Real-Time Signal Processing and State Estimation for Spaceflight Applications

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Abstract

This thesis presents real-time data processing in spaceflight sensing systems under onboard computational constraints. Field-Programmable Gate Array (FPGA) based architectures are leveraged for high-throughput, low-latency operations while addressing inherent performance degradation due to finite-precision arithmetic.

The first part of this thesis develops a signal processing front-end for interferometric optomechanical sensing. A **digital phase measurement system is conceived to enable high-precision phase readout and tracking** with minimal noise floor. Simulations are presented to analyze system performance while experimental validation demonstrates the precision and reliability of the phase sensing system.

The second part focuses on **optimal state estimation back-end for inertial navigation**. Kalman filter algorithms are reformulated to incorporate finite-precision numerical errors in states, inputs, and measurements. Performance trade-offs with numerical precision are captured to provide insights into the best possible filter accuracy achievable for a given numerical representation. Numerical simulations and experimental results underscore the significance of modeling quantization errors into state estimation pipelines for embedded implementations.

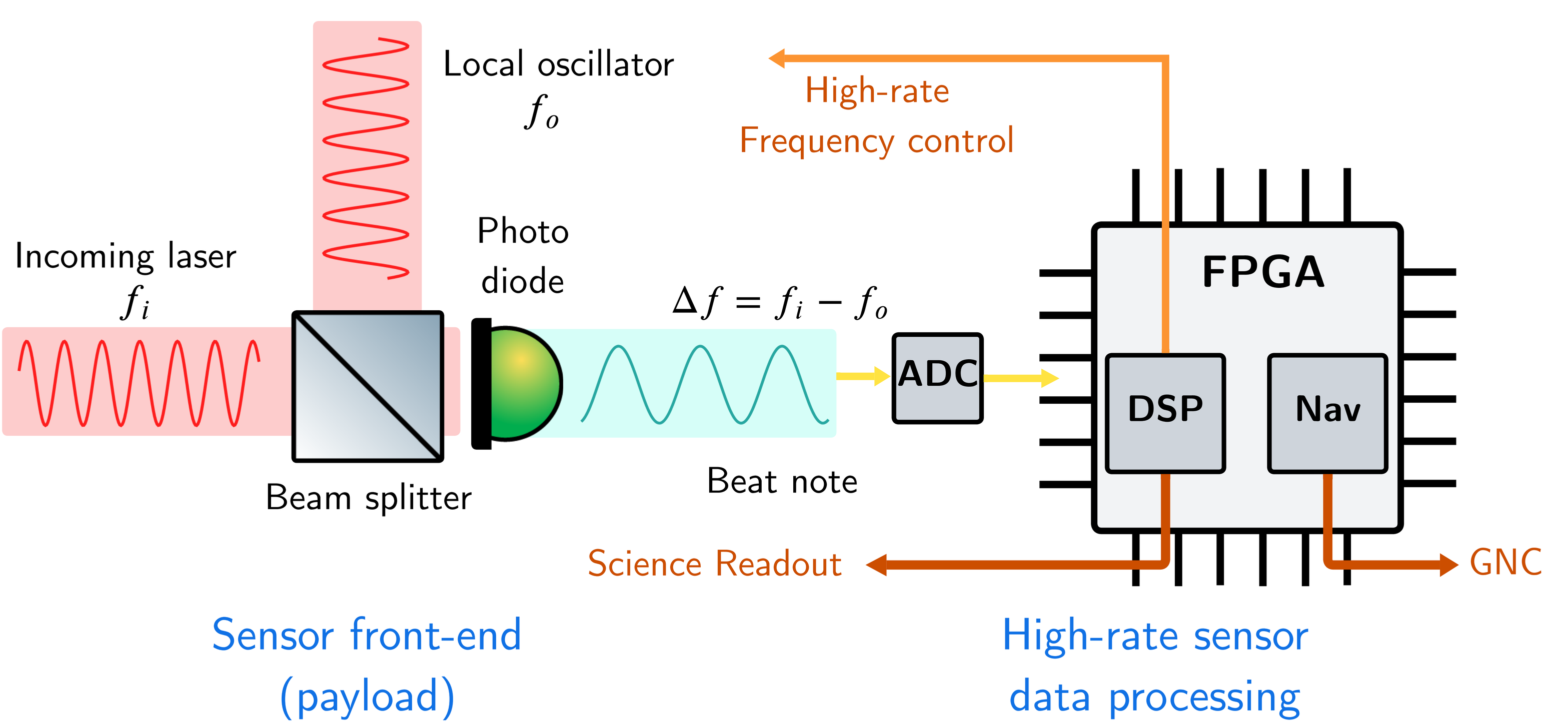

Figure 1. Interferometric sensing systems require high-frequency data processing operations for science readout. Field Programmable Gate Arrays (FPGAs) enable the demanding Digital Signal Processing (DSP) and navigation (Nav) algorithms to be deployed at the edge.

Motivation

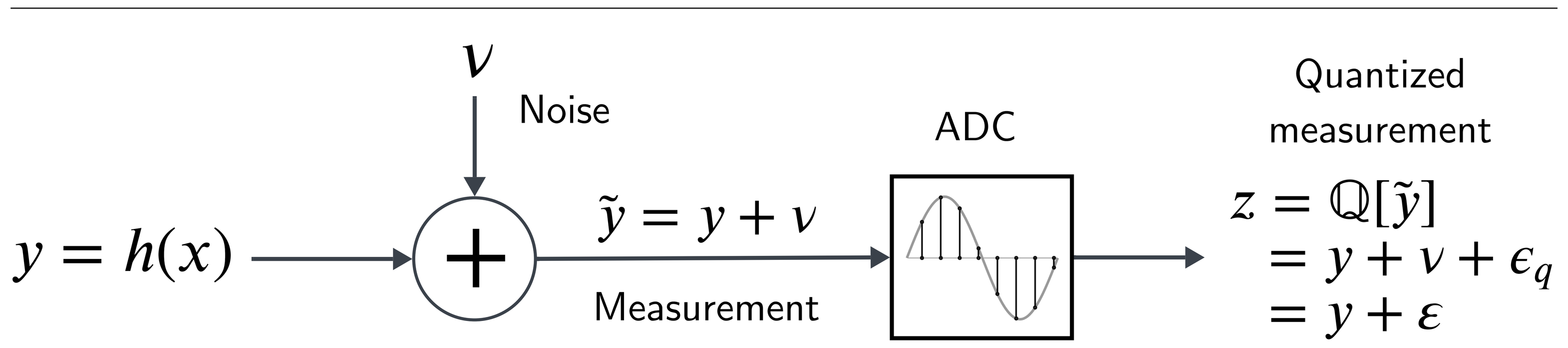

Figure 2. Quantization errors in measurements (states, and inputs) degrade signal-to-noise ratio (SNR) in fixed-point sensing and navigation systems.

Challenge: High-precision optical sensors require low-cost, resource-efficient DSP implementations, but quantization noise from fixed-point arithmetic degrades SNR and navigation accuracy.

Research Questions:

1. Can low-cost fixed-point DSP systems achieve **high-precision optical sensor requirements**?
2. How can quantization-aware algorithms **optimize SNR** in resource-constrained systems?
3. Can navigation filter performance be enhanced by **modeling finite-precision hardware errors**?

Goal: Develop signal processing systems that reduce noise floors while ensuring stable, cost-effective DSP operation.

Key Contributions

This research advances signal processing methods for precision spaceflight applications through integrated system and algorithm design:

- **High-Precision Optical Sensing**: Real-time high-rate DSP system achieving microradians phase measurement precision with fixed-point arithmetic.
- **Quantized Navigation Algorithms**: Novel Kalman filter variants (QDKF, QSRKF) that explicitly model and compensate for finite-precision errors in states, inputs, and measurements.

Impact: Enables low-cost, high-precision sensing and navigation systems for future space missions requiring both computational efficiency and scientific accuracy.

Phase Measurement System

- Intersatellite laser interferometry detects gravitational accelerations by measuring spacecraft motion through ultra-precise optical phase metrology.
- Gravitational forces → test mass displacement → Phase change in beat note.
- Laser Interferometric Space Antenna (LISA) requirements: Phase measurement precision of $6\,\mu\text{rad}/\sqrt{\text{Hz}}$ enabling displacement sensitivity of $\approx 10^{-12}\text{m}/\sqrt{\text{Hz}}$.

Phasemeter System Design

The digital phasemeter system performs real-time phase measurements using an FPGA System-on-Chip (SoC) platform (Fig. 3). High-rate DSP operations execute on the FPGA fabric at the ADC sampling frequency. A multi-stage decimation filter chain, implemented the programmable logic (PL) and the processing system (PS) reduces the data rate to 3.81 Hz for precision science readout.

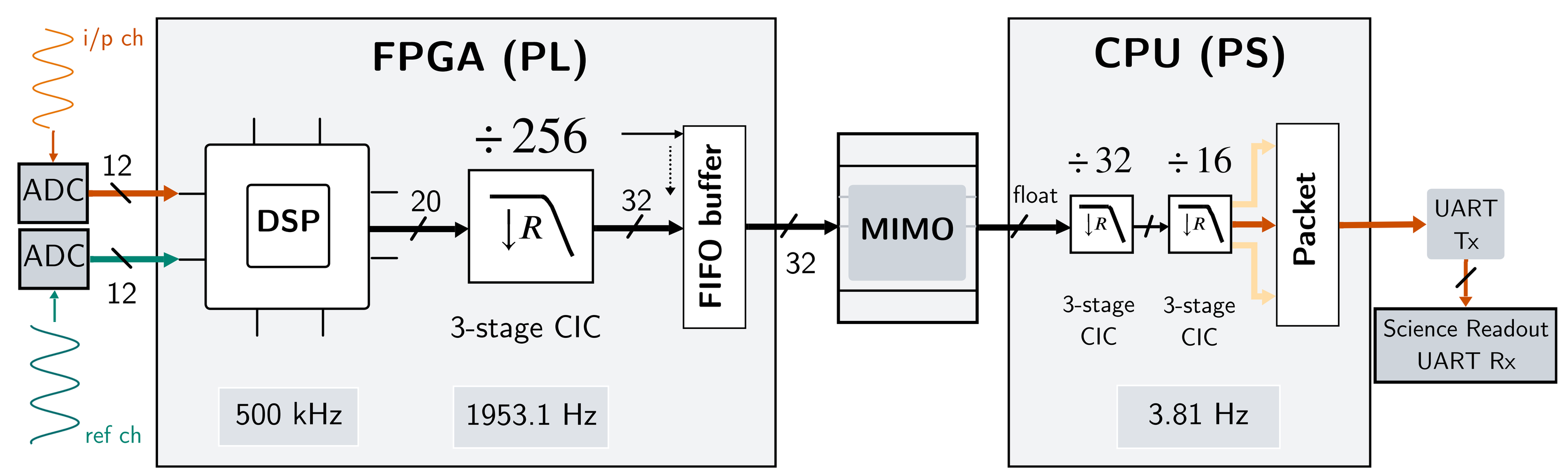

Figure 3. FPGA-SoC for optical phase metrology: The DSP processor (Fig. 4) on the FPGA fabric computes differential phase between input and reference channels for readout.

The FPGA implements dual instances of all-digital phase-locked loop (ADPLL) cores to compute the phase difference between the input and reference channels (Fig. 4). An ADPLL is a closed-loop feedback control system that locks onto the frequency of an incoming signal and provides instantaneous phase values of the input.

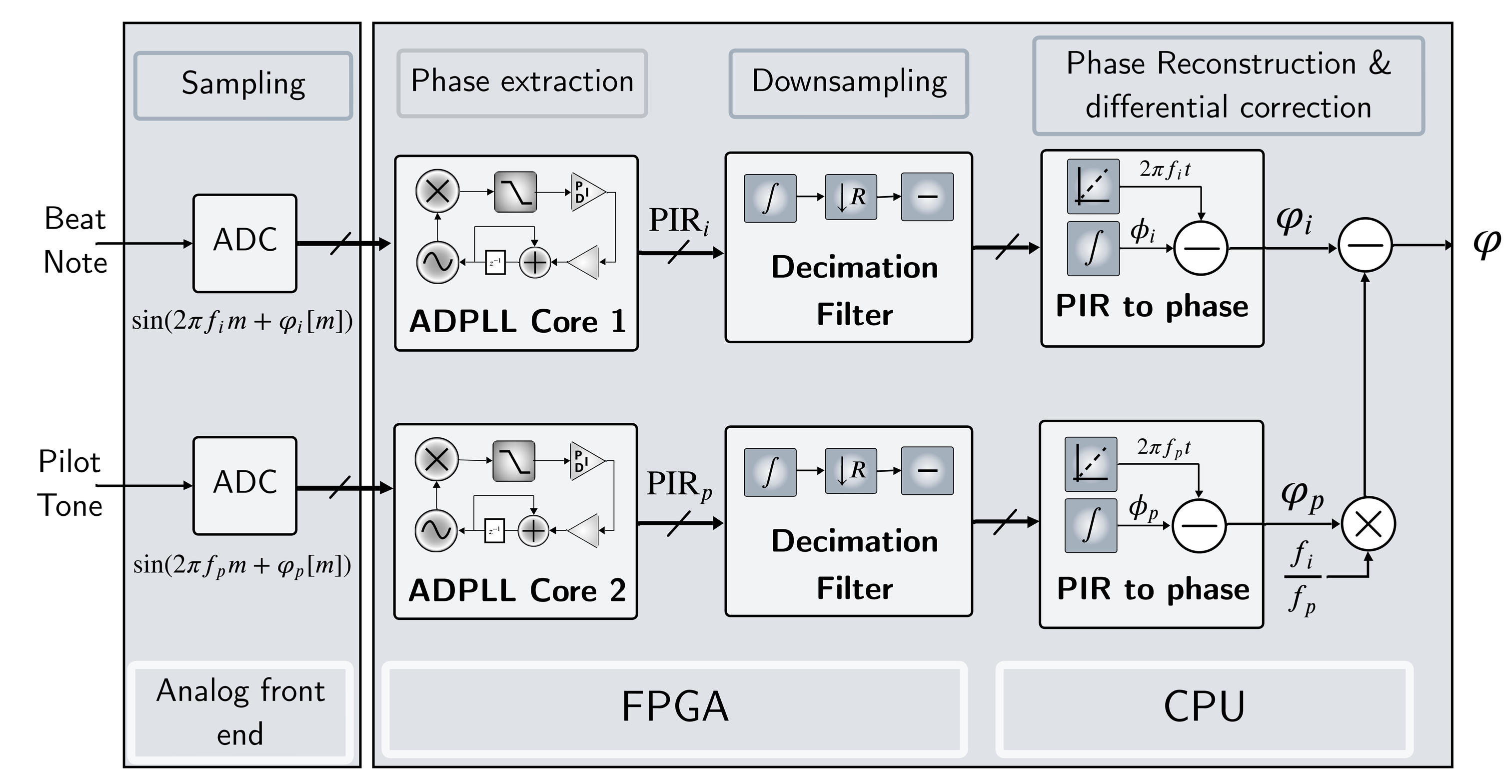

Figure 4. Phase measurement principle: Independent ADPLL cores track input and reference signals. The differential phase measurement $\Delta\varphi = \phi_1 - \phi_2$ provides the phase readout.

Experiments

The phasemeter hardware is verified using Simulink® floating-point simulations. Results from the RF testbench demonstrate that, within the measurement band (0.1 mHz–1 Hz), the phasemeter meets the LISA precision requirements above 1 mHz. NSF: Noise Shaping Function.

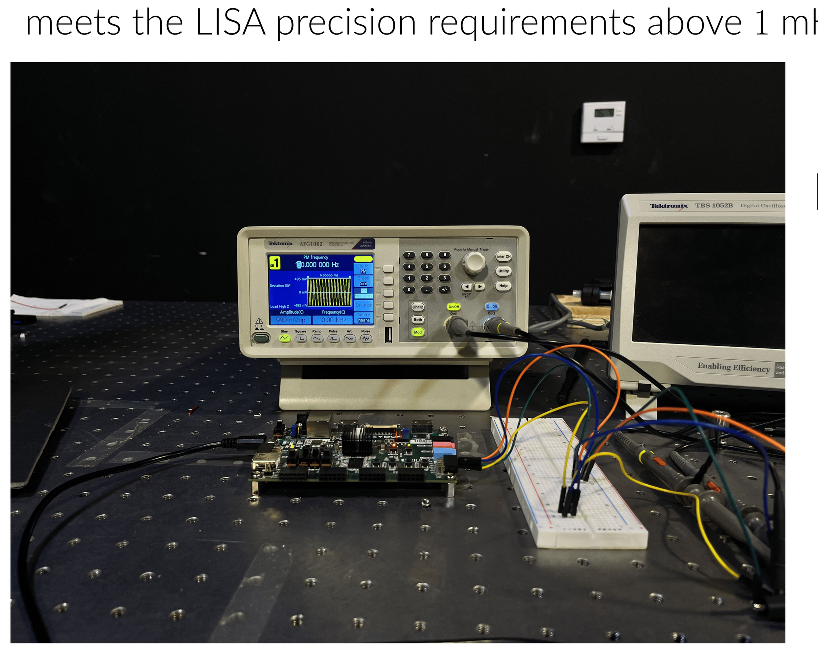

Figure 5. RF Benchtop testing setup for phasemeter hardware demonstration.

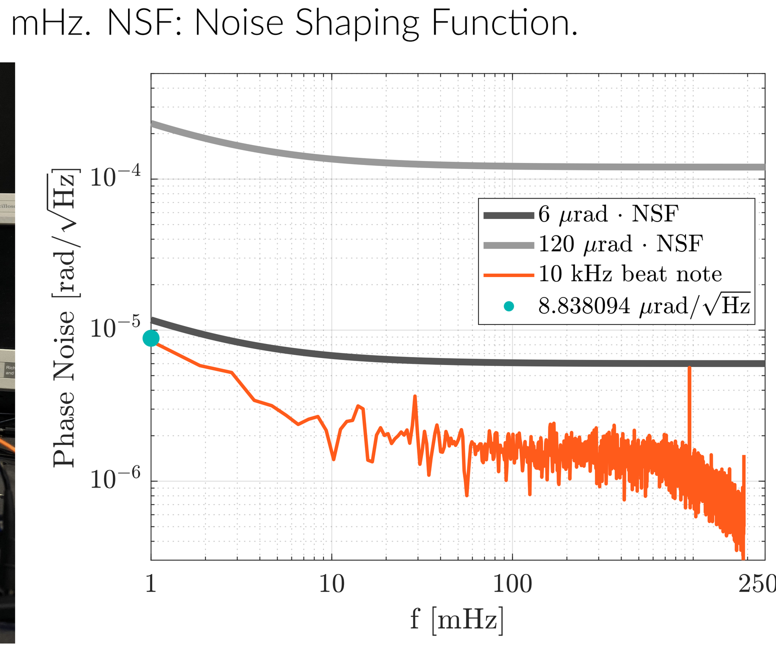

Figure 6. Phase noise performance compared $6\,\mu\text{rad}/\sqrt{\text{Hz}}$ LISA requirement.

Quantized State Estimation

- Optimal quantized filtering methods for finite-precision in states, inputs, and measurements.
  - Quantized minimum variance estimator
  - Quantized Discrete-time Kalman Filter (QDKF)
  - Quantized Square-Root Kalman Filter (QSRKF)
- Application: Estimation of forcing input (acceleration) from optical interferometry.
- Approach:

Sensor dynamics → Reformulated dynamics with quantization noise → Filter description → Simulations and hardware experiments

Sensor Dynamics and State Estimation

- 1 DoF accelerometer sensor dynamics: perturbed harmonic oscillator

$$\ddot{x} + 2\omega\zeta\dot{x} + \omega^2 x = g(t) + b(t) + n_v(t) \qquad \text{(► Mass displacement } x \text{ for acceleration } g\text{)}$$
$$\dot{b}(t) = n_u(t) \qquad \text{(► Stochastic bias: Wiener process)}$$

- Discretized dynamics with quantized states, inputs, and measurements ($\mathbb{Q}[\cdot]$).

$$\mathbf{X}_{k+1} = \mathbf{\Phi}(t_{k+1}, t_k)\mathbb{Q}[\mathbf{X}_k] + \mathbf{\Gamma}(t_{k+1}, t_k)\mathbb{Q}[g_k] + \mathbf{w}_k \qquad \text{(► Quantized states)}$$
$$y_k = [1 \quad 0 \quad 0]\mathbb{Q}[\mathbf{X}_k] + \nu_k \qquad \text{(► Discrete measurements)}$$
$$\mathbb{Q}[y_k] = y_k + \epsilon_{y,k} \qquad \text{(► A/D conversion error: } \epsilon_{y,k}\text{)}$$

- Quantized state estimation:
  - Kalman gain augments round-off error covariances as optimal weighting factors
  - Amplifies covariance updates accommodating additional uncertainties due to finite-precision realization

$$\hat{\hat{\mathbf{X}}}(k) = [\mathbf{H}_k^T \mathbf{P}_{\boldsymbol{\mu\mu}}^{-1} \mathbf{H}_k]^{-1} \mathbf{H}_k^T \mathbf{P}_{\boldsymbol{\mu\mu}}^{-1} (\tilde{\mathbf{y}} - \boldsymbol{\eta}_k \hat{b}) \qquad \text{(► Minimum variance state estimate)}$$
$$\mathbf{P}_{\boldsymbol{\mu\mu}} = \mathbb{E}[\boldsymbol{\mu}\boldsymbol{\mu}^T] = \mathbf{H}_k \mathbf{\Sigma}_{\tilde{\mathbf{X}}} \mathbf{H}_k^T + \boldsymbol{\eta}_k \Sigma_{\hat{b}} \boldsymbol{\eta}_k^T + \mathbf{P}_{\tilde{\boldsymbol{\nu}}\tilde{\boldsymbol{\nu}}} + \mathbf{\Sigma}_{\tilde{\mathbf{y}}} \qquad \text{(► Error covariance)}$$

Simulations and Hardware Results

- Embedding quantization noise into filters → **Reduced errors & improved confidence** (Fig. 7).
- Steady-state covariance analysis: measurement precision v. model uncertainty and estimation errors (Fig. 8) → **Important tool for sensor selection, parameter modeling, and tuning**.

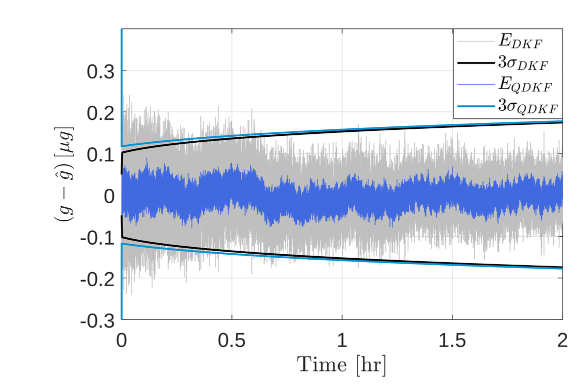

Figure 7. Estimation errors and 3σ bounds from DKF and QDKF with 12-bit measurements.

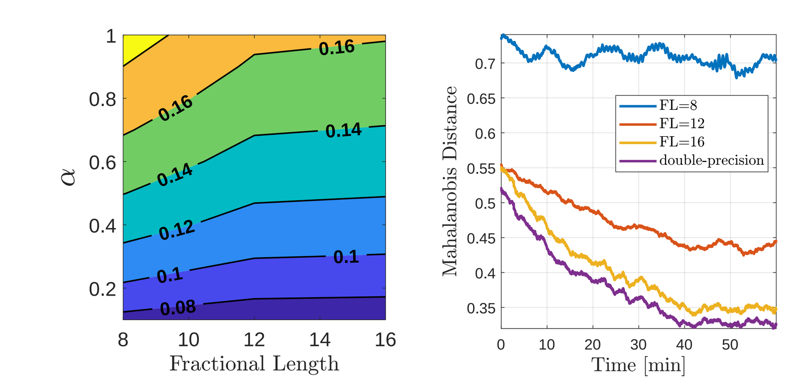

Figure 8. Steady-state: (Left) 1σ contours. (Right) Mahalanobis distance of estimates.

- Hardware implementation and testing → benchmarks estimation accuracy for flight compute.

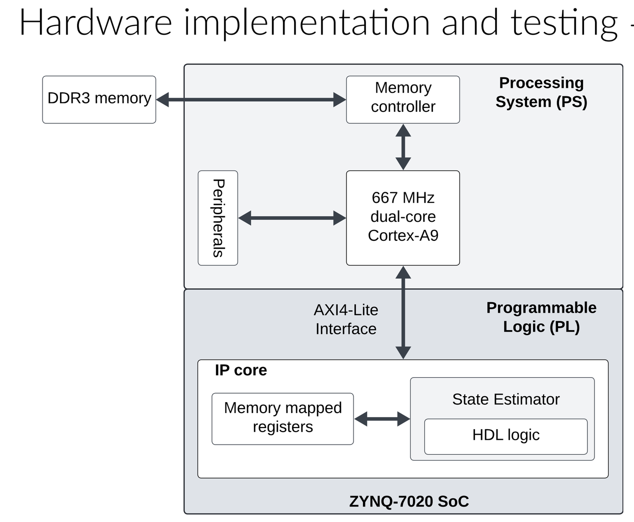

Figure 9. Nav filter operations on FPGA-SoC.

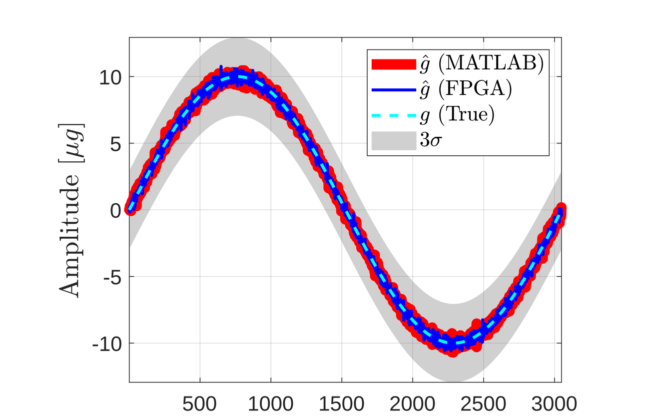

Figure 10. FPGA v. double-precision simulations.

Acknowledgments

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