

Lidar Approach for Global Atmospheric Column CO₂ Measurements

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Introduction

- Atmospheric CO₂ is a major greenhouse gas and strongly connected to the earth's biosphere.
- The CO₂ concentration has been significantly increased due mainly to anthropogenic processes during the last 150 years. It is estimated that the concentration has increased from about 280 parts per million (ppm) in pre-industrial era to more than 390 ppm at present.
- There is a lack of quantitative knowledge of the global distribution of atmospheric CO₂ and its sinks and sources. Even for the annual global mean atmospheric CO₂ budgets, a large part of carbon amounts within the carbon cycle cannot be accounted for.

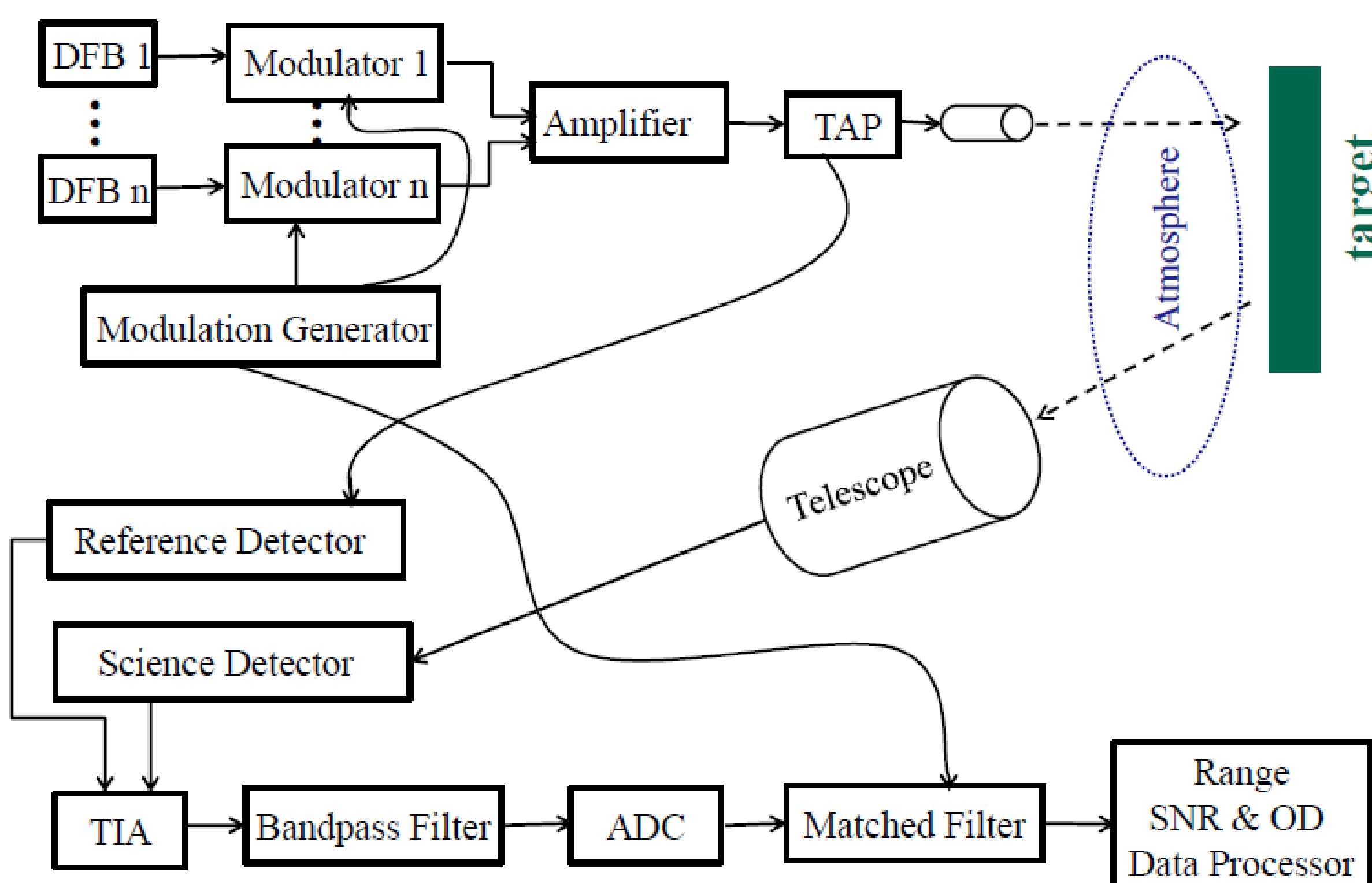
Atmospheric CO₂ Measurements and Modeling

- Recently, the U.S. National Research Council's Decadal Survey (DS) of Earth Science and Applications from Space (2007) identified the need of a future NASA Active Sensing of CO₂ Emissions during Nights, Days, and Seasons (ASCENDS) mission for improving modeling of atmospheric carbon sources and sinks.
- NASA Langley Research Center (LaRC) and Exelis, Inc are jointly assessing the space measurement capability using an Exelis airborne laser absorption spectrometer (LAS) [1][2].
- This LAS is an intensity-modulated continuous-wave (IM-CW) multi-channel instrument operating at 1.57 μm CO₂ absorption wavelengths.
- Modeling and predicting the performance of proposed satellite sensors and their measurements is critical for the development and applications of the ASCENDS mission.
- The objective of this effort is the model development and simulation of LAS instrument and its CO₂ measurements. The focus is on the estimation of the signal-to-noise ratios (SNR) of differential absorption optical depths (τ_d) of CO₂ column.
- The results of this modeling study indicate that the development of space-based LAS system with the given system characteristics meets the high accuracy CO₂ column measurement requirements of the ASCENDS mission.

Modeled System Characteristics

- | | | | |
|-----------------------------------|---|--------------------------|------------------------------------|
| Orbit: | 390km | Laser power: | 42 W |
| Telescope : | 1.5 m diameter | Sampling rate: | 2 MHz |
| TIA-Detector: | APD gain 308 | Excess noise factor | 1.3 |
| | Post processing gain 2.648 kV/mA | Noise spectral density | 3.26 $\mu\text{V}/\text{Hz}^{1/2}$ |
| | Temperature 77 K | Bandwidth (signal/noise) | 6.8/8.1 MHz |
| Signal integration time: | 0.1 S | Modulation scheme: | swept sine |
| Unambiguous range: | 15 km | | |
| Calibration & normalization: | | reference channels | |
| CO ₂ absorption lines: | +3 (Side 1), +10 (Side 2), and +50 (Off) pm of 1.5711 μm line | | |
| Airborne system: | smaller telescope, lower power & at center and $\pm 50\text{pm}$ wavelengths[1] | | |

Diagram of the Simulated Measurement System

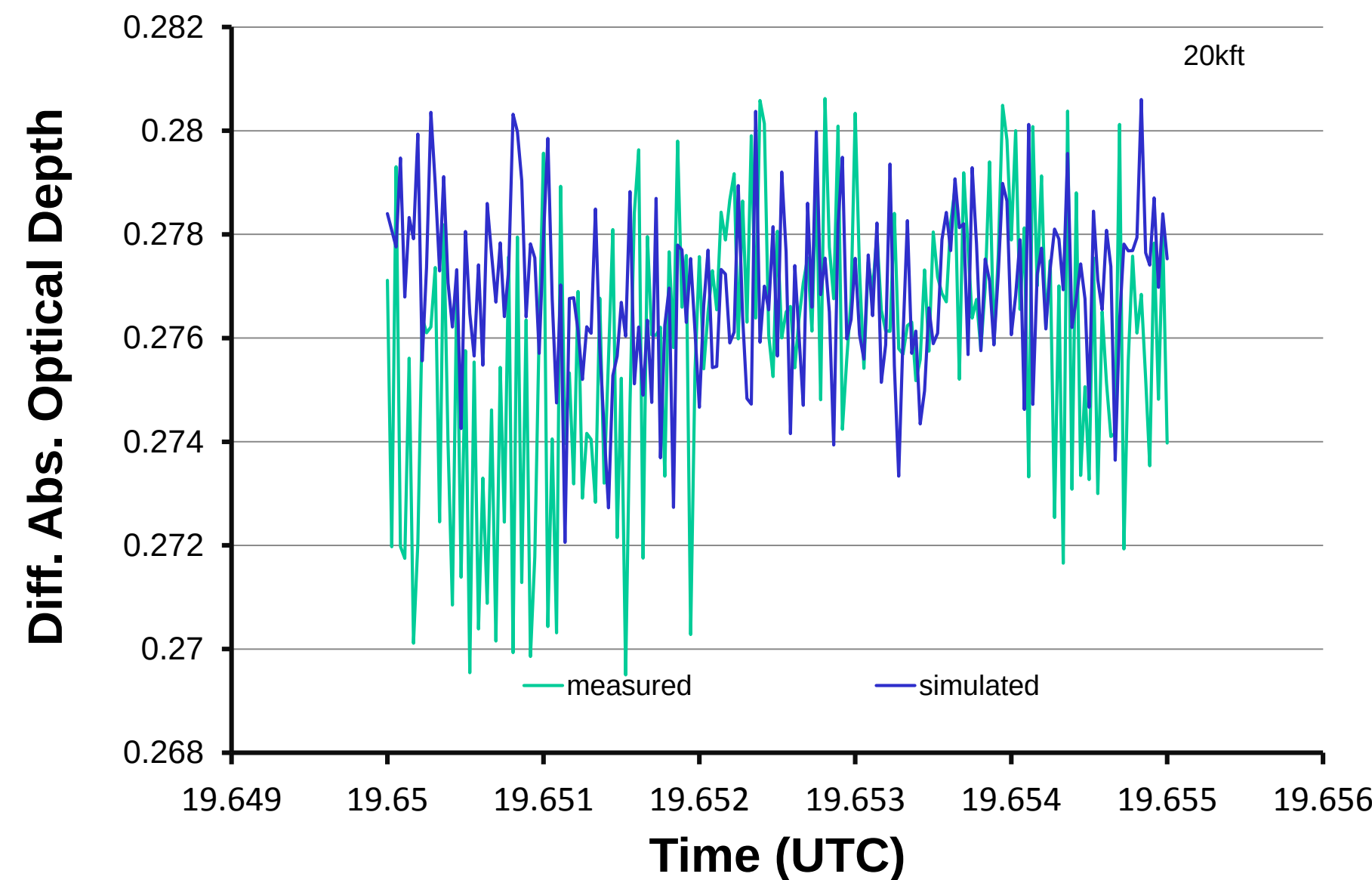


Simulation Model

- Signal power time series
 $P_T(t_i)$, $i = 0, \dots, L$ (lock-in integration time)
- Solar background power
Planck function, Earth-Sun distance, optical filter
- Lidar equation for returned power
 $P_{\text{ret}} = \rho P_T D_{\text{tele}}^2 / (4R^2) T_{\text{atm}} T_{\text{opt}}$ (ρ : albedo)
 P_T : transmitted power; D_{tele} : telescope diameter; R : range
 T_{atm} : atmospheric transmission; T_{opt} : optical throughput
- Signal returns: surface, aerosols, clouds
 - Backscatters
 $P_{\text{ref}} = \sum_0^K \gamma_k P_T (t - 2R_k/c) T_k^2$ $k = 0$ for surface
 T_k : transmission; γ_k : reflectance; R_k : range; c : light speed
 - Thin cloud rejection: ranging-encoded modulation schemes
- Environmental related noises
 - Speckle: variance shrinks with M_s $M_s = M_A * M_I$
numbers of independent cells within receiving aperture (M_A) and during integration period (M_I)
 - Turbulence: log-normal distribution of laser intensity
 - Surface reflection uncertainty
surface albedo: $\rho = \rho_0 + G(0, \sigma_\rho)$
 G : Gaussian distribution,
 ρ_0 & σ_ρ : mean & standard deviation, respectively
- Detector & TIA noises
dark current, solar background & signal power shot, detector & TIA Johnson, inputs (voltage & current)
- Data processing
matched filter, peak finder, range, power ratio, τ_d

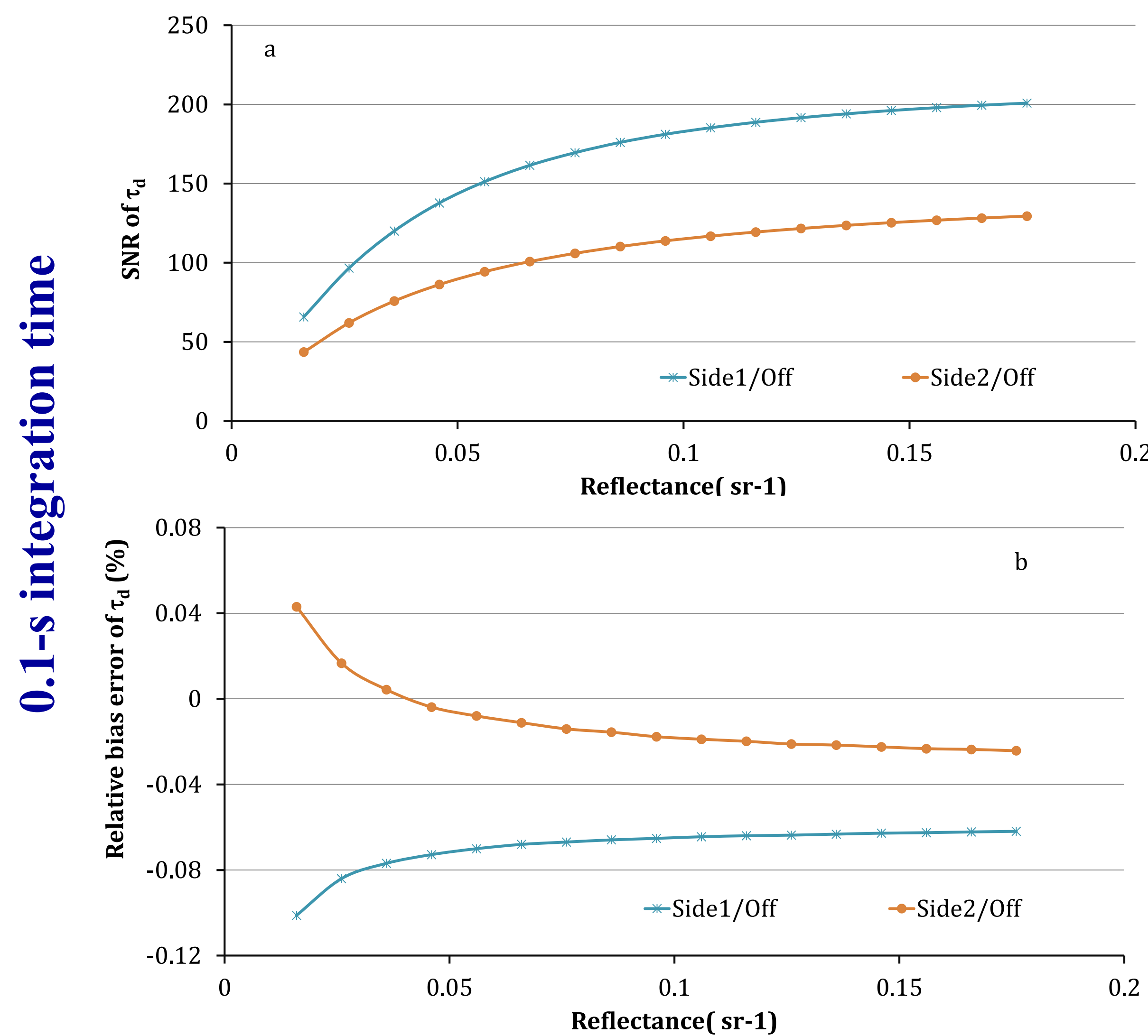
Simulation Results

Airborne Validations

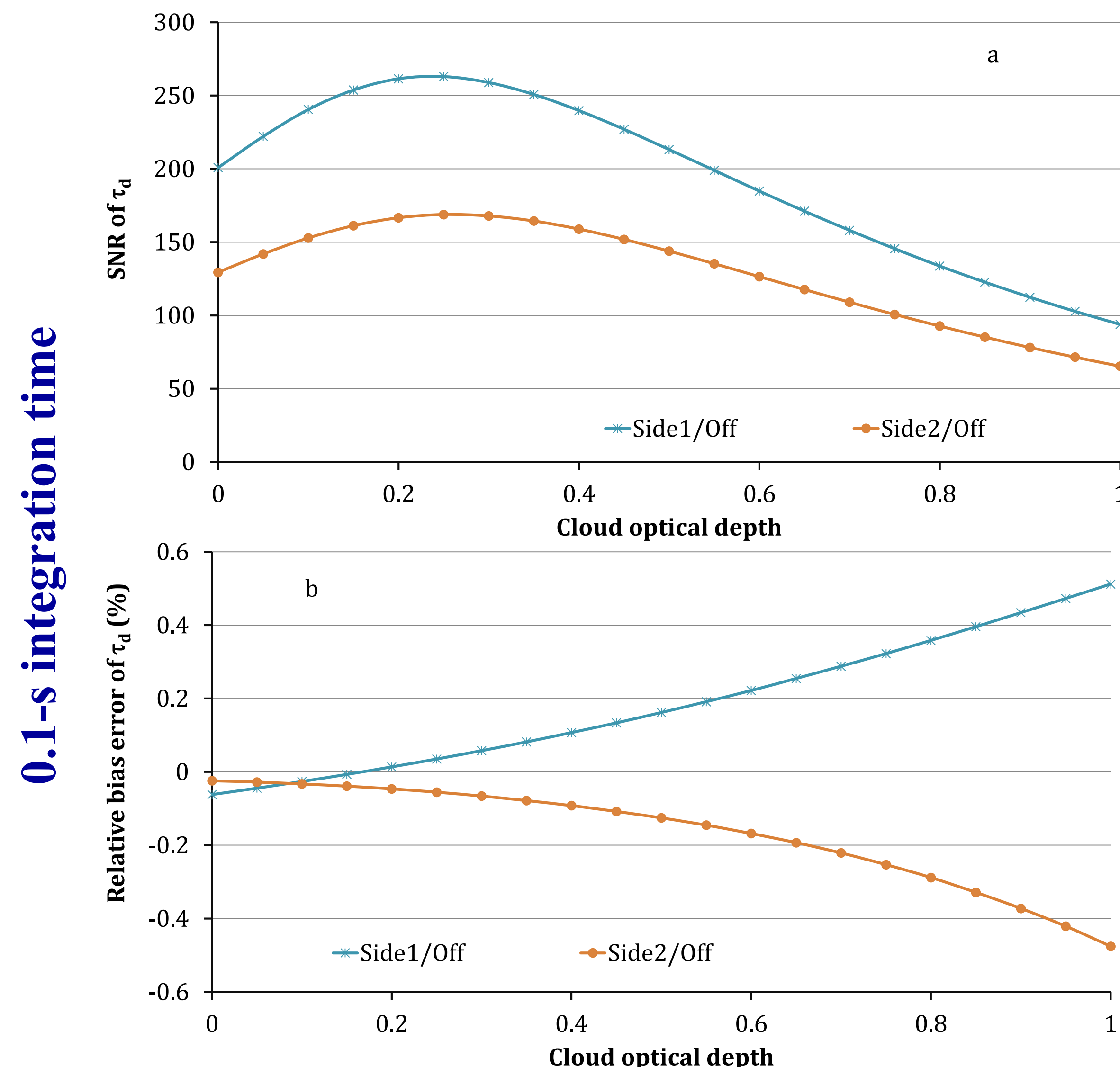


Comparison of the differential absorption optical depths from simulations (blue curve) with those of LAS flight measurements (green curve) from 20 kft altitude on Aug. 8, 2011 over Railroad Valley, NV. The simulations for other altitudes yield similar results. Generally, the differences between model results and observations are about 20%.

Space Measurement Simulations



Simulated results of spaceborne IM-CW LAS instrument for different surface reflectance values. The SNR (a) and relative bias error (b) values are for CO₂ differential absorption optical depths (τ_d) in clear skies.



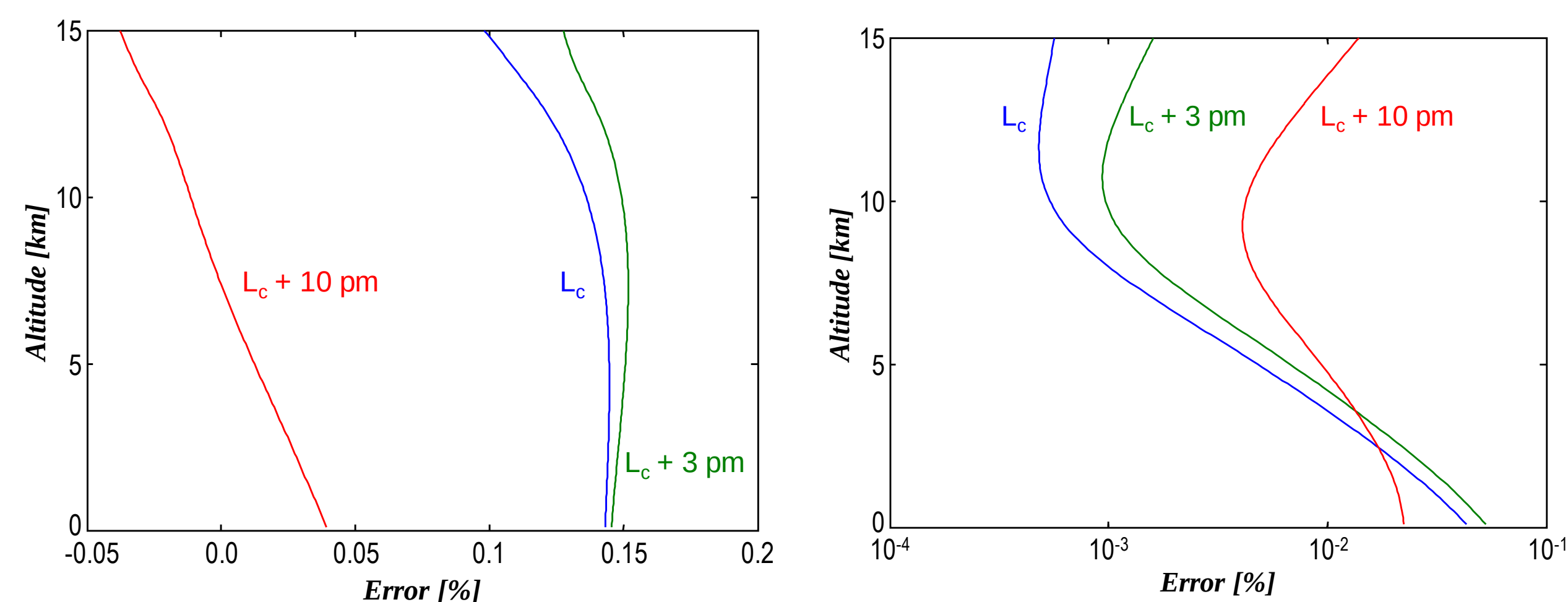
Simulated results for spaceborne instrument under thin cirrus cloud conditions. The SNR (a) and relative bias error (b) values of CO₂ differential absorption optical depth are calculated for the surface with the reflectance of Railroad Valley, NV. Clouds may produce non-negligible bias errors.

Fundamental Mission Requirement

- Measurement
Day, night, season; 10-s temporally or ~ 70 km spatially
- Reference ground site
Railroad Valley, NV; surface reflectance: 0.176 sr⁻¹
- Accuracy
Column CO₂ mixing ratio: 1 ppm or 0.26 %

Estimated Requirement for CO₂ Column Measurements

- Errors in CO₂ mixing ratio measurements
CO₂ column measurements: CO₂ LAS
O₂ column measurements: O₂ LAS (for surface dry air pressure)
Other error sources: temperature, humidity, instrument alignment, etc



Temperature Error
CO₂ optical depth measurement error due to a 0.5°C temperature bias error. It potentially sets the required temperature accuracy.

Relative Humidity Error
CO₂ optical depth measurement error due to a 20% relative humidity bias error from mid-latitude summer profiles.

- Requirement from CO₂ mixing ratio to CO₂ column measurements
 $1 \text{ ppm} / \sqrt{3} = 0.58 \text{ ppm}$ or 0.15 %
- Signal-to-noise ratio requirements for CO₂ column measurements
670 for 10-s or 67 for 0.1-s integration time
- Different surface types and cloudy conditions
rescaled to corresponding requirements
based on their surface reflectance and/or cloud transmission

Results

- High accuracy of simulated space CO₂ column measurements
- Meet the requirements of ASCENDS mission

Conclusions

Development of space sensors for CO₂ column measurements needs full understanding of instrumentation and space observational conditions, which requires sensor simulations and measurement predictions. The model developed from this study is to meet these space mission needs. The model results are validated by various lab and range test measurements and flight observations. Simulations of satellite CO₂ column retrievals indicate that with the current design, the proposed space LAS system meets the measurement requirement for the ASCENDS mission.

Future Work

- Current airborne system analysis and optimization
- Modulation and retrieval algorithm assessment
- Space CO₂ measurement modeling for different conditions
- ASCENDS mission CO₂ error budget analysis

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References

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- [2] Lin, B., S. Ismail, F. Harrison, E. Browell, A. Nehrir, J. Dobler, B. Moore, T. Refaat, and S. Kooi, Modeling of Intensity-Modulated Continuous-Wave Laser Absorption Spectrometer Systems for Atmospheric CO₂ Column Measurements, Applied Optics, 52, 7062-7077, 2013.

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