Published in final edited form as:

Appl Opt. 2017 August 10; 56(23): 6531–6547. doi:10.1364/AO.56.006531.

Feasibility study of a space-based high pulse energy 2- μ m CO₂ IPDA lidar

UPENDRA N. SINGH¹, TAMER F. REFAAT², SYED ISMAIL³, KENNETH J. DAVIS⁴, STEPHAN R. KAWA⁵, ROBERT T. MENZIES⁶, MULUGETA PETROS²

¹NASA Engineering and Safety Center, NASA Langley Research Center, Hampton, Virginia 23681, USA

²NASA Langley Research Center, Hampton, Virginia 23681, USA

³Analytical Services and Materials, Inc., Hampton, Virginia 23666, USA

⁴The Pennsylvania State University, University Park, Pennsylvania 16802, USA

⁵NASA Goddard Space Flight Center, Greenbelt, Maryland 20771, USA

⁶Jet Propulsion Laboratory, Pasadena, California 91109, USA

Abstract

Sustained high-quality column carbon dioxide (CO₂) atmospheric measurements from space are required to improve estimates of regional and continental-scale sources and sinks of CO₂. Modeling of a space-based 2- μ m, high-pulse-energy, triple-pulse, direct-detection Integrated Path Differential Absorption (IPDA) lidar was conducted to demonstrate CO₂ measurement capability and to evaluate random and systematic errors. Parameters based on recent technology developments in the 2- μ m laser and state-of-the-art HgCdTe (MCT) electron-initiated avalanche photodiode (e-APD) detection system were incorporated in this model. Strong absorption features of CO₂ in the 2- μ m region, which allows optimum lower tropospheric and near surface measurements, were used to project simultaneous measurements using two independent altitude-dependent weighting functions with the triple-pulse IPDA. Analysis of measurements over a variety of atmospheric and aerosol models using a variety of Earth's surface target and aerosol loading conditions were conducted. Water vapor (H₂O) influences on CO₂ measurements were assessed, including molecular interference, dry-air estimate and line broadening. Projected performance shows <0.35 ppm precision and <0.3 ppm bias in low-tropospheric weighted measurements related to column CO₂ optical depth for the space-based IPDA using 10 second signal averaging over the Railroad Valley (RRV) reference surface under clear and thin clouds conditions.

1. INTRODUCTION

Quantifying the current global distribution of atmospheric carbon dioxide (CO₂) sources and sinks with sufficient accuracy and spatial resolution to attribute them to specific biogeochemical processes is a critical requirement for improving models of carbon-climate interactions and, thus, reducing large uncertainties in projecting future change [1–2]. The key unknowns are the responses of atmospheric fluxes to and from the ocean and terrestrial

biosphere to changes driven by anthropogenic emissions, i.e., feedbacks. Regional surface sources and sinks can potentially be constrained across the globe using space-based measurements of CO₂ abundance. Many regions critical to the global carbon cycle would benefit from dense, high-accuracy lower-tropospheric CO₂ measurements. These regions include high latitude ecosystems, tropical ecosystems, the southern ocean, managed ecosystems, urban and industrial systems, and coastal systems. Understanding the global carbon cycle remains limited by a lack of comprehensive understanding of processes on regional scales [3]. While the total global carbon budget can be quantified [4], the ability to quantify it at the regional scale [5–7] remains limited to a few high-density field campaigns [8–10], and thus attribution of global trends to regional ecosystem or anthropogenic processes remains out of reach. This limited ability to quantify regional carbon budgets and attribute the global CO₂ budget to specific processes also limits our ability to verify greenhouse gas (GHG) mitigation efforts [11], and to evaluate and improve the carbon cycle components of Earth systems models [12–13]. In addition, fundamental questions regarding the processes that control the atmospheric carbon fraction remain unanswered [14–15].

Measurement of CO₂ from space has rightfully received a great deal of attention due to the promise of enhanced global data density. This requires sustained atmospheric CO₂ observations with high precision and low bias for high accuracy, and spatial and temporal dense representation. The launch of GOSAT [16] and OCO-2 [17] have greatly advanced our understanding of space-based CO₂ measurements. However, coverage over high latitudes particularly during winter periods, nighttime measurements, biases caused by the presence of aerosols and clouds, and influences of complex surfaces, with rapidly changing reflectivity and terrain height, are issues that need to be addressed [18]. The USA 2007 Decadal Survey [19] recognized the importance of space-based active remote sensing of CO₂ and recommended deployment of the Active Sensing of CO₂ Emissions over Nights, Days, and Seasons (ASCENDS) mission to meet CO₂ global observational needs [20]. Progress over the last decade in science and technology development activities for the ASCENDS mission have been well documented [21]. In Europe, the European Space Agency conducted a Candidate Earth Explorer Core Mission study called an Advanced Space Carbon and Climate Observation of Planet Earth (ASCOPE) [22] for the observation of spatial and temporal gradients of CO₂ using lidar active remote sensing to improve the gas flux estimates. In addition, assessment of random and systematic errors for some future space-based integrated path differential absorption (IPDA) lidar concepts have been presented in literature [23–24].

Development, airborne testing, and validations of a high pulse-energy 2- μ m CO₂ IPDA lidar in conjunction with continual progress in laser and detector technologies promise a new avenue for space-based CO₂ active remote sensing [25–29]. Strong CO₂ absorption lines in the 2- μ m region allow optimum lower tropospheric and near surface measurements. The ASCOPE study found that due to optimum lower tropospheric weighting of the 2- μ m IPDA, surface flux uncertainty estimates improve by a factor of two compared to similar measurements conducted by 1.6- μ m systems [22]. Current development of high energy triple-pulse IPDA lidar provides a platform for progressing and testing new laser transmitter, detector, and receiver technologies for future application to space. High pulse energy provides high single-shot signal-to-noise ratio and low sensitivity to background and

detection noise. Triple-pulse laser operation with independent wavelength tuning capability provides simultaneous measurements using two weighting functions [30]. Transmitted laser propagation geometry allows low bias measurements in presence of aerosols and thin clouds; and the high laser pulse repetition rate and narrow laser foot-print allow measurements in regions of broken clouds and over complex terrain. In addition the system will provide simultaneous precise direct ranging, and aerosol and cloud observations.

The concept of space-based, high energy, 2- μm , triple-pulse, direct detection CO_2 IPDA lidar is presented in this paper. Assessment of space-based CO_2 column differential optical depth measurements and random and systematic errors are performed over a variety of atmospheric temperature, pressure, water vapor, and aerosol loading conditions over land and ocean, a variety of target surfaces, and under clear and thin cloud conditions. This type of space-based system will provide coverage over all latitudes and seasons during days and nights. While a combination of uncompensated systematic biases from the atmospheric parameters and instrument offsets could be rather large, knowledge and calibration of these effects is expected to result in the reduction of the systematic errors. An approach for evaluating these systematic errors based upon the uncertainties in their knowledge is presented here. A method to minimize the influence of interference effects of water vapor (H_2O) on CO_2 measurements, and an evaluation of the influence of the broadening of CO_2 absorption lines by H_2O in the measurement of column CO_2 are investigated for the first time. A unique feature of the triple-pulses IPDA is its rapid wavelength tuning and switching that enables simultaneous measurements of column CO_2 and H_2O if required [30]. However, measurement of lower tropospheric weighted column CO_2 is the focus of this paper. Therefore, triple-pulse IPDA capability of providing two independent column CO_2 measurements with different altitude weighting in the troposphere is assessed. This can aid in the assessment of CO_2 exchange and transport in the troposphere. The primary IPDA measurement is the CO_2 column optical depth that is used in combination with column dry-air density to retrieve CO_2 weighted-average column dry-air volume mixing ratio (X_{cd}) needed for science investigations. Errors in the measurement of CO_2 optical depth are assessed in this study. In this paper the science rationale and measurement requirements are presented in Section 2, IPDA technical performance simulations and characteristics of the 2- μm spectral region are presented in Section 3, IPDA technological concepts toward space-based applications and instrument parameters are presented in Section 4, IPDA performance evaluation and random and systematic error analysis are presented in Section 5 and discussions and conclusions are given in Section 6.

2. SCIENCE MEASUREMENT REQUIREMENTS

Quantifying fluxes from specific critical regions of large carbon stocks and/or high activity and high importance to the carbon cycle. These regions are: high latitude ecosystems, tropical ecosystems, the southern ocean, managed ecosystems, urban and industrial systems, and coastal systems. Remote observations of atmospheric CO_2 are limited in many of these regions. This is due to the limited sunlight and high sun angles in high latitudes, and/or due to heavy cloud and aerosol cover. *In situ* data are also limited in many cases due to remote locations. High latitude ecosystems are changing rapidly in a warming climate that could result in the release of large amounts of carbon stored in soils to the atmosphere. Tropical

ecosystems have the most vigorous carbon cycles on the planet and rapid rates of land use change and their sensitivity to changing climate is not well understood. The southern ocean may be the largest global marine carbon sink [31], and is sensitive to changing atmospheric circulation [32]. Finally, the majority of anthropogenic GHG emissions come from urban areas, and only a small number of cities contain any atmospheric data suitable for monitoring their emissions. To meet these science objectives high quality, high precision and accuracy measurements with a space-based active remote sensor, such as IPDA lidar, is required. IPDA lidar will provide the capability to make measurements over all regions from the Arctic to high latitude southern oceans; over all seasons including the winter; over a variety of surface reflectivities including land, vegetation, desert, ocean, and snow; under a variety of aerosol loading conditions, in clear air and in the presence of optically thin clouds. H_2O varies strongly with latitude, altitude, time of day and seasons, and influences CO_2 measurements in several ways. These include interference from H_2O absorption in the 2.0- μm region, broadening of CO_2 absorption linewidths, and its influence in estimating dry-air density for CO_2 mixing ratio. To investigate these objectives, the capability of the 2- μm triple-pulse IPDA is assessed under a variety of global Earth's scenarios as listed in Table 1 [30–35].

High precision range measurements are required to define the column length of CO_2 to the surface and to define terrain and canopy heights. Narrow laser foot prints and high sampling rates are expected to avoid biases arising from complex terrain and to conduct measurements between broken clouds. Column CO_2 measurement errors are classified into two categories—random and systematic errors. Random error is the precision in the measurement of the CO_2 optical depth that results from the noise associated with the detection of the lidar signals. Systematic errors are the residual bias errors in the retrieval of CO_2 optical depth and result from the uncertainty in the knowledge of atmospheric parameters and instrument characteristics. High precision and accuracy in the measurements of X_{cd} are required as specified by the ASCENDS science definition team. A full discussion of X_{cd} retrievals using dry-air density column is presented in the literature [20–21]. The overall CO_2 column differential optical depth measurements and sampling requirements from the space-based IPDA are specified in Table 2. Assuming that dry-air number density are obtained independently, and therefore can be added geometrically to CO_2 optical depth errors; the specifications in Table 2 allow precision and accuracy (bias) errors up to 0.35 ppm each in the knowledge of dry air to meet the science objective of 0.5 ppm random and 0.5 ppm systematic errors in X_{cd} retrievals. Meteorological analyses has demonstrated the capability to provide high precision and accuracy surface pressure estimates globally. Comparison between models and observations indicates that the average root-mean-square (RMS) pressure errors are 0.09 mb and the bias error is about -0.06 mb over regions from the tropics to high latitude [21]. This is a viable approach for getting dry-air number densities globally. The sampling rate of the lidar measurements allows trading between precision and shot averaging. For example, in low reflectivity Polar Regions, shot averaging can be increased significantly to improve the precision required. Observing systems simulation experiments, conducted under both ASCENDS and A-SCOPE programs, demonstrate significant improvements in flux uncertainty estimates using CO_2 measurement from space-based IPDA active remote sensors [20–22].

3. IPDA LIDAR TECHNIQUE FOR CO₂ MEASUREMENT

The pulsed 2- μm IPDA lidar remote sensing technique relies on the hard target lidar equation, in which the received power, P , is given by [30]

$$P(\lambda, R_A, R_G) = \eta_r \cdot \varphi_r \cdot \frac{A_t}{(R_A - R_G)^2} \cdot \frac{E(\lambda)}{t(\lambda)} \cdot \frac{\rho}{\pi} \cdot \exp[-\tau(\lambda, R_A, R_G)] \quad (1)$$

for a nadir pointing airborne platform at a fixed altitude, R_A , with target elevation, R_G , from the Earth's surface, where $(R_A - R_G)$ is the measurement column length. In this equation, η_r is the receiver optical efficiency, φ_r is the overlap function, A_t is the receiver telescope area, E is the transmitted laser energy at the operating wavelength λ , t is the effective width of the return pulse, ρ is the surface reflectivity and τ is the double-path optical depth. For CO₂ sensing, the operating wavelength of the IPDA is tuned over an absorption feature to optimize the atmospheric measurement of the gas. Therefore, the double-path optical depth, τ , will be dominated by CO₂ absorption in addition to absorption by other interfering molecules and aerosols, according to

$$\tau(\lambda, R_A, R_G) = \tau_{cd}(\lambda, R_A, R_G) + \tau_{wv}(\lambda, R_A, R_G) + \tau_a(\lambda, R_A, R_G) \quad (2)$$

where τ_{cd} , τ_{wv} , and τ_a are the double-path differential optical depth of CO₂, H₂O and aerosol respectively. In this analysis, influence of H₂O only is considered since it represents the major interfering atmospheric molecule while interference from other atmospheric molecules, such as ozone (O₃), nitrous oxide (N₂O), and ammonia (NH₃), were neglected due to either weaker absorption strength around the 2- μm wavelength or lower abundance. The CO₂ double-path optical depth can be modeled using the equation

$$\tau_{cd}(\lambda, R_A, R_G) = 2 \cdot \int_{R_A}^{R_G} \sigma_{cd}(\lambda, r) \cdot N_{cd}(r) \cdot dr \quad (3)$$

where σ_{cd} and N_{cd} are the CO₂ absorption cross section and number density, respectively, and r is the range. In this analysis N_{cd} is obtained from the CO₂ dry-air mixing ratio, x_{cd} (in ppm), defined by

$$x_{cd}(r) = 10^6 \cdot N_{cd}(r) / N_{dry}(r), \quad (4)$$

where N_{dry} is the dry-air number density calculated as the difference between the total air number density, N_{air} obtained from temperature, T , and pressure, P_r , using the Ideal Gas Law, and the water vapor number density, N_{wv} , according to

$$N_{dry}(r) = P_r(r) / [k \cdot T(r)] - N_{wv}(r), \quad (5)$$

where k is the Boltzmann's constant.

A. Absorption Spectra and H₂O Interference

The 2- μm wavelength region offers many suitable absorption features for CO₂. The R30 CO₂ line, located at 2050.9670 nm (4875.7487 cm⁻¹), provides an attractive absorption cross section with unique characteristics that include low temperature sensitivity and low interference from H₂O molecules. This is indicated in Fig. 1, which shows CO₂ and H₂O double-path integrated optical depth spectra. The spectra were derived using Eq. (3), which is applicable to H₂O, while considering IPDA operation from space-based platform pointing nadir toward Earth's surface at sea level and operating at a fixed altitude of 400 km (i.e., $R_A = 400\text{km}$ and $R_G = 0$). Absorption line parameters in the neighborhood of R30 line were obtained from the HITRAN 2012 database for cross section calculations [36]. The absorption cross sections were evaluated assuming a Voigt line profile, with 5550 CO₂ lines spanning the wavelength range from 2044.2207 to 2059.5682 nm. Similarly for H₂O, 1816 lines were included over the wavelength range 2022.2090 to 2080.3638 nm [28, 30]. Optical depth calculations were repeated for different atmospheric models considered in this study as listed in Table 1. Fig. 2 compares the atmospheric temperature, T , pressure, P , and water vapor dry-air mixing ratio, x_{wv} , vertical profiles for these models [33]. The figure also presents carbon dioxide dry-air mixing ratio, x_{cd} , vertical profile for USA standard model, which was scaled to a current typical surface value of 400 ppm. The carbon dioxide profile of the USA model was assumed to be the same for all scenarios. All profiles are defined for up to 120 km altitude, after which atmospheric effects are negligible. Overlap between CO₂ optical depth spectra for different atmospheric models, as shown in Fig. 1, is the result of temperature insensitivity in this 2- μm wavelength region and the assumed fixed x_{cd} profile.

The presence of H₂O influences CO₂ measurements in several ways. First, the interference of H₂O in the measurement of CO₂, as shown in Fig. 1. Uncertainty in the knowledge of H₂O can result in error in the measurement of CO₂. This interference effect is minimized by operating the IPDA on the longer wavelength side of the R30 line. Second, the presence of H₂O causes significant broadening of CO₂ lines [34], which depends upon the amount of H₂O in the atmosphere. Third, according to Eq. (4) and (5), knowledge of the amount of H₂O is required for dry-air CO₂ mixing ratio calculations. These effects directly influence the measurement of CO₂ optical depth by the IPDA and are therefore included in the error estimates of the CO₂ optical depths. It should be noted that the third influence will further affect X_{cd} retrieval through weighting function definition, which is not part of this IPDA error budget.

B. Dry-Air Weighted-Average Column CO₂ Mixing Ratio

In the IPDA technique, at least two laser pulses are transmitted through the atmosphere to monitor CO₂. The wavelengths of these pulses are precisely tuned and locked to relatively strong and weak absorptions by the gas, namely on-line, λ_{on} , and off-line, λ_{off} , respectively. Lidar signals reflected off the Earth's surface and atmosphere are recorded using the IPDA lidar receiver and data acquisition system. Ground return signals can be represented by repeating Eq. (1) and (2) for both wavelengths, and are used in the calculation of CO₂ double-path differential optical, $\Delta\tau_{cd}$, according to

$$\Delta\tau_{cd}(\lambda_{on}, \lambda_{off}) = \tau(\lambda_{on}, R_A, R_G) - \tau(\lambda_{off}, R_A, R_G) = \ln \left[\frac{P(\lambda_{off}) \cdot t(\lambda_{off}) / E(\lambda_{off})}{P(\lambda_{on}) \cdot t(\lambda_{on}) / E(\lambda_{on})} \right] \quad (6)$$

assuming H₂O optical depths are negligible and aerosols' optical depths cancel out due to the relatively small on- and off-line wavelength separation in the differential measurement [30]. Similarly, repeating Eq. (3) twice and substituting N_{cd} with Eq. (4), $\Delta\tau_{cd}$ can be modeled by

$$\Delta\tau_{cd}(\lambda_{on}, \lambda_{off}) = 2 \times 10^{-6} \cdot \int_{R_A}^{R_G} \Delta\sigma_{cd}(\lambda_{on}, \lambda_{off}, r) \cdot N_{dry}(r) \cdot x_{cd}(r) \cdot dr \quad (7)$$

where σ_{cd} is the CO₂ differential cross section for the λ_{on} and λ_{off} wavelengths. Unlike H₂O, CO₂ vertical distribution can be approximated as a well-mixed atmospheric gas. Therefore, Eq. (4) is approximated to a constant value with respect to range, defined as the CO₂ weighted-average column dry-air volume mixing ratio, X_{cd} . In such case, Eq. (7) can be reduced to

$$\Delta\tau_{cd}(\lambda_{on}, \lambda_{off}) \approx 2 \times 10^{-6} \cdot X_{cd} \cdot \int_{R_A}^{R_G} \Delta\sigma_{cd}(\lambda_{on}, \lambda_{off}, r) \cdot N_{dry}(r) \cdot dr \quad (8)$$

Equation (8) implies the simplicity of the IPDA technique, where X_{cd} can be directly obtained as the ratio of the measured CO₂ differential optical depth to the integrated CO₂ range-based weighting function, W_{cd} in the form

$$X_{cd} = \frac{\Delta\tau_{cd}(\lambda_{on}, \lambda_{off})}{2 \times 10^{-6} \cdot \int_{R_A}^{R_G} W_{cd}(\lambda_{on}, \lambda_{off}, r) \cdot dr} \quad (9)$$

where

$$W_{cd}(\lambda_{on}, \lambda_{off}, r) = \Delta\sigma_{cd}(\lambda_{on}, \lambda_{off}, r) \cdot N_{dry}(r) \quad (10)$$

is independent of the IPDA lidar measurements and obtained through supplementary spectral analysis and meteorological data.

Although X_{cd} is generally independent of altitude, since it represents the average content of CO₂ within a column, it has wavelength dependence, as indicated in Eq. (9). This wavelength dependence defines the weighting of the average column content, which can be varied through $\Delta\tau_{cd}$, in Eq. (10), by tuning the on-line wavelength [30]. This wavelength dependence is presented in Fig. 3 for three different on-line wavelengths, λ_T , λ_B and λ_S , as marked in Fig. 1. These wavelengths were selected to produce three different weighting functions optimized for CO₂ measurements in the lower troposphere, boundary layer and near-surface, respectively. In this analysis, the offline wavelength was fixed at the nearest minimum of the CO₂ optical depth to the line center, as indicated in Fig. 1. Table 3 lists the simulated space-based CO₂ double-path differential optical depths at the selected on-line

wavelengths for the different atmospheric models considered in this study. Results for H₂O are also included for comparison.

4. PULSED 2- μ m LIDAR TECHNOLOGY DEVELOPMENT

Recently, an airborne 2- μ m double-pulse IPDA lidar was successfully demonstrated and validated at NASA Langley Research Center (LaRC) for atmospheric CO₂ measurement. With 10-s averaging, a CO₂ differential optical depth measurement of 1.0054 ± 0.0103 was retrieved from a 6-km altitude over low reflectivity ocean surface. As compared to the CO₂ weighted-average column dry-air volume mixing ratio of 404.08 ppm, derived from *in-situ* air sampling, the IPDA measurements resulted in a value of 405.22 ± 4.15 ppm with 1.02% uncertainty and 0.28% bias [28]. Ranging, using this IPDA, resulted in measurement uncertainty less than 3 m. Currently, an updated version of this instrument is under development that operates in a triple-pulse mode [30]. The triple-pulse transmitter can produce two on-lines and one common off-line that are selected to enable two pairs of simultaneous CO₂ measurements with different weighting functions. The development of this instrument enables the IPDA lidar demonstrations applicable for future space-based missions [26]. Thus, the projected space-based 2- μ m CO₂ IPDA lidar is based on this current airborne triple-pulse IPDA development. Key state-of-the-art laser and detector technologies are incorporated in this instrument. The projected 2- μ m IPDA lidar parameters for the space-based system, and environmental parameters are listed in Table 4.

A. IPDA Lidar 2- μ m Transmitter

The 2- μ m triple-pulse laser transmitter is the key component for this IPDA lidar system. The performance of this transmitter is critical for CO₂ measurement sensitivity, accuracy, and range. A unique feature of this laser is that it produces three successive Q-switched pulses using a single pump pulse. Therefore, the 50 Hz pump pulse repetition rate, reported in Table 4, results effectively in 150 Hz single pulse generation. Developed at NASA LaRC, this laser transmitter is based on Ho:Tm:YLF crystal technology [26]. The benefit of generation of multiple pulses is facilitated by the co-doping of thulium (Tm) and Holmium (Ho) in YLF. A 792 nm pump laser excites the Tm, which pumps the Ho. The Tm long lifetime results in Ho repopulation after every Q-switch pulse. Thus, the energies for the second and third pulse are extracted by simply reopening the Q-switch. It has been shown that the energy ratio of these pulses, listed in Table 4, can be adjusted by controlling the Q-switch timing with respect to the pump pulse [26]. With this configuration, an additional 40% energy, which otherwise would have been dissipated, is converted into useful laser output. This results in increasing the overall efficiency by the same amount compared to single- and double-pulsing.

The pulses produced by Q-switching are seeded at three different wavelengths. For the last two decades, NASA LaRC has been developing capabilities for 2- μ m laser wavelength control through enhanced seeding, locking and narrowing the frequencies for wind and CO₂ active remote sensing applications [26]. The updated triple-pulse wavelength control uses a single laser and provides three seed outputs, the frequency of which can be tuned independently to any frequency within 35 GHz of both sides of the CO₂ R30 line center

using offset locking. The three seed outputs are synchronized with the laser Q-switch and exhibit longtime frequency jitter, or trend, to less than ± 650 kHz [34]. Any seed wavelength can be applied to any of the three pulses as selected through operational software. The projected seeding range of the space-based triple-pulse transmitter is indicated by the shaded area of Fig. 1. Typically, off-line seeding is applied to the third pulse with lowest-energy, to preserve higher energy pulses for the on-line to accommodate higher transmission losses due to molecular absorption. In addition, all three pulses can be seeded with the same wavelength, off-line for example to conduct off-off-line testing for IPDA instrument calibration [28]. At 400 km altitude, 100 μ rad beam divergence results in an 80 m diameter laser footprint at the surface. Assuming 200- μ s pulse time separation and 28,000 km/hr platform speed (Table 4), distance separation between the first and the second pulse is only 1.6 m. This translates to a successive laser pulse surface footprint overlap of 97.5%. This ensures nearly the same CO₂ sampling volume for different wavelengths.

B. IPDA Lidar 2- μ m Receiver

The 2- μ m IPDA receiver is based on a 1.5 m diameter Cassegrain all metal, light-weight, telescope that provides good thermal and alignment stabilities while conserving volume. The telescope field-of-view (FOV) is set with a limiting aperture to accommodate full transmitter-receiver overlap. The IPDA detection system is based on a state-of-the-art, low-noise, HgCdTe (MCT) electron-initiated avalanche photodiode (e-APD) detector array [39–40]. This detection system was developed and evaluated at NASA Goddard Space Flight Center in a different IPDA lidar for active remote sensing of atmospheric trace gases such as CO₂ and methane (CH₄) [39]. The detection system has a wide, visible to mid-wave-infrared spectral response, high dynamic range, substantially improved sensitivity, and an expected improvement in operational lifetime. The MCT e-APD is in 8 $\times$ 8 pixel format with 80 μ m pitch supplemented by a custom metal–oxide–semiconductor readout integrated circuit that has been tested and characterized. It is assumed that custom design aft-optics focuses the radiation onto a single pixel, which can be selected and activated through the readout electronics to generate the electrical output. The projected performance parameters for a typical e-APD device operating at 78 k and 11 V bias are listed in Table 4. A 1-nm optical cold narrow band-pass filter was included in this system to reduce background and associated noise. System electronic bandwidth limit of 10 MHz is selected to enable range measurement to an accuracy of 3 m as demonstrated in earlier airborne IPDA measurements [28–29].

The IPDA detected return signals are digitized and stored through a data acquisition unit. The data acquisition unit is based on two similar 12-bit, 1 GS/s, high-performance digitizers. The digitizers are triggered from the laser Q-switch to enable receiver and transmitter synchronization. One digitizer is dedicated to the IPDA return signals, while the other is dedicated to monitor the transmitted laser energies. The completed triple-pulse IPDA data acquisition software includes raw data reduction algorithms and real-time data processing that is currently under evaluation.

C. Space Based Platform

A 400-km altitude, 88° inclination, near-nadir viewing orbiter is assumed in this analysis. The satellite is assumed to be in dawn/dusk Sun synchronous orbit with a 16 day repeat cycle. The projection of the satellite track on the surface over one week period is shown in Fig. 4 [41]. Latitudinal sampling over 100×100 km² grid is given in Table 5 for 22 days sensing interval. For this orbit, cumulative observation period increases with higher latitude, which allows higher shot averaging for lower surface reflectivity Polar Regions resulting in lower random errors. The dawn/dusk orbit provides two measurements per day; one near dawn when cloud development is at a minimum, and another in the late afternoon under well-developed boundary layer conditions. This orbit minimizes solar background signal variations and associated noise. Preliminary estimate of a spacecraft mass of 400 kg and power of

5. IPDA SIMULATION RESULTS AND ERROR BUDGET

Modeling the performance of a space-based, 2-μm, triple-pulse IPDA lidar was conducted to demonstrate CO₂ measurement capability and to evaluate random and systematic errors using the concept of a high pulse energy, triple pulse, and direct detection IPDA system. The projected return power of the 2-μm IPDA lidar is calculated using Eq. (1). Fig. 5 presents the on-line return power, P_{on} , associated noise power, $P_{n,on}$, and signal-to-noise ratio, SNR_{on} versus possible on-line operating wavelength, λ_{on} , shown in Fig. 1, for the different scenarios, listed in Table 1. In these calculations, the two highest transmitted energies of 50 and 15 mJ are assumed for the on-line pulses. The off-line return, P_{off} , and noise, $P_{n,off}$ powers and SNR_{off} for a single off-line wavelength of 2051.1915 nm are listed in Table 6, assuming lowest transmitted energy of 5 mJ. The total noise power associated with the return signal, P_n (in Watt) per-pulse, includes fixed detection system electronic noise represented by the noise-equivalent-power, NEP , background shot noise due to background radiation, P_{BG} , and signal-dependent shot noise according to

$$P_n(\lambda) = \sqrt{BW \cdot \{NEP^2 + 2 \cdot q \cdot [P_{BG} + P(\lambda)] \cdot M \cdot F / \Re\}} \quad (11)$$

where BW is the detection system electronic bandwidth, q is the electron charge and M , F and $\Re$ are the MCT e-APD gain, excess noise factor and responsivity, respectively. The background power associated with the return signals depends on the receiver geometry and the background irradiance, S_b (in W/m²·nm·sr) according to

$$P_{BG} = \frac{\pi}{4} \cdot S_b \cdot A_t \cdot FW \cdot FOV^2 \quad (12)$$

where FW is the optical filter bandwidth (in nm). The return power signal-to-noise ratio, SNR , is given as the ratio of the power calculations of Eqs. (1) and (11) as

$$SNR(\lambda) = P(\lambda) / P_n(\lambda) \quad (13)$$

On-line return power is proportional to the on-line transmitted energy and increases with longer on-line operating wavelength due to weaker absorption further away from the R30

line center. As a result increased on-line total noise is observed due to the domination of signal shot noise. Closer to the line center, on-line total noise is constant, at about 10^{-11} W, which is dominated by the fixed electronic and background shot noises. The off-line SNR are lower, compared to on-line, due to the lower off-line transmitted energy. Therefore off-line SNR is the dominating parameter for random error calculations. Results indicated RRV is the best measurement scenario. Thin clouds (Scenario 10) contribute negligible influence on the measurement as compared to RRV. Polar snow exhibits lowest surface reflectivity, in either summer or winter (scenarios 8 and 9), which provides the worst measurement cases.

A. CO₂ IPDA Error Budget

According to Eq. (9), X_{cd} is obtained by measuring the differential optical depth using the IPDA lidar and estimating the integral of the weighting function from the spacecraft to the surface. Errors in X_{cd} retrievals result from random and systematic sources. Although, partitioning of the errors to optical depth and dry air surface pressure was discussed earlier, this error analysis is focused on the IPDA product, $\Delta\tau_{cd}$, where the total error, ϵ , in $\Delta\tau_{cd}$ measurement is given by [30]

$$\epsilon = \frac{\delta[\Delta\tau_{cd}]}{\Delta\tau_{cd}} = (\epsilon_R / \sqrt{f_p \cdot T_{avg}}) + \epsilon_S \quad (14)$$

where ϵ_R and ϵ_S are the total random and total systematic errors, respectively, and f_p and T_{avg} are the repetition rate of the transmitted triple-pulses and the integration time, respectively, with their product equal to the number of shots averaged. Total systematic error in $\Delta\tau_{cd}$ measurements are mainly dominated by the atmospheric and instrument systematic errors, ϵ_A and ϵ_T , respectively and is given by

$$\epsilon_S = \sqrt{\epsilon_A^2 + \epsilon_T^2} \quad (15)$$

In this analysis, systematic errors due to spectral line parameters, assuming they are well calibrated, are neglected [20].

1. Random Errors—The random errors in the $\Delta\tau_{cd}$ measurement are related to the noise associated with the detection of the IPDA lidar signals. Although, ϵ_R can be reduced by shot averaging, measurements are affected by the variability of the surface reflectivity and slope and speckle noise [42]. Assuming that the ratio of the on- and off-line signals are appropriately normalized, per-shot, with respect to the ratio of the transmitted energies [see Eq. (6)], and speckle noise is reduced by shot averaging and receiver aperture [42], then ϵ_R is related to the SNR, Eq. (13), according to

$$\epsilon_R = \frac{\sqrt{SNR_{on}^{-2} + SNR_{off}^{-2}}}{\Delta\tau_{cd}} \quad (16)$$

In this equation, laser energy monitor SNRs are considered high enough by instrument design and calibration and therefore not significantly contributing to the error budget [27]. Fig. 6 shows the 2- μm CO₂ IPDA random error variation with the on-line wavelength for the different scenarios using both 50 and 15mJ on-line transmitted energies. For all scenarios the minimum random error occurs at 2051.0000 nm for 50 mJ on-line transmitted energy and shifts by 6 pm, toward longer wavelength, for 15 mJ reduced energy. The minimum random error associated with CO₂ measurement is presented in Table 7 for each scenario. The Table also lists the random errors for the selected on-line wavelengths for the optimum weightings of Fig. 3.

2. Atmospheric Systematic Errors—Atmospheric systematic errors, ϵ_A , result from a combination of sensitivities to meteorological data and the interference from molecules other than the measured molecule. According to Eq. (7), atmospheric systematic error calculations are dependent only on the atmospheric models and independent of aerosol and surface reflectivity. The systematic error from the atmospheric variable is given by

$$\epsilon_A = \sqrt{\epsilon_{A,t}^2 + \epsilon_{A,p}^2 + \epsilon_{A,m}^2 + \epsilon_{A,h}^2 + \epsilon_{A,w}^2} \quad (17)$$

where $\epsilon_{A,t}$, $\epsilon_{A,p}$, $\epsilon_{A,m}$, $\epsilon_{A,h}$, and $\epsilon_{A,w}$ are the systematic errors due to temperature, pressure, molecular interference, dry-air and line broadening, respectively. Systematic error simulations for temperature and pressure were conducted using a normally distributed random representation of the fluctuations in these independent variables. For temperature, $\epsilon_{A,t}$ was computed by calculating the optical depth sensitivity to atmospheric temperature uncertainty of $\delta T = 0.5\text{K}$. This was obtained by randomly generating a set of numbers (random seeding) that follow a normal distribution defined by a mean of zero and a standard deviation equal to δT , as shown in Fig. 7. This random seeding was added to the temperature profiles and the CO₂ differential optical depth, $\Delta\tau_{cd}(T + \delta T)$, was recalculated. This process was repeated 500 times, simulating and equivalent to 10-s shot averaging, for both the off-line and on-line wavelengths. The mean differential optical depth profile, $\overline{\Delta\tau_{cd}}(T + \delta T)$, was then used to obtain $\epsilon_{A,t}$ according to

$$\epsilon_{A,t} = \frac{|\Delta\tau_{cd}(T) - \overline{\Delta\tau_{cd}}(T + \delta T)|}{\Delta\tau_{cd}(T)} \quad (18)$$

Again, this was repeated for the different atmospheric models assumed in this study as shown in Fig 8a. Similarly, systematic error due to pressure, $\epsilon_{A,p}$, was computed by calculating the optical depth sensitivity to pressure deviation δP_r , which was achieved by assuming that pressure uncertainty is randomly generated through normal distribution, with a mean of zero and a standard deviation of $\delta P_r = 100$ Pascal. These random fluctuations were added to the pressure profiles and the perturbed CO₂ differential optical depth, $\Delta\tau_{cd}(P_r + \delta P_r)$ was recalculated 500 times for the off-line and on-line wavelengths. The mean profile was then used to obtain $\epsilon_{A,p}$ according to

$$\varepsilon_{A,p} = \frac{|\Delta\tau_{cd}(P_r) - \overline{\Delta\tau_{cd}}(P_r + \delta P_r)|}{\Delta\tau_{cd}(P_r)} \quad (19)$$

as shown in Fig. 8b. Results indicate that both temperature and pressure errors are small closer to the line center. Pressure errors are consistent among different models due to lower deviations between profiles of Fig. 2. Tropical model (TRO) exhibit highest temperature errors. Variation of the temperature errors with the operating on-line wavelength indicates consistent minima around 2050.98 and 2050.99 nm, depending on the assumed model.

3. Water Vapor Systematic Errors—Atmospheric systematic errors in the CO₂ IPDA measurement due to H₂O, as shown in Fig. 9, result from the influences discussed in Section 3A that include molecular interference, dry-air number density determination, and CO₂ line broadening due to H₂O, $\varepsilon_{A,m}$, $\varepsilon_{A,h}$, and $\varepsilon_{A,w}$ respectively. These influences arise due to uncertainty in H₂O determination, which is related to relative humidity, H , for example through the Goff-Gratch approximation [43]. Thus, the deviation in relative humidity is equal to the relative uncertainty in H₂O number density, which is assumed 10% in the following calculations (i.e., $\delta H/H = \delta N_{wv}/N_{wv} = 10\%$). Then, similarly, the fluctuations in N_{wv} are randomly generated through normal distribution, with a mean of zero and a standard deviation of $\delta N_{wv} = 0.1 \times N_{wv} \text{ m}^{-3}$. This process was repeated 500 times to obtain the mean deviations in H₂O and CO₂ optical depths. The ratio of the mean fluctuations of the differential optical depth of H₂O, $\delta(\Delta\tau_{wv})$, to the differential optical depth of CO₂ defines the interference error at the sensing wavelengths, according to

$$\varepsilon_{A,m} = \frac{\delta(\Delta\tau_{wv})}{\Delta\tau_{cd}} \quad (20)$$

According to Eq. (7), $\Delta\tau_{cd}$ is obtained through N_{dry} that is dependent on N_{wv} , through Eq. (5). Therefore, δN_{wv} , would result in $\Delta\tau_{cd}$ error according to

$$\varepsilon_{A,h} = \frac{|\Delta\tau_{cd}(N_{wv}) - \overline{\Delta\tau_{cd}}(N_{wv} + \delta N_{wv})|}{\Delta\tau_{cd}(N_{wv})} \quad (21)$$

Finally, CO₂ presence with gases, other than nitrogen and oxygen in the atmospheric environment, leads to broadening of CO₂ absorption spectra that is dominated by H₂O [34]. With H₂O making up approximately 1 to 4% of Earth's lower atmosphere, it further interfere with CO₂ remote sensing measurements by acting as a foreign broadening factor for CO₂ lines. The influence of H₂O on line broadening of CO₂ was evaluated based upon the uncertainty in the H₂O knowledge. This was quantified by high-precision spectroscopy in a study for the CO₂ R16e transition at 6359.967 cm⁻¹ [37]. Assuming the line broadening at 2-μm is relatively similar to that at 1.6-μm, $\varepsilon_{A,w}$ is represented by

$$\varepsilon_{A,w} = \frac{|\Delta\tau_{cd}(\Delta\sigma_{cd}[H]) - \overline{\Delta\tau_{cd}}(\Delta\sigma_{cd}[H + \delta H])|}{\Delta\tau_{cd}(\Delta\sigma_{cd}[H])} \quad (22)$$

where $\Delta\sigma_{cd}$ represents the updated CO₂ differential absorption cross section after including the water-broadening parameter [37]. The results of these H₂O uncertainty errors on CO₂ measurements are represented in Fig. 9 for the different models.

Fig. 9 indicates that the highest H₂O related errors are produced from tropics, where near-surface H₂O is the highest among other models, as shown in Fig. 2. All H₂O related errors are reduced closer to the line center where optimum lower free-tropospheric weighting measurements (using λ_T) can be achieved. In this spectral region, dry-air related errors are dominant. For a longer on-line operating wavelength above λ_B , line broadening errors are dominant including near-surface weighting (using λ_S). Interference error is the lowest, provided the knowledge of H₂O within 10%, and only dominate at much longer wavelengths close to λ_{off} . Interference error profiles always exhibit a minima where the on- and off-line wavelengths result in approximately equal H₂O differential optical depth where zero crossing occurs leading to negative values as indicated in Table 3 (i.e., on- and offline for CO₂ are flipped for H₂O). The minima for the USA was the basis on which λ_S was selected for CO₂ sensing for the current triple-pulse PDA [30].

4. Instrument Systematic Errors—Dominant instrument related systematic errors result from ranging uncertainty and transmitted laser beam wavelength locking control and spectral quality. These translate to measurement column length and dependence on the wavelength jitter and spectral profile of the laser lines. The total instrument systematic error is given by

$$\varepsilon_T = \sqrt{\varepsilon_c^2 + \varepsilon_{j,on}^2 + \varepsilon_{j,off}^2 + \varepsilon_{p,on}^2 + \varepsilon_{p,off}^2} \quad (23)$$

where ε_c is the $\Delta\tau_{cd}$ error due to ranging or column length uncertainty as measured by the IPDA, $\varepsilon_{j,on}$ and $\varepsilon_{j,off}$ are the errors due to on- and off-line laser line jitter, and $\varepsilon_{p,on}$ and $\varepsilon_{p,off}$ are the errors due to on- and off-line laser spectral line shape for the on- and off-line, respectively. Ranging error is obtained by injecting a normally distributed uncertainty of the ground elevation with a mean of zero and $\delta R_G = 3$ m standard deviation to the integral of Eq. (7). The average result of 500 runs of which is used to evaluate

$$\varepsilon_c = \frac{|\Delta\tau_{cd}(R_G) - \overline{\Delta\tau_{cd}}(R_G + \delta R_G)|}{\Delta\tau_{cd}(R_G)} \quad (24)$$

The on- and off-line laser line jitter errors are given by the differential optical depth sensitivity to the laser lines wavelength position variance of $\Delta\lambda_{on/off} = \pm 650$ kHz [38], according to

$$\varepsilon_{j,on/off} = \frac{|\Delta\tau_{cd}(\lambda_{on/off}) - \overline{\Delta\tau_{cd}}(\lambda_{on/off} \pm \Delta\lambda_{on/off})|}{\Delta\tau_{cd}(\lambda_{on/off})} \quad (25)$$

The on- and off-line laser spectral profile errors are estimated by computing the effective differential optical depth, $\Delta\tau_{cd,ef}$, using the effective absorption cross section, σ_{eff} defined by [40]

$$\sigma_{eff} = \frac{\int G(L, r) \cdot \sigma(L, r) \cdot dL}{\int G(L, r) \cdot dL} \quad (26)$$

where G is the laser spectral intensity distribution profile, assumed to be an altitude-independent Gaussian function, and L is the wavenumber (in cm^{-1}). Assuming diffraction-limited operation, the FWHM correlates to the laser temporal pulse width, according to

$$FWHM = \frac{2 \cdot \ln(2)}{\pi \cdot t} \quad (27)$$

which results in worst case of ± 7.35 MHz for the 30 ns pulse. Thus, the on- and off-line laser spectral errors are given by

$$\varepsilon_{p, on/off} = \frac{|\Delta\tau_{cd}(\sigma_{on/off}) - \overline{\Delta\tau_{cd}}(\sigma_{eff, on/off})|}{\Delta\tau_{cd}(\sigma_{on/off})} \quad (28)$$

In this analysis, errors due to Doppler shifts are neglected compared to transmitter line jitter errors. As an example, for a typical large-payload spacecraft, the pointing angle uncertainty is about 24 μrad . This results in a Doppler frequency shift of 100 kHz in the near nadir pointing line-of-sight at the 2- μm wavelength, which is negligible compared to the ± 650 kHz shifts considered due to laser jitter errors. Fig. 10 shows the results of the instrument errors for $\Delta\tau_{cd}$ measurement. Since these errors are instrument related, they are fixed and independent of the measurement scenario or the atmospheric model used. For comparison, Fig. 11 summarizes the individual systematic error sources and the total systematic errors for USA model. It is evident that the total systematic error is dominated by on-line laser jitter and ranging instrument related errors. Jitter error is dominant on-line operation near the line center while ranging is for longer on-line wavelengths, with negligible other instrument related errors. Table 8 lists a summary of the total systematic errors obtained for different models, according to Eq. (15), by combining all the systematic error sources. The minimum ε_S is listed in the second column of Table 8 for the different atmospheric models. All minimum ε_S occurs at 2050.986 nm except for MLW and SAS where it shifts to 2050.996 nm. Table 8 also lists ε_S for the selected online for the different weighting function peaks at λ_T , λ_B , and λ_S .

After combining all errors, according to Eq. (14), Table 9 lists a summary for the CO_2 differential optical depth total error budget obtained for the different scenarios. Targeting the atmospheric boundary layer for RRV, 0.074% total error is projected using λ_B and 50 mJ on-line transmitted energy. This translates to 0.296 ppm total differential optical depth error, which is lower than 0.70 ppm combined random and systematic errors requirement, presented in Table 2. Fig. 12 shows the total differential optical depth error profiles for selected extreme scenarios. These scenarios include the RRV reference with best performance, tropical land with the highest H_2O loading, South Ocean with low reflectivity ocean surface and worst Polar winters low snow reflectivity. This analysis is useful for studies relating the transmitted laser energy and number of averages in the error budget. For

example, if the instrument is operated on the RRV scenario, targeting the boundary layer, λ_B , then increasing the transmitted laser energy would not help reducing the total error, since it is dominated by the fixed systematic error. Another example is the Polar Snow Summer, which exhibits the worst case scenario with 1.1375% total error, targeting lower free-troposphere using λ_T and 15 mJ on-line transmitted energy. Nevertheless, higher averaging in the Polar Region can be obtained through the selected orbit due to the longer observation period for the surface footprint, as indicated in Fig. 4 and Table 5. This increases the shot averaging by a factor 5.3, reducing random error by a factor of 2.3. This results in reducing the total error from 4.55 ppm to 3.26 ppm.

B. Adaptive Targeting

Adaptive targeting is conducted by tuning the on-line wavelength to meet a certain measurement objective depending on observational time and location. This was demonstrated using the double-pulse IPDA system where the on-line was varied from 1 to 6 GHz away from the R30 line center. With the same instrument, another demonstration of the technique was conducted to perform off-off-line testing, in which the online wavelength was tuned to exactly match the off-line. Although off-off-line tests overestimate random errors, as indicated in Fig. 6, it can be applied to characterize instrument biases [30]. Since the outcome of this test is precisely known (zero optical depth), it is recommended that this be conducted as an IPDA instrument calibration resource for the different operating conditions. The 2- μm CO₂ IPDA lidar triple-pulse capability allows simultaneous and independent measurement of CO₂ using two different weighting functions. For example, weighting function selection allows measuring CO₂ concentration near the surface for studying source and sink interactions. With the same off-line the third pulse can be tuned to a different weighting function that is optimized for measurements in free troposphere. These can be targeted simultaneously and independently for studying the CO₂ exchange and transport. The unique tuning ability of the system for a given scenario is a significant advantage in optimization of measurements to a given target conditions. On the other hand the triple-pulse capability can be used to independently and simultaneously measure CO₂ and H₂O column amounts. The characteristics of the new triple-pulse laser under development meets or exceeds most of the transmitter requirements for space-borne CO₂ measurement. The unique triple-pulse capability has additional advantages. Having one laser delivering, near simultaneously, three pulses at different frequencies eliminates the complexity and need of three different lasers. This is a significant step towards reducing mass, size and power consumption of the instrument significantly while increases the efficiency. The triple pulsing eliminates the challenge and complexity in co-aligning and bore-sighting three independent beams. Measurements with adaptive targeting would be valuable tool for a space mission.

5. CONCLUSIONS

Modeling the performance of a space-based high-energy, 2- μm triple-pulsed IPDA was conducted to demonstrate CO₂ measurement capability and to evaluate random and systematic errors using the concept of a direct detection IPDA system. Features of 2- μm lidar technology developments at NASA LaRC include low-noise and high-efficiency MCT e-APD detection system, which was included in the model to investigate performance under

a variety of model atmospheric and surface conditions. Jitter of the transmitted on-line pulses of ± 650 KHz, limits the measurement accuracy close to the R30 line center. Ranging uncertainty of 3 m limits the accuracy for longer on-line operating wavelength. Projected performance shows <0.35 ppm precision and <0.3 ppm bias in low-tropospheric measurements related to column CO_2 optical depth measurements with the IPDA from space for a 10s signal averaging over RRV reference surface. These measurements, in combination with reanalysis of global surface pressure data, enable high precision (0.5 ppm) and high accuracy (<0.5 ppm) X_{cd} measurements (for measurements over the reference target conditions). Such precision and accuracy are required for improving sources and sinks of CO_2 estimates for enhancing climate and carbon cycle studies. Development of this capability will provide critically needed high quality CO_2 data over all regions including the Tropics, the Arctic and the Southern Oceans; over days and nights; over all seasons including winter; over a variety of surfaces reflectivity under a variety of aerosol loading conditions, and in clear and in the presence of optically thin cloud conditions. Influences of H_2O on CO_2 measurements were assessed, including molecular interference, line broadening and dry-air derivation assuming 10% uncertainty in lower tropospheric H_2O .

Current development and evaluation of a new airborne high-pulse energy, triple-pulsed IPDA at NASA LaRC will provide a new platform for testing the performance of the instrument on ground and aircraft. This is useful to evaluate performance models under a variety of atmospheric and surface conditions and for further technical improvements; data acquisition, analysis, and reduction techniques applicable for space. Triple-pulse IPDA testing plans include new methodologies and characterization for improvements in calibration of laser energy monitoring, laser pulse width effects, digitizers and detection systems non-linearity. Flight testing, calibration and validation studies will be used to reduce systematic effects from atmosphere, target surface, and the instrument characteristics.

Acknowledgment.

The authors acknowledge the contribution from NASA Goddard Space Flight Center providing lidar detection system under ESTO guidance. The authors would like to thank Xiaoli Sun and Luis Ramos-Izquierdo for their help integrating and testing the detection system. Thanks are also due to George Komar, Parminder Ghuman and Keith Murray for their continual support and encouragements. The authors are grateful to the efforts of Jirong Yu for leading the double-pulse laser development that made this work possible. Thanks also are due to Paul Speth, for space track analysis, Michael Kavaya and Stephen Horan for their fruitful discussions in preparation of this paper.

Funding. NASA Earth Science Technology Office (ESTO IIP-13-0048).

References

1. Ciais P, Sabine C, Bala G, Bopp L, Brovkin V, Canadell J, Chhabra A, DeFries R, Galloway J, Heimann M, Jones C, Le Quéré C, Myneni RB, Piao S. and Thornton P, "Carbon and Other Biogeochemical Cycles". Climate Change 2013: The Physical Science Basis. Contribution of Working Group I to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change (Cambridge University Press, 2013).
2. Hoffman F, Randerson J, Arora V, Bao Q, Cadule P, Ji D, Jones C, Kawamiya M, Khatiwala S, Lindsay K, Obata A, Shevliakova E, Six K, Tjiputra J, Volodin E. and Wu T, "Causes and implications of persistent atmospheric carbon dioxide biases in Earth System Models," Journal of Geophysical Research: Biogeosciences 119, 141–162 (2014).
3. Michalak A, Jackson R, Marland G, Sabine C, and the Carbon Cycle Science Working Group, A U.S. Carbon Cycle Science Plan, 2011.

4. Le Quéré C, Raupach M, Canadell J, Marland G, Bopp L, Ciais P, Conway T, Doney S, Feely R, Foster P, Friedlingstein P, Gurney K, Houghton R, House J, Huntingford C, Levy P, Lomas M, Majkut J, Metz J, Ometto J, Peters G, Prentice I, Randerson J, Running S, Sarmiento J, Schuster U, Sitch S, Takahashi T, Viovy N, van der Werf G. and Woodward F, "Trends in the sources and sinks of carbon dioxide", *Nature Geosciences* 2, 831–836 (2009).
5. King A, Andres R, Davis K, Hafer M, Hayes D, Huntzinger D, de Jong B, Kurz W, McGuire A, Vargas R, Wei Y, West T, and Woodall C, "North America's net terrestrial CO₂ exchange with the atmosphere 1990–2009," *Biogeosciences* 12, 399–414 (2015).
6. Huntzinger D, Post W, Michalak A, Wei Y, Jacobson A, West T, Baker I, Chen J, Davis K, Hayes D, Hoffman F, Jain A, Liu S, McGuire D, Neilson R, Raczka B, Poulter B, Tian H, Thornton P, Tomelleri E, Viovy N, Xiao J, Zeng N, Zhao M, and Cook R, "North American Carbon Project (NACP) regional interim synthesis: terrestrial biospheric model intercomparison," *Ecological Modelling* 232, 144–157 (2012).
7. Peylin P, Law R, Gurney K, Chevallier F, Jacobson A, Maki T, Niwa Y, Patra P, Peters W, Rayner P, Rodenbeck C, van der Laan-Luijkx I, and Zhang X, "Global atmospheric carbon budget: results from an ensemble of atmospheric CO₂ inversions," *Biogeosciences* 10, 6699–6720 (2013).
8. Lauvaux T, Miles N, Deng A, Richardson S, Cambaliza M, Davis K, Gaudet B, Gurney K, Huang J, O'Keefe D, Song Y, Karion A, Oda T, Patarasuk R, Razlivanov I, Sarmiento D, Shepson P, Sweeney C, Turnbull J, and Wu K, "High-resolution atmospheric inversion of urban CO₂ emissions during the dormant season of the Indianapolis flux experiment (INFLUX)," *J. Geophys. Res.* 121, 5213–5236 (2016).
9. Ogle S, Davis K, Lauvaux T, Schuh A, Cooley D, West T, Heath L, Miles N, Richardson S, Breidt F, Smith J, McCarty J, Gurney K, Tans P, and Denning S, "An approach for verifying biogenic greenhouse gas emissions inventories with atmospheric CO₂ concentration data," *Environmental Research Letters* 10, 034012 (2015).
10. Lauvaux T, Schuh A, Bocquet M, Wu L, Richardson S, Miles N., and Davis K, "Network design for mesoscale inversions of CO₂ sources and sinks," *Tellus* 64B, 17980 (2012).
11. Sarmiento J, Gloor M, Gruber N, Beaulieu C, Jacobson A, Fletcher S, Mikaloff, Pacala S, and Rodgers K, "Trends and regional distributions of land and ocean carbon sinks," *Biogeosciences* 7, 2351–2367, (2010).
12. Friedlingstein P, Meinshausen M, Arora V, Jones C, Anav A, Liddicoat S. and Knutti R, "Uncertainties in CMIP5 climate projections due to carbon cycle feedbacks," *Journal of Climate* 27, 511–526 (2014).
13. Friedlingstein P, Cox P, Betts R, Bopp L, Von Bloh W, Brovkin V, Cadule P, Doney S, Eby M, Fung I, Bala G, John J, Jones C, Joos F, Kato T, Kawamiya M, Knorr W, Lindsay K, Matthews H, Raddatz T, Rayner P, Reick C, Roeckner E, Schnitzler K, Schnur R, Strassmann K, Weaver A, Yoshikawa C. and Zeng N, "Climate-carbon cycle feedback analysis: Results from the C⁴MIP model intercomparison," *Journal of Climate* 19, 3337–3353 (2006).
14. Schimel D, Stephens B, and Fisher J, "Effect of increasing CO₂ on the terrestrial carbon cycle," *Proceedings of the National Academy of Sciences of the United States of America* 112, 436–441 (2015). [PubMed: 25548156]
15. McKinley G, Pilcher D, Fay A, Lindsay K, Long M, and Lovenduski N, "Timescales for detection of trends in the ocean carbon sink," *Nature* 530, 469–472 (2016). [PubMed: 26911782]
16. Tadic J, Loewenstein M, Frankenberg C, Iraci L, Yates E, Gore W, and Kuze A, "A comparison of in-situ aircraft measurements of carbon dioxide to GOSAT data measured over Railroad Valley playa, Nevada, USA," *Atmos. Meas. Tech. Discuss* 5, 5641–5664 (2012).
17. Hammerling D, Michalak A, and Kawa S, "Mapping of CO₂ at high spatiotemporal resolution using satellite observations: global distributions from OCO-2," *J. Geophys. Res.* 117, D06306 (2012).
18. Bréon F. and Ciais P, "Space borne remote sensing of greenhouse gas concentrations," *Comptes Rendus Geoscience* 342, 412–424 (2010).
19. National Research Council, *National Imperatives for the Next Decade and Beyond Committee on Earth Science and Applications from Space: A Community Assessment and Strategy for the Future* (National Academies, 2007).

20. ASCENDS Science Definition and Planning Workshop Report (University of Michigan, 2008).
21. Jucks K, Neeck S, Abshire J, Baker D, Browell E, Chatterjee A, Crisp D, Crowell S, Denning S, Hammerling D, Harrison F, Hyon J, Kawa S, Lin B, Meadows B, Menzies R, Michalak A, Moore B, Murray K, Ott L, Rayner P, Rodriguez O, Schuh A, Shiga Y, Spiers G, Wang J, and Zaccheo T, "Active sensing of CO₂ emissions over nights, days, and seasons (ASCENDS) mission," Science Mission Definition Study (California Institute of Technology, 2015).
22. Ingmann P, Bensi P, Duran Y, Griva A, and Clissold P, "A-SCOPE advanced space carbon and climate observation of planet Earth," in ESA Report for Assessment SP-1313/1 Candidate Earth Explorer Core Missions (European Space Agency, 2008).
23. Ehret G, Kiemle C, Wirth M, Amediek A, Fix A, and Houweling S, "Space-borne remote sensing of CO₂, CH₄ and N₂O by integrated path differential absorption lidar: a sensitivity analysis," Appl. Phys. B 90, 593–608 (2008).
24. Lawrence J, Differential Absorption Lidar for the Total Column Measurement of Atmospheric CO₂ from Space (University of Leicester, 2011).
25. Singh U, Yu J, Petros M, Refaat T, Remus R, Fay J, and Reithmaier K, "Airborne 2-micron double-pulsed integrated path differential absorption lidar for column CO₂ measurement," Proc. SPIE 9246, 924602 (2014).
26. Singh U, Walsh B, Yu J, Petros M, Kavaya M, Refaat T, and Barnes N, "Twenty years of Tm:Ho:YLF and LuLiF laser development for global wind and carbon dioxide active remote sensing," Opt. Mater. Express 5, 827–837 (2015).
27. Refaat T, Singh U, Petros M, Remus R, and Yu J, "Self-calibration and laser energy monitor validation for a double-pulsed 2- μ m CO₂ integrated path differential absorption lidar application," Appl. Opt 54, 7240–7251 (2015). [PubMed: 26368759]
28. Refaat T, Singh U, Yu J, Petros M, Remus R. and Ismail S, "Double-pulse 2- μ m integrated path differential absorption lidar airborne validation for atmospheric carbon dioxide measurement," Appl. Opt 55, 4232–4246, 2016. [PubMed: 27411155]
29. Yu J, Petros M, Singh U, Refaat T, Reithmaier K, Remus R, and Johnson W, "An airborne 2- μ m double-pulsed direct-detection lidar instrument for atmospheric CO₂ column measurements," Journal of Atmospheric and Oceanic Technology 34, 385–400 (2017).
30. Refaat T, Singh U, Yu J, Petros M, Ismail S, Kavaya M, and Davis K, "Evaluation of an airborne triple-pulsed 2- μ m IPDA lidar for simultaneous and independent atmospheric water vapor and carbon dioxide measurements," Appl. Opt 54, 1387–1398 (2015). [PubMed: 25968204]
31. Lovenduski N, Gruber N, and Doney S, "Toward a mechanistic understanding of the decadal trends in the Southern Ocean carbon sink," Global Biogeochemical Cycles 22, GB3016 (2008).
32. Fletcher S, Mikaloff, Gruber N, Jacobson A, Doney S, Dutkiewicz S, Gerber M, Follows M, Joos F, Lindsay K, Menemenlis D, Mouchet A, Müller S, and Sarmiento J, "Inverse estimates of anthropogenic CO₂ uptake, transport, and storage by the ocean", Global Biogeochemical Cycles 20, GB2002, (2006).
33. Anderson G, Clough S, Kneizys F, Chetwynd J, and Shettle E, "AFGL atmospheric constituent profiles (0-120 km)," Air Force Geophys. Lab. AFGL-TR-86-0110, 954 (1986).
34. Srivastava V, Rothermel J, Clarke A, Spinhirne J, Menzies R, Cutten D, Jarzembski M, Bowdle D, and McCaul E, "Wavelength dependence of backscatter by use of aerosol microphysics and lidar data sets: application to 2.1- μ m wavelength for space-based and airborne lidars," Appl. Opt 40, 4759–4769 (2001). [PubMed: 18360517]
35. Spiers G, Menzies R, and Jacob J, "Lidar reflectance from snow at 2.05 μ m wavelength as measured by the JPL Airborne Laser Absorption Spectrometer," Appl. Opt 55, 1978–1986 (2016). [PubMed: 26974792]
36. Rothman L, Gordon I, Babikov Y, Barbe A, ChrisBenner D, Bernath P, Birk M, Bizzocchi L, Boudon V, Brown L, Campargue A, Chance K, Cohen E, Coudert L, Devi V, Drouin B, Fayt A, Flaud J, Gamache R, Harrison J, Hartmann J, Hill C, Hodges J, Jacquemart D, Jolly A, Lamouroux J, LeRoy R, Li G, Long D, Lyulin O, Mackie C, Massie S, Mikhailenko S, Muller H, Naumenko O, Nikitin A, Orphal J, Perevalov V, Perrin A, Polovtseva E, Richard C, Smith M, Starikova E, Sung K, Tashkun S, Tennyson J, Toon G, Tyuterev V, and Wagner G, "The HITRAN2012 molecular spectroscopic database," J. Quant. Spectrosc. Radiat. Transfer 130, 4–50 (2013).

37. Wallace CJ, Jeon C, Anderson CN, and Havey DK, “H₂O Broadening of a CO₂ Line and Its Nearest Neighbors Near 6360 cm⁻¹”, The Journal of Physical Chemistry A, 115, 13804–13810 (2011). [PubMed: 22013917]
38. Refaat T, Petros M, Antill C, Singh U. and Yu J, “Wavelength locking to CO₂ absorption line-center for 2-μm pulsed IPDA lidar application,” Proc. SPIE 9879, 987904 (2016).
39. Beck J, Welch T, Mitra P, Reiff K, Sun X, and Abshire J, “A highly sensitive multi-element HgCdTe e-APD detector for IPDA lidar applications,” Journal of Electronic Materials 43, 2970–2977 (2014).
40. Sun X, Abshire J, and Beck J, “HgCdTe e-APD detector arrays with single photon sensitivity for space lidar applications,” Proc. SPIE 9114, 91140K (2014).
41. Kawa S, Mao J, Abshire J, Collatz G, Sun X. and Weaver C, “Simulation studies for a space-based CO₂ lidar mission,” Tellus 62B, 759–769 (2010).
42. Menzies R, “Coherent and incoherent lidar – an overview,” in Tunable Solid State Lasers for Remote Sensing, 17–21 (Springer-Verlag, 1985).
43. Goff J. and Gratch S, “Low-pressure properties of water from–160 to 212 °F,” J. Am. Soc. Heat. Vent. Eng 52, 95–122 (1946).

Fig. 1. Integrated double-path optical depth of CO_2 and H_2O around CO_2 R30 line obtained from 400 km altitude to mean sea level using different atmospheric models. Vertical lines mark the R30 line center, λ_C , off-line, λ_{off} , and on-lines for weighting function peaks at lower troposphere, λ_T , boundary layer, λ_B , and near surface, λ_S . Shaded region represents the tuning capability of any of the transmitted pulses.

Fig. 2.

U.S. Standard (USA), Mid-Latitude Summer (MLS), Mid-Latitude Winter (MLW), Tropics (TRO), Sub-Arctic Summer (SAS) and Sub-Arctic Winter (SAW) atmospheric models (a) temperature, (b) pressure and (c) H₂O mixing ratio vertical profiles as well as (d) USA CO₂ mixing ratio profile used for space-based IPDA lidar simulations [33].

Fig. 3.

Pressure-based normalized weighting functions, using USA model, for the three selected on-line wavelengths, λ_S , λ_B and λ_T targeting surface, boundary layer and lower troposphere CO_2 column measurement, respectively.

Fig. 4.
Projection of dawn/dusk Sun synchronous satellite track on the surface over one week sensing interval illustrating the latitude/longitude sampling coverage by the IPDA. Cumulative observation period increases with higher latitude, as summarized in Table 5. This allows higher shot averaging, resulting in lower random errors, for lower surface reflectivity Polar Regions.

Fig. 5. Space-based 2- μ m CO₂ IPDA lidar on-line return signal and associated noise powers for (a) 50 mJ and (b) 15 mJ on-line transmitted energies for the scenarios listed in Table 1. These are used to obtain the on-line single-shot SNR for (c) 50 mJ and (d) 15 mJ transmitted energies.

Fig. 6.

Space-based 2- μm CO₂ IPDA lidar random error variation with on-line wavelength for the scenarios listed in Table 1, obtained for 5 mJ off-line and (a) 50 mJ and (b) 15 mJ on-line transmitted energies assuming 500 (10-sec) shot averaging.

Fig. 7.
Normal distribution of the temperature random deviation δT injected to the temperature profiles assuming zero mean and 0.5 K standard deviation.

Fig. 8.

Space-based 2- μm CO₂ IPDA lidar atmospheric systematic errors due to (a) temperature and (b) pressure as a function of on-line wavelength for different atmospheric models listed in Table 1. Each profile is an average of 500 independent profiles generated by introducing a normally distributed uncertainties with standard deviations of $\delta T=0.5\text{K}$ and $\delta P=100$ Pascal for temperature and pressure, respectively. These errors are independent of the transmitted laser energy.

Fig. 9. Space-based 2- μm CO₂ IPDA lidar atmospheric systematic errors due to water vapor interference, $\epsilon_{A,m}$, dry-air estimates, $\epsilon_{A,h}$ and line broadening, $\epsilon_{A,w}$, as a function of on-line wavelength for different atmospheric models listed in Table 1. Each profile is an average of 500 independent profiles generated by introducing a normally distributed uncertainty in relative humidity of $\delta H/H = 10\%$. These errors are independent of the transmitted laser energy.

Fig. 10.

Space-based 2- μm CO₂ IPDA lidar instrument systematic errors due to (a) Ranging and (b) transmitter as a function of on-line wavelength. Ranging error was calculated for different atmospheric models listed in Table 1 with each profile is an average of 500 independent profiles generated by introducing a normally distributed uncertainty with standard deviations of $\delta R=3.0\text{m}$. Transmitter uncertainties include $\pm 650\text{kHz}$ on- and off-line laser position jitters resulting in errors, $\epsilon_{j,on}$ and $\epsilon_{j,off}$ respectively, and on- and off-line laser linewidth (profile) uncertainty of $\pm 7.35\text{ MHz}$ resulting in $\epsilon_{p,on}$ and $\epsilon_{p,off}$ errors respectively.

Fig. 11. Space-based 2- μm CO₂ IPDA lidar total systematic error compared to atmospheric and instrument errors, presented for scenario 1 (RRV reference) as a function of on-line wavelength. Total systematic error is dominated by on-line jitter closer to the line center and by ranging away from the line center.

Fig. 12.

Space-based 2- μm CO₂ IPDA lidar total systematic and random errors and their combination to evaluate the differential optical depth total error budget as a function of on-line wavelength. For comparison, extreme scenarios were selected that include RRV reference, tropics land (high H₂O loading), South Ocean (low reflectivity ocean surface) and Polar winters (low snow reflectivity).

Table 1.Global scenarios considered for 2- μm CO₂ IPDA performance simulations^a

	Surface Condition	Model	ρ	τ_a
1	Rail Road Valley (RRV) ^b	USA	0.510	0.0165
2	Land, Desert	USA	0.410	0.2380
3	Land, Vegetation	USA	0.090	0.0289
4	Tropics, Land	TRO	0.090	0.0530
5	Tropics, Ocean	TRO	0.079	0.0420
6	South Ocean, Summer	MLS	0.079	0.0273
7	South Ocean, Winter	MLW	0.079	0.0475
8	Polar Snow, Summer	SAS	0.020	0.0210
9	Polar Snow, Winter	SAW	0.020	0.0210
10	Thin Clouds ^c	USA	0.510	0.0500
11	Urban Plumes, Wet Land	USA	0.079	0.1340
12	Urban Plumes, Dry Land	USA	0.090	0.1340

^a Atmospheric models included in this study are U.S. Standard (USA), Mid-Latitude Summer (MLS), Mid-Latitude Winter (MLW), Tropics (TRO), Sub-Arctic Summer (SAS) and Sub-Arctic Winter (SAW); ρ is the surface reflectivity; and τ_a is the aerosol/thin cloud optical depth [30–35].

^b RRV is a reference surface with high reflectivity that includes a 1.23 enhancement factor.

^c Assuming RRV surface conditions.

Table 2.

Measurement requirements for space-based CO₂ IPDA lidar system.

Parameter	Requirement
Random error in CO ₂ dry-air column mixing ratio	0.50 ppm
Systematic error in CO ₂ dry-air column mixing ratio	0.50 ppm
Random error in CO ₂ differential optical depth, ϵ_R ^a	0.35 ppm
Systematic error in CO ₂ differential optical depth, ϵ_S	0.35 ppm
Ranging error to the surface, ϵ_C	< 3.0 m
Laser footprint diameter	100 m
Laser pulse frequency	50 Hz

^aOver RRV reference surface reflectivity, under clear conditions and 10 s observational interval [21].

Table 3.

Space-based differential optical depth simulation results for different models at selected on-line wavelengths.

		$\Delta\tau_{cd}$			$\Delta\tau_{wv}$		
		λ_T	λ_B	λ_S	λ_T	λ_B	λ_S
USA	8.0469	5.1539	0.4499	0.0013	0.0011	0.0001	
TRO	8.4641	5.3914	0.4607	0.0029	0.0024	-0.0005	
MLS	8.3961	5.3464	0.4586	0.0023	0.0019	-0.0002	
MLW	7.8076	5.0115	0.4445	0.0009	0.0008	0.0002	
SAS	8.1714	5.2080	0.4503	0.0019	0.0016	0.0001	
SAW	7.4698	4.8036	0.4318	0.0005	0.0004	0.0001	

Table 4.Space-based 2- μm triple-pulse CO₂ IPDA lidar parameters.

IPDA Lidar Transmitter	
On-Line Wavelength, λ_{on}	Tunable ^a
Off-Line Wavelength, λ_{off}	2051.1915 nm
Pulse Energy, E	50 / 15 / 5 mJ
Pulse Width, t_p	30 / 60 / 100 ns
Pulse Separation, T_s	150 – 300 μs
Triple-Pulse Repetition Rate, f_p	50 Hz
Beam Quality	2.0 (M^2)
Beam Divergence, ϕ_b	100 μrad
Laser Line Width	Transform Limited
Frequency Control Accuracy	± 650 kHz
Spectral Purity	99.9%
Electrical to Optical Efficiency	4%
Beam Expansion	$\times 10$
IPDA Lidar Receiver	
Optical Efficiency, η_r	60%
Telescope Diameter, D_T	1.5 m
Telescope Obscuration, O_T	10%
Optical Filter Spectral Width, FW	1 nm
Field-of-View, FOV	150 μrad
Detector Responsivity, $\mathcal{R}^b$	295.3 A/W
Detector Gain, M	308
Detector Excess Noise Factor, F	1.03
Detection Bandwidth, BW	10 MHz
Noise-Equivalent-Power, NEP	1 fW/Hz ^{1/2}
Laser-to-Telescope Overlap, ϕ_r	1.00
Operating Environment	
Background Solar Irradiance, S_b	0.5 mW/m ² .nm.sr
Shot Integration Time, T_{avg}	10 s (500 triple-pulses)
Platform Altitude, R_A	400 km
Platform Speed, U	28,000 km/hr

^aTwo independent on-line wavelengths, tunable from 2050.9670 to 2051.1900 nm, as indicated in Fig. 1.^bDetection system is developed by NASA Goddard Space Flight Center and is based on MCT e-APD.

Table 5.

Cumulative observation period during 22-days interval for $100 \times 100 \text{ km}^2$ surface bins as a function of latitude.

Latitude	Observation Period
Equator	19.298 s
30°N	27.226 s
60°N	56.060 s
75°N	102.426 s

0.75 kW for the 2- μm triple-pulse CO_2 IPDA payload were conducted. This IPDA payload can be accommodated on Orbital 300HP or LEOstar bus and Antares or Minotacer V/VI launch vehicle.

Table 6.Space-based 2- μm CO₂ IPDA lidar off-line return signal, noise and single-shot SNR for 5 mJ off-line

#	P_{off} (nW)	$P_{n,off}$ (nW)	SNR_{off}
1	37.73	0.36	104.7
2	24.31	0.29	84.0
3	6.58	0.15	43.7
4	6.29	0.15	42.7
5	5.58	0.14	40.2
6	5.71	0.14	40.7
7	5.70	0.14	40.6
8	1.47	0.07	20.5
9	1.49	0.07	20.7
10	36.49	0.35	102.9
11	5.20	0.13	38.8
12	5.92	0.14	41.4

Table 7

Random errors (in %) for different scenarios.

Scenario	ϵ_R min		ϵ_R at 50 mJ			ϵ_R at 15 mJ		
	% at 50mJ	% at 15mJ	λ_T	λ_B	λ_S	λ_T	λ_B	λ_S
1	0.0086	0.0158	0.0265	0.0103	0.0486	0.0754	0.025	0.0545
2	0.0107	0.0197	0.0333	0.0129	0.0606	0.0996	0.0312	0.0679
3	0.0206	0.0379	0.0692	0.0249	0.1166	0.2584	0.0619	0.1306
4	0.0211	0.0388	0.0873	0.0270	0.1166	0.3614	0.0688	0.1307
5	0.0224	0.0412	0.0943	0.0287	0.1238	0.4007	0.0735	0.1387
6	0.0221	0.0407	0.0897	0.0280	0.1228	0.3734	0.0714	0.1377
7	0.0221	0.0407	0.0674	0.0259	0.1268	0.2466	0.0638	0.1419
8	0.0438	0.0810	0.2053	0.0544	0.2475	1.0754	0.1517	0.2771
9	0.0435	0.0804	0.1332	0.0491	0.2560	0.6052	0.1270	0.2861
10	0.0087	0.0161	0.0269	0.0105	0.0494	0.0770	0.0254	0.0554
11	0.0232	0.0427	0.0798	0.0280	0.1312	0.3136	0.0703	0.1469
12	0.0217	0.0400	0.0737	0.0262	0.1229	0.2815	0.0655	0.1376

Table 8

Systematic errors (in %) for different atmospheric models.

Model	$\varepsilon_S \min$ %	$\varepsilon_S \lambda_T$ %	$\varepsilon_S \lambda_B$ %	$\varepsilon_S \lambda_S$ %
USA	0.0506	0.0623	0.0614	0.0624
TRO	0.0509	0.0638	0.0641	0.0695
MLS	0.0505	0.0625	0.0621	0.0650
MLW	0.0507	0.0631	0.0629	0.0671
SAS	0.0505	0.0629	0.0626	0.0653
SAW	0.0507	0.0628	0.0624	0.0672

Table 9

Total errors (in %) for different scenarios.

Scenario	ϵ min		ϵ at 50 mJ			ϵ at 15 mJ		
	% at 50mJ	% at 15mJ	λ_T	λ_B	λ_S	λ_T	λ_B	λ_S
1	0.0698	0.0770	0.0887	0.0717	0.1110	0.1377	0.0864	0.1169
2	0.0719	0.0809	0.0956	0.0743	0.1230	0.1618	0.0926	0.1303
3	0.0818	0.0991	0.1314	0.0863	0.1790	0.3206	0.1233	0.1930
4	0.0860	0.1045	0.1511	0.0911	0.1861	0.4251	0.1329	0.2002
5	0.0873	0.1069	0.1581	0.0927	0.1933	0.4645	0.1376	0.2083
6	0.0844	0.1033	0.1522	0.0901	0.1878	0.4359	0.1335	0.2026
7	0.0854	0.1045	0.1305	0.0888	0.1939	0.3097	0.1267	0.2090
8	0.1066	0.1441	0.2682	0.1170	0.3129	1.1383	0.2142	0.3424
9	0.1061	0.1436	0.1960	0.1115	0.3232	0.6680	0.1894	0.3533
10	0.0700	0.0772	0.0892	0.0719	0.1119	0.1393	0.0868	0.1178
11	0.0844	0.1039	0.1420	0.0894	0.1936	0.3759	0.1317	0.2093
12	0.0830	0.1012	0.1359	0.0876	0.1853	0.3437	0.1269	0.2000