

A Doppler wind lidar based atmospheric energy harvesting system for autonomous in-flight guidance and path planning of small aircraft

SBIR Phase II Final Technical Report

1.0 Introduction

The objective of this SBIR was to develop software and algorithms that can be used to extend the endurance (measured in hours) of UAV's flight time by "harvesting" energy from the atmosphere. By simulation, the approach developed is expected to extend time aloft by factors as high as 300% in the case of autonomous mountain wave surfing. In the Figure 1 description of the Atmospheric Energy Opportunity Ranking Algorithm (AEORA) system, the "Pre-flight" activities involve consideration of the large scale atmosphere (model) and the probability or general likelihood of various atmospheric energy features occurring within the region of interest. As mentioned in the Phase I proposal, the energy opportunities that we considered suitable for DWL detection, characterization (location, life-cycle state, energy harvesting potential,,) and ranking by AEORA include thermals, cloud updrafts, mountain waves, obstacle flow, shear zones and Organized Large Eddies (OLEs). The "rapid update" of the "In-flight" DWL prospecting would happen in intervals of less than 1 minute and be continually updating the opportunity detection, life cycle status, platform energy/power utilization, predictions for future opportunities and the generation of trajectories/flight path instructions.

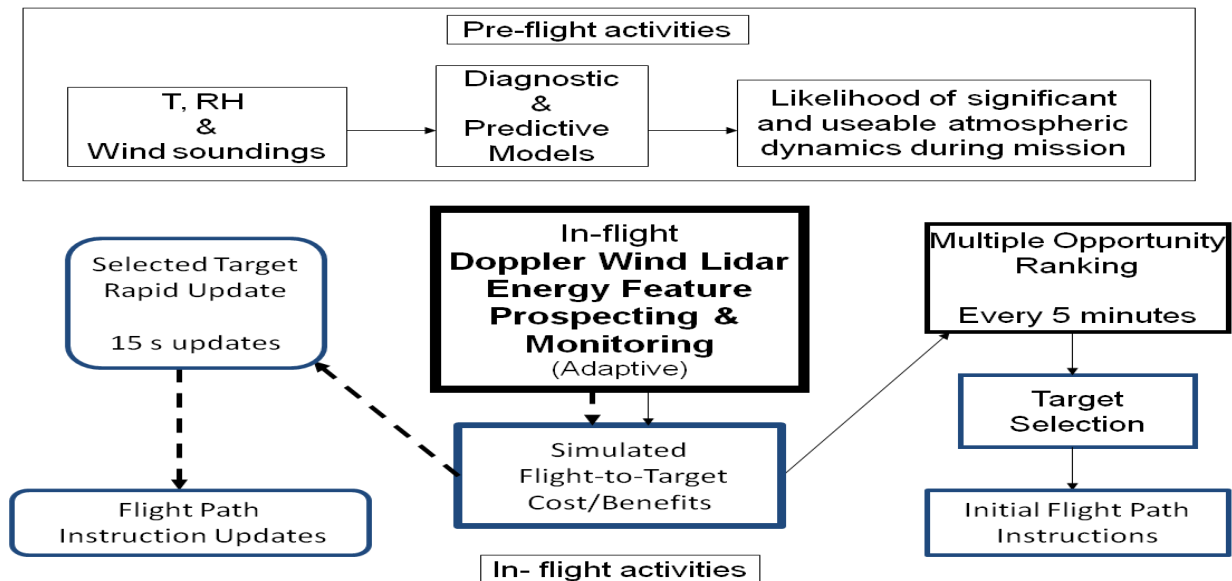


Figure 1: Flow diagram of the envisioned Atmosphere Energy Opportunity and Ranking Algorithms (AEORA).

This document serves as both a final report and an users guide to using the tool called AEORA Mission Planning Tool (AMPT), main screen shown in Figure 2.0. A Power Point slide presentation is also included on the AEORA laptop for a condensed description of the rationale for this SBIR project and a brief

summary of its accomplishments. There is also significant and helpful information in the SBIR's progress reports which are available from SWA or the SBIR COR.

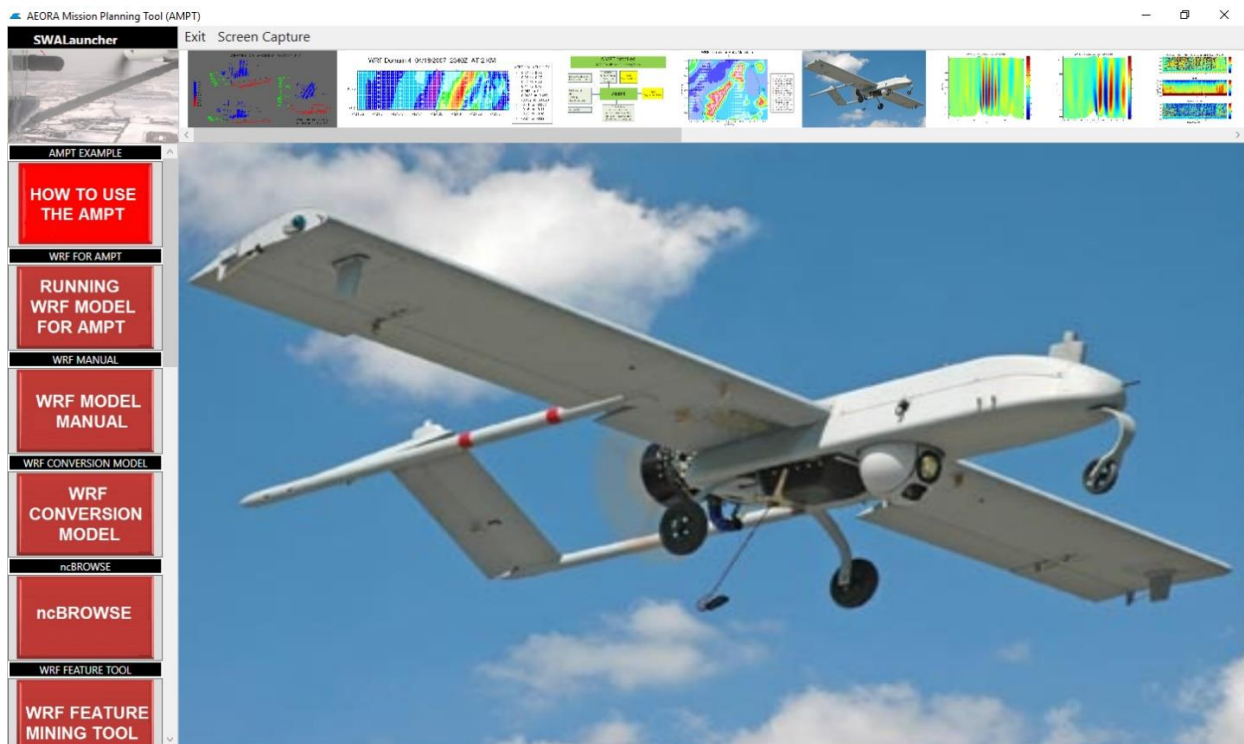


Figure 2.0 AEORA Mission Planning Tool Main Screen

2.0 Atmospheric Energy Opportunity Ranking Algorithm (AEORA) system

Here, we briefly describe the essence of the AMPT and the expected impact on UAV missions determined by simulation per the SBIR I Final Report (Simpson Weather Associates, Inc., 2012). The inspiration for this project has been, in large part, Simpson Weather Assoc., Inc. (SWA)'s 15 years experience flying research aircraft (e.g. Twin Otter) instrumented with DWLs and recognizing the value of “seeing” where the mountain waves are (troughs vs ridges) or where the thermals are relative to the location of the aircraft. (Emmitt et. al., 2014; Emmitt et. al., 2014; Emmitt et. al., 2008).

Validation of our ability to recognize the signatures of advantageous vertical motions on or near flight level has been done in a limited fashion and need further validation and refinement with dedicated flights.

The use or harvesting of energy for the purpose of staying aloft and/or extending the endurance of an airborne platform is not new. Birds use atmospheric energy to their advantage as well as glider pilots who use thermals and mountain waves to gain altitude or maintain an altitude for long periods of time. What we have done with AMPT is to construct a methodology for the autonomous use of these energy sources and to introduce the use of a DWL to maximize the energy extraction by micro navigating the craft along paths that avoid or minimize downward motions and lead to areas of upward motion. What we have not done (consistent with original proposal) is to demonstrate this proposed capability with a

real flight program that includes a DWL. That phase is currently being discussed and plans to perform such a demonstration are in progress at ARL.

AEORA, designed and managed by SWA, is composed of four primary components or function modules:

1. A mission planning tool, AMPT, built upon a 'state of the art' fine scale numerical weather model running together with a 6 degree of freedom flight simulator. (SWA's primary contribution)
2. A flight path planner and optimal energy extraction algorithm that uses input from the platform instruments and the DWL to provide instructions to the flight control module. (Earthly Dynamics Corporation (EDC)'s primary contribution)
3. The flight control module that carries out the set of instructions generated by path planner (Aurora Flight Sciences Corporation's primary contribution)
4. The mission objective manager that includes instructions that may limit flight levels, basis for Return To Base (RTB), and any other restrictions on the mission that may not always optimize the extraction of the available energy (SWA contribution)

The harvesting of energy from the atmosphere is accomplished in four phases;

1. Use the Weather Research and Forecasting (WRF) Model to estimate the potential of various modes of vertical energy potential within a region of interest (e.g. a CONOPS to establish a secure communications relay station above the ridge of a nearby mountain range).
2. By simulation, use the AMPT and UAV platform performance metrics to generate several "routes to energy target" that allow the user to juggle fuel consumption, time to target and mission constraints (e.g. flight over threatening terrain).
3. Identify the entry point to the energy rich field (e.g. thermals, mountain waves, small active clouds, etc.) where "micro navigation" using an onboard Doppler Wind Lidar(DWL) would optimize the identification of vertical motions that are advantageous or deleterious to positive energy extraction.
4. Adjust the flight path with the help of an onboard DWL and stored (or uplinked in real time) locations of alternative harvestable atmospheric energy based upon numerical models. The RTB instructions will terminate the energy extraction.

The simulated fractional improvement to the endurance of our chosen test UAV (RQ-7B Shadow 200), shown in the AMPT User's Guide, exceeded our expectations going into this project. Based upon conversations with persons interested in the potential of AEORA, we expected energy harvesting improvements on the order of 10-50% over that of flight ignoring energy harvesting opportunities. In our simulations of mountain wave surfing the endurance advantages were on the order of 100-300% and in some instances 500%.

2.0 Field Evaluation Design

In our SBIR II proposal we identified the final task as a plan for evaluating the AEORA.

Task 10: Design a UAS field evaluation program for AEORA.

Near the end of the 24 month SBIR effort, we will design a test program using a OPA or a UAS. In this case, the platform may be provided by the DoD or leased from a private company such as Aurora. The DWL would have to be provided by the government (e.g. ARL). The integration of the DWL onto the platform would require additional funding. Aurora is capable of doing this integration and conducting the flight tests.

Although not officially a task under this SBIR Phase II effort, attempts were made to organize an early test of the mountain wave energy harvesting algorithm using a UAV provided by AURORA. Several potential sites were identified. Due to flight restrictions, costs and no assurance of being on station long enough to get several good mountain wave cases, this effort was postponed until the follow-up to Phase II.

We have considered two options for a flight demonstration of AEORA, particularly the mountain wave energy harvesting case. The two options are:

Option1: A tandem flight of a DWL instrumented manned aircraft and a UAV flying without a DWL but programmed to extract energy from mountain waves and thermals.

The DWL instrumented aircraft would be the Navy's Twin Otter with the TODWL system (Figure 3) flown out of Marina, CA. The UAV would be a civilian craft provided by AURORA of Manassas, VA.

The general plan would be to prospect for energy sources with the TODWL and then relay the relevant information (location, strength, path to feature, etc) to the UAV's on board navigation planner. The UAV would navigate to the energy feature and then execute the energy harvesting algorithm appropriate for the opportunity. This demo could be carried out at an Army facility such as YPG in Arizona or DPG in Utah where the TODWL system as flown several times in the past.

Option 2: A smaller research DWL hosted by a military UAV flown semi-autonomously. In this case we envision the use of an ARL small SWAP DWL such as Dr. Ligon's MPL (Man Portable Lidar) on a capable UAV such as the Army's Shadow (Figure 2). This option is the most aggressive in terms of moving AEORA concept forward. However, it would delay an early evaluation of a complex concept and also require investments in UAV instrument integrations and flight certifications.

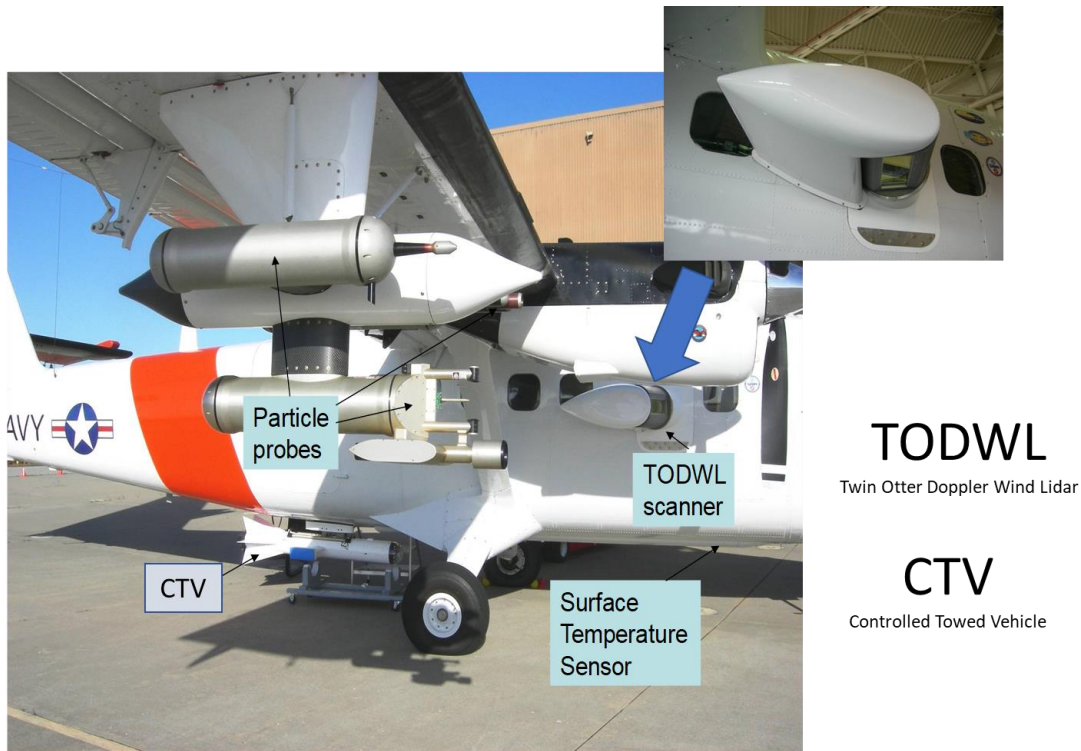


Figure 3: The Twin Otter Doppler Wind Lidar (TODWL) used to explore energy harvesting features.

Details on this option would need to be worked out with other Army interests before developing an operations plan.

3.0 Phase II follow-on recommendations

While SWA and its subcontractors were guided by the SBIR research plan, there are several issues that we have identified that should be addressed in any follow-on development/application. These issues are in addition to the flights and demo mentioned above and fall under “algorithm improvement”.

3.1 Airborne missions to support feature identification

Beginning in 2002, and as recently as September-October 2012, over 100 hours of airborne DWL missions (Emmitt et. al. , 2013, Emmitt et. al. , 2005) using a variety of scanning strategies were flown on a Navy Twin Otter aircraft based out of Marina, CA. In this Phase II effort, a good portion of the Twin Otter DWL (TODWL) data archives (including model and auxiliary meteorological data) have been reviewed and numerous days/data sets were selected that included significant atmospheric energy features of interest to AEORA (like those in Table 1.0). However these missions were not designed to specifically target these energy features. It is intended to fly new dedicated TODWL missions targeting energy features, especially Mountain Waves and Thermals, in order to improve the feature detection and ranking codes in the AMPT.

A critical product of these dedicated AEORA flights would be a set of DWL “flight level signatures” of various energy sources at various stages of their lifecycles. These flights would also be an excellent opportunity to co-fly other sensors (passive and/or active) that could enhance situational awareness needed to optimize energy harvesting.

3.2 Model improvements

Currently the AMPT codes support WRF atmosphere data bases of 1 Km resolution for a single time period (one hour). The codes need to be modified to support the finer grid scales of WRF (333 m) data and temporal updates for the UAV flights.

In addition, the SWA models for Mission Definition, initial Flight Trajectory and Sensor Energy Target Detection need to be integrated into a single model. These codes may remain in Modern Fortran or be re-coded into C#. The Sensor Energy Target Detection Model (SETDM) capabilities for feature detection and ranking should be updated once more DWL flights have been completed.

CASSY production code is currently coded in C++ that was generated from its original code written MathLab. The C++ code was modified in order to be compiled within Visual Studio on Windows. The main issues with the generated C++ code is poor memory management, poor looping structure design and the loading and processing of the WRF file information. The process takes more than 1 hour to process a 1 Km resolution WRF file due to the lack of multithreading and parallel processing.

It is recommended that the C++ codes be re-written in C# to take advantage of multithreading and parallel processing capabilities in the .NET Framework. This will allow faster optimization of the CASSY code. If after optimizing the code, more execution run time performance is required, CUDA parallel computing using NVIDIA GPU can be used with the implementation the C# CUDA processing libraries.

Phenomenology	Description (dimensions)	Lifecycle Metrics	Remote Sensing Signatures
Thermals (non-orographic); triggered by differential surface heating <i>Normal Magnitudes: 1-5 m/s</i>	Few 100 meters in diameter; vertical extent controlled by environ. structure	May last for large fraction of an hour; daytime features only	Convergence Optical depth Temperature Refractive turbulence
Thermals (slopes); driven by differential heating of sloped surfaces during direct solar illumination <i>Normal Magnitudes: 1-5 m/s</i>	100's meter diameter; vertical extent limited by environmental structure	May last for hours during the daytime.	Convergence Optical depth Temperature Refractive turbulence
*Organized Large Eddies (OLEs); upward branch of a semi-closed vertical circulation within the PBL <i>Normal Magnitudes: 1-3 m/s</i>	A few 100 meters in diameter; vertical extent defined by depth of PBL; organized in lines	May last for hours but with much variation in strength;	Convergence Optical depth Refractive turbulence
*Obstacle flow ; Strong horizontal flow deflected upward by orography and airmass collisions; (ridge soaring; frontal soaring) <i>Normal Magnitudes: 1-5 m/s</i>	Many miles in horizontal extent; vertical extent usually a few 100 meters above ridge line	May last for many hours and vary as the horizontal flow varies; Occurs at all hours of the day.	The obstacle Convergence Optical depth Refractive turbulence
*Cloud updrafts ; main targets are cloud base updrafts of non- or lightly precipitating cumuli. <i>Normal Magnitudes: 1-5 m/s</i>	Dimensions similar to thermals (a few 100's of meters); vertical extent can be 1000's of meters	A few minutes, maximum duration ~ 10 minutes.	The cloud Convergence Temperature Precipitation
*Mountain Waves (bands downwind of ridge line) <i>Magnitudes: Up to 10 m/s</i>	Horizontal extent of many km; Vertical extent of 10's of km possible	May last for hours throughout entire diurnal cycle	Vertical motions; visual wave clouds
*Shear layers <i>Normal Magnitudes: 10-25 m/s (max near 100-300m)</i>	Horizontal extent of many kms defined by surface topography and atmospheric structures; vertical extent a few 100 meters	May persist for several days lasting through the nighttime	Hor. wind speed; Optical depths

*Table 1: Potential atmospheric energy sources for AEORA. * = features studied by PI with airborne Doppler lidar*

4. References

Simpson Weather Associates, Inc., 2012: A Doppler wind lidar based atmospheric energy harvesting system for autonomous in-flight guidance and path planning of small aircraft. SBIR Phase I Final Technical Report submitted to ARMY XXXX W911QX-12-C0060.

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