Long-Time Coherent Integration for High Precision Weak Signal LiDAR on Lunar Rover

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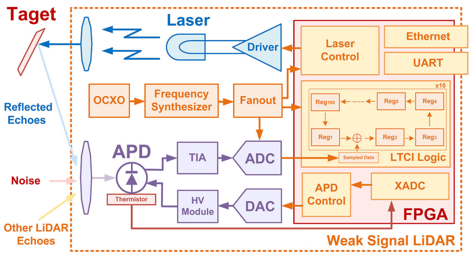
Introduction

- **Lunar Rover Navigation:** LiDAR enables centimeter-level ranging for autonomous navigation and obstacle avoidance on lunar rovers.
- **Harsh Lunar Environment:** Low surface reflectivity, strong solar background radiation, and strict power and thermal constraints make echo detection extremely challenging.
- **Weak-Signal Ranging:** Lunar rover LiDAR must detect low-SNR echoes while maintaining high ranging accuracy and system reliability.
- **Long-Time Coherent Integration:** FPGA-based LTCI enhances weak echo signals and suppresses interference, enabling robust low-energy LiDAR operation.

FPGA-Based Weak-Signal LiDAR Architecture

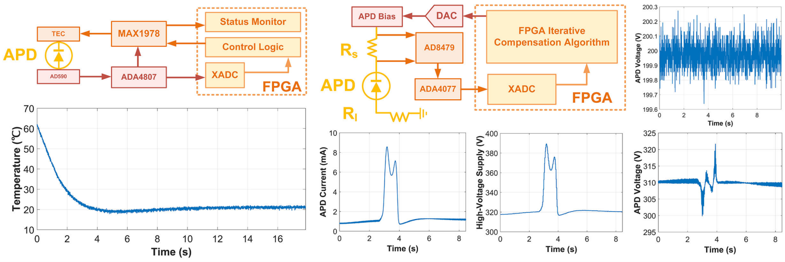
Overall Structure

- Laser Transmitter: The FPGA controls the laser driver to generate periodic laser pulses, which are collimated and transmitted toward the target.
- Echo Receiver: The reflected weak echoes are detected by an APD, converted to voltage by a TIA, and digitized by a high-speed ADC.
- Clock Synchronization: An OCXO-based clock system synchronizes the laser repetition frequency, ADC sampling clock, and FPGA processing clock.
- FPGA Backend: The FPGA performs long-time coherent integration, digital timing extraction, APD temperature & bias control, and data communication.



APD Temperature Control and Bias Compensation

- APD Temperature Control: An AD590 sensor, ADA4807 signal conditioner, MAX1978 TEC driver, and FPGA XADC form a closed-loop temperature control system, stabilizing the APD temperature within ±1 °C.
- Thermal Monitoring and Protection: The FPGA monitors the APD temperature and MAX1978 UT/OT status signals in real time, enabling digital supervision and abnormal-temperature protection.
- DC Photocurrent Monitoring: Background light induces APD DC current, which causes a voltage drop in the bias path and shifts the effective APD operating voltage.
- Bias Compensation: A current-sense resistor, AD8479 high common-mode voltage precision difference amplifier, FPGA XADC, and high-voltage supply form a real-time compensation loop, maintaining the effective APD bias stability.



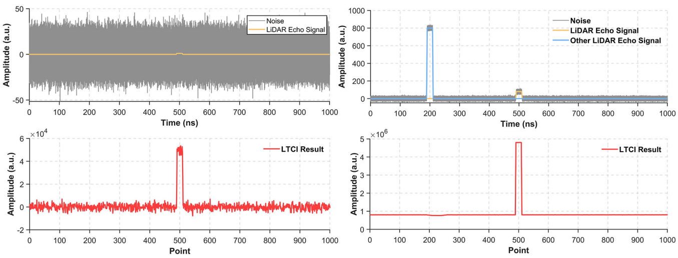
Frequency-Selective Coherent Integration for LiDAR

Principle

- Laser Repetition Frequency Encoding:
  Different LiDAR sources or operating modes are assigned slightly different laser pulse repetition frequencies. In this system, the laser operates around a central repetition frequency of 100 kHz, with selectable frequency offsets such as 419 Hz for frequency-domain separation.
- Synchronized Sampling and Accumulation:
  The ADC sampling clock, laser pulse repetition frequency, and FPGA processing clock are derived from the same precision clock system. For the selected laser repetition frequency, each laser period contains a fixed number of ADC samples, allowing the FPGA to perform period-by-period coherent accumulation.
- Coherent Enhancement of Target Echoes:
  The desired echo is synchronized with the selected laser repetition frequency, so its arrival position remains fixed in each acquisition period. During long-time coherent integration, the target echo is repeatedly aligned and accumulated, leading to significant signal enhancement.
- Suppression of Crosstalk Echoes:
  Crosstalk echoes from other LiDAR sources have different laser pulse repetition frequencies. When they are accumulated using the target frequency window, their apparent positions drift from period to period. Therefore, they cannot be coherently accumulated and are averaged out over long integration time.
- Selective Echo Extraction:
  By matching the coherent accumulation frequency to the desired laser repetition frequency, the FPGA backend selectively extracts the target echo while suppressing off-frequency LiDAR interference, improving robustness without increasing laser transmit power.

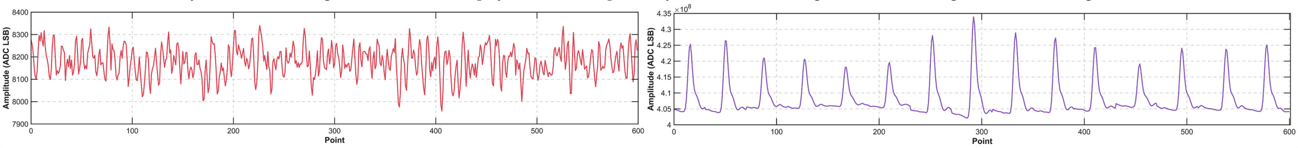
Simulation

- Weak-Signal Extraction:
  With the laser repetition frequency matched to the coherent accumulation frequency, a target echo with a signal-to-noise ratio of 0.1 can be clearly recovered from noise.
- Crosstalk Suppression:
  A 100.419 kHz interference signal with 10× larger amplitude is effectively rejected when the FPGA performs coherent integration synchronized to the 100 kHz target echo.
- Result:
  These simulations verify that the proposed method can extract extremely weak target echoes and suppress strong LiDAR crosstalk through laser-repetition-frequency-selective coherent integration.



Outdoor Weak-Echo Detection Test

- Weak APD echo signals were measured from a target approximately 1 km away. Before coherent integration, the echo is buried in noise and cannot be identified; after coherent integration, clear and repeatable echo waveforms are observed.
- For better visualization, only the echo-containing time windows are displayed. Fifteen independently accumulated echo segments are shown together, while the long no-echo intervals are omitted.



Conclusion

A weak-signal LiDAR system with APD detection and FPGA-based long-time coherent integration was developed for lunar rover ranging. The system enhances low-SNR echoes, suppresses off-frequency crosstalk, and improves APD stability through temperature and bias compensation. Outdoor 1 km measurements verify that clear echo signals can be recovered after coherent integration.

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