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

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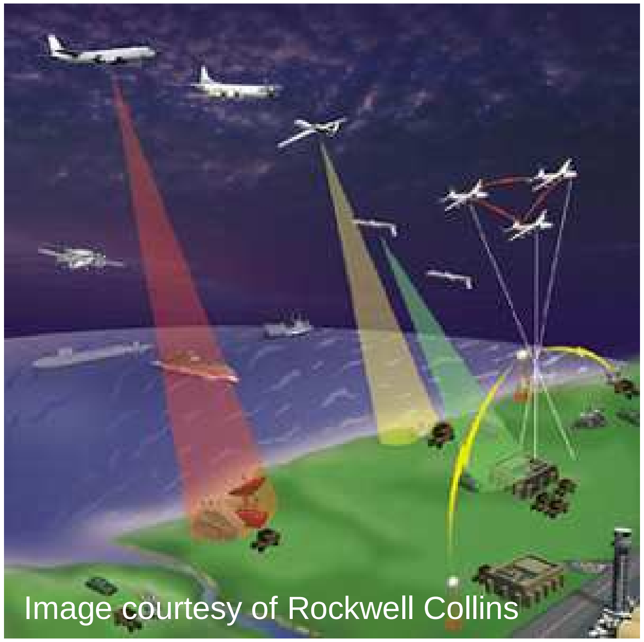
Signal Intelligence (SIGINT)

- 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)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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

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Digital Radio Frequency Memory (DRFM) Research and Development at the CSIR

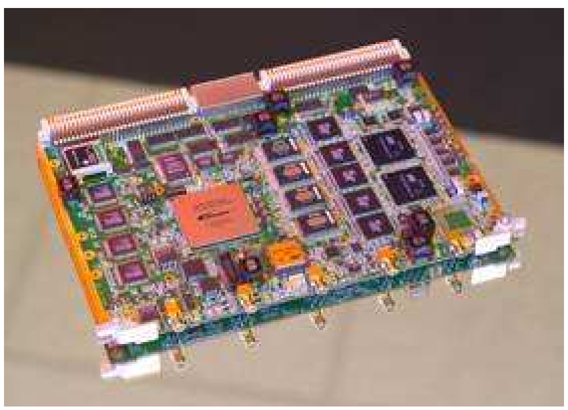
- Active R&D field since 1999

- 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



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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

DIGITAL IFM RECEIVER CHARACTERISTICS

	L-Band	*S-Band*	*C-Band*	*X-Band*	*Ku-Band*
Frequency Range (GHz)	1-2	2-4	4-8	[illegible]	12-18
Unambiguous Bandwidth (MHz)	1060	2120	4240	4240	6360
Sensitivity (threshold) (dBm)	-65	[illegible]	[illegible]	-65	-60
Dynamic Range (dB)	70	70	70	70	65
Input Impedance (nom.) (Ω)	50	50	50	50	50
VSWR (max.)	2.1	2.1	2.1	2.1	2.1
Capture Ratio (at discriminator input) (dB)	10	10	10	10	10
Resolution (11 bits) (MHz)	.52	1.04	2.08	2.08	3.12
Accuracy (RMS) (MHz)	1.25	2.5	5.0	6.5	12
Through-put Delay (ns)	185	150	135	135	130
Shadow Time (ns)	70	50	50	50	50
Pulsewidth (min. for full accuracy) (ns)	95	60	45	45	40

Preferred frequency estimation technique

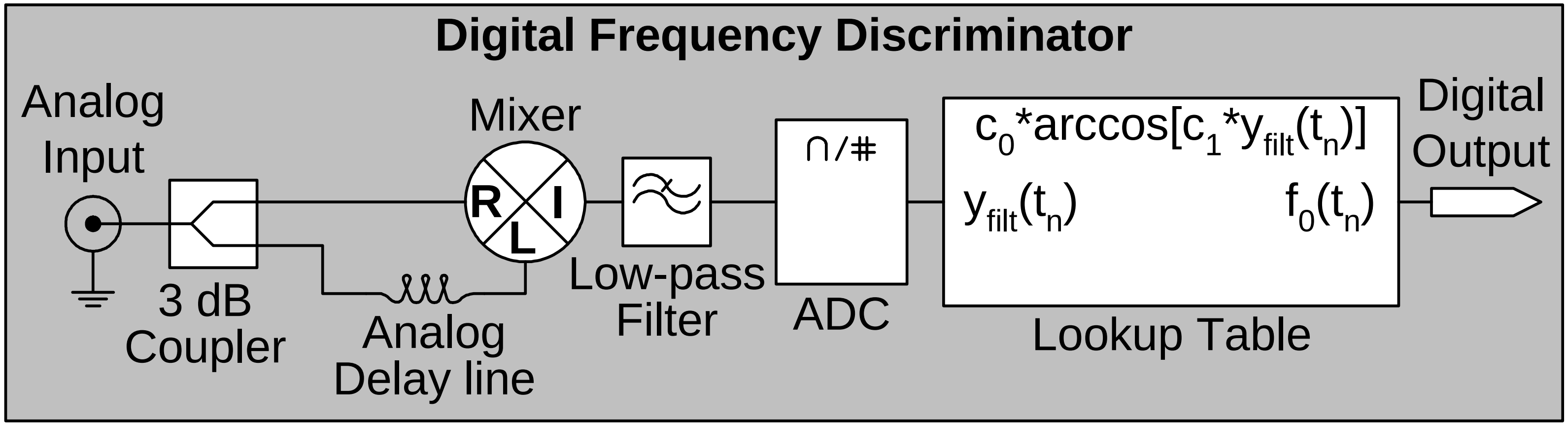
Table taken from Sullivan (1986)

Graph courtesy of Alsa

Instantaneous Frequency Measurement Theory

Instantaneous Frequency Measurement

$y(t) = A_0 \cos(2\pi f_0 t)$



- Multiply signal with delayed replica

$$y_{mix}(t) = \frac{A_0^2}{8}\left[\cos(2\pi f_0 \tau) + \cos(4\pi f_0 t - 2\pi f_0 \tau)\right]$$

- Low-pass filter

$$y_{filt}(t) \approx \frac{A_0^2}{8}\left|H(0)\right|\cos(2\pi f_0 \tau) \quad , \quad \left|H(2f_0)\right| << \left|H(0)\right|$$

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

$$f_0 \approx \frac{1}{2\pi\tau}\arccos\left[\frac{8y_{filt}(t)}{A_0^2 H(0)}\right]$$

Optimal Time Delay

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Delay Line Calculation

- One-to-one mapping: Input frequency → output value
- Maximum one-to-one input frequency calculated as

$$\tau = \frac{1}{2\pi f_{0(\max)}} \arccos(-1) = \frac{1}{2\pi f_{0(\max)}} (1+2n)\pi = \frac{1}{2 f_{0(\max)}} \quad , \quad n=0$$

- Inverse of twice the maximum input frequency

- IFM with frequency range equal to ADC IBW
- Unambiguous input frequency range $[0, f_s/2)$ chosen

$$\tau = \frac{1}{2 f_{0(\max)}} = \frac{1}{2\left(\frac{f_s}{2}\right)} = \frac{1}{f_s} = t_s$$

- Optimal time delay = one ADC sampling period

Digital Instantaneous Frequency Measurement Basics

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Steps 1&2: Sampling, Quantisation and Multiplication

- Sampling and quantisation

$$y_q(n) = Q[y(nt_s)] = Q\left[A_0 \cos\left(2\pi \frac{f_0}{f_s} n\right)\right] = Q[A_0 \cos(2\pi F_0 n)] \quad , \quad F_0 = \frac{f_0}{f_s}$$

$$= round\left[\frac{2A_0}{D} 2^{N-1} \cos(2\pi F_0 n)\right] = \frac{A_0}{D} 2^N \cos(2\pi F_0 n) + \varepsilon_q(n)$$

- Multiplication with time-delayed replica

$$y_{mix}(n) = y_q(n) y_q(n-1)$$

$$= \frac{A_0^2}{D^2} 2^{2N-1} [\cos(2\pi F_0) + \cos(4\pi F_0 n - 2\pi F_0)]$$

$$+ \frac{A_0}{D} 2^N \{\cos(2\pi F_0 n)\varepsilon_q(n-1) + \cos[2\pi F_0 (n-1)]\varepsilon_q(n)\} + \varepsilon_q(n)\varepsilon_q(n-1)$$

Step 3: Low-Pass Filtering

- Finite Impulse Response (FIR) digital filter

$$y_{filt}(n) = \sum_{k=0}^{N} c_k y_{mix}(n-k)$$

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

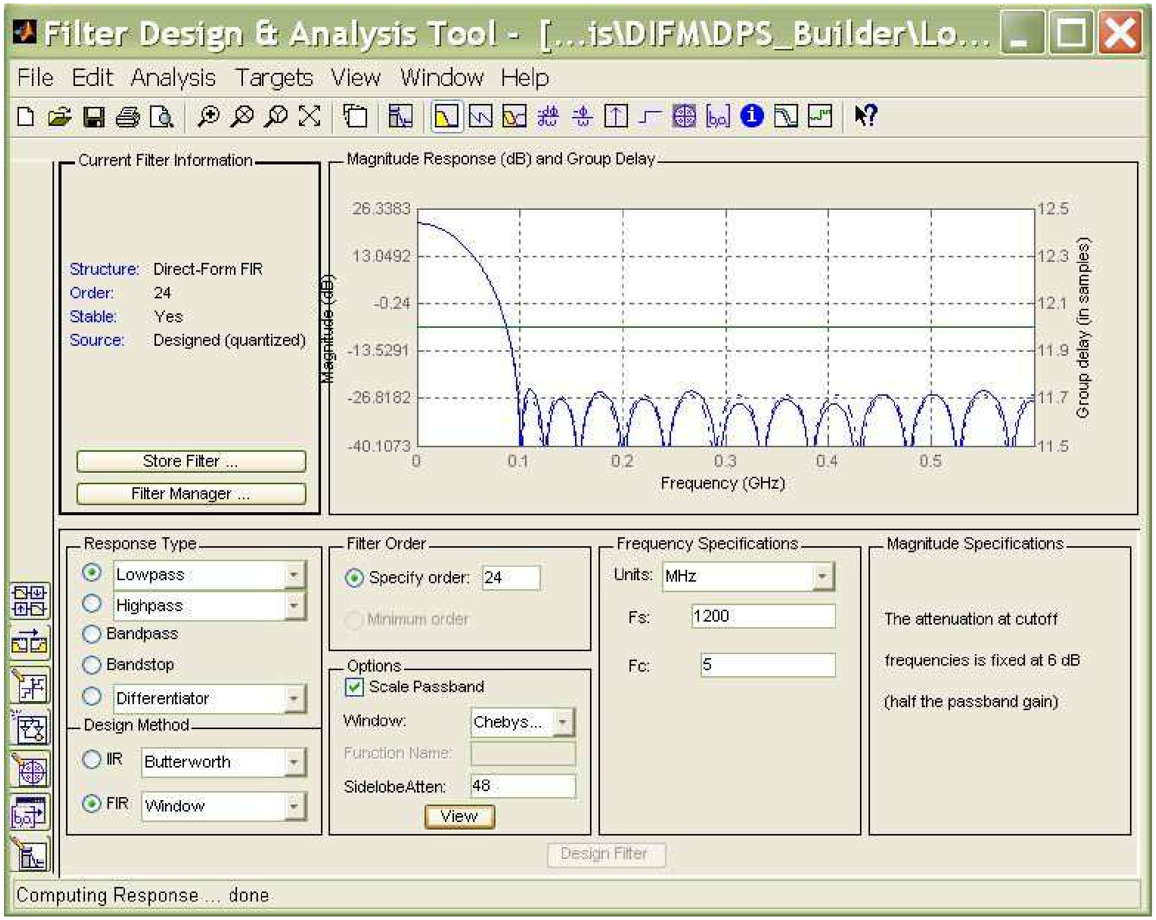
where

$$F_0' = 2F_0 \quad , \quad f_0 \le f_s / 4$$

$$F_0' = 1 - 2F_0 \quad , \quad f_0 > f_s / 4$$

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

$$y_{out}(n) = \frac{2^{N_{out}} - 1}{2\pi} \arccos\left(\frac{y_{filt}(n) D^2}{A_0^2 2^{2N-1} \left| H_{LPF}(0) \right|} \right)$$

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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 demulitplex
    - 75 MSPS 160-bit
- Calculate in a single FPGA clock cycle
  - 15 multiplications
  - 14th order FIR filter
- Possible to artificially extend the bus width

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Amplitude Insensitive DIFM

- Suppose an estimate of the input amplitude was available

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

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

- Technique analogous to DIFM with time delay equal to 0
  - Multiply $\quad y'_{mix}(n)=y_q(n)y_q(n-0)=y_q(n)y_q(n)=\mathrm{y}_\mathrm{q}^2(\mathrm{n})$
  - Low-pass $\quad y'_{filt}(n)=\frac{A_0^2}{D^2}2^{2N-1}\left[\left|H_{LPF}(0)\right|+\left|H_{LPF}(F_0')\right|\cos\left(2\pi F_0'n+\angle H_{LPF}(F_0')\right)\right]+\varepsilon_q''(n)$

Amplitude Insensitive DIFM

- Divide basic DIFM filter output with amplitude estimation

$$y_{div}(n) \approx \cos(2\pi F_0) + \frac{|H_{LPF}(F_0')|}{|H_{LPF}(0)|}\cos(2\pi F_0' n - 2\pi F_0 + \angle H_{LPF}(F_0')) + \varepsilon_q'''(n)$$
$$\approx \cos(2\pi F_0)$$

- Inverse cosine lookup table yield frequency estimation

$$y_{lt}(n) \approx 2\pi F_0 = 2\pi \frac{f_0}{f_s}$$

- Advantages
  - Amplitude estimation exactly aligned with frequency estimation
  - No external calibration or alignment required
  - Time-domain multiplex hardware

Example Implementation

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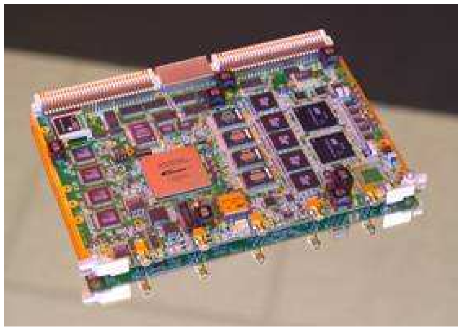
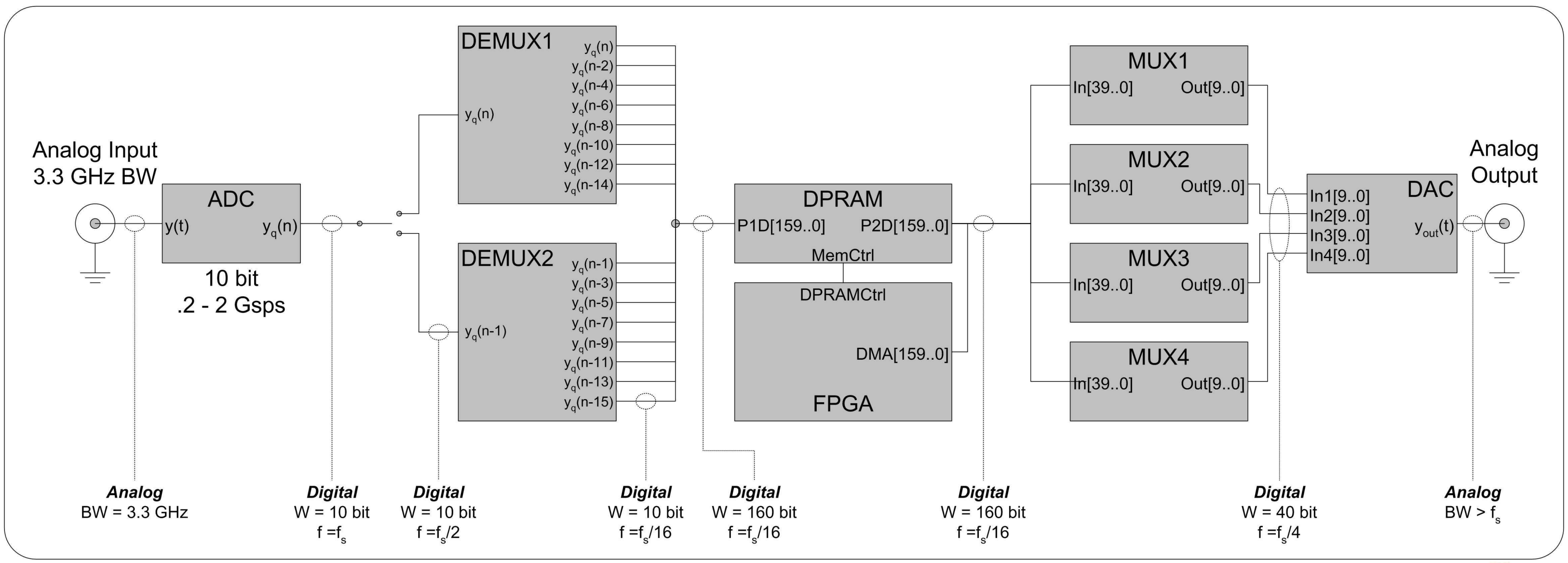
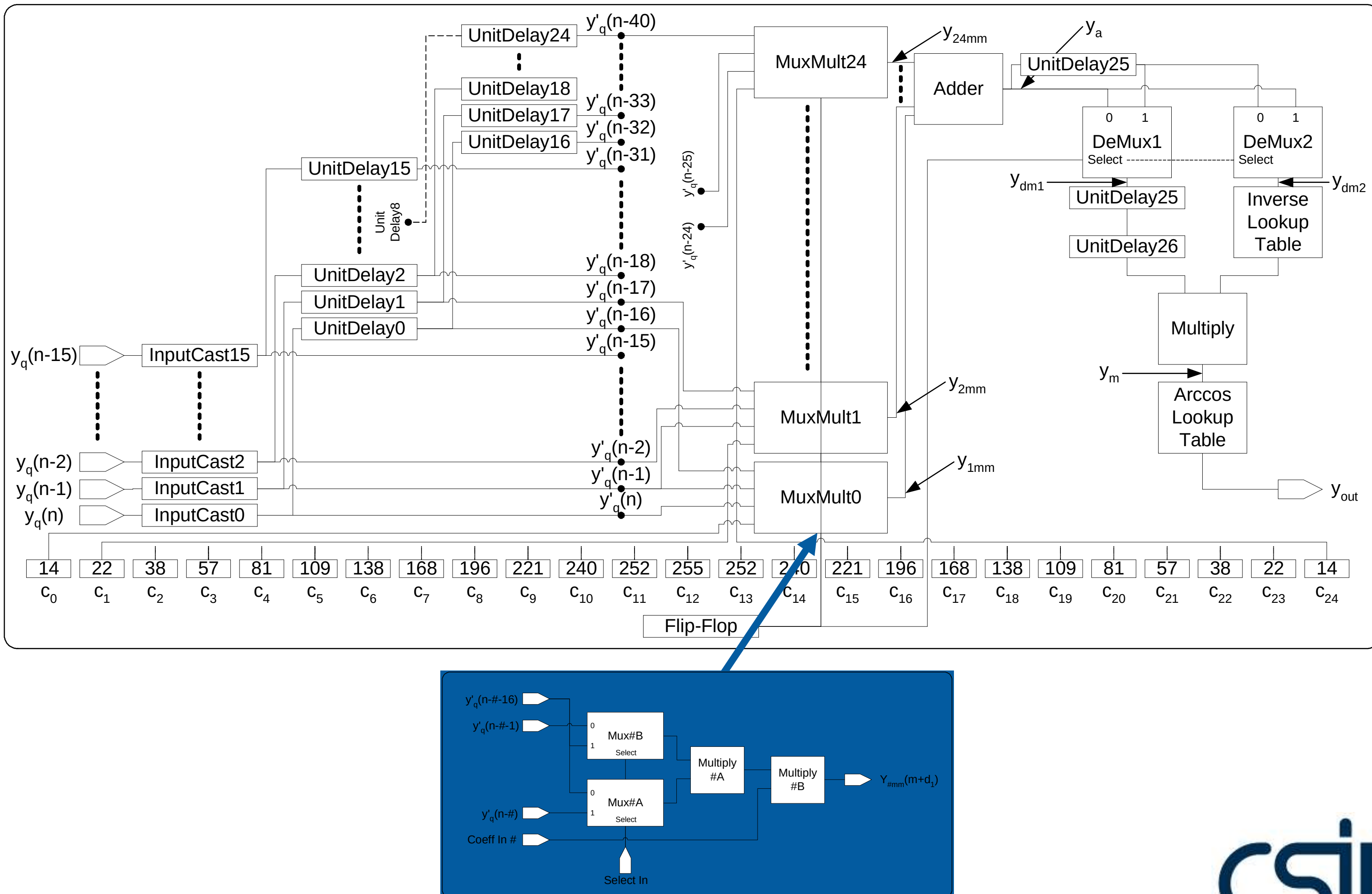
SWIFT500 Digital DRFM Module with Built-In Amplitude Insensitive DIFM



- 1.2 GSPS , 500 MHz IBW
- 16x demultiplexing
- Stratix 1S30 with 96 9x9 multipliers



SWIFT500 Digital DRFM Module with Built-In Amplitude Insensitive DIFM

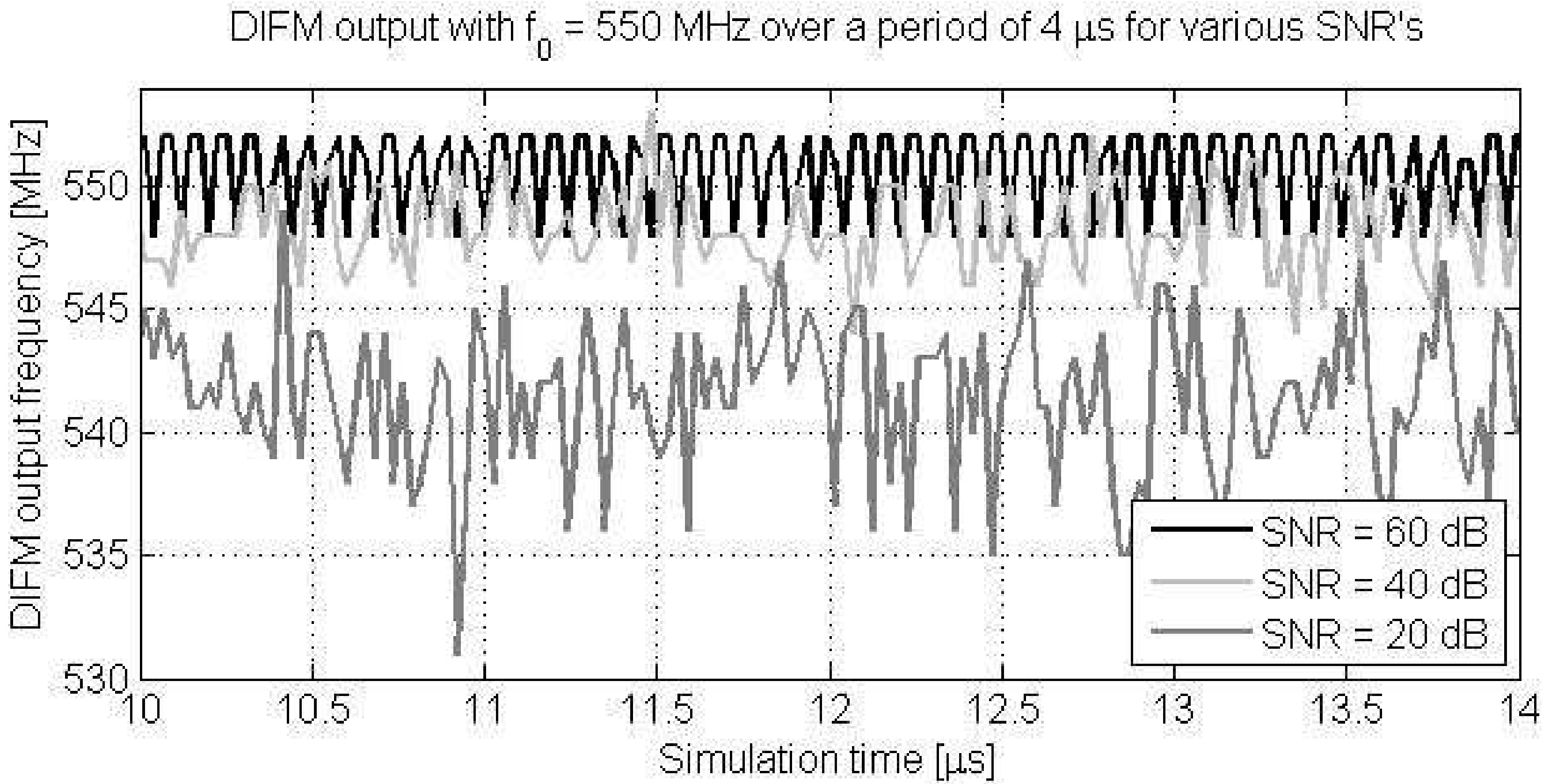


SWIFT500 Digital DRFM Module with Built-In Amplitude Insensitive DIFM

- 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



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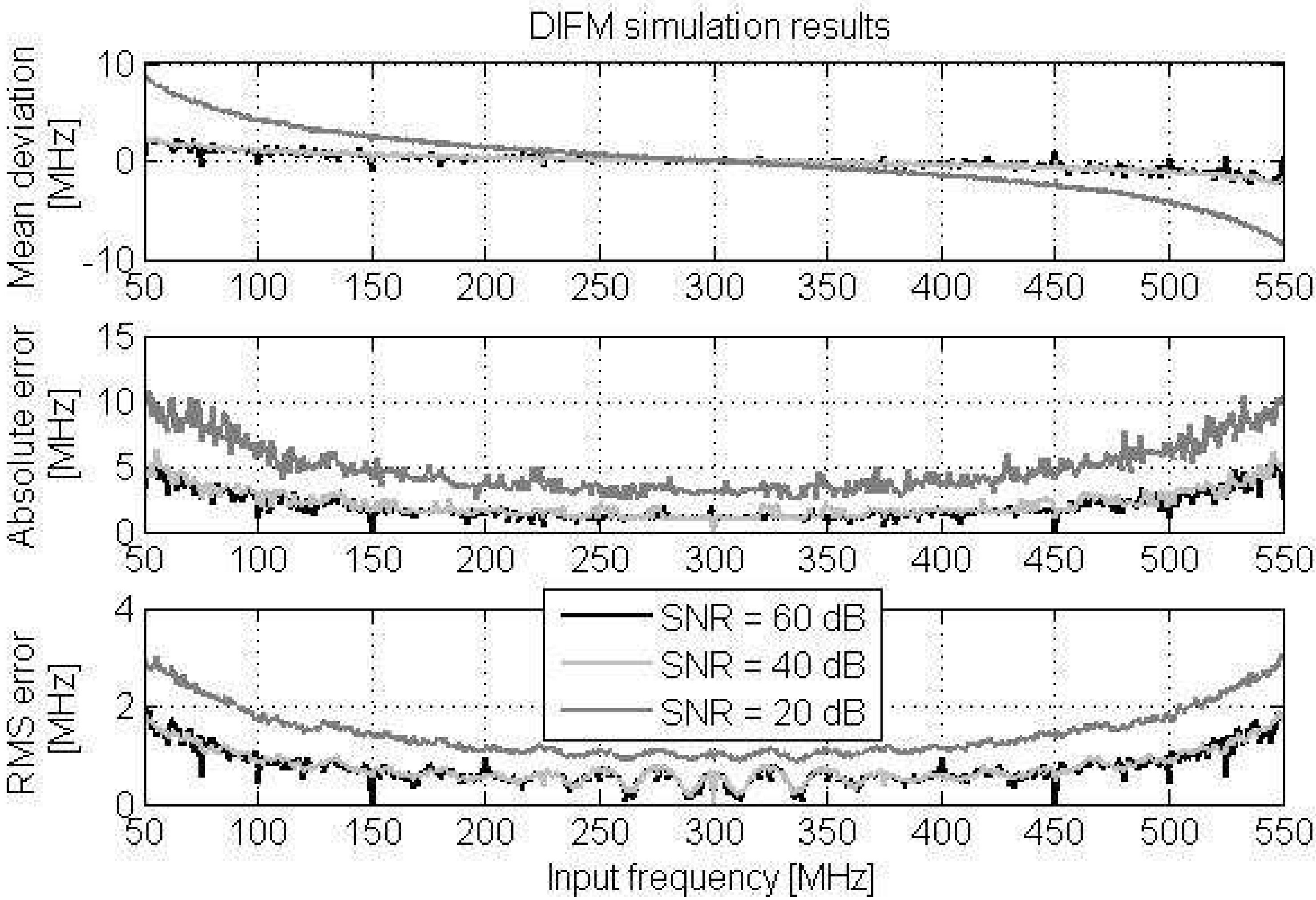
Analysis of DIFM Accuracy

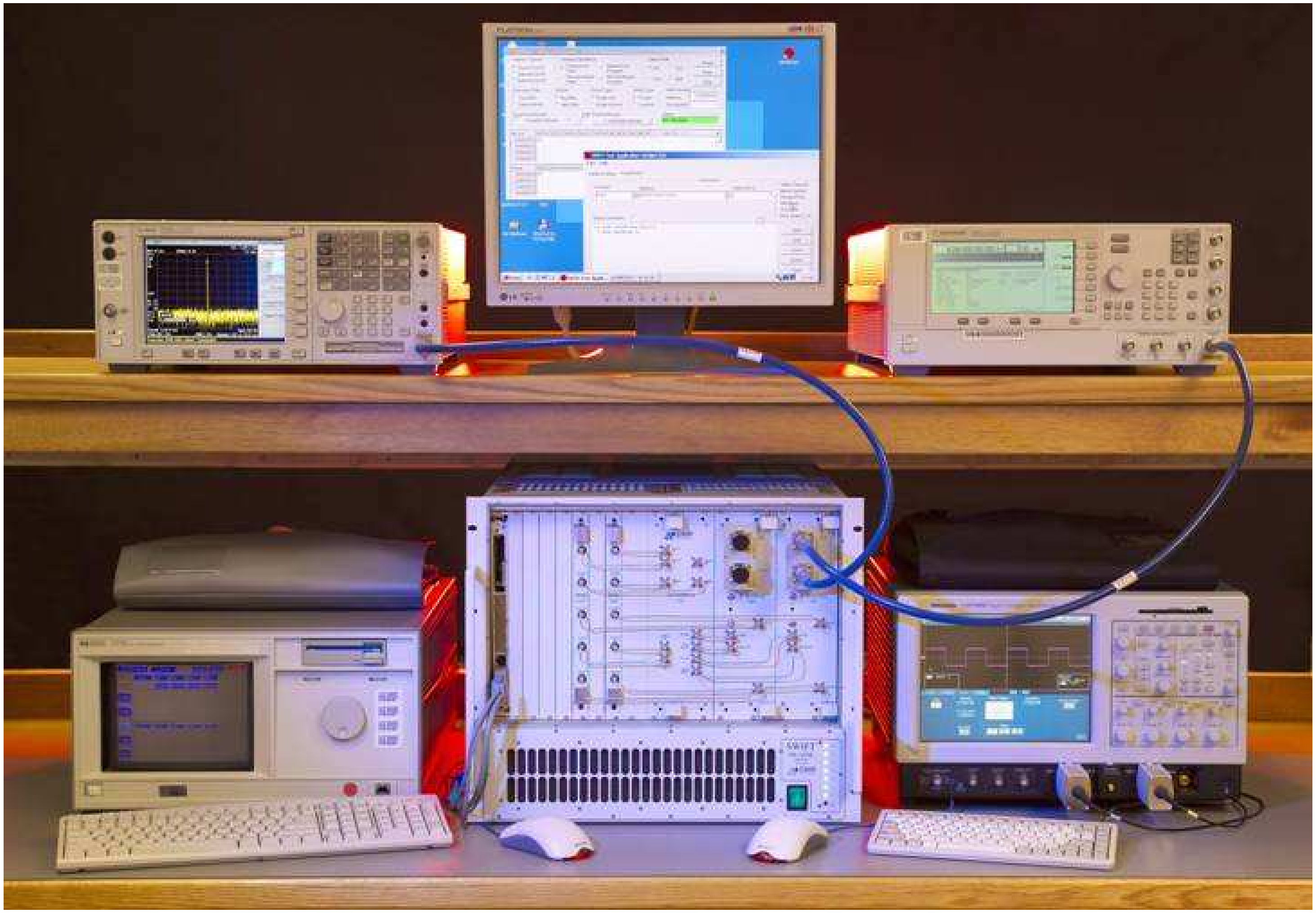


Key Performance Specifications

- 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



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Conclusions

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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