12.5 Airborne Doppler Wind Lidar: In-flight visualization and analysis using Google Earth

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1. INTRODUCTION

An airborne Doppler Wind Lidar (DWL) is coupled with Google Earth (GE) for real-time in-flight visualization of wind speed and direction, and atmospheric backscatter cross section. External user interfaces are added to enhance GE capabilities and usability in the airborne environment. Additional information including gridded meso-scale model output is superimposed in GE for comparison studies and flight experiment planning. The system architecture supports real-time feedback for in-flight experiment plan modification, and reprogramming of the scanning DWL sampling pattern. Various DWL products are demonstrated in post-flight analysis mode using GE for several topographic environments.

2. In-Flight Data Processing & Operations

Over the past ten years, the US Navy and the Integrated Program Office (IPO) of National Polar-orbiting Operational Environmental Satellite System (NPOESS) has funded the development of an airborne coherent DWL. The DWL was initially mounted in a Navy Twin Otter aircraft to conduct a

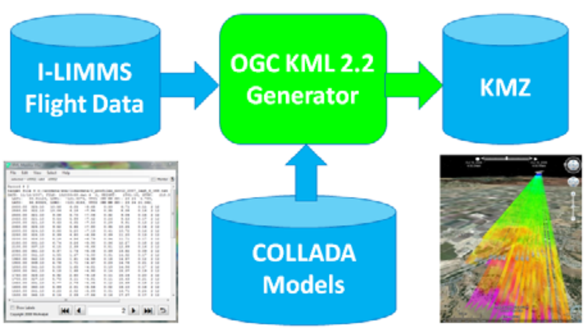

Figure 1 – Onboard algorithms are used to generate KML/COLLADA structures for DWL real-time data during flight operations.

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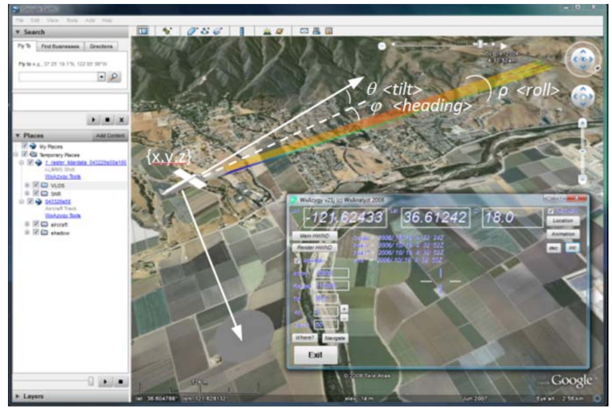

Figure 2 – Geometry of a scanning DWL profile, shown *in situ* from an arbitrary perspective with respect to the aircraft platform. WxAnalyst's WxAzygy™ Interactive Interface is overlaid onto Google Earth for data visualization and user control of flight data processing.

variety of atmospheric investigations. Under the direction of Simpson Weather Associates (SWA) and operated by the Navy's Center for Interdisciplinary Remotely Piloted Research Studies (CIRPAS), the Twin Otter DWL (TODWL) has flown more than 125 hours of atmospheric missions since 2002 with most of that within 50 - 100 km of the shore near Monterey, CA. The most recent TODWL missions took place in April and November of 2007. In addition, the DWL was flown aboard a P3 aircraft during the 2008 TPARC experiments to measure winds in the vicinity of typhoons.

Among the major objectives of the past TODWL campaigns were the following:

- Characterization and description of the low-level 3-D wind field over water and complex terrain, and comparison with meteorological observations (Greco and Emmitt, 2005; Greco et al., 2008)
- Study of returns from water surfaces (Emmitt et al., 2005a)
- Investigation of Organized Large Eddies (OLE) over the open ocean (Emmitt et al., 2005b)
- Validation of numerical model predictions of flow over complex terrain (Greco and Emmitt, 2005; Greco et al., 2008)
- Validation of space-based wind sensors such as scatterometers and cloud motion vector imagers (Emmitt et al., 2004)

More recently, SWA has been funded by the Office of Naval Research (ONR) to develop an In-flight Lidar Integrated Mission Management System (I-LIMMS) for TODWL that would provide real-time on-board data processing and data visualization for flight missions. Such processing is performed "on the fly" using a laptop computer aboard the aircraft, and is fast enough to keep up with in-flight data rates.

A flow diagram of the I-LIMMS in-flight data processing chain is shown in Figure 1. In-flight DWL data (plain text) are coupled with pre-designed COLLADA models to generate compressed Keyhole Markup Language (KML) packages (*.KMZ) for display on a Virtual Globe (VG) such as GE. The resulting "structures" can be used to display raw lidar shot data as shown in Figure 2. Google Earth is also able to support these operations in real-time without connection to the internet.

KML makes it relatively easy to locate a DWL shot using aircraft position {x,y,z} and orientation {heading or bearing, pitch, roll} plus the 3-axis orientation of each laser scan. The use of VG technology relieves the authors of the details of display mechanics, so we can concentrate on data content, calibration, and field experiment conduct. The DWL creates multiple parameters along each laser shot, including radial wind speed (left) and laser backscatter (right) as shown in Figure 3. KML can also be used to simultaneously display multiple parameters. Tests for spatial registration were performed to verify that each laser profile was correctly located with respect to geographic features. Vertical stare samples were also used to verify the accuracy of GE terrain height.

The WxAnalyst WxAzygy™ Interface is shown in Figure 2 as a coupled overlay on top of GE. This

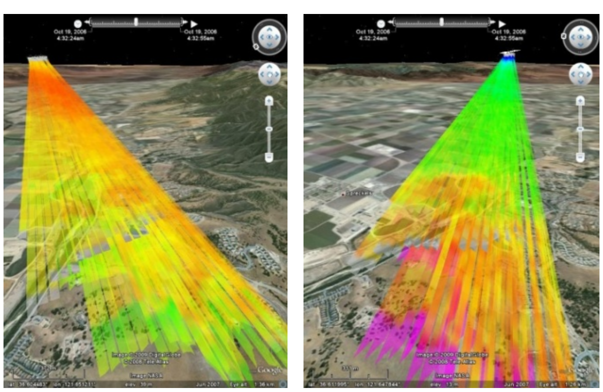

Figure 3 – Forward perspective of accumulated laser shots for radial velocity (left) and backscatter cross section (right).

interface uses the standard GE API to provide alternative user controls, including larger buttons for use in the aircraft environment. This interface also allows user point and click to extract "location at cursor" for use in flight planning. As shown later in Section 4, the GE API also supports coupling of experimental data records with ICONS as KML Placemarks.

3. Wind Profile Generation and Display

KML and GE are utilized together for real-time in-flight visualization of wind and aerosol data taken by an airborne DWL. KML and COLLADA models have been used to display DWL products within GE as vertical profiles and cross-sections as shown in Figure 4, with color scale as defined by Figure 5. Additional DWL products are provided on-line for several topographic environments at http://www.swa.com/ald/ILIMMS/. After much experimentation, the wind barb stack shown in Figure 4 was found to provide the best visualization for DWL wind profile speed *AND* direction. Wind speed is conveyed both by color and wind barb length. The DWL wind barbs are defined at vertical intervals of 50 m.

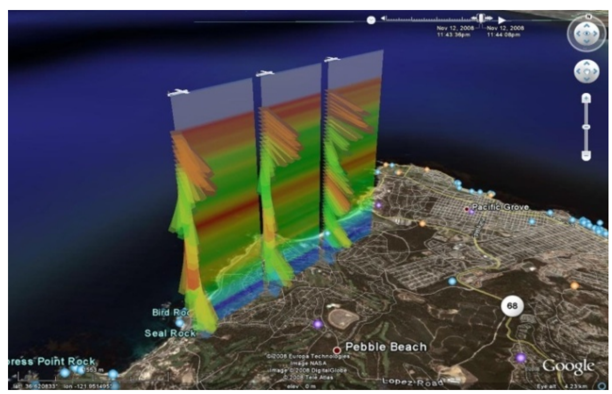

Figure 4 – Wind speed and direction shown as wind barbs, with wind speed cross section over Monterey, CA. Wind Speed color scale is given in Figure 5.

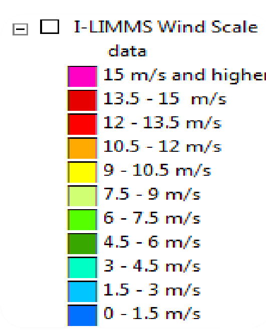

Figure 5 –Wind Speed color scale for all figures in this paper.

4. Interactive Coupling of Google Earth with an External Application

We have exploited the GE API to provide interactive coupling of KML visualization with an external application. A typical application named "KML Monitor" is shown in Figures 6 and 7, where data records are encoded in the display as ICONs. When the KML Monitor application is running, a user click on an enabled ICON provides data record information, which is then used to display the corresponding raw data as inset in Figure 6. Since the user has full control of the coupled external application, arbitrary processes can be invoked in real time, such as the more conventional wind profile plot shown in Figure 7. The KML Monitor coupling concept opens up GE applications to a wider range of functions using visualized information to guide user actions and understanding.

5. Comparison to Simultaneous Collocated Data Sources

An example of part of a typical TODWL flight mission is shown in Figure 8. This sortie occurred during the most recent TODWL campaign on November 12, 2007. These profiles were used to help characterize the boundary layer in the coastal regions of central California near Monterey. From Figure 8 we can see the existence of an elevated jet or wind maximum (over 10 to 12 m s^{-1}) over both the inland and coastal terrain. However, the transition to a stronger jet and a deeper layer of high winds as we go from inland to the coast is also clearly illustrated. These data are also shown in Figure 9 together with near-simultaneous 4km MM5 model forecasted wind profiles for the same vicinity.

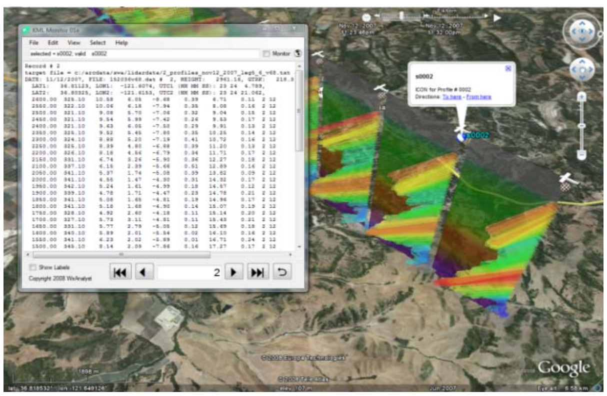

Figure 6 – KML Monitor function, supporting user applications through ICON. Table is shown for processed lidar data corresponding to clicked ICON.

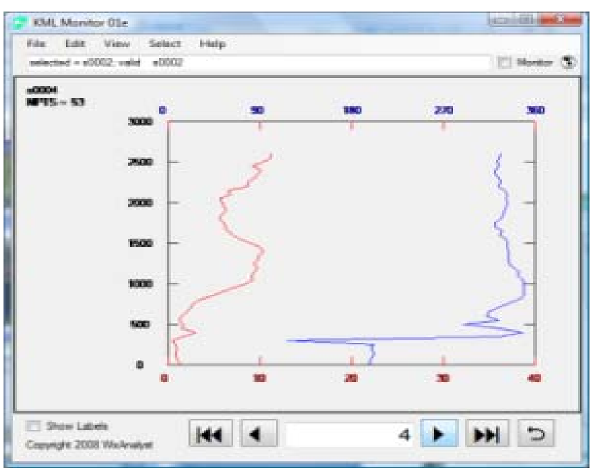

Figure 7 – Alternate KML Monitor panel showing traditional height plots of wind speed (red, left) and direction (blue, right).

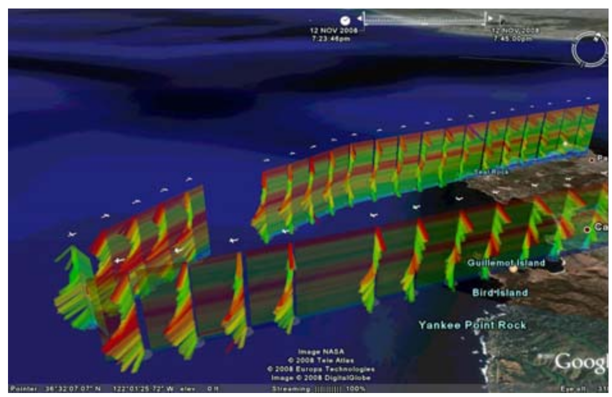

Figure 8 – Legs 5 and 6 of the 12 November 2007 field sortie in the vicinity of Monterey, CA.

Figure 9 – Juxtaposition DWL wind cross sections with 4km MM5 meso-scale model output for same time period. The MM5 does not resolve low-level wind shear associated with fine scale flow about the local terrain.

The DWL was flown aboard a P3 aircraft in the western Pacific Ocean as part of the 2008 TPARC field experiment. One of the initial missions occurred on 16-17 August 2008 in the vicinity of Tropical Cyclone Nuri as shown in Figure 10. DWL KML/COLLADA products described in this paper were derived during the field experiment. A close up of DWL data near the TC track is shown in Figure 11.

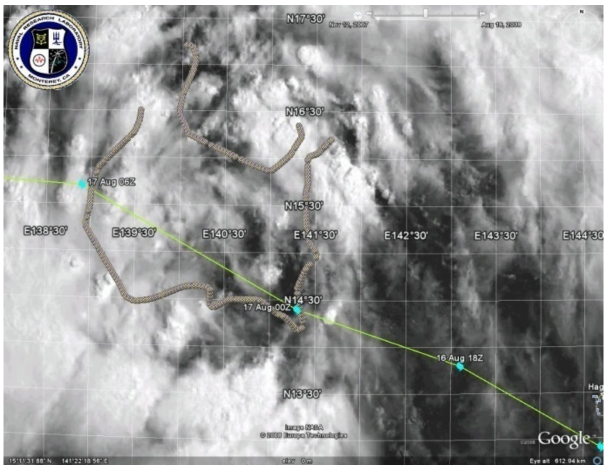

Figure 10 – Typhoon Nuri penetrations by a DWL instrumented P3 aircraft operating out of Guam, *TPARC 2008*.

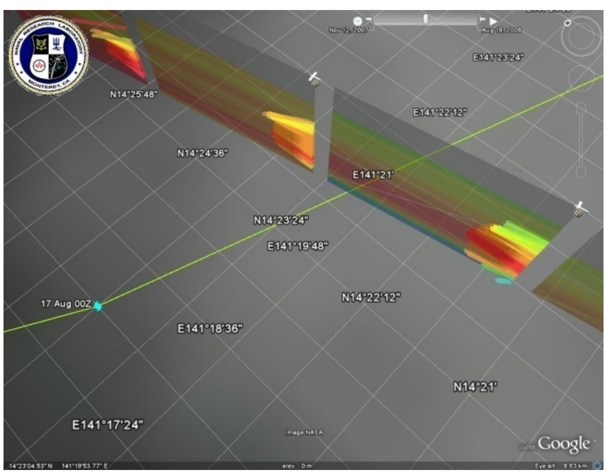

Figure 11 – Close up of GE visualization during Typhoon Nuri penetrations by a DWL instrumented P3 aircraft operating out of Guam, *TPARC 2008*.

6. CONCLUSIONS

We have demonstrated in-flight Google Earth (GE) operations for in situ experiment support. KML was generated "on the fly" with sufficient throughput to keep up with DWL data generation speed. The GE Applications Programmer Interface (API) was also used to demonstrate custom tools and coordinated operation of external user-defined applications. External API-based tools such as the WxAnalyst WxAzygy™ Interface can be used to change DWL scanning patterns in flight, and will enable new strategies for adaptive experiment modification.

7. ACKNOWLEDGMENTS

Google Earth is a Trademark of Google, Inc., copyright (2008) Google, Inc. WxAzygy™ Tools copyright (2008) WxAnalyst, LTD. *This work has been made possible through the support of the Office of Naval Research (ONR).*

8. REFERENCES

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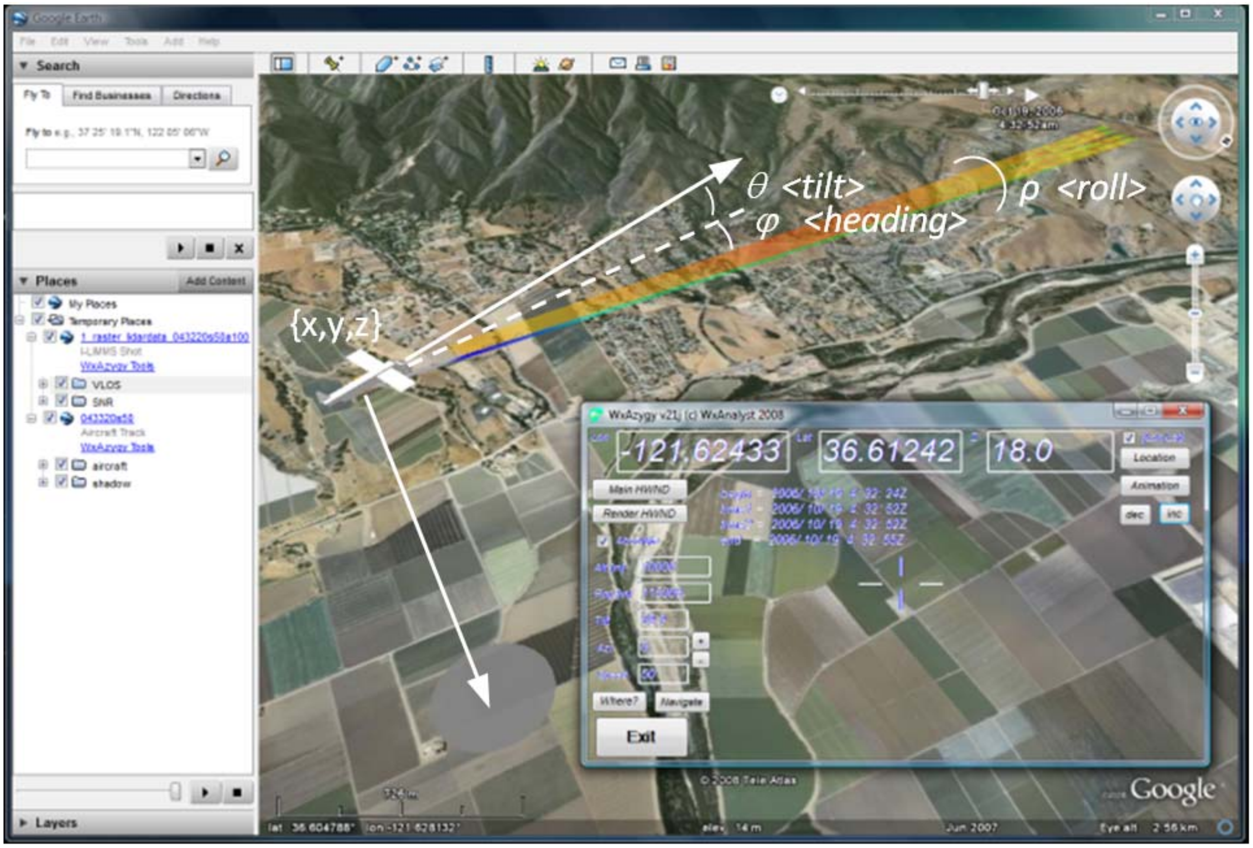
Addendum – Higher resolution versions of Figures 2, 3 and 6 for inspection.



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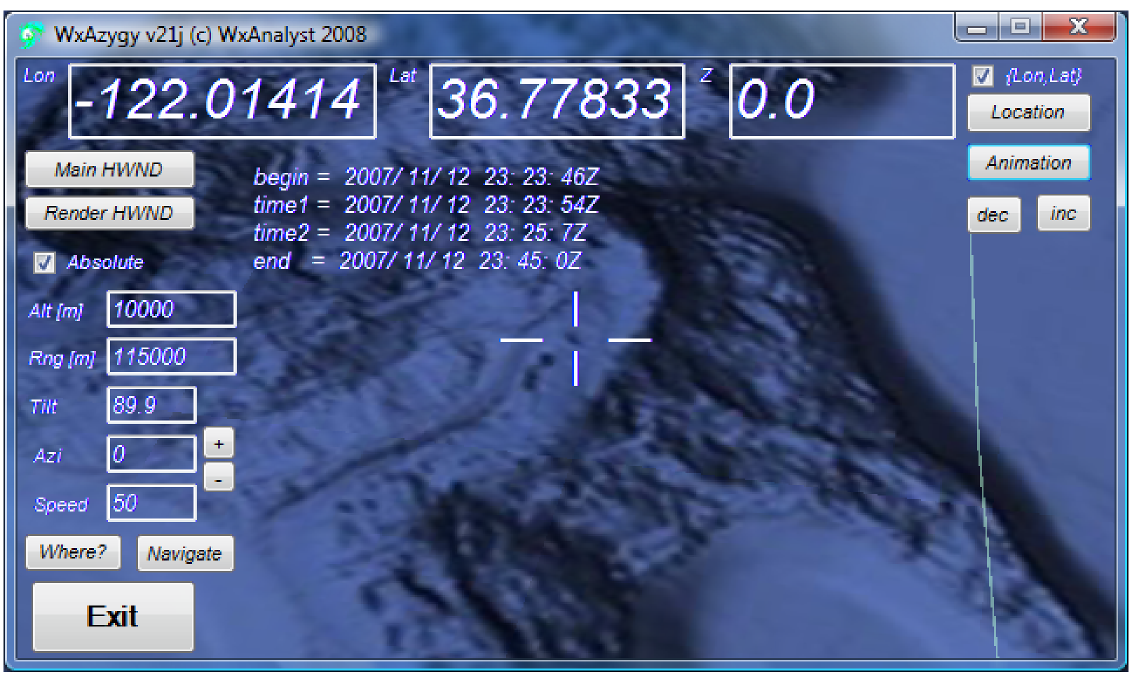
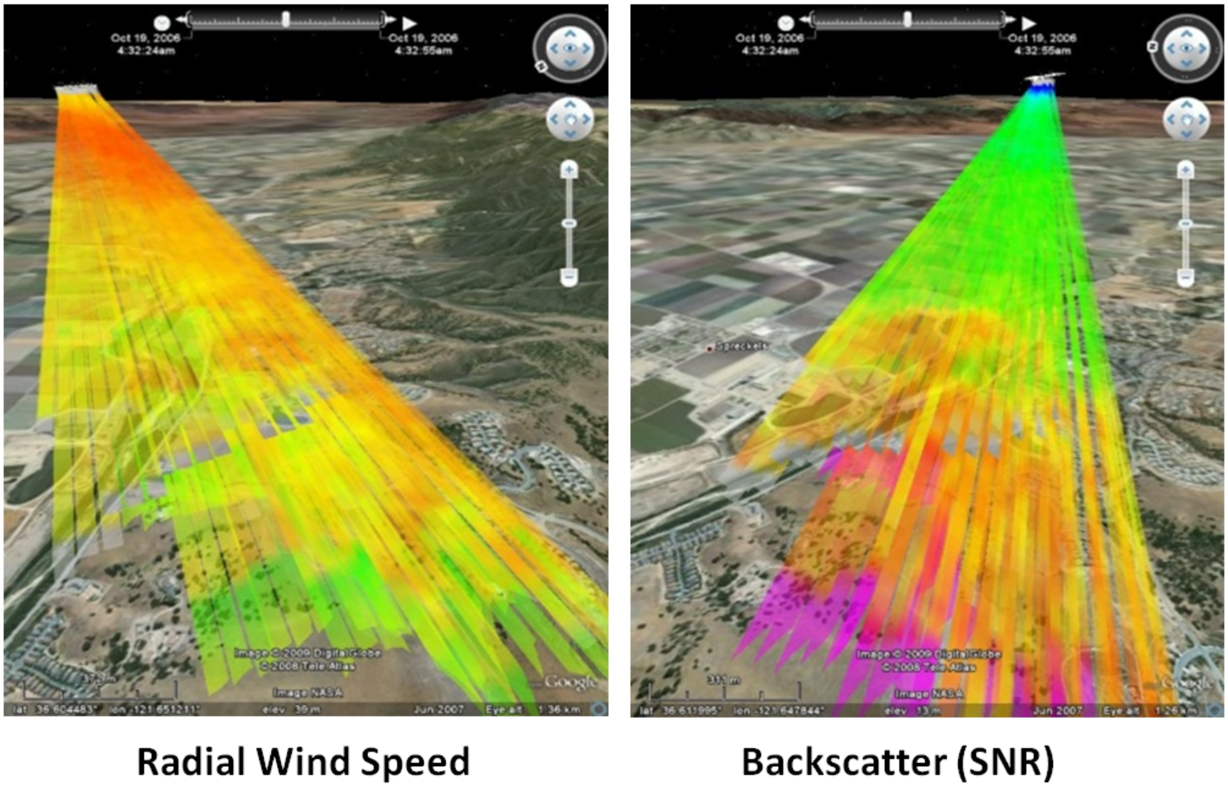


Figure 2 inset – WxAzygy™ interface (at different location).



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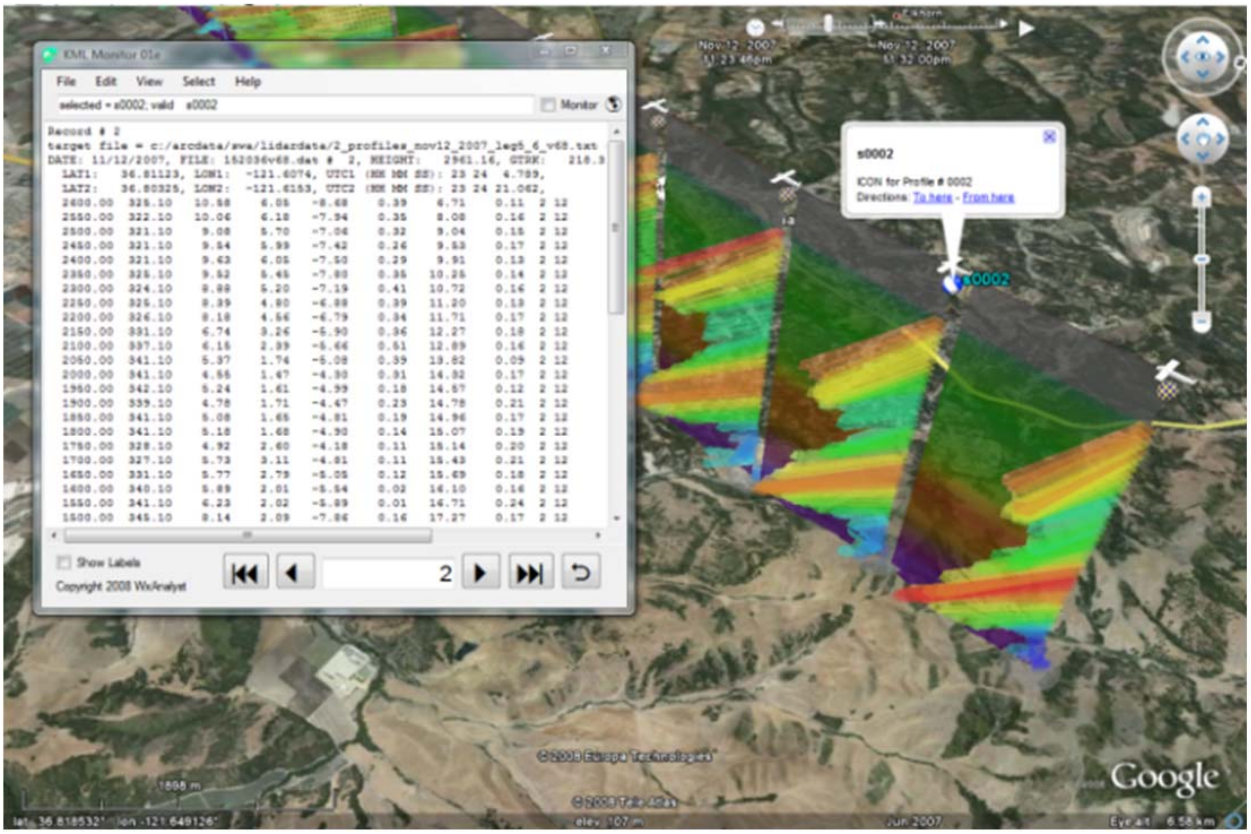

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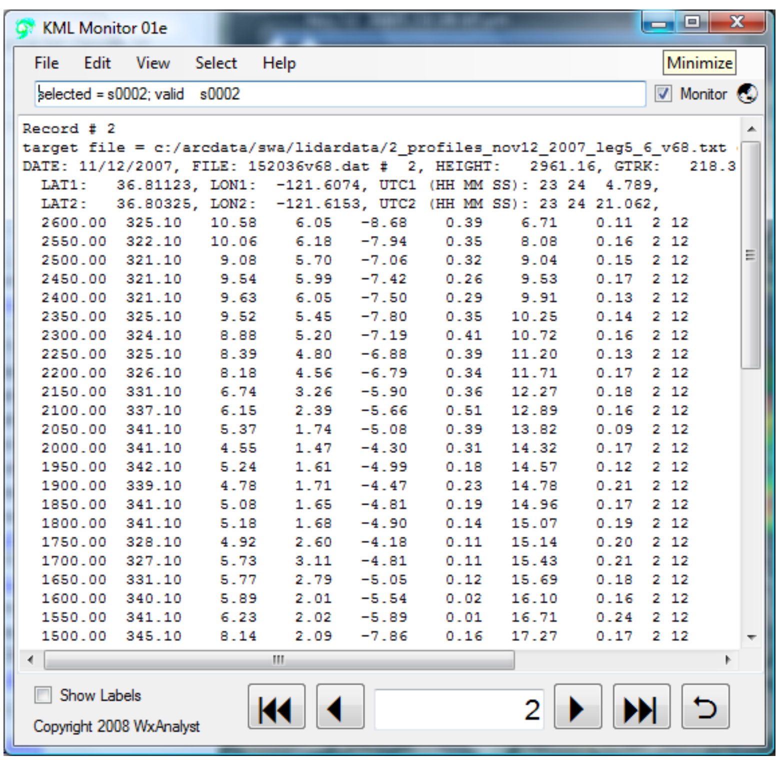

Figure 6 inset – KML Monitor.