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MOBILE FREE-ELECTRON LASER FOR REMOTE ATMOSPHERIC SURVEY

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Abstract

The application of using accelerator-science to improve current remote atmospheric survey techniques has been explored. A literature review has been conducted to asses the needs of NASA 's Active Sensing of CO_2 Over Nights, Days and Seasons (ASCENDS) versus the current capabilities of contemporary atmospheric survey technology, and the parameters of a free electron laser (FEL) source were calculated for a lidar system that will meet these needs. By using the "Next Linear Collider" accelerating structure from the Stanford Linear Accelerator Center (SLAC) [1], a mobile FEL-based lidar may be constructed for airborne surveillance. The calculated energy of the lidar pulse is 0.1 joule -a three orders of magnitude gain over current lidar systems [2]. Therefore in principle, the mobile FEL will exceed the needs of ASCENDS.

INTRODUCTION

We seek to assess the feasibility of applying accelerator-based sources of EM radiiation to advance the state of the art of atmospheric survey. To that purpose, we propose an improvement to airborne lidar techniques by introducing a higher intensity, accelerator based seed laser: a mobile platform free electron laser (FEL). This beneficial intersection of two previously disjoint fields of research offers promising solutions to obstacles facing NASA 's Active Sensing of CO_2 Over Nights, Days and Seasons (ASCENDS) mission through the implementation of well vetted accelerator technology.

Airborne Lidar for Atmospheric Survey

Airborne lidar is a prevailing method of remote detection of atmospheric concentrations of various molecular species. Lidar sensors emit a paired laser signal and compute target species concentration by calculating the difference in absorption levels and returns from the paired signal: one beam has a wavelength matched to an absorption frequency of the target and the second beam is off of the absorption frequency. This difference in the two signals reflected back upon the sensor apparatus is directly proportional to the number of target species present in the laser column. For a pulsed lidar signal, the time lapse between the initial pulse and the received signal can be resolved to determine the distance between the sensor and the carbon dioxide. Ultimately the data received may be rendered to build a three dimensional topography of the species density in the area of surveillance.

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Needs of the NASA ASCENDS Mission

The Intergovernmental Panel on Climate Change has concluded that global industrialization has dramatically increased the production and subsequent emission into the atmosphere of carbon dioxide [3]. Increased abundance of atmospheric carbon dioxide is understood to be the largest human created function for climate change [4]. The current background concentration of carbon dioxide has grown to approximately 406 ppm; historically carbon density never exceeded 280 ppm before the industrial revolution [5]. Since carbon dioxide is chemically inert, it can last for hundreds of years once it has accumulated in the atmosphere [6]. Estimates for limiting global warming to a 2 degree centigrade increase call for a one third reduction in these emissions within the next twenty years.

To be useful in reducing uncertainties about carbon sources and sinks, the atmospheric carbon dioxide measurements need to have a high resolution with at least a 0.3% precision, or an accuracy of about 1-2 ppm. Substantial increase to the power emitted by the laser, however, would significantly increase the signal-to-noise ratio and thereby increase the precision of the CO_2 measurement [4].

The solid state lasers used in most remote lidar sources limit the spatial range of survey. The common practice is to take measurements from aircraft within the Earth's atmosphere as opposed to taking measurements from orbiting satellites because the range of most lidar assemblies is less than 12 kilometers. The aircraft mobility grants the researcher an advantageous line of sight for the lidar that is unavailable to ground based remote sensors, and this demand for mobility limits the size of the laser and receiver apparatus. As with radar, measurement resolution decreases precipitously as a square of the range. The range of the measurements may be extended only through substantial gains in the laser intensity output. Ultimately, the ASCENDS mission intends to conduct atmospheric surveys from orbit, so there is a critical need for increases in the lidar signal laser power in order to increase the range of the remote sensor to 400 kilometers [7].

Mobile FEL for Atmospheric Survey

The power gains necessary to overcome the shortfalls in both range and precision of contemporary lidar techniques may be achieved by abandoning the solid state lasers in favor of a compact FEL. More specifically, a high-energy FEL, or wiggler, may be implemented to provide substantial gains in pulse intensity, and the FEL will create monochromatic infrared pulses with the same general properties as the current leading lidar sources. Historically, a high intensity, high

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quality FEL capable of lidar operations would have been the size of a large building [8], but advances in particle accelerator technologies [1] have made it possible to construct the same powerful laser in a mobile shipping container or in the fuselage of a small jet.

The scope of this work is to show that the construction of a high-performance, mobile FEL-based lidar is possible in principle. Further research, specifically sensitivity tests, will be required to identify and overcome practical considerations for deploying this technology. Since all of the components of the proposed device have already been developed and well vetted, this avenue of research will be relatively low risk.

FEASIBILITY OF A MOBILE FEL

To illustrate the advantages of mobilizing FEL technology for the purpose of atmospheric survey, it will first be shown that a well-established FEL, specifically the Vanderbilt Free-Electron Laser Center [8], can generate a pulsed laser that will exceed the current goals of ASCENDS. As a point of reference, the feasibility of the proposed improvements will be compared to a highly effective pulsed lidar system developed by NASA Goddard Space Flight Center (GSFC) [2]. Since the FEL at Vanderbilt is much too large to be mobilized for atmospheric survey, it will be shown here that a similar FEL may be constructed into a compact platform. The key to downsizing this technology lies in the powerful, yet small accelerator structures, “The Next Linear Collider,” developed at the Stanford Linear Accelerator Center (SLAC) [1]. A prescription that is based on developed, well-vetted accelerator components for a mobile FEL platform will be presented. This mobile FEL will exceed the range and precision demands of the ASCENDS mission.

The Current State of Atmospheric Survey

The GSFC team has been chosen to represent the the current state of atmospheric survey because they have a decade long track record of airborne lidar campaigns in pursuit of the ASCENDS mission goals. Their publication record reflects significant improvements in lidar technology. This team has executed many successful atmospheric survey mission under a variety of environmental conditions [4]. The team has produced lidar output pulse energy at 0.475 mJ, which places their apparatus amongst the most sensitive operating survey lasers. Their current research involving planar waveguide(PWG)-based power amplifiers has modeled output energies in a higher order of magnitude: 6.7 mJ [2]. The GSFC team’s years of experience and dedication to the ongoing development of lidar technology make them a fine representative of the current state of atmospheric survey technique.

In order to gauge the feasibility of a FEL-based lidar, the free-electron laser would first have to be shown to replicate the beam quality of the solid state laser at the prescribed frequency. Once the beam quality at the desired wavelength has been established, substantial increases to the laser pulse energy will need to be illustrated in order to show meaningful

Table 1: NASA Goddard Space Flight Center Airborne Lidar Parameters [2] V. Vanderbilt Free-Electron Laser Center [8].

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Parameter	GSFC	Vanderbilt
Emission Wavelength [nm]	1572.33	1572.33
Pulse Repetition [Hz]	10^4	60
Pulse Width [μs]	1.5	0.5-6
Laser Pulse Energy [mJ]	0.475	400

improvements to the range and precision of the atmospheric survey: specifically, the goal of ASCENDS s to produce a lidar laser pulse at 3.2 mJ [2].

As shown in Table(1), the pulse energy of the Vanderbilt FEL far exceeds the current state of atmospheric lidar signals. Now, the task is to rebuild this accelerator-based laser source into a much smaller package.

Proposed Mobile FEL

It would have to be shown that a FEL with this electron beam energy demand could be constructed within a mobile, airborne platform. There are five main components necessary to build the FEL within the given size constraints: the electron gun, the accelerator structure, the RF source for the accelerator structure, the optical cavity of the wiggler, and the laser delivery apparatus. This survey does not represent an exhaustive optimization of an FEL; this prescription serves to show it is possible, in principle, to construct a compact FEL with substantial energy gains over current lidar seed lasers.

Table 2: ASCENDS Laser Requirements [2] v. Proposed Mobile FEL

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Parameter	ASCENDS	MFEL
Emission Wavelength [nm]	1572.33	1572.33
Pulse Width [μs]	0.1-1	0.5 – 6
Pulse Repetition [Hz]	7.5×10^3	60
Average Power [W]	20	11
Laser Pulse Energy [mJ]	2.5	400

The Vanderbilt University Free-Electron Laser Center uses a model FEL I built by Sierra Laser Systems that may be used to produce an equivalent laser pulse quality as that used by the GSFC team [8]. The optical cavity, the component which houses the wiggler itself, from this FEL will meet the needs of the proposed lidar. Additionally, the Vanderbilt optical cavity is able to deliver the emitted radiation throughout their laboratory space into various tools and equipment via an optical-beam transport system designed and constructed by Optomec Design Company. This system may be used to

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further reduce sources of error incurred while delivering the lidar signal through the fuselage of the aircraft.

The energy needs of electron beam can be met by the “Next Linear Collider" developed by SLAC at Stanford [1]. These NLC structures provide stable, long term operation at very high gradient (65 MeV/m). Since our minimum requirement for the electron beam is 50 MeV, two of these one meter long structures in series will provide sufficient energy to the electron beam. This accelerator structure is the key to making the FEL compact: older linear accelerators would have required tens of meters to reach these energy requirements, but the SLAC structures require only two meters to meet the energy needs of the lidar. The frequency of the emitted laser pulse is a function of the electron energy; therefore, the tunability of the accelerator structures allows the laser emitted from the FEL to also be tunable. These accelerator structures requires an 11.4 GHz RF source which may be satisfied by the X-band klystron [9].

The FEL requires a high voltage dc photonemission electron gun with high brightness and tight emittance, i.e. low deviation from the beam trajectory axis, because linear accelerators, while having a relatively small foot print, are unable to correct electron beam quality. The high voltage electron gun from Cornell University provides an adjustable anode-cathode gap which has been proven to provide consistent emittance control under realistic breakdown conditions [10]. This gun also features a segmented insulator and guard rings to ensure proper operation even while operating at extremely high voltage levels.

All of these components together could be used to construct an FEL with a high quality, high intensity laser pulse, and this free-electron laser will have a relatively small foot print: the entire apparatus should be about 10 meters in length and no more than 5 meters in width, as shown in Fig. (1).

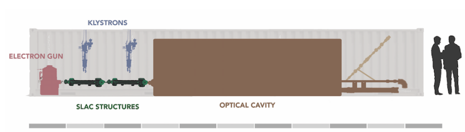

Figure 1: Proposed compact free-electron laser.

CONCLUSIONS

The signal power of airborne lidar systems may be increased by three orders of magnitude by mobilizing existing FEL technology. As shown in Table (2), these energy gains far exceed the requirements of the NASA ASCENDS mission to accurately record carbon distributions in the atmosphere over and extended period of time. All of the components of the proposed FEL device have been developed and well vetted, so continuing along this avenue of research will be a relatively low risk endeavor. This research concludes with confidence that the application of accelerator technology may indeed lead to substantial advancements in the field of atmospheric survey techniques. In fact, the mobile FEL may prove to be a powerful tool that advances many fields of research that require high intensity, narrow bandwidth emissions in the infrared red regime.

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