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THE CLOUD PHYSICS LIDAR AND APPLICATION TO SPACEBORNE LIDAR VALIDATION

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1. INTRODUCTION

The NASA Cloud Physics Lidar (CPL) has been used for validation and simulation of satellite lidar instruments. The CPL operates on the high-altitude ER-2 aircraft, thereby providing an excellent validation and simulation tool for spaceborne lidar instruments. In October 2003, CPL provided validation measurements for the Geoscience Laser Altimeter System (GLAS) on the ICESat satellite.[Zwally *et al*, 2002] Because CPL provides a unique high-altitude downward-looking lidar perspective, data from CPL has been used extensively to simulate measurements from the Cloud-Aerosol Lidar and Infrared Pathfinder Satellite Observations (CALIPSO) mission [Winker *et al*, 2002].

In this presentation we will show examples of CPL validation of GLAS measurements. We will also show examples of CPL data used to simulate various aspects of the upcoming CALIPSO mission, which will eventually lead to validation of the CALIPSO lidar. Finally, we will provide a brief introduction to CPL and other airborne data used as proxies for future A-Train measurements for the purpose of developing synergistic algorithms.

2. THE CPL INSTRUMENT

The CPL is a compact elastic backscatter lidar system that provides multi-wavelength measurements of cirrus, subvisual cirrus, and aerosols with high temporal and spatial resolution. The instrument provides information to permit a comprehensive analysis of the radiative and optical properties of optically thin clouds (< optical depth 3). The CPL utilizes state-of-the-art technology with a high repetition rate, low pulse energy laser and photon-counting detection.

The CPL uses a Nd:YVO_4 laser operating at 1064, 532, and 355 nm with a repetition rate of 5 kHz. Use of a low pulse energy, high repetition-rate laser permits photon-counting detection while still maintaining an adequate dynamic range for the measurement. Further details of the instrument design can be found in McGill *et al* [2002].

The CPL instrument is similar to both the GLAS and CALIPSO spaceborne lidars, those also being elastic backscatter systems. Because the ER-2 aircraft typically flies at 65,000 ft (~20 km), the CPL acts as a quasi-spaceborne instrument. The measurement similarity and high-altitude operation therefore permit CPL to act as a simulator and validation tool for the spaceborne lidars.

3. CPL VALIDATION FOR GLAS

The GLAS atmospheric lidar instrument is the first satellite-based lidar. Launched in January 2003, the GLAS lidar provides atmospheric profiling at both 1064 and 532 nm. The 532 nm channel of GLAS relies on photon-counting detectors, similar to those used in CPL.

During October 2003 the CPL was used on seven calibration/validation flights in support of the GLAS mission. Flying from NASA Dryden, flights targeted a variety of cloud and aerosol conditions to verify GLAS operation over a wide dynamic range of signals.[Hlavka *et al*, 2004]

Difficulties inherent to validation of spaceborne lidar include homogeneity of the viewing scene, temporal and spatial alignment of the airborne instrument relative to the spacecraft, and different multiple scattering contributions to each measurement. In each of the underflights, the ER-2 pilot was able to get within 10's of meters of the sub-satellite track at the time of overpass (one case was within 10 m). Figure 1 shows the CPL and GLAS data from the underflight of October 19, 2003. The similarity in the vertical and horizontal structure is truly remarkable and lends credibility to the concept of calibrating the spaceborne lidar using an airborne system.

To obtain cloud or aerosol optical depth from airborne or spaceborne lidar data requires an assumption that multiple scattering can either be

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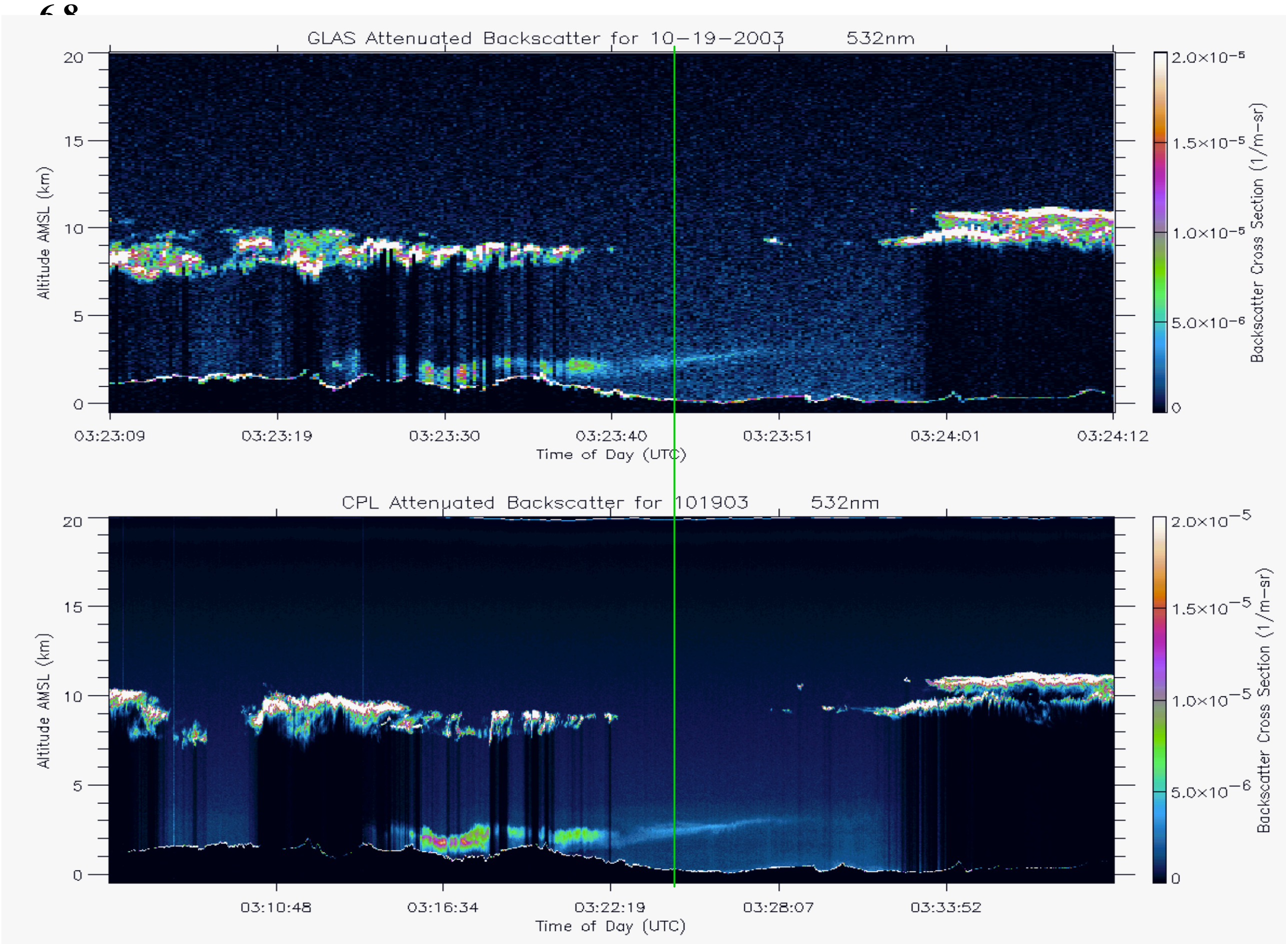

Figure 1: Comparison of CPL and GLAS 532 nm backscatter profiles from October 19, 2003. The green line marks the overpass time of the satellite. At the overpass time, the ER-2 was within 167 m of the sub-satellite track. CPL requires 45 minutes to traverse the same 1.5 minute orbit track of the GLAS lidar. Results have been generated comparing layer location and type, optical depth, and extinction retrievals between CPL and GLAS, and those results will be shown in the presentation.

reliably quantified or neglected. For the CPL instrument multiple scattering is small due to the narrow field of view of the receiver (100 μradians, full angle). The CPL field of view limits multiple scattering contributions to ~5-10%, and the effect is largely ignored in data processing. Multiple scattering in GLAS is usually too significant to be ignored, so an operational procedure has been developed to quantify it using a multiple scattering correction factor.

4. CPL APPLICATIONS TO CALIPSO

The CALISPO mission, scheduled for launch in early 2005, has made extensive use of CPL data for instrument performance simulation and testing of data processing algorithms. The CALIPSO lidar operates at 1064 and 532 nm, so CPL data provides a good proxy for the CALIPSO measurements.

One example of CPL data being used to test CALIPSO algorithms is given in Figure 2. This figure shows results of the CALIPSO threshold-based, multi-resolution feature finder algorithm that will be used to find cloud and aerosol layer boundaries in the CALIPSO backscatter data.[Vaughan *et al*, 2004] The top panel in Figure 2 shows the CPL 532 nm attenuated backscatter profiles from February 19, 2003. The center panel shows synthetic CALIPSO data derived directly from the CPL measurements using the CALIPSO simulation software.[Powell *et al*, 2002] The bottom panel shows the layer boundaries determined by the CALIPSO feature finding algorithm. Use of CPL data by the CALIPSO algorithm development team provides two significant benefits. First, the synthetic data used in algorithm testing contains all of the natural variability of real-world measurements. Second, the results obtained using the CALIPSO algorithm

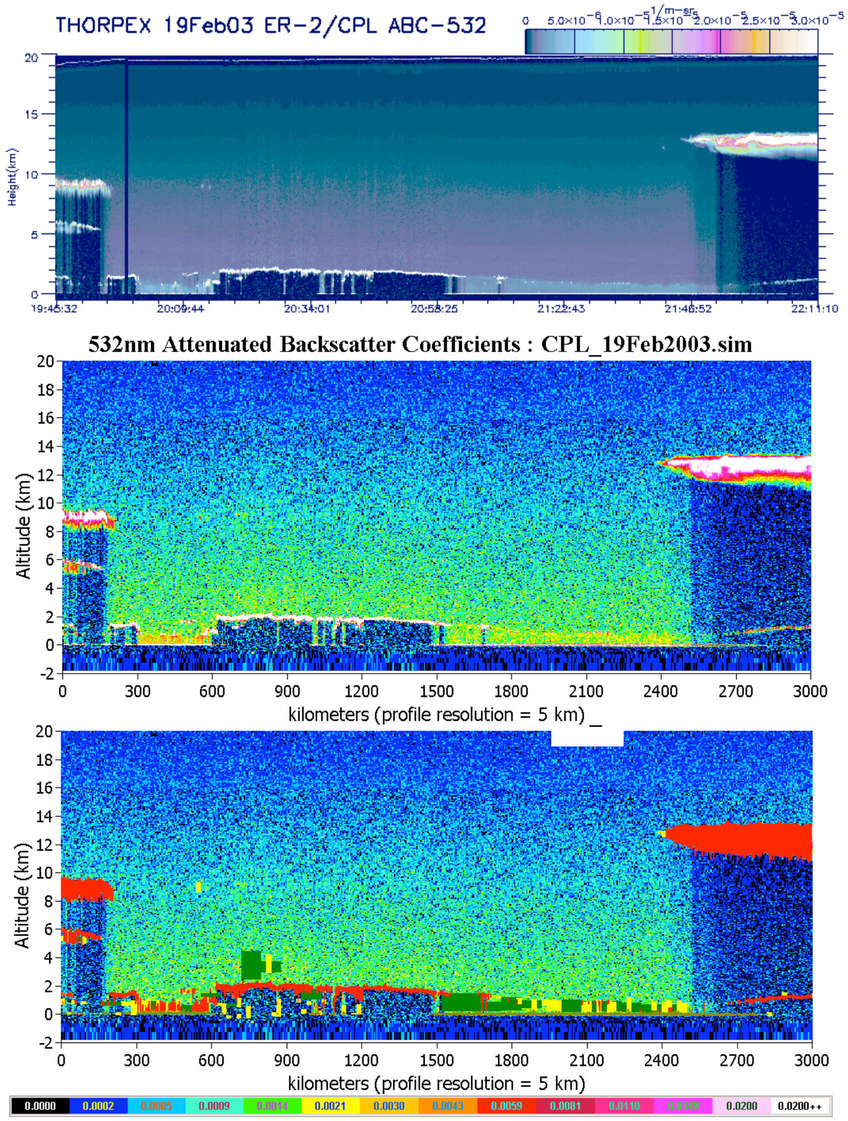

Figure 2: Using CPL data to test the CALIPSO feature-finder algorithm. The top panel shows CPL attenuated backscatter measurements at 532 nm. The center panel shows results of processing the CPL measurements using the CALIPSO simulation software. The bottom panel shows layer boundaries obtained by applying the CALIPSO multi-resolution feature-finder algorithm. The red, yellow, and green colors indicate layers found at horizontal averaging resolutions of 5-km, 20-km, and 80-km, respectively [Vaughan *et al*, 2002]

can be compared directly to those provided in the CPL data product.

Unlike GLAS, CALIPSO makes a depolarization measurement in addition to the total backscatter measurement. Data from the CPL depolarization channels has been used to simulate CALIPSO measurements and to generate a calibration scheme for the depolarization channels.[Liu *et al*, 2004]

After CALIPSO launches in 2005, the CPL instrument will provide, as possible, calibration/validation underflights similar to those done for GLAS.

5. DATA SYNERGY FOR NASA's A-TRAIN

Both CALIPSO and CloudSat [Stephens *et al*, 2002] will fly as part of NASA's A-Train of Earth observing satellites. During the Cirrus Regional

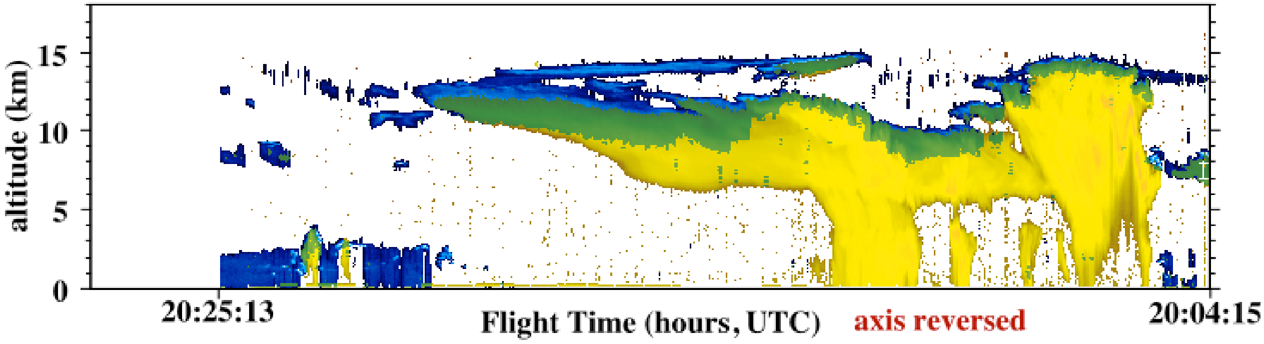

Figure 3: Example of lidar-radar data synergy from CRYSTAL-FACE (July 23, 2002). In this image, areas shaded blue represent cloud/aerosol layers observed only by the lidar, areas shaded yellow were observed only by the radar, and areas shaded green were observed by both the lidar and the radar. This data synergy demonstrates the potential of the future CALIPSO and CloudSat missions. From McGill *et al* (2004).

Study of Tropical Anvils and Cirrus Layers – Florida Area Cirrus Experiment (CRYSTAL-FACE) field campaign [Jensen *et al*, 2004] during 2002 the ER-2 aircraft carried the CPL, the new 94 GHz Cloud Radar System (CRS) [Li et al, 2004], and the MODIS Airborne Simulator (MAS) [King and Herring, 1992; King *et al.*, 1996]. This suite of instruments is an ideal simulator for the A-Train instruments.

An immediate result from CRYSTAL-FACE was an example of the power of data synergy among multiple instruments. CRYSTAL-FACE permitted the first high-altitude combined lidar-radar measurements, an accomplishment that simulated measurements from the future CALIPSO and CloudSat missions. The CPL and the CRS acted as proxies for the CALIPSO and CloudSat instruments, respectively. Figure 3 shows an example of the data synergy that results from combining the lidar and radar data. Note in Figure 3 that neither instrument alone senses all cloud or aerosol layers. The lidar is ideal for detecting thin cirrus and aerosol layers, while the radar is ideal for probing optically thick clouds that are impenetrable by the lidar.[McGill *et al*, 2004]

Another important effort that is developing from CRYSTAL-FACE is development of multi-instrument data fusion techniques to combine data from the A-Train satellites. Figure 4 illustrates the inherent synergy between passive and active remote sensing instruments. Development of algorithms to combine active and passive sensors (we call it MIDAS, for Multi-Instrument Data Analysis and Synthesis) will be an important contribution to A-Train measurements. Combining the horizontal coverage of passive instruments with the excellent vertical resolution provided by lidar will greatly improve the identification and classification of atmospheric features.

6. SUMMARY

The CPL instrument provides profiling of cloud and aerosol properties with high spatial and temporal resolution. The CPL has been used for calibration/validation of the GLAS atmospheric lidar. The forthcoming CALIPSO mission will also utilize CPL for validation, and in the meantime that mission has made extensive use of CPL data for simulation and algorithm testing.

Validation of satellite lidar instruments is an obvious application of CPL data. But, as is being shown from our MIDAS effort, CPL data can be used to develop advanced retrieval algorithms that exploit the inherent synergy of active and passive remote sensors. Development of such algorithms will improve the utility of NASA's A-Train of satellites.

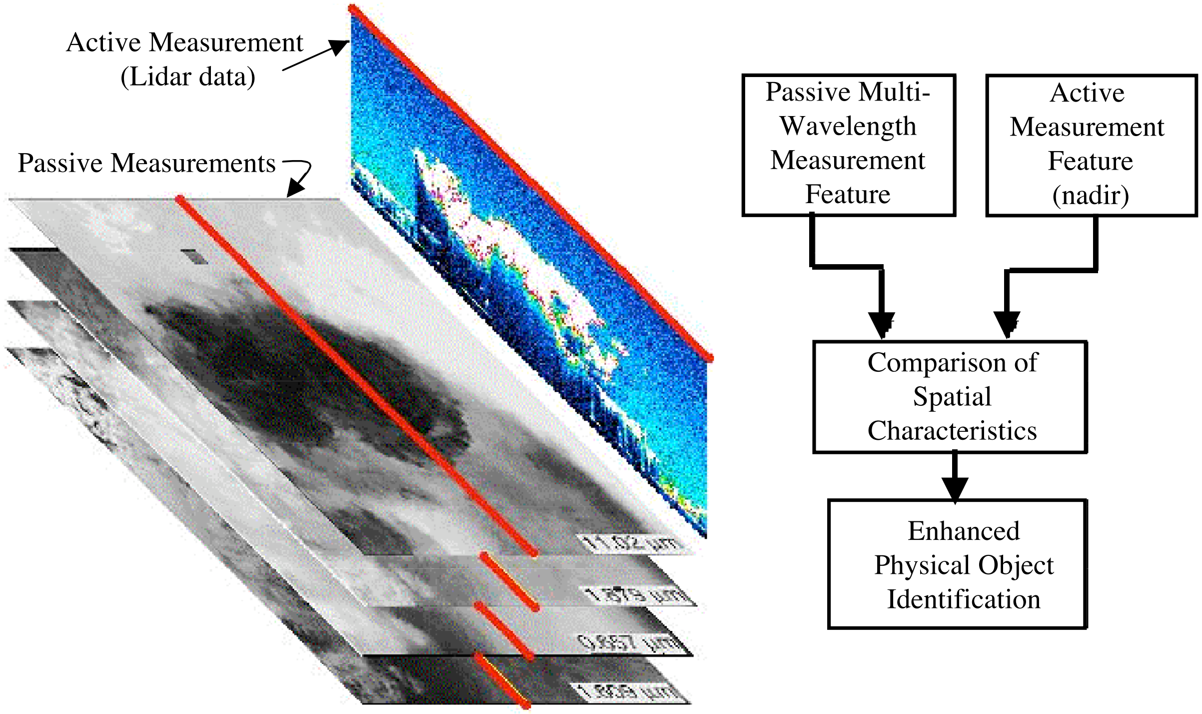

Figure 4: Concept of combining passive and active measurements. The vertical resolution of the lidar measurement is a natural complement to the horizontal coverage provided by passive imagers. At nadir view, most cloud and aerosol objects can be well identified using combined active and passive measurements.

7. REFERENCES

Hlavka, D.L., W.D. Hart, S.P. Palm, M.J. McGill, and J.D. Spinhirne, 2004: "Initial validation and results of Geoscuience Laser Altimeter System optical properties retrievals," in Proceedings of the International Geoscience and Remote Sensing Symposium (IGARSS), Anchorage, Alaska, 20-24 September 2004.

King, M. and D. Herring, 1992: "The MODIS Airborne Simulator (MAS)," *Earth Observer Magazine*, Nov-Dec 1992.

King, M.D., W.P. Menzel, P.S. Grant, J.S. Myers, G.T. Arnold, S.E. Platnick, L.E. Gumley, S.C. Tsay, C.C. Moeller, M. Fitzgerald, K.S. Brown, and F.G. Osterwisch, 1996: "Airborne scanning spectrometer for remote sensing of cloud, aerosol, water vapor, and surface properties," *Journal of Atmospheric and Oceanic Technology*, **13**, 777-794.

Li, L., G.M. Heymsfield, P.E. Racette, L. Tian, and E. Zenker, 2004: "The 94 Ghz Cloud Radar System on the NASA ER-2 Aircraft," *Journal of Atmospheric and Oceanic Technology*, **21**, 1378-1388.

Liu, Z., M. McGill, Y. Hu, C.A. Hostetler, M. Vaughan, and D. Winker, 2004: "Validating lidar depolarization calibration using solar radiation scattered by ice clouds," *Geoscience Remote Sensing Letters,* **1**, 157-161.

McGill, M.J., D.L. Hlavka, W.D. Hart, V.S. Scott, J.D. Spinhirne, and B. Schmid, 2002: "The Cloud Physics Lidar: instrument description and initial measurement results," *Applied Optics*, **41**, 3725-3734.

McGill, M.J., L. Li, W.D. Hart, G.M. Heymsfield, D.L. Hlavka, P.E. Racette, L. Tian, M.A. Vaughan, and D.M. Winker, 2004: "Combined lidar-radar remote sensing: initial results from CRYSTAL-FACE," *Journal of Geophysical Research*, **109**, doi: 10.1029/2003JD004030.

Palm S., W. Hart, D. Hlavka, E. Welton, A. Mahesh, and J. Spinhirne, 2002: *Geoscience Laser Altimeter System (GLAS) Algorithm Theoretical Basis Document Version 4.2: GLAS Atmospheric Data Products*, NASA Goddard Space Flight Center, October 2002.

Powell, K. A., W. H. Hunt, and D. M. Winker, 2002: "Simulations of CALIPSO Lidar Data", in *Lidar Remote Sensing in Atmospheric and Earth*

Sciences, L. R. Bissonnette, G. Roy and G. Vallée (editors), Defence R&D Canada - Valcartier, Québec, Canada, pp. 781-784.

Stephens, G.L., D.G. Vane, R.J. Boain, G.G. Mace, K. Sassen, Z. Wang, A.J. Illingworth, E.J. O'Connor, W.B. Rossow, S.L. Durden, S.D. Miller, R.T. Austin, A. Benedetti, C. Mitrescu, and the CloudSat Science Team, 2002: "The CloudSat mission and the A-Train: A new dimension of space-based observations of clouds and precipitation," *Bulletin of the American Meteorological Society*, **83**, 1771-1790.

Vaughan, M. A., D. M. Winker, and C. A. Hostetler, 2002: "SIBYL: a Selective Iterated Boundary Location Algorithm for Finding Cloud and Aerosol Layers in CALIPSO Lidar Data", in *Lidar Remote Sensing in Atmospheric and Earth Sciences*, L. R. Bissonnette, G. Roy and G. Vallée (editors), Defence R&D Canada - Valcartier, Québec, Canada, pp. 781-784.

Vaughan, M., S. Young, D. Winker, K. Powell, A. Omar, Z. Liu, Y. Hu, and C. Hostetler, 2004: "Fully automated analysis of space-based lidar data: an overview of the CALIPSO retrieval algorithms and data products", in *Laser Radar Techniques for Atmospheric Sensing*, U. Singh (editor), Proc. SPIE Vol. 5575 (in press).

Winker, D.M., J. Pelon and M.P. McCormick, 2002: "The CALIPSO Mission: spaceborne lidar for observation of aerosols and clouds," in *Proceedings of SPIE*, Vol. 4893 (U. Singh, T. Itabe, Z. Liu eds.), 1-11, Hangzhou, China, 24-25 October 2002.

Zwally, H.J., B. Schutz, W. Abdalati, J. Abshire, C. Bentley, A. Brenner, J. Bufton, J. Dezio, D. Hancock, D. Harding, T. Herring, B. Minster, K. Quinn, S. Palm, J. Spinhirne, and R. Tomas, 2002: ICESat's laser measurements of polar ice, atmosphere, ocean, and land," *Journal of Geodynamics*, **34**, 405-445.