A Digital Instantaneous Frequency Measurement Technique Utilising High-Speed ADC’s and FPGA’s

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CSIR Defence, Peace, Safety and Security
Dr PL Herselman
Visiting Researcher at the University College London
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Electronic Warfare

Image courtesy of Altera, www.altera.com
Signal Intelligence (SIGINT)

- Complex battlefield → multiple RF emitters
- Receiver analyses intercepted waveforms
  - Situational awareness
  - Queuing of defensive/evasive action(s)
- Compact packaging for operational systems
- Employed on a range of systems
  - Airborne Warning and Control System (AWACS)
Agenda

- **Background**
  DIFM research as part of CSIR Defence, Peace, Safety and Security R&D strategy

- **IFM Theory**
  Overview of basic theory

- **Optimal Time Delay**
  Led to DIFM invention

- **DIFM Basics**
  Digital implementation of IFM using innovative parallel DSP techniques

- **Example Implementation**
  Shared aperture DIFM on SWIFT500 DRFM system

- **Simulation Results**
  Bit-true functional simulations for a range of input signals

- **Experimental Verification**
  Results of a prototype system

- **Conclusions**
Background
Digital Radio Frequency Memory (DRFM)
Research and Development at the CSIR

- Active R&D field since 1999

- Advanced and highly configurable repeater
  - Analog to digital converter → memory → digital to analog converter
  - Information bandwidth limited to half the sampling rate

- Utilised in a range of applications
  - Field (electronic countermeasures)
    - Obscure the platform (e.g aircraft)
    - Deceive the hostile radar
  - Laboratory (test equipment)
    - Coherently simulate the signals emitted by electronic countermeasures and the signals reflected from targets
Digital Radio Frequency Memory (DRFM) Research and Development at the CSIR

- Levels of development
  - Digital DRFM Module
  - DRFM Kernel
  - DRFM-based simulator system
Need for Frequency Measurement in DRFM-Based Systems

- **Pulse qualification**
  Deceive and obscure only hostile systems

- **Frequency dependant techniques**
  Accurate Doppler response
  RF bandwidth is a scarce resource
  Maximise ECM effectiveness

- **Compensate DRFM-induced phase perturbations**
  Poster presentation

Estimate required in less than a microsecond
Frequency Measurement Solutions

- **Instantaneous Frequency Measurement (IFM)**
  - Analog technique
  - Combined with analog-to-digital converter → DFD
  - Multiple parallel IFM’s
  - Single output
  - Dual aperture

- **Discrete Fourier Transform (DFT)**
  - Measures spectral response
  - Aliased to \([0, f_s/2)\) frequency range
  - Multiple input signals
  - Multiple outputs

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**Preferred frequency estimation technique**

**Table**

<table>
<thead>
<tr>
<th>Band</th>
<th>Frequency Range (MHz)</th>
<th>Unambiguous Bandwidth (MHz)</th>
<th>Sensitivity (Threshold) (dBm)</th>
<th>Dynamic Range (dB)</th>
<th>Input Impedance (nom.) (Ω)</th>
<th>VSWR (max.)</th>
<th>Capture Ratio (at discriminator input) (dB)</th>
<th>Resolution (11 bits) (MHz)</th>
<th>Accuracy (RMS) (MHz)</th>
<th>Through-put Delay (ns)</th>
<th>Shadow Time (ns)</th>
<th>Pulselength (min. for full accuracy) (ns)</th>
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<tbody>
<tr>
<td>L-Band</td>
<td>1.2-12.4</td>
<td>10050-12120</td>
<td>20</td>
<td>80</td>
<td>50</td>
<td>2.1</td>
<td>10</td>
<td>0.52</td>
<td>1.25</td>
<td>185</td>
<td>70</td>
<td>95</td>
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<tr>
<td>S-Band</td>
<td>2.4-12.4</td>
<td>2120-6240</td>
<td>50</td>
<td>80</td>
<td>50</td>
<td>2.1</td>
<td>10</td>
<td>1.04</td>
<td>2.5</td>
<td>150</td>
<td>50</td>
<td>60</td>
</tr>
<tr>
<td>C-Band</td>
<td>4.4-12.4</td>
<td>6240-12420</td>
<td>50</td>
<td>80</td>
<td>50</td>
<td>2.1</td>
<td>10</td>
<td>2.08</td>
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<td>135</td>
<td>50</td>
<td>45</td>
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<tr>
<td>X-Band</td>
<td>8.0-12.4</td>
<td>12420-24240</td>
<td>50</td>
<td>80</td>
<td>50</td>
<td>2.1</td>
<td>10</td>
<td>2.08</td>
<td>6.5</td>
<td>135</td>
<td>50</td>
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<tr>
<td>Ku-Band</td>
<td>10.0-12.5</td>
<td>24240-36320</td>
<td>50</td>
<td>80</td>
<td>50</td>
<td>2.1</td>
<td>10</td>
<td>3.12</td>
<td>12</td>
<td>130</td>
<td>50</td>
<td>40</td>
</tr>
</tbody>
</table>

*Table taken from Schleher (1986)*

*Graph courtesy of Altera*
Instantaneous Frequency Measurement Theory
Instantaneous Frequency Measurement

\[ y(t) = A_0 \cos(2\pi ft) \]

Digital Frequency Discriminator

- Multiply signal with delayed replica
  \[ y_{\text{mix}}(t) = \frac{A_0^2}{8} \left[ \cos(2\pi f_0 \tau) + \cos(4\pi f_0 t - 2\pi f_0 \tau) \right] \]

- Low-pass filter
  \[ y_{\text{filt}}(t) \approx \frac{A_0^2}{8} |H(0)| \cos(2\pi f_0 \tau) \quad , \quad |H(2f_0)| \ll |H(0)| \]

- Inverse cosine operation
  - Typically preceded with ADC
  - Lookup table
  - Digital Frequency Discriminator (DFD)

\[ f_0 \approx \frac{1}{2\pi \tau} \arccos \left[ \frac{8y_{\text{filt}}(t)}{A_0^2 H(0)} \right] \]
Optimal Time Delay
Delay Line Calculation

- One-to-one mapping: Input frequency → output value
- Maximum one-to-one input frequency calculated as
  \[
  \tau = \frac{1}{2\pi f_{0(\text{max})}} \arccos(-1) = \frac{1}{2\pi f_{0(\text{max})}} (1 + 2n)\pi = \frac{1}{2f_{0(\text{max})}}, \quad n = 0
  \]
- Inverse of twice the maximum input frequency
- IFM with frequency range equal to ADC IBW
- Unambiguous input frequency range \([0,f_s/2]\) chosen
  \[
  \tau = \frac{1}{2f_{0(\text{max})}} = \frac{1}{2\left(\frac{f_s}{2}\right)} = \frac{1}{f_s} = t_s
  \]
- Optimal time delay = one ADC sampling period
Digital Instantaneous Frequency Measurement Basics
Steps 1&2: Sampling, Quantisation and Multiplication

- **Sampling and quantisation**
  \[ y_q(n) = Q[y(nt_s)] = Q\left[A_0 \cos\left(2\pi \frac{f_0}{f_s} n\right)\right] = Q[A_0 \cos(2\pi F_0 n)] , \quad F_0 = \frac{f_0}{f_s} \]
  \[ = \text{round}\left[\frac{2A_0}{D} 2^{N-1} \cos(2\pi F_0 n)\right] = \frac{A_0}{D} 2^N \cos(2\pi F_0 n) + \varepsilon_q(n) \]

- **Multiplication with time-delayed replica**
  \[ y_{mix}(n) = y_q(n) y_q(n-1) \]
  \[ = \frac{A_0^2}{D^2} 2^{2N-1} \left[\cos(2\pi F_0) + \cos(4\pi F_0 n - 2\pi F_0)\right] \]
  \[ + \frac{A_0}{D} 2^N \left\{\cos(2\pi F_0 n)\varepsilon_q(n-1) + \cos[2\pi F_0 (n-1)]\varepsilon_q(n)\right\} + \varepsilon_q(n)\varepsilon_q(n-1) \]
Step 3: Low-Pass Filtering

- Finite Impulse Response (FIR) digital filter

\[ y_{\text{filt}}(n) = \sum_{k=0}^{N} c_k \cdot y_{\text{mix}}(n-k) \]

\[ = \frac{A_0^2}{D^2} 2^{2N-1} \left[ |H_{\text{LPF}}(0)| \cos(2\pi F_0) + |H_{\text{LPF}}(F_0')| \cos(2\pi F_0' n - 2\pi F_0 + \angle H_{\text{LPF}}(F_0')) \right] + \epsilon_q(n) \]

where

\[ F_0' = 2F_0 \quad , \quad f_0 \leq \frac{f_s}{4} \]

\[ F_0' = 1 - 2F_0 \quad , \quad f_0 > \frac{f_s}{4} \]
Step 3: Low-Pass Filtering

- Interactive filter design tools (e.g. MATLAB FDATool)
Step 4: Inverse Cosine Operation

- Digital inverse cosine estimation
  - Cordic algorithm
  - Lookup table
- Output of low-pass filter is used as the input to a lookup table
- Lookup table output estimates frequency of the input signal

\[ y_{out}(n) = \frac{2^{N_{out}} - 1}{2\pi} \arccos \left( \frac{y_{filt}(n)D^2}{A_0^2 2^{2N-1}|H_{LPF}(0)|} \right) \]
Digital Instantaneous Frequency Measurement

• **Advantages**

  Mixing product relatively linear yielding lower spurious response

  Filter response can be optimised for the specific requirements, i.e. fast response versus measurement accuracy

• **Issues**

  FPGA clock speeds > 100 MHz

  DIFM up to 50 MHz bandwidth with serial processing

  Exhibit the same amplitude sensitivity as an analog IFM
Parallel Processing DIFM

- High-speed flash converter ADC’s
  - > 10 bits
  - > 2 GSPS

- Techniques often employed include time-domain demultiplexing, i.e. wider bus, lower data rate
  - ASIC or commercial demultiplexers
  - For 1.2 GSPS 10-bit ADC
    - 16x demultiplex
    - 75 MSPS 160-bit

- Calculate in a single FPGA clock cycle
  - 15 multiplications
  - 14th order FIR filter

- Possible to artificially extend the bus width
Amplitude Insensitive DIFM

- Suppose an estimate of the input amplitude was available

\[ y_{\text{div}}(n) = \frac{y_{\text{filt}}(n)}{A^2(n)} = \frac{y_{\text{filt}}(n)}{[A_0 + \varepsilon_a(n)]^2} \approx \frac{y_{\text{filt}}(n)}{A_0^2}, \quad A_0 >> \varepsilon_a(n) \]

\[ \approx \frac{4}{D^2} 2^{2N-1} \left[ |H_{LPF}(0)| \cos(2\pi F_0) + |H_{LPF}(F'_0)| \cos(2\pi F'_0 n - 2\pi F_0 + \angle H_{LPF}(F'_0)) \right] + \frac{\varepsilon'_q(n)}{A_0^2} \]

- Technique analogous to DIFM with time delay equal to 0

- Multiply

\[ y'_{\text{mix}}(n) = y_q(n) y_q(n-0) = y_q(n) y_q(n) = y_q^2(n) \]

- Low-pass

\[ y'_{\text{filt}}(n) = \frac{A_0^2}{D^2} 2^{2N-1} \left[ |H_{LPF}(0)| + |H_{LPF}(F'_0)| \cos(2\pi F'_0 n + \angle H_{LPF}(F'_0)) \right] + \varepsilon''_q(n) \]
Amplitude Insensitive DIFM

• Divide basic DIFM filter output with amplitude estimation

\[ y_{\text{div}}(n) \approx \cos(2\pi F_0) + \frac{|H_{\text{LPF}}(F_0')|}{|H_{\text{LPF}}(0)|} \cos(2\pi F'_0 n - 2\pi F_0 + \angle H_{\text{LPF}}(F_0')) + \epsilon^m(n) \]

\[ \approx \cos(2\pi F_0) \]

• Inverse cosine lookup table yield frequency estimation

\[ y_{\text{ht}}(n) \approx 2\pi F_0 = 2\pi \frac{f_0}{f_s} \]

• Advantages
  • Amplitude estimation exactly aligned with frequency estimation
  • No external calibration or alignment required
  • Time-domain multiplex hardware
Example Implementation
SWIFT500 Digital DRFM Module with Built-In Amplitude Insensitive DIFM

- 1.2 GSPS, 500 MHz IBW
- 16x demultiplexing
- Stratix 1S30 with 96 9x9 multipliers
SWIFT500 Digital DRFM Module with Built-In Amplitude Insensitive DIFM
SWIFT500 Digital DRFM Module with Built-In Amplitude Insensitive DIFM

- Key specifications
  - 9-bit multiplication
  - 24th order low-pass FIR filter with Chebyshev windowing
  - Cut-off frequency of 100 MHz and 48 dB side-lobe suppression
  - Frequency response 50 MHz to 550 MHz
  - Time-multiplexed resources to estimate amplitude and frequency
  - Division implemented in a two-step process
    - Inversion of denominator using lookup table (12-bit x 12-bit)
    - Multiplication of numerator with inversed denominator
  - 12-bit by 10-bit inverse cosine lookup table
Simulation Results
Monochromatic Input Signal With Additive Coloured Noise

DIFM output with $f_0 = 550$ MHz over a period of 4 $\mu$s for various SNR's.
Analysis of DIFM Accuracy
Key Performance Specifications

• **High signal-to-noise ratios**
  • Mean deviation less than ± 2 MHz
  • Absolute error less than 6 MHz across bandwidth
  • Absolute error less than 2 MHz in > 300 MHz bandwidth
  • RMS error less than 3 MHz across bandwidth
  • RMS error less than 1 MHz in > 300 MHz bandwidth

• **Low signal-to-noise ratios**
  • Bias in frequency estimation
  • Due to bias in amplitude estimation
  • Reduced by implementing higher order FIR filter (longer latency)

• **Latency (processing time)**
  • 13 FGPA clock cycles (173.33 ns)

• **Throughput rate**
  • 2 FGPA clock cycles (37.5 MHz)
Experimental Verification
Quantitative Laboratory Experiments
Conclusions
Conclusions

- Viable, shared aperture, frequency estimation technique
- Implemented efficiently in current commercial hardware
- Results comparable to existing analog techniques
- Flexibility and ability to be optimised for the specific requirements
- Real-time changing the filter coefficients
- Insensitive to temperature
- Does not require periodic calibration to maintain accuracy
- Operationally superior to its analog counterparts

- South African provisional patent application 2006/00946, 2006-02-01