<td>Device Select 2</td>
</tr>
<tr>
<td>9</td>
<td>O</td>
<td>Data Out 7</td>
<td>18-25</td>
<td></td>
<td>Ground</td>
</tr>
</tbody>
</table>

The communication protocol

Besides a good hardware definition of the communication system, a protocol has to be designed. The used protocol is the result of the following constraints:
- Minimum processor time occupation
- ASCII commands and answers must be possible
- transmission error detection and recovery
Minimum processor occupation is achieved by using interrupt-driven procedures. By using Cyclic Redundancy Check (CRC) for error detection and timers for time-out detection, errors can be detected and recovered.

The designed communication packet sent by the PC has the following structure:

```
SOH LEN D1 D2 ... Dlen-4 CRCn CRCi EOT
```

The meaning of the fields are:
SOH: Start of Header
LEN: Length of the packet in bytes (not including SOH)
D1,...,Dn: Data fields
CRCn, CRCi: 16 bit CRC-word from SOH to Dlen-4
eOT: End of Transmission
Every character transmitted by the PC is coded as an 8 bit wide word.
A Communication packet send by a device has the following structure:

<table>
<thead>
<tr>
<th>SOH</th>
<th>LEN₂</th>
<th>LEN₁</th>
<th>LEN₀</th>
<th>D₁₈</th>
<th>D₁₁</th>
<th>D₂₈</th>
<th>D₂₁</th>
<th>D₉₂</th>
<th>D₂₄</th>
<th>D₃₆</th>
<th>D₃₉</th>
<th>D₄₁</th>
<th>D₄₄</th>
<th>CRC₂</th>
<th>CRC₁</th>
<th>CRC₀</th>
<th>EOT</th>
</tr>
</thead>
</table>

The meaning of the fields are:

SOH: Start of Header
LEN₂..LEN₁: Length (LEN₂*256+LEN₁*16+LEN₀) of the packet in nibbles (not including SOH)
D₁₈..D₁₁...D₃₆..D₃₉: Low and High data fields
CRC₂, CRC₁, CRC₀: 16 bit CRC-word from SOH to D₉₂
EOT: End of Transmission

Every character transmitted is 4 bit wide.

### 6.2 Solutions for Error Detecting

Error detection and recovery is done by using time-outs and Cyclic Redundancy Check (CRC) on both the master and the slave.

Using a Time-Out signal will prevent a device waiting for an answer.

Cyclic redundancy check is one of the most common error detecting codes. It is based on the use of polynoms. At both sides a generator polynom has been agreed upon. The algorithm used in this program is based on a lookup table and was published in Byte [8].
6.3  The communication between the FLL/PLL and the decimator/detector

The First In, First Out communication passes the in-phase and quadrature demodulated signals of both channels from the FLL/PLL to the decimator/detector. This one way communication is based on a FIFO buffer. The data are transmitted in parallel. Handshaking is done with a clock and ready signal. The specification of the FIFO data format is as follows:

**Table 6.3 Data protocol for the FIFO-bus**

<table>
<thead>
<tr>
<th>word</th>
<th>bit 0</th>
<th>bit 1</th>
<th>bit 2</th>
<th>bit 3</th>
<th>bit 4</th>
</tr>
</thead>
<tbody>
<tr>
<td>0</td>
<td>Ce bit 12</td>
<td>Ce bit 13</td>
<td>Ce bit 14</td>
<td>Ce bit 15</td>
<td>status data available</td>
</tr>
<tr>
<td>1</td>
<td>Ce bit 8</td>
<td>Ce bit 9</td>
<td>Ce bit 10</td>
<td>Ce bit 11</td>
<td>status PLL</td>
</tr>
<tr>
<td>2</td>
<td>Ce bit 4</td>
<td>Ce bit 5</td>
<td>Ce bit 6</td>
<td>Ce bit 7</td>
<td>status FLL</td>
</tr>
<tr>
<td>3</td>
<td>Ce bit 0</td>
<td>Ce bit 1</td>
<td>Ce bit 2</td>
<td>Ce bit 3</td>
<td>undefined</td>
</tr>
<tr>
<td>4</td>
<td>Qe bit 12</td>
<td>Qe bit 13</td>
<td>Qe bit 14</td>
<td>Qe bit 15</td>
<td>undefined</td>
</tr>
<tr>
<td>5</td>
<td>Qe bit 8</td>
<td>Qe bit 9</td>
<td>Qe bit 10</td>
<td>Qe bit 11</td>
<td>undefined</td>
</tr>
<tr>
<td>6</td>
<td>Qe bit 4</td>
<td>Qe bit 5</td>
<td>Qe bit 6</td>
<td>Qe bit 7</td>
<td>undefined</td>
</tr>
<tr>
<td>7</td>
<td>Qe bit 0</td>
<td>Qe bit 1</td>
<td>Qe bit 2</td>
<td>Qe bit 3</td>
<td>undefined</td>
</tr>
<tr>
<td>8</td>
<td>Ix bit 12</td>
<td>Ix bit 13</td>
<td>Ix bit 14</td>
<td>Ix bit 15</td>
<td>undefined</td>
</tr>
<tr>
<td>9</td>
<td>Ix bit 8</td>
<td>Ix bit 9</td>
<td>Ix bit 10</td>
<td>Ix bit 11</td>
<td>undefined</td>
</tr>
<tr>
<td>10</td>
<td>Ix bit 4</td>
<td>Ix bit 5</td>
<td>Ix bit 6</td>
<td>Ix bit 7</td>
<td>undefined</td>
</tr>
<tr>
<td>11</td>
<td>Ix bit 0</td>
<td>Ix bit 1</td>
<td>Ix bit 2</td>
<td>Ix bit 3</td>
<td>undefined</td>
</tr>
<tr>
<td>12</td>
<td>Qx bit 12</td>
<td>Qx bit 13</td>
<td>Qx bit 14</td>
<td>Qx bit 15</td>
<td>undefined</td>
</tr>
<tr>
<td>13</td>
<td>Qx bit 8</td>
<td>Qx bit 9</td>
<td>Qx bit 10</td>
<td>Qx bit 11</td>
<td>undefined</td>
</tr>
<tr>
<td>14</td>
<td>Qx bit 4</td>
<td>Qx bit 5</td>
<td>Qx bit 6</td>
<td>Qx bit 7</td>
<td>undefined</td>
</tr>
<tr>
<td>15</td>
<td>Qx bit 0</td>
<td>Qx bit 1</td>
<td>Qx bit 2</td>
<td>Qx bit 3</td>
<td>undefined</td>
</tr>
<tr>
<td>16</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

The hardware at the transmitter side consists of a 74F245 output buffer. At the receiver, a First In, First out (FIFO) buffer (74F225) is used. This buffer is 5 bit wide and is able to contain 16 words. The use of the FIFO eliminates the need for special synchronisation because the FLL/PLL is able to fill the FIFO independent of what the decimator/detector is doing. The Decimator/Detector receives an interrupt from the FIFO if the buffer is full (all data are available).
7 Implementation of the FLL/PLL software

7.1 Function description of and improvements made in the FLL/PLL program

The function description of the procedures and the improvements made in the program of Franken [9] are discussed in this paragraph. The FLL/PLL program consists of a main loop program, 2 interrupt driven procedures, a parallel command interpreter and the FLL algorithm. When not executing any (interrupt)procedure, the main loop program is executed.

The improvements are discussed in the following chapters, using the flow diagrams of the FLL/PLL program.

The interrupt 0 routine

This routine is called on every interrupt 0. The A/D converters, which are initiated by the 12.288kHz clock, generate this interrupt when the analog signals are converted. The samples are read and adapted to Q15 format. The PLL procedures are called for. Every sample is evaluated by the PLL algorithm.

The PLL algorithm that is used is an exact implementation of the block diagram shown in Figure 5.2. An ideal Hilbert transform will shift every frequency component 90°, however, an ideal Hilbert transform takes an infinite number of samples. To prevent this, a finite Hilbert transform is implemented which uses 35 samples. This will result in a delay equal to 17 samples. A table in memory is used for storage of the Hilbert constants. The time delay is compensated with a delay of the Xj(k) signal. The two signals, which represent a sine $X_j(k)$ and a cosine $Y_j(k)$, are divided. The result is an index to the arctangent table, which is only present from 0° to 45°. Values from 45° to 90° are calculated by its mirror value. By using the signs of $X(k)$ and $Y(k)$, angles in other quadrants can be calculated (table 7.1).
Table 7.1 Determination of the angle between $X(k)$ and $Y(k)$

<table>
<thead>
<tr>
<th>$X(k)$</th>
<th>$Y(k)$</th>
<th>Argument</th>
</tr>
</thead>
<tbody>
<tr>
<td>+</td>
<td>+</td>
<td>$\phi=\theta$</td>
</tr>
<tr>
<td>+</td>
<td>-</td>
<td>$\phi=180^\circ-\theta$</td>
</tr>
<tr>
<td>-</td>
<td>-</td>
<td>$\phi=180^\circ+\theta$</td>
</tr>
<tr>
<td>-</td>
<td>+</td>
<td>$\phi=-\theta$</td>
</tr>
</tbody>
</table>

The result of the calculation represents a phase angle. The Phase detector is implemented by subtracting the desired angle from the measured angle. This implementation will result in a linear phasedetector characteristic.

The loop filter is implemented using a normal digital first-order filter with two constants $C_1$ and $C_2$. These constants are normalized to 16 bits by multiplying them with $2^{16}$.

The Digital Voltage Controlled Oscillator adds $C_0$ to the filtered signal. The calculation of the cosine of the output angle $\phi_o$ is done using a cosine-table. The sine of the phase angle $\phi_o$ can also be calculated with the cosine-table.

The interrupt routine also collects the samples for use with the FFT algorithm and stores every n-th (n=2) sample in bit reversed order in the memory. If a memory bank is full, a flag is set and another memory bank is filled. There are two memory banks for the storage of the samples.

Changes made to the interrupt 0 procedures and the called procedures are:

- The sequence of the PLL procedures is changed. The sequence was: output routines, Hilberttransform, delaylines, demodulation, lowpass filters, phasedetection, Phase-Locked Loop algorithm and is changed to: delaylines, Hilberttransform, phase detection, Phase-Locked Loop algorithm, demodulation, low pass filter, output routines.

- An extra procedure for testing is added (OUTPUT2). This procedure transfers the values of a specified memory location to the D/A converter. This procedure is not shown in the flowchart because it is for testing purposes only. In the finite program the D/A converter should be used for VCO control.

- The possibility to change the sample rate of the data stored in the FFT memory bank is added.

- A PLL lock detection is added. The absolute value of the phase error is added to a register. Every 1024 samples this register is read and compared with a threshold value. If this value is exceeded, the PLL is said to be out of lock. The PLL is reset.

- The interrupt 0 procedure is placed in block B0. This improves the performance of execution.

Figure 7.1 The flowchart of the interrupt 0 procedure
The Main loop

If the program is started, all variables are initialized. The main program consists of a loop which controls whether the FFT-memory bank is full and whether a parallel command is received. If the FFT-memory bank is full the FFT algorithm is called, the spectrum of the signal is calculated and the carrier is detected. If a parallel command is received the command interpreter is called.

The FFT algorithm consists of two separate parts. In the first part the memory banks are filled, as described in the previous chapter. In the second part of the FFT algorithm is started, all data are collected. In this case the memory bank is full and the calculation of the FFT will start. The FFT algorithm is implemented using the Butterfly algorithm [7] described in Chapter 4.2. A procedure which calls for the butterfly routine arranges the decomposition of the data.

Calculation of the FFT is done in place. Extra memory locations are required for the imaginary part of the calculated results.

When finished calculating the FFT, all values are squared and stored in a separate memory bank which represents the frequency spectrum. While squaring, the largest value and its location are searched. The location of this value determines the frequency of the carrier.

Dependent on the type of VCO, the calculated carrier frequency can be the input for a control loop with P or PI characteristic and with a desired nominal frequency of 124.519 kHz. A control loop for use with the VCO is not yet implemented.

Changes made to the main loop and the called procedures are:
- The Decimation in Time(DIT) Radix-2 Butterfly is replaced by the butterfly algorithm from [7].
- The procedures to calculate the spectrum and to search the carrier are optimized by rewriting several parts.
- The parallel command interpreter is replaced by the interpreter designed by Kooistra [6] because this procedure is more flexible.

Figure 7.2 The flowchart of the mainloop

The interrupt 2 routine

This procedure is called when a parallel command is sent or received. A status variable is used. At first the PAR_status variable is 0, during receiving PAR_status equals 1 and after the successful completion of PAR_status equals 2. During transmission PAR_status equals 3, as initialized by the procedure transmit. After transmission PAR_status is set to zero.

There are no changes made to this procedures.
General

Some improvements are made to the variable declaration and look-up tables. The tables, which remain constant while debugging the code, are stored in a separate file which is linked with the source code. This improves readability and compilation time. The variables are sorted and placed in one memory block. Due to this improvement the memory usage is more efficient and the usage of memory pages is prevented.

7.2 Unsolved problems

When separated, the software parts (FLL/communication and PLL) function correctly. When the parts of the software are combined, the FFT is not correctly calculated. This is the result of lack of processing power. When the sample frequency is decreased to 5 kHz, the combined software parts function correctly. The solution might be found in two possible explanations of the problem:

- The development system is slowing down the execution of the program. This problem can be solved using the FLL/PLL without development system by programming the EPROMs with the FLL/PLL software.
- The interrupt 0 procedure is too large. By optimizing the code or by increasing the processing power by using a faster version of the TMS320C25, this problem can be solved.

7.3 Memory Allocation

As shown in Chapter 3, the RAM of the TMS320C25 is divided into on-chip and off-chip memory. On-chip memory is addressed by 0h-3FFh, off-chip is addressed by 400h-2000h. 544 words of the 1000 addressable words are available to the user. These words are divided into three memory blocks: B0 (200h-2FFh), B1(300h-3FFh) and B2(60h-7Fh). Other memory blocks are for internal use by the processor. It is possible to execute a procedure from block B0. The advantage of this configuration is the fast execution of the procedure placed in this block, disadvantage is the loss of 100h memory space.

In the FLL/PLL software, block B0 is configured as program memory. The INTO routines copied into block B0 when the program is started. Block B1 is used for storing variables. The total number of variables is 88 (58h) and will fit into the lower half of block B1 (300h-37Fh). The upper half (380h-3FFh) is used for the three delaylines and the Hilberttransform constants.

Block B2 is used for the stack. The function of the stack is saving variables and the processor state when executing an interrupt.

The memory allocation is defined in a .CMD file (Appendix D). The assembler source code contains only names which represent the memory allocations. The command file is used by the linker to connect these names to memory locations.
8.1 Conclusions

- The Frequency-Locked Loop for a digital beacon receiver is implemented using a 1024-point FFT. The reduced size of the number of points is the result of the lack of memory in the DSP development system.

- The Phase-Locked Loop is implemented using an All-Digital Phase-Locked Loop. The characteristics of this type of Phase-Locked Loop proved to be superior to those of the analog counterpart. Using $f_n=100$ Hz and $\zeta=0.707$ results in a hold-in range of 2500 Hz and a lock-in range of 600 Hz. The C/N ratio at the input of the FLL/PLL may decrease to -14.5 dB before loss of lock occurs.

- Communication between the PC and the FLL/PLL was tested and improved. Another communication procedure allows free programming of the command set. Using the current setup, data representing the discrete spectrum of the signal are sent every second to the PC.

- Coherent detection of the co- and crosspolar signals results in the in-phase and quadrature signals. It is possible to measure the phase difference between the co and crosspolar signal and the amplitudes of these signals.

- An accurate oscillator has been built, which produces the sampling clock.

- The software has been annotated, in order to improve accessibility.
8.2 Recommendations

- The exact characteristics of the FLL and PLL have to be determined using input signals with a well defined Carrier to Noise ratio.

- A computer program has to be written which logs the data. This program must be able to use the DCF-77 signal for time alignment.

- The interrupt routine calculating the PLL has to be optimized or a faster processor has to be used, to accomplish that the separate parts of the software cooperate. When functioning, this software has to be programmed in an EPROM.

- A voltage controlled oscillator has to be designed and built for converting the 10 MHz signal down to 124.516 kHz.

- Modern personal computers have high processing power. Using a 16-bit A/D-converter card for sampling the data, a fast computer and a C program may result in a simple and well organized system, which combines all advantages of a digital implementation of the receiver.
References

[1] Camp, Op Den, R.H.C.M.
_Digital Beacon receiver for propagation experiments, Part I: Design and implementation of an FLL/PLL for coherent detection._
Eindhoven University of Technology, Department of electrical Engineering, Graduation Report, October 1992

[2] Strik, M.
_Digital Beacon receiver for propagation experiments, Part II: A Decimator/Detector for Phase and Amplitude Measurements._
Eindhoven University of Technology, Department of electrical Engineering, Graduation Report, October 1992

_DSP-type first order digital phase-locked loop using linear phase detector._
Electronics and Communications in Japan, Part 1, Vol. 69, No. 6, 1986

_All digital phase-locked loop: concepts, design and applications._

_PhaseLock Techniques._
New York, John Wiley & Sons, 1979

_On the development of a spread spectrum transceiver based on a digital signal processor._
Eindhoven University of Technology, IVO, IVO-report, 1995

Optimization and testing of a digital FLL/PLL.
Texas Instruments.

[8]  Le Van, J.
*A fast CRC*

*Digital beacon receiver for propagation experiments: Design, testing and optimization of a Frequency-Locked Loop / Phase-Locked Loop*
Eindhoven University of Technology, Department of electrical Engineering, Graduation Report, April 1994

[10]  *Propagation experiments in the Netherlands in the 12,20 and 30 GHz band with the Olympus-satellite.*
PTT research Dr. Neher laboratories, Delft University of Technology, Eindhoven University of Technology.

*Fase- en amplitude metingen met behulp van een digitale signaal processor*
Eindhoven University of Technology, Department of electrical Engineering, Graduation Report, July 1991

[12]  Enden, A.W.M. van den, N.A.M. Verhoeckx
*Digitale Signaalbewerking*
Amerongen, Delta Press BV, 1987

[13]  Shanmugam, K. Sam
*Digital and analog communication systems*
John Wiley and Sons, 1985
Appendix

The 12.288 kHz Oscillator

The clock signal of the A/D converters need to be very accurate to ensure that further calculations are accurate. The demands on the clock signal are:
- Square wave TTL-signal
- Frequency = 12.288 kHz ± 0.09Hz
- $T_1=5 \mu s$.

Crystal oscillators are very suitable for high accuracy clock signals. Unfortunately oscillators at the desired frequency are not available. To obtain the desired frequency a frequency divider should be used. Several are available, but IC 74HCT4059 is ideal because all natural dividers can be implemented. A suitable crystal oscillator is 19.6608 MHz, which can be divided by 1600, which results in 12288Hz. The duty cycle however is 50%. To reach the demands this should be adapted by a one-shot multivibrator 74HCT4538. The low time is adaptable with a RC-combination and can be calculated using $0.7\times R\times C$. C is chosen 680 pF, so R should be 5147 $\Omega$. To adjust the timing, a potentiometer of 10K is used.

![Figure 7.3 The 12.288 kHz oscillator](image)
The calculation of the FFT constants

B.1 Hanning Window factors

The Hanning window is calculated using Formula B.1.

\[ h(n) = 0.5 + 0.5 \cdot \cos\left(\frac{2\pi n}{N}\right) \]  \hspace{1cm} (B.1)

The Quick Basic program listed below will calculate these factors and will generate a table which contains all these factors. The table can be copied into the TMS320 program.

```
'*******************************************************************
'** HAMMING.BAS   Written in Quick Basic
'** D.J. Aalberts  april 1995
'*******************************************************************
'** calculates the Hamming Factors for a N-point FFT
'** for use with the FLL/PLL program for the TMS320C25
'** The file generated by this program has to be copied
'** FLL/PLL software
'*******************************************************************
'** initialization
INPUT "N=",N
teller = 0
PI = 3.141592654#

'** Open file Hamming.dat
OPEN "hamming.dat" FOR OUTPUT AS 1

'** calculation of N Hamming Factors
PRINT "Calculation started"
PRINT #1, "\:.word\n"
FOR i = (-N / 2) TO (N / 2 - 1)
  h = .5 + .5 * COS(2 * PI * (i + .5) / N)
  h = INT(h * ((2 ^ 15) - 1))
  IF teller = 10 THEN PRINT #1, : teller = 0: PRINT #1, "\:.word\n";
  PRINT #1, USING "#####": h;
  IF teller < 9 THEN PRINT #1, ";": PRINT ".\n";
  teller = teller + 1
NEXT i
PRINT "Calculation finished"
'** end of calculation, Close file
CLOSE (1)
```
B.2 Twiddle factors

To calculate the twiddle factors the following Formula is used:

$$W_N^k = e^{-j2\pi k/N} = \cos(2\pi k/N) + j\sin(2\pi k/N)$$

(B.2)

This formula is implemented in the Quick Basic program listed below. It generates a table TWIDDLE.DAT which can be copied into the software. The tables is filled with N/2 real and imaginer parts of equation B.1.

```
'******************************************************
'** TWIDDLE.BAS    Written in Quick Basic
'******************************************************
'** calculates the Twiddle Factors for a N-point FFT
'** for use with the FLL/PLL program for the TMS320C25
'** The file generated by this program has to be copied
'** into the FLL/PLL software
'******************************************************
'** initialization
PI = 3.1415927#
INPUT "N ":N
Q15 = (2 ^ 15) - 1
'** Open file Hanning.dat
OPEN "TWIDDLE.DAT" FOR OUTPUT AS 1
'** calculation of N Twiddle factors
PRINT #1, " .word ";
FOR k = 0 TO N / 2
  X = 2 * PI * (k / N)
  RE = INT(COS(X) * Q15 + .5)
  IM = INT(SIN(X) * Q15 + .5)
  PRINT #1, USING "########"; RE; ", ";
  PRINT #1, USING "########"; IM;
  IF INT((k + 1) / 5) = (k + 1) / 5 THEN
    PRINT #1, :, PRINT #1, " .word ";
    ELSE PRINT #1, ", ";
NEXT k
'** End of calculation, close file
CLOSE (1)
```
Appendix

The (sub)sampling theorem

Analog signals have to be sampled at certain moments to convert these signals to a digital value. The Nyquist theorem states that a signal with frequency $f$ should be sampled with a sample frequency $2f$. Signals with a frequency spectrum with frequency components higher than $f$ should be filtered by a lowpass filter. If the sample rate is lower than $2f$, the higher frequency components will return in the baseband. This effect is called aliasing.

If a signal is bandlimited, sampling at a lower frequency as stated by the Nyquist theorem is possible. This is called subsampling.

$$\frac{mf_s}{2} < f < \frac{(m+1)f_s}{2} \quad , \quad m \in \mathbb{N} \quad (B.1)$$

The principle of aliasing is used in the subsampling theorem. The bandpassed signal is copied to the baseband.

*Figure B.1 Subsampling at 12.288 kHz of the 124.952 kHz signal*

The subsampling theorem is used in the FLL/PLL hardware. A carrier at 124.516 kHz is sampled at 12.288 kHz. The carrier will appear in the baseband at 1636 Hz. Attention should be payed to the fact that a shift of 100 Hz of the carrier will result in a shift of the subsampled signal of 100Hz. This principle is used in the Frequency Tracking Algorithm.
The programs for the TMS320C25

A program for the TMS320C25 consists of a file with extension .ASM contains the code and a file with extension .CMD is needed by the compiler to place all data block in the appropriate memory blocks.
```c
/*****************************/
/*
 * Linker Command File
 */
/*****************************/

TMSPRG.OBJ
TABLES.OBJ
-o TMSPRG.out
-m TMSPRG.MAP

MEMORY
{
    PAGE 0 : VECTORS : origin = 00H, length = 020H
    CODE : origin = 020H, length = 03FEOH
    ProgB0 : ORIGIN = OFF00H, LENGTH = 100H

    PAGE 1 : RAMB2 : origin = 060H, length = 020H
    RAMB1P6 : origin = 0300H, length = 080H
    RAMB1P7 : origin = 0380H, length = 080H
    PARRAM : origin = 400H, length = 700H
    FFTRAM : origin = 1000H, length = 1000H
}

SECTIONS
{
    vectors : > VECTORS PAGE = 0
    .text : > CODE PAGE = 0
    Strings : > CODE PAGE = 0
    tables : > CODE PAGE = 0
    }
    
    TMSPRG.MAP
    load = CODE run=OFF00H
    page6 : > RAMB1P6 PAGE = 1
    p1IRAM : > RAMB1P7 PAGE = 1
    global : > RAMB2 PAGE = 1
    parRAM : > PARRAM PAGE = 1
    fftram : > FFTRAM PAGE = 1
```
Digital FLL/PLL software for propagation experiments

Eindhoven University of Technology, The Netherlands

august 1992 / december 1995

Frequentie Locked Loop, Parallelle communicatie interface, Phase Locked Loop

The necessary tables are separated from the mainprogram.

Two delay lines are added.

The PLL functionality is added but does not function

A part of the PLLs activated and the PLL still functions

Two delay lines are added.

Delay = -1 used.

V PLL05, by Daniel Aalberts, november 1995

Lock detection and Reset functionality for the PLL is added

Variables declaration

Int 0/sample variables

C .usect "page6",1 ;Co-Polar input samples
X .usect "page6",1 ;X-Polar input samples
CBP .usect "page6",1 ;C Bandpass (Q15)
XBP .usect "page6",1 ;X Bandpass (Q15)
TEMP .usect "page6",1
EVNODD .usect "page6",1 ;Determines if the input sample is even/odd
AR1BCCUP .usect "page6",1 ;Next storage adress in the InterruptHandl

FFT variables

FTFPOW .usect "page6",1 ;FPT power
N .usect "page6",1 ;number of FPT input points
NMIN1 .usect "page6",1 ;number of FPT input points - 1
NBY2 .usect "page6",1 ;Number of current input bank
NBY2MIN1 .usect "page6",1 ;number of FPT input points / 2 - 1

ERF .usect "page6",1 ;FPT ERF factor
ERFMIN1 .usect "page6",1 ;FPT ERF factor - 1
DATRDY .usect "page6",1 ;if enough samples collected -> DATRDY = 1

INFBNK .usect "page6",1 ;number of current input bank
FTTBNK .usect "page6",1 ;start address of current FPT bank
FTTINF .usect "page6",1 ;input sample to FPT routine
MGSPMP .usect "page6",1 ;number of samples currently read
RANCOF .usect "page6",1 ;hanning multiplication coefficient

TDWINC .usect "page6",1 ;twiddle exponent incrementation factor
TDWSTG .usect "page6",1 ;twiddle stage counter
TDWTPN1 .usect "page6",1 ;address of first twiddle input data
TDWTPN2 .usect "page6",1 ;address of second twiddle input data
TDWSIN .usect "page6",1 ;real twiddle exponent factor
TDWCOSS .usect "page6",1 ;imaginary twiddle exponent factor

MAXPOWLC .usect "page6",1 ;Lower byte of the Maximum power
MAXPOWR .usect "page6",1 ;Higher byte of the maximum power
MAXPAR .usect "page6",1 ;Address of the maximum power
MAXPOFFS .usect "page6",1 ;Offset of the addr which contains maxpower
FREQUENCY .usect "page6",1 ;Scaled Maximum frequency
FPTCOUNT .usect "page6",1 ;Number of FPT-calculations

PAR_ZeroCnt .usect "page6",1
PAR_Status .usect "page6",1

ARVAR .usect "page6",1 ;Memory location to save AR1
VAR1 .usect "page6",1 ;Multi purpose variable
VAR2 .usect "page6",1 ;Multi purpose variable
DATA .usect "page6",1
TRDATA .usect "page6",1
TTIMEOUT .usect "page6",1
PAR_ZeroCnt .usect "page6",1
PAR_Status .usect "page6",1

0 = No communications,
1 = Receiving command,
2 = Command available,
3 = Transmitting answer
PAR_CRC .usect "pages",1
PAR_RecCRC .usect "pages",1
PAR_RecLen .usect "pages",1
PAR_RecCnt .usect "pages",1
PAR_TrnLen .usect "pages",1
PAR_TrnCnt .usect "pages",1
Temp1 .usect "pages",1
Temp2 .usect "pages",1
Help1 .usect "pages",1
Help2 .usect "pages",1
*PLL variables*

CD .usect "pages",1
XD .usect "pages",1
HD .usect "pages",1
CSHIFT .usect "pages",1
CDELAY .usect "pages",1
MDELAY .usect "pages",1
NUMER .usect "pages",1
DENOM .usect "pages",1
QUOT .usect "pages",1
PHI1 .usect "pages",1
PHI2 .usect "pages",1
PHICO .usect "pages",1
PHIC2 .usect "pages",1
PHILF .usect "pages",1
C0 .usect "pages",1
C1 .usect "pages",1
C2 .usect "pages",1
LFREGL .usect "pages",1
LFREGH .usect "pages",1
VCO .usect "pages",1
INDEX .usect "pages",1
IDENOM .usect "pages",1
DENOM .usect "pages",1
CI .usect "pages",1
CQ .usect "pages",1
XI .usect "pages",1
XQ .usect "pages",1
ONE .usect "pages",1
SIGNEXT .usect "pages",1
AR4BCUP .usect "pages",1
AR5BCUP .usect "pages",1
AR6BCUP .usect "pages",1
DVAR .usect "pages",1
INV_FLAG .usect "pages",1
SHIFT .usect "pages",1
AR0BCUP .usect "pages",1
LOCKSTAT .usect "pages",1
LOCKCTR .usect "pages",1
LOCKCRIT .usect "pages",1
DELVAC .usect "plrAM",Ndelay .usect "pages",1
DELAYX .usect "plrAM",Ndelay .usect "pages",1
DELAYH .usect "plrAM",Ndelay .usect "pages",1
HTFONCH .usect "plrAM",LHILDB .usect "pages",1
*Post detection LPF variables, Memory Req: 50h*
--- Restore Environment ---

- Interrupt service routine

- Copied from SECONDE GENERATION TMS320 USER'S GUIDE, PAGE 5-21

- Restore Environment

- Interrupt service routine

- Copied from SECONDE GENERATION TMS320 USER'S GUIDE, PAGE 5-21

**--- CopyStrToAnswer ---**

- This macro copies a measurement reply message for PC in AnswerStr with format
  - as used by transmit. Possible messages are defined in "Strings" and must have
  - an even length. Afterwards Temp2 contains the string length sofar.

**--- LptWrtC, LptWrtA ---**

- Sends 4 bit character (called a nibble) to the parallel communications output
  - port 1h. If the device is selected by the PC then the character will be put
  - on the centronics bus. Both macros perform the same, however:
    - LptWrtA expects the character to be already in the accumulator
    - LptWrtC expects a constant as parameter

**--- LptWrtC, LptWrtA ---**

- the interrupt service routine PAR_Int2

- In Transmit it only sends the SOH to start a communication. The macro does not
  - yet generate an IRQ-on-PC signal. However it does load the data nibble with bit
    - 4 in IRQ-on-PC set to 1 (active) into the variable TRDATA and it (re)enables/
      - starts the timer with period WAITLEN = 1875 = 0.15 msec at 12.5 MIPS). Later
        - on after the first deliberate time-out of the timer TRDATA is then put to the
          - centronics bus and will generate IRQ-on-PC. The period WAITLEN is probably
            - necessary to ensure that the data nibble signal values have settled on the
              - centronics bus. (See also the PAR_Tint interrupt service routine.)
IDStr .word Sayhelloback
ResetStr .word Reset ; Check RESET
GetSpecStr .word PCSPEC

* *** Parallel port possible answers ***
Hello .string 0, 41, "Hello, I am a digital PLL version 1.2"
NotInitStr .string 0, 40, "This function is not initiated by the PC"
Spectrum .string 0, 6, "Data2"
UnknownCmdStr .string 0, 15, "Unknown command"
Ok .string 0, 2, "Ok"

;Parralel interrupts

; Program initialisation

* Initialize PLL

; Initialize system

; Clear memory

; Use block 82 as stack, top address 7CH

; Set power of FFT to FFTPOWER

; Copy register to accumulator

; Copy accumulator to register

; Datapage = 6

; Calculate number of FFT input points N

; and store

; Calculate N-1

; and store

; Back to N

; Initialize FFT constants

; Initialize auxiliary registers

; Initialize input bank start address and FFT bank start address

; Current input bank is bank 0

; Set FFT bank start addr to FFTBANK1

; Initialize PLL
LALK 1 ;load ONE with 1
SACL ONE
LALK ARl, RAMB0 ;init address of the variable used for D/A
LAC ONE,15 ;load SIGNEXT with 8000H
SACL SIGNEXT
LALK 150h ;init lockcriterion
SACL LOCKCRIT

* Initialize LPF
* Initialize bit reversal counter
SACL EVNODD ;reset even/odd counter

Copy IntO routine into Block B0
Hilbert coefficients in Block B0

LARP ARl
LRLK ARl, ARIBCKUP
RPTK PrgLenB1k0
BLKP PrgB1k0,**

LRLK ARl, HILBERT
RPTK LHILB
BLKP HILBCOF,**

* Initialize parallel port

LRLK ARl, PAR_Answer ;copy parallel port strings
RPTK ParStrEnd-ParStrBeg-1
BLKP ParStrBeg,**

IN VARl, PA1 ;Clear par port D-PF and read dipsw

LDPK 0
LALK TMOUTL
SACL TIM
LDPK 6

* End of initialize
EINT ;interrupts allowed

* Main program

---

MAIN ZALS DATRDY
BZ MAIN_L1 ;FFT memory bank full?
ZAC
SACL DATRDY ;reset dataready
CALL FFT ;Calc FFT
CALL POWER ;Calc1 Power spectrum
CALL OUTPUT ;VCO control output routine

MAIN_L1 LAC PAR_Status ;par command received?
SUBK 2
BZ PARCommand
B MAIN

---

* Interrupt routines

INTO

* Interrupt 0
* New sample is arrived
* This block is placed in internal RAM, Adress FF00
* X Samples are sorted out and stored in the appropriate BANK for FFT
* X and C samples are stored in a delay line.

sect ·ProcB0·
.label PrgB0Blk0

SaveEnv ;save STO, ST1, P, T en Acc registers
LDPK 6 ;select data page 6

SCEM
IN C, PA1 ;get sample from receive register
IN X, PA0 ;get sample from receive register
LAC C, 2 ;scale input samples to 015 and store in C
SACL CBP ;or X BandPass
LAC X, 2 ;
SACL XBP ;
CALL DELAY ;Delay routine IN: CBP,XBP
CALL WAIT ; Hilbert Transf on CBP.OUT: CSHIFT
CALL PHASE ;IN MD,CSHIFT OUT: PHIN
CALL PLL ;IN PHIN,PHIVCO OUT: PHIVCO
CALL DEMOD ;Demodulatie routine bereken I en Q
CALL LPFDEC ;Roep de filters van I en Q aan.
CALL OUTPUT2 ; universele uitgangs routine
LAC EVNODD ;Determine if this is een even or odd sample
BZ EVEN ;If EVENODD equals 1 (ODD), EVENODD is reset and
ODD ;then the procedure stops; if EVENODD equals
SUBK 1 ;0 (EVEN), EVENODD is incremented and the procedure

RestoreEnv ;continues, At this way the samplefreq is halved.

EVEN
LALK 7 ;12288 Hz / 4 = 3072 Hz
SACL EVNODD ;
LARP ARl, ARIBCKUP ;set register ARl
LARP ARl ;ARl is active
SCEM
LAC NOSAMP ;copy NOSAMP to accumulator and
ADLK RAMWIN ;add start address of Hanning table
TBLR HANCOF ;read Hanning coefficient
LT CBP ;Copy SAMPLE into T register and
MPY HANCOF ;multiply by HANCOF (result in P register)
SIM 1 ;Set product Mode
Interrupt service routine for INT2 from the parallel communications port. For a description of the protocol and data formats see [2].

- PAR_L2 up to PAR_L9 for receiving data from the PC. At the first beginning PAR_Status = 0, during the receiving PAR_Status = 1 and after the successful completion PAR_Status = 2.
- PAR_L10 up to PAR_L14 and PAR_Berryfm for transmitting data to the PC (via conditional branches in PAR_L2 and PAR_L2.). During a transmission PAR_Status = 3 as initialized by the routine Transmit. After completion, whether successful or not, PAR_Status = 0.

Auxiliary registers:
- ARl points to AR1 in the whole routine.
- ARl is restored by means of AR1VAR and contains the current position in the area where received data bytes must be stored (PAR_RecData) or where the to be transmitted data nibbles are stored (PAR_TrmData).

PAR_Interrupt SaveEnv
LDPK 0 ;Switch to register space
LAC IMR
ANDK 0FFFh ;Disable parallel port and timer interrupt
SACL IMR
EINT ;Enable DCF en ADC int dep on prev status
LDPK 6
LARP ARl
LAR ARl,AR1VAR ;Restore AR1
IN DATA, PA2 ;Get Data from parallel interface

** Interrupt service routine for INT2 --------

** Interrupt service routine for INT2 from the parallel communications port. For a description of the protocol and data formats see [2].

- PAR_L2 up to PAR_L9 for receiving data from the PC. At the first beginning PAR_Status = 0, during the receiving PAR_Status = 1 and after the successful completion PAR_Status = 2.
- PAR_L10 up to PAR_L14 and PAR_Berryfm for transmitting data to the PC (via conditional branches in PAR_L2 and PAR_L2.). During a transmission PAR_Status = 3 as initialized by the routine Transmit. After completion, whether successful or not, PAR_Status = 0.

Auxiliary registers:
- ARl points to AR1 in the whole routine.
- ARl is restored by means of AR1VAR and contains the current position in the area where received data bytes must be stored (PAR_RecData) or where the to be transmitted data nibbles are stored (PAR_TrmData).

PAR_Interrupt SaveEnv
LDPK 0 ;Switch to register space
LAC IMR
ANDK 0FFFh ;Disable parallel port and timer interrupt
SACL IMR
EINT ;Enable DCF en ADC int dep on prev status
LDPK 6
LARP ARl
LAR ARl,AR1VAR ;Restore AR1
IN DATA, PA2 ;Get Data from parallel interface

** Interrupt service routine for INT2 --------

** Interrupt service routine for INT2 from the parallel communications port. For a description of the protocol and data formats see [2].

- PAR_L2 up to PAR_L9 for receiving data from the PC. At the first beginning PAR_Status = 0, during the receiving PAR_Status = 1 and after the successful completion PAR_Status = 2.
- PAR_L10 up to PAR_L14 and PAR_Berryfm for transmitting data to the PC (via conditional branches in PAR_L2 and PAR_L2.). During a transmission PAR_Status = 3 as initialized by the routine Transmit. After completion, whether successful or not, PAR_Status = 0.

Auxiliary registers:
- ARl points to AR1 in the whole routine.
- ARl is restored by means of AR1VAR and contains the current position in the area where received data bytes must be stored (PAR_RecData) or where the to be transmitted data nibbles are stored (PAR_TrmData).

PAR_Interrupt SaveEnv
LDPK 0 ;Switch to register space
LAC IMR
ANDK 0FFFh ;Disable parallel port and timer interrupt
SACL IMR
EINT ;Enable DCF en ADC int dep on prev status
LDPK 6
LARP ARl
LAR ARl,AR1VAR ;Restore AR1
IN DATA, PA2 ;Get Data from parallel interface
The timer is used to detect parallel communications port time-outs and can have two periods:
- WAITLEN=0.15 msec, this period is started by the LptWrt macro and defines the time that a nibble is put onto the centronics bus before an IRQ-on-PC is issued.
- TMOUTL=5.2 msec, this period is enabled in TI_L0 and states the time within which the PC should react on IRQ-on-PC.

The timer is enabled or remains enabled in:
- LptWrt with WAITLEN
- TI_L0 with TMOUTL

and is disabled in:
- PAR_Tint when PAR_Status=0 and the last EOT was transmitted in transmit mode
- TI_L1 when the PC has not reacted on IRQ-onPC.

The timer interrupt is reallotchable by means of the macro RelocInVec. For the parallel communications protocol the timer is allocated in the following way:

--- PAR_Tint interrupt service routine (TINT) ---

**Timer**

<table>
<thead>
<tr>
<th>SaveEnv</th>
<th>;Interrupt: Timeout occurred</th>
</tr>
</thead>
<tbody>
<tr>
<td>LDPK 5</td>
<td></td>
</tr>
<tr>
<td>LAC 6</td>
<td></td>
</tr>
<tr>
<td>BNZ TI_L1</td>
<td>Generate interrupt on acquis computer</td>
</tr>
<tr>
<td>OUT TRDATA,PA1</td>
<td></td>
</tr>
<tr>
<td>LACK 1</td>
<td></td>
</tr>
<tr>
<td>SACL TimeOut</td>
<td></td>
</tr>
<tr>
<td>LAC PAR_Status</td>
<td></td>
</tr>
<tr>
<td>LDPK 0</td>
<td></td>
</tr>
<tr>
<td>BNZ TI_L0</td>
<td></td>
</tr>
<tr>
<td>LAC IMR</td>
<td>;Disable Time-out interrupt</td>
</tr>
<tr>
<td>ARDK OFFFF7h</td>
<td></td>
</tr>
<tr>
<td>SACL IMR</td>
<td>;Last trans compl, no anaw expected</td>
</tr>
<tr>
<td>RestoreEnv</td>
<td></td>
</tr>
</tbody>
</table>

**TI_L0**

| LALK TMOUTL |                              |
| SACL TIM |                          |
| RestoreEnv |                          |

**TI_L1**

| LDPK 0 | ;Disable Time-out interrupt |
| LAC IMR |                              |
| ARDK OFFFF7h |                     |
| SACL IMR | ;Disable Time-out interrupt |
| LDPK 6 |                              |
Subroutines

Performs in-place N-point radix-2 DIT FFT transform
Data should be in bit-reversed order

Theory, Algorithms and implementations, Texas Instruments, page 77

Writers: Panos Papamichalis, John So

BUTTERFLY
Performs FFT butterfly

Copied from Digital Signal Processing Applications (with the TMS320 Family)

Article: Implementation of FFT algorithms with the TMS32020.
Calculates power in each frequency bin

This FIR Hilbert transformer uses on-chip memory block B0 (page 5) for storage of delay-tap data samples. The newest input samples should be in memory location CBP when returned. The number of delays is specified by the constant NDELAY.

This routine delays co- and x-polar bandpass filtered samples. The newest input samples should be in memory locations CBP and XBP. The output (delayed) samples will be in memory locations CB and XD when returned. The number of delays is specified by the constant NDELAY.

This routine determines the co-polar signal argument. The newest input samples should be in memory locations CBP and XBP. The output (delayed) samples will be in memory locations CB and XD when returned. The number of delays is specified by the constant NDELAY.
samples should be in memory locations `CD` and `CSHIFT`. The calculated argument will be in memory location `PHI IN`. The procedure uses the variable `PHI0` as temporary helpvariable.

---

**PLL**

This routine generates an argument `PHIVCO` that is phase locked to the input signal argument `PHIIN`.

---

**DEMOD**

Demodulate the I Q signals from the delayed input lines.
BIT PHIVCO, 0: ; test sign-bit of PHIVCO
    BBZ DEMOD2: ; if PHIVCO >= 0, branch to DEMOD2
    BIT PHIVCO, 1: ; if PHIVCO < 0, branch to DEMOD1
    BBNZ DEMOD1: ; if -16384 <= PHIVCO < 0, branch to DEMOD1
    ANDX 16383: ; calc index of sine table (delete 2 MSBs)
    SACL INDEX: ; and store result in INDEX
    SFR: ; Acc = Acc/2: Shift Right
    SFR: ; ... ...
    ADLK SINTBL: ; add start address of sine table
    TBLR IDEMOD: ; read sine
    LAC IDEMOD: ; calculate in-phase demodulation value and
    NEG: ; store result in IDEMOD
    SACL IDEMOD: ; calculate index of sine table
    SBLK 16384: ; ... ...
    TBLR IDEMOD: ; read sine table and store in-phase
    LAC INDEX: ; calculate index of sine table
    SBLK 16384: ; ... ...
    DEMOD1: ; branch to DEMOD4
    ANDX 16383: ; calc index of sine table (delete 2 MSBs)
    SACL INDEX: ; and store result in INDEX
    SFR: ; ... ...
    ADLK SINTBL: ; add start address of sine table
    TBLR QDEMOD: ; read sine
    LAC QDEMOD: ; calculate quadrature demodulation value and
    NEG: ; store result in QDEMOD
    SACL QDEMOD: ; calculate index of sine table
    SBLK 16384: ; ... ...
    B DEMOD4: ; branch to DEMOD4
    ANDX 16383: ; calc index of sine table (delete 2 MSBs)
    SACL INDEX: ; and store result in INDEX
    SFR: ; ... ...
    ADLK SINTBL: ; add start address of sine table
    TBLR IDEMOD: ; read sine
    LAC IDEMOD: ; calculate in-phase demodulation value and
    NEG: ; store result in IDEMOD
    SACL IDEMOD: ; calculate index of sine table
    SBLK 16384: ; ... ...
    DEMOD2: ; branch to DEMOD4
    BIT PHIVCO, 1: ; test if PHIVCO >= 16384
    BBNZ DEMOD3: ; if PHIVCO <= 16384, branch to DEMOD3
    ANDX 16383: ; delete 2 MSBs
    SACL INDEX: ; and store result in INDEX
    SFR: ; ... ...
    ADLK SINTBL: ; add start address of sine table
    TBLR IDEMOD: ; read sine table and store in-phase
    LAC INDEX: ; calculate index of sine table
    SBLK 16384: ; ... ...
    DEMOD3: ; branch to DEMOD4
    ANDX 16383: ; delete 2 MSBs
    SACL INDEX: ; and store result in INDEX
    SFR: ; ... ...
    ADLK SINTBL: ; add start address of sine table
    TBLR QDEMOD: ; read sine table and store quadrature
    LAC QDEMOD: ; demodulation value in QDEMOD
    SFR: ; ... ...
    ADLK SINTBL: ; add start address of sine table
    TBLR IDEMOD: ; read sine table and store in-phase
    LAC QDEMOD: ; demodulation value in QDEMOD
    SFR: ; ... ...

* Output

OUTPUT LT FREQOFFS: ; calculate frequency
    MPYR 32: ; multiply CD by IDEMOD and store result
    LACK 5000H: ; load T-register with CD
    APAC: ; multiply XD by QDEMOD and store result
    SACL Temp1, : and store result in FREQUENCY
    RET: ;... ...

* This routine sends the value of the var in address DAVAR to
  the da converter, it can be complemented by the var inv_flag

OUTPUT2 LT COMPL_NOT: ; calculate complement
    MPYQ DAVAR: ; load ARO with DAVAR (adress of var)
    LAR 0: ; Save contents of ARO
    LAR 0,AROBCKUP: ; load ARO with DAVAR (adress of var)
    LARP 0,DAVAR: ; load ARO with DAVAR (adress of var)
    LAC Inv_FLAG: ; Need a complement?
    BZ COMPL_NOT: ;... ...
    LAC *: ;... ...
    B WRIT: ;... ...
    WRIT XORK: ;... ...
    LAR 0,AROBCKUP: ;... ...

* PARALLEL COMMUNICATIONS PORT ROUTINES
  * - Transmit
    * - PARCommand

*...*
PAR RetryTrm restarts a packet transmission all over again by making PAR_TrmCnt:=1, resetting AR1 and sending the SOH. This can happen up to TMOUTL received from the PC. This routine then finds out which command and jumps to the corresponding command service program part as defined in the PAR Answer area (see also the section "Strings" and Beg_L1). - AR0 points to PAR_RecData buffer with the received command from the PC, after a command has been found it points to the first word of other data (if any) send along with the command word. - AR1 counts the number of characters in a command word - AR2 goes through a command information string in PAR_Answer - AR3 successively contains the command information addresses - AR4 counts the number of possible commands - Temp1 contains a character of a stored command word to be compared - Temp2 contains the address of a command service program - AR0 counts the number of possible commands - AR2 goes through a command information string in PAR_Answer - AR3 successively contains the command information addresses - AR4 counts the number of possible commands - Variables:
- Temp1 contains a character of a stored command word to be compared with the received command in PAR_RecData

PAR Command routine
- Find subroutine for received command on entry PAR_RecData contains received command if no command is recognized "Unknown command" message is transmitted if command is recognized AR0 points to character after last checked char in receive buffer (usefull to retrieve time information following command ID string)
IC_L1
LAR AR2,,*+AR2 ; AR2 points to command ID
LAC *+ ; Subroutine address
SAACL Temp2
LAR AR1,*,AR1 ; Number of characters to check
MUL *+,AR2 ; AR1 = number of char to check - 1
LRLK AR0,PAR_RecData
LAC *+.AR0 ; AR2 points to known command char
SACH Temp1 ; Save high byte
LAC *+,AR1 ; AR0 points to received character
SUB Temp1 ; compare with known character
BNZ PC_L4 ; equal ?
BANZ PC_L3,,+.AR2 ; equal yes, more characters to check?
LARP AR0
LAC Temp2 ; command found
BACC ; goto subroutine
PC_L3
LAC *+,AR0 ; AR2 points to known command char
ANDK OFFh ; get low byte
SUB *+,AR1 ; compare with received character
BNZ PC_L4 ; equal ?
BANZ PC_L2,,+.AR2 ; equal yes, more characters to check?
LARP AR0
LAC Temp2 ; Command found
BACC ; Goto subroutine
PC_L4
LARP AR4
BANZ PC_L1,,+.AR3
LRLK AR0,UnknwCmdStr ; Command not recognized!
CALL Transmit ; Transmit "Unknown command"
B MAIN

**************

Algorithm with lookup table from BYTE magazine November 1987 page 339

- CRC = CRCTable[(CRC >> 8) "Character"] (CRC << 8)
- Assumed:
  - PAR_CRC contains previous CRC result (first time should be set to 0)
- Data page pointer = 160

**************

Par_CRC,8 :Get old CRC and shift 8 places
SACH VAR1 ;Save high order byte CRC >> 8
LAC VAR1 ;
XOR DMA ;Calculate (CRC>>8)"Character"
ADLK CRCTable ;Add offset
TBLR VAR1
LAC VAR1
XCR VAR2
SACL VAR_CRC ;Save new CRC
RET

**************

Answers and actions taken on received command

**************

Reset
LRLK AR0,OK
CALL Transmit
RS_L1
LAC PAR_Status
BNZ RS_L1
RPTX 255
LAC 300h ;Do nothing, give timer chance to generate
;last interrupt of "Ok" transmission
B 0000h

**************

* Spectrumout
* Transmit power density spectrum to PC

**************

PCSPEC
DINT CopyStrToAnswer Spectrum
SAR AR1,Help1 ;Help1=startposition
LRLK AR4,FFTBANK2
LRLK AR0,2 ;Increment factor
LARK AR6,255
LAC PAR_Frequency
SACL *,0,4 ;Frequency in eeste woord
SACL *,2,6 ;gemiddelde truc
BANZ PCSAVE_L1,*,.AR4
LRLK AR1,Help2 ;help2=eindpositie
LARP 1
LAC Help2
SUB Help1 ;Length of the data
ADD Temp2 ;+ de al bewaarde lengte
LRLK AR0,AnswerStr ;
LARP 0 ;Store Length field
SACL *+ ;CALL Transmit
EINT
B MAIN

**************

Sayhelloback
* Says back "Hello, I'm a digital FLL-PLL"

**************

Sayhelloback
LRLK AR0,Hello
CALL Transmit
B MAIN

**************

Program end

.end