



# Quantifying Autonomous Soaring on a Surveillance and Communications Relay Mission

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July 18, 2019

**REPORT DOCUMENTATION PAGE**

*Form Approved  
OMB No. 0704-0188*

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<b>4. TITLE AND SUBTITLE</b>	<b>5a. CONTRACT NUMBER</b>		
	<b>5b. GRANT NUMBER</b>		
	<b>5c. PROGRAM ELEMENT NUMBER</b>		
<b>6. AUTHOR(S)</b>	<b>5d. PROJECT NUMBER</b>		
	<b>5e. TASK NUMBER</b>		
	<b>5f. WORK UNIT NUMBER</b>		
<b>7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES)</b>		<b>8. PERFORMING ORGANIZATION REPORT NUMBER</b>	
<b>9. SPONSORING/MONITORING AGENCY NAME(S) AND ADDRESS(ES)</b>		<b>10. SPONSOR/MONITOR'S ACRONYM(S)</b>	
		<b>11. SPONSOR/MONITOR'S REPORT NUMBER(S)</b>	
<b>12. DISTRIBUTION/AVAILABILITY STATEMENT</b>			
<b>13. SUPPLEMENTARY NOTES</b>			
<b>14. ABSTRACT</b>			
<b>15. SUBJECT TERMS</b>			
<b>16. SECURITY CLASSIFICATION OF:</b>			<b>19a. NAME OF RESPONSIBLE PERSON</b>
<b>a. REPORT</b>	<b>b. ABSTRACT</b>	<b>c. THIS PAGE</b>	
<b>17. LIMITATION OF ABSTRACT</b>			<b>18. NUMBER OF PAGES</b>
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## **EXECUTIVE SUMMARY**

A notional surveillance and communications relay mission places a demand on an unmanned aircraft's available energy supply. Autonomous soaring algorithms and solar photovoltaic systems both provide a means to extract energy from the environment (from thermal updrafts and solar radiation respectively) to extend endurance beyond the aircraft's stored energy limits. Furthermore, multiple aircraft can improve their soaring success by sharing information.

This report describes a demonstration system that combines multiple coordinated aircraft, each with autonomous soaring algorithms and integrated solar-photovoltaic power systems. Flight testing with two aircraft is planned to quantify the notional mission performance when both autonomous soaring and solar power systems are used.

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# QUANTIFYING AUTONOMOUS SOARING ON A SURVEILLANCE AND COMMUNICATIONS RELAY MISSION

## INTRODUCTION

Missions for small unmanned aircraft (Group 1 and Group 2) include over-the-hill surveillance and providing airborne communications relay points. Greater endurance is almost universally desired by operators to increase the time spent on station performing the mission and reduce the number and frequency of takeoffs and landings.

Autonomous soaring techniques were first proposed by Wharington [1] and refined by Allen [2] as a method to find convective thermal updrafts and gain altitude energy. While several autonomous soaring algorithms have been implemented on unmanned aircraft and demonstrated significant endurance gains [3–8], the technology of autonomous soaring has not yet bridged the gap from research to practical application for a mission.

Rather than providing a fixed geometric orbit to continuously track a target on the ground, an aircraft in autonomous soaring mode maneuvers into and moves with thermal updrafts. This maneuvering is often believed to be counterproductive to a surveillance mission, especially if the ground target is moving against the wind, since thermals tend to drift downwind. However, this report shows a surveillance mission is still achievable while performing autonomous soaring.

Cooperative autonomous soaring is a technique in which multiple aircraft flying in close proximity share information about the local conditions in order to improve each individual aircraft's performance. Theoretical [9–11] and implemented demonstrations [12, 13] have shown promising results of two vehicles sharing soaring information. Depenbusch demonstrated multiple aircraft flying simultaneously and sharing soaring data, while also using memory of prior soaring conditions. Storing and remembering areas of lift is a way for a single agent to cooperate with itself, and should be explored in future research.

To the authors' knowledge, no research has tried to use autonomous soaring techniques to carry out a specific mission. Edwards [14] demonstrated autonomous soaring with mission constraints, but did not attempt to quantify the performance of the mission payload itself. This report attempts to quantify the effect of autonomous soaring on an imagery mission using imagery resolution and time-on-station as metrics. For additional realism, the demonstration also includes a communications relay payload to further add real-world transmission effects.

This report examines the mission concept and constraints; describes the unmanned aerial vehicle (UAV), system architecture, and software; and then proposes how to analyze results of the system during flight testing.

## SURVEILLANCE AND COMMUNICATIONS RELAY MISSION

Edwards described a single-vehicle communications relay concept of operation (CONOP) in a prior paper [14] as shown in Fig. 1. This setup uses a single airborne asset providing service to two remote sites. However, maneuvering within the given airspace constraint area may not provide sufficient coverage, and requires the aircraft to operate over the obstruction. Instead, this report proposes two aircraft: one over the base and one over the remote user.

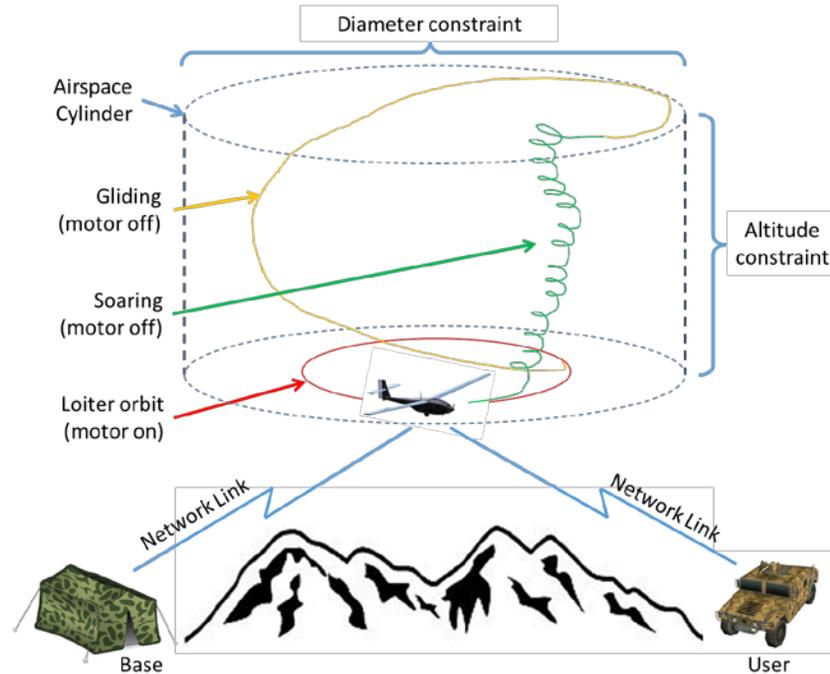


Fig. 1—Communications relay CONOP using one UAV performing autonomous soaring

A notional over-the-hill surveillance and communications relay mission is designed to show the potential mission performance enhancement offered by using autonomous soaring technologies. Figure 2 shows a command site that is out of radio frequency (RF) line of sight (LOS) to a remote unit. The RF blockage could be a mountain range, significant distance, urban obstructions, or any other number of complicating factors. In this scenario, two unmanned aircraft provide a communication link between the command base and remote user. Also, the remote user has direct access to the video product, since s/he is on the same network.

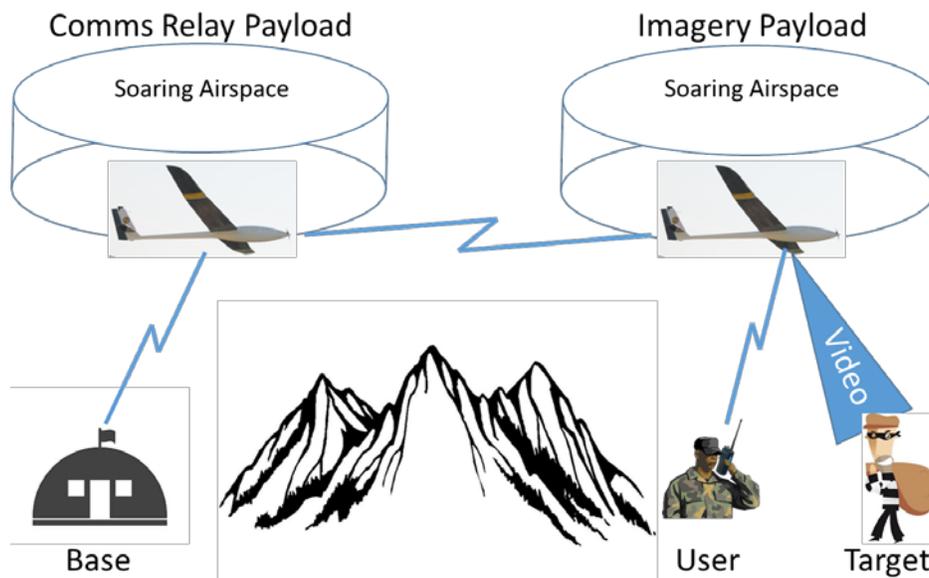


Fig. 2—Notional imagery and communications relay mission with autonomous soaring

A typical Group 1 UAV has only two to four hours of endurance. If the remote site is one to two flight hours away from the launch site, this leaves little or no time on-station actually performing the mission. This report shows how a Group 1 UAV using autonomous soaring and a solar power system can extend the aircraft’s four hours battery-only endurance to more than 12 hours. This will provide uninterrupted imagery over the remote target site.

**UAV OVERVIEW**

The U.S. Naval Research Laboratory’s Solar-Soaring testbed UAV was used as host for this experiment. The PV-SBXC, shown in Fig. 3, is derived from the SBXC sailplane airframe from RnR Products (Milpatas, CA). Two identical aircraft were built and used for this experiment.



Fig. 3—NRL’s PV-SBXC UAV used for flight experiments



An oDroid XU4 computer from Hardkernel Inc. (South Korea) is connected to the autopilot and runs the soaring algorithms. It has two connections to the autopilot:

1. Autopilot telemetry data and control input
2. Soaring command and control

An enable line allows the UAV operator to disable the soaring system during takeoff/landing or other times when soaring is not desired.

The mission payload is a Wave Relay mesh-network radio from Persistent Systems (New York, NY) and an Orion HD-25 electro-optical camera gimbal from Trillium Engineering (Hood River, OR). Geo-referenced digital video and camera control are available to users on the Wave Relay network via the SkyLink software (also from Trillium Engineering). The camera resolution is 720 x 1280 high definition (HD) visible with a minimum 5.1° optical field of view. The airborne radios are 2 W at 2.3 GHz through a 7 db circularly polarized cloverleaf antenna.

Multi-agent communication is made transparent to the ground user by utilizing a mesh-network radio. The command-and-control network architecture is shown in Fig. 5. Unlike a typical Piccolo autopilot setup, the aircraft is controlled through the Wave Relay link to the Piccolo Command Center software on the ground. For manual control (takeoffs and landings), a pilot transmitter console from JR (JR Radios, Japan) connects the pilot's manual control to the servos through the autopilot.

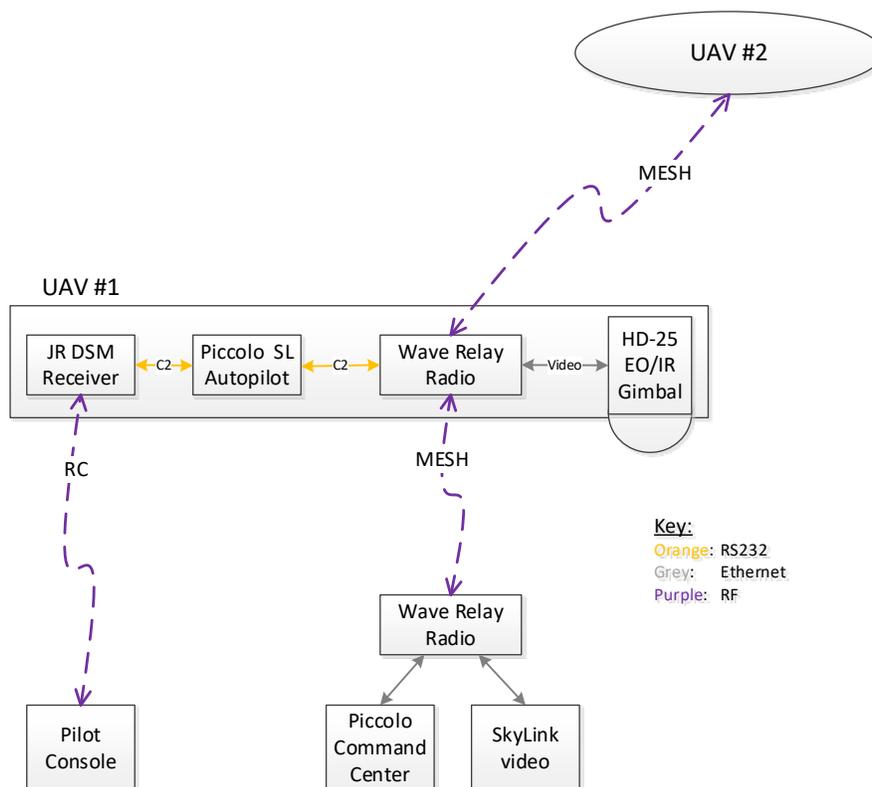


Fig. 5—RF Network Architecture

The payload system in the downrange UAV (#2) sends its digital video product through the mesh-network link, via the overhead UAV (#1), and to the video display in the ground segment. The UAV

operator can thus see the real-time video from multiple downrange aircraft. Alternately, if a remote user has a network radio and is within RF LOS of the UAV with imagery payload, that user can also see and control the video gimbal directly via the SkyLink software.

## SOFTWARE

Autonomous soaring software has been examined in prior offerings [5, 6, 19] and is not covered in full depth in this report. However, this current implementation has several new features described below.

The soaring algorithms are now run onboard the UAV coded in C and run in Robot Operating System (ROS) as opposed to on the ground running in MATLAB (Mathworks Inc.). Being onboard enables a hard-wired connection to the autopilot telemetry that addresses a previously limiting factor: at long ranges, running offboard meant the aircraft stopped soaring when the connection was poor. No changes have been made to the actual algorithms described in Edwards [19] other than the hardware drivers and conversion to C language.

The soaring computer interfaces with the autopilot by reading selected aircraft telemetry (latitude, longitude, altitude, airspeed, time, etc.) and sending it commands (airspeed and waypoints).

The notional CONOP does not put the two aircraft in close proximity, so a highly capable collision-avoidance algorithm was not needed. While the high bandwidth link between the two aircraft provides opportunity for intelligent collision-avoidance guidance algorithms, the implementation chosen for this experiment was simple altitude separation when the aircraft are close (1 km). Future work with this hardware could expand performance to allow for very close proximity flight.

There is no link between the soaring controller and the payload. Instead, the imagery target waypoint is also the autonomous soaring cylinder center.

## TEST FLIGHT

Flight testing is planned to take place in controlled airspace at the U.S. Army's Aberdeen Proving Ground, MD, in 2019. Two PV-SBXC's will be used. The down-range aircraft will carry the camera gimbal, a mesh-network radio, and fly with the Sharp solar wing [18]. The overhead aircraft will carry only the mesh-network radio payload and fly with the Microlink solar wing [18]. Takeoff is planned for daybreak and the total demonstration flight expected to last more than 12 hours.

In Fig. 6, the white outline is the available soaring area, from 500 m to 1500 m above ground level. The takeoff and base station location is  $39.456439^\circ$  N,  $76.174004^\circ$  W and the target is at  $39.401310^\circ$  N,  $76.224333^\circ$  W. The yellow line shows a 7.5 km RF transmission distance. The soaring volume allowed is 1000 m radius around the target and altitude ranges 500 m to 1500 m.

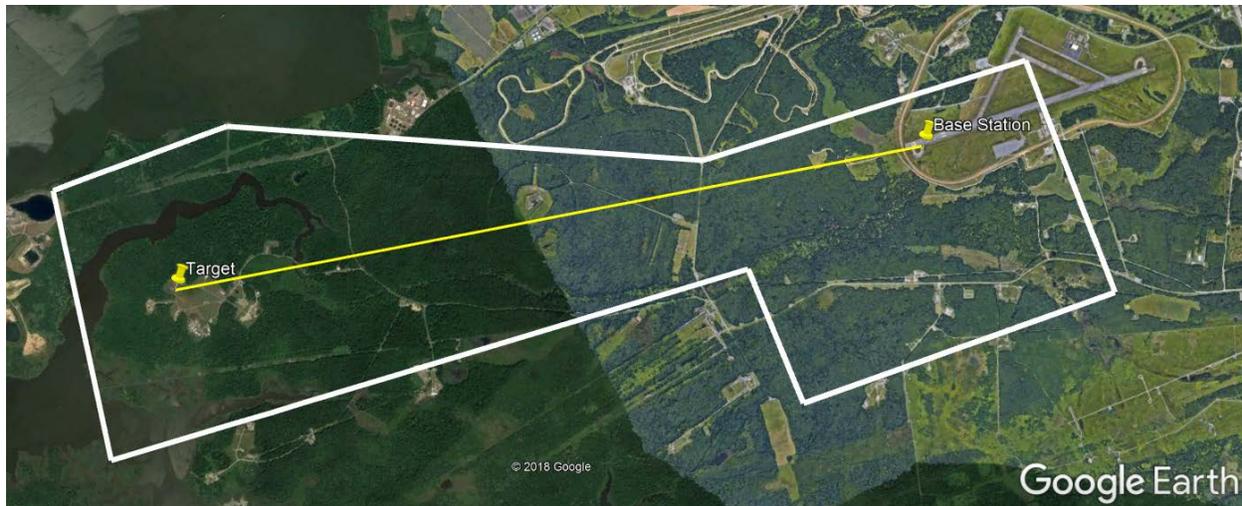


Fig. 6—Map of flight test location at Aberdeen Proving Ground, MD

The remote target to observe is a large analog clock (3 m diameter, 30 cm wide clock hands, shown in Fig. 7) and an optical resolution target. This clock will give a referenceable time-on-target while the optical resolution target (Fig. 8) will measure the quality of the imagery.

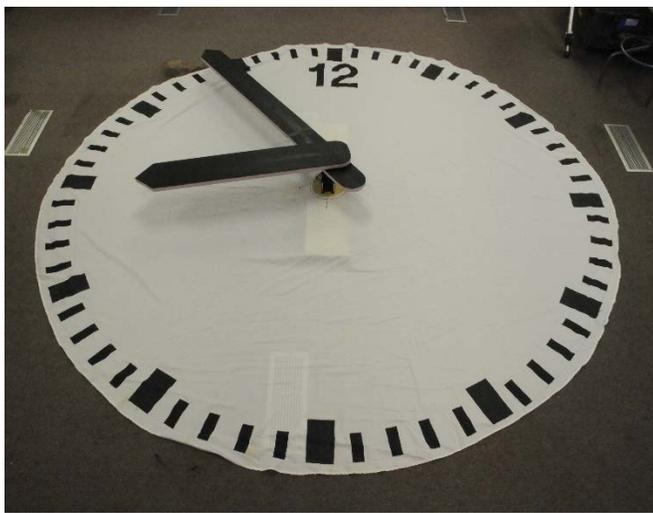


Fig. 7—3 m diameter analog clock for time-on-target tracking

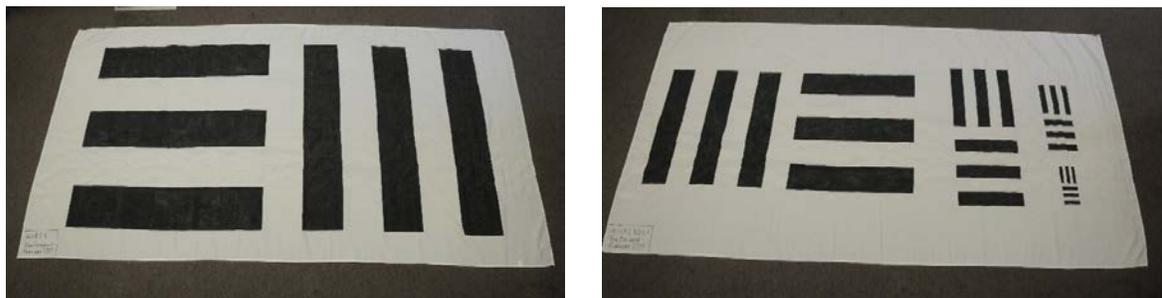


Fig. 8—NIIRS 5 (left) and NIIRS 6 to 9 (right) optical bar target for imagery quality measurement

The experiment will follow a simple sequence:

1. Launch aircraft #1 and #2 and climb to a hold orbit at 1000 m altitude
2. Fly aircraft #1 to the target along the corridor
3. Perform mission with autonomous soaring disabled for one hour
4. Enable autonomous soaring and continue to perform mission for one hour
5. Repeat steps 3-4 until completion of the 12 hour planned mission, or available range time
6. Fly aircraft #1 back to base along the corridor
7. Manual landing of aircraft #1 and #2

The down range aircraft will perform the surveillance mission while the overhead aircraft will perform the communications relay mission only.

## ANALYSIS AND DISCUSSION

Imagery quality will be measured using the National Image Interpretability Rating Scales (NIIRS) levels [22]. Table 1 relates NIIRS resolutions to ground resolvable distances (GRD).

Table 1—NIIRS Level to Ground Resolvable Distance

NIIRS level	GRD [m]
5	0.75 - 1.20
6	0.40 - 0.75
7	0.20 - 0.40
8	0.10 - 0.20
9	<0.10

Video will be post-processed to evaluate the NIIRS level, including if the imagery is occluded by trees or the aircraft body. Manual evaluation of the resolution level will be integrated using the clock times. The result of this analysis will be a histogram of NIIRS level to time (Fig. 9).

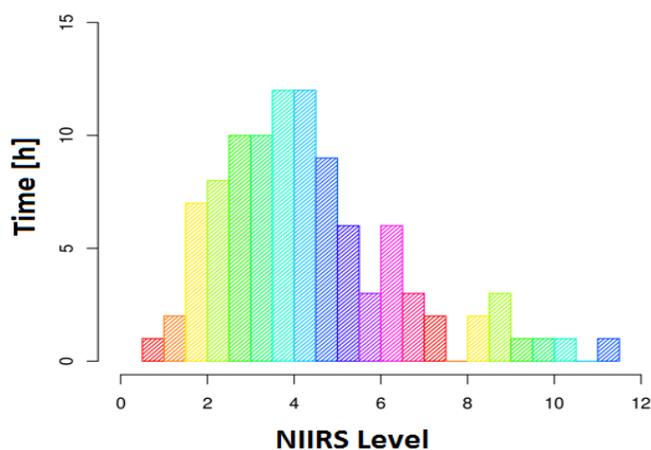


Fig. 9—Example of a histogram plot for NIIRS level versus integrated time-on-target

Two histograms, similar to the one shown in Fig. 8, will show the time-on-target versus NIIRS level. This will quantify how the autonomous soaring technique affects the quality of imagery. It is expected that the autonomous soaring technique will reduce the energy consumption, thus the total mission time could be increased. It is also expected that further restrictions on the allowed soaring airspace could mitigate the slant-range increase and thus NIIRS level degradation.

## CONCLUSIONS

This report has outlined a notional communications and surveillance mission for a UAV to quantify the effects of autonomous soaring. It has also documented the system configuration for a UAV that includes a solar photovoltaic power system for in-air recharging. Finally, it proposes a flight test and method to quantify the performance of autonomous soaring algorithms on a notional surveillance mission.

## ACKNOWLEDGEMENTS

The authors would like to thank Major Chew at the U.S. Marine Corps Expeditionary Energy Office (E2O) for supporting this experimental demonstration and the U.S. Marine Corps Warfighting Laboratory for sponsoring the effort. The authors also thank Trenton Young, Christopher Bovais, Steven Carruthers, and David Indyke of the Naval Research Laboratory for their support in flight testing and aircraft fabrication.

## REFERENCES

1. John Wharington, "Autonomous Control of Soaring Aircraft by Reinforcement Learning," Ph.D. dissertation, Royal Melbourne Institute of Technology, 1998.
2. Michael Allen, "Autonomous Soaring for Improved Endurance of a Small Uninhabited Air Vehicle," presented at the AIAA Guidance, Navigation, and Control Conference, Reno, Nevada, 2005, doi:10.2514/6.2005-1025.
3. Michael Allen, "Guidance and Control of an Autonomous Soaring UAV," NASA TM-214611, 2007.
4. Michael Allen and Victor Lin, "Guidance and Control of an Autonomous Soaring Vehicle with Flight Test Results," presented at the 45th AIAA Aerospace Sciences Meeting and Exhibit, 2007.
5. Daniel J. Edwards, "Implementation Details and Flight Test Results of an Autonomous Soaring Controller," presented at the AIAA Guidance, Navigation, and Control Conference and Exhibit, 2008.
6. Daniel J. Edwards and Larry Silverberg, "Autonomous Soaring: The Montague Cross Country Challenge," *AIAA Journal of Aircraft*, **47**(5), 1763-1769 (2010), doi:10.2514/1.C000287.
7. Klas Andersson, Isaac Kaminer, Vladimir Dobrokhodov, and Venanzio Cichella, "Thermal Centering Control for Autonomous Soaring; Stability Analysis and Flight Test Results." *Journal of Guidance, Control, and Dynamics* **35**(3), 963-975 (2012).
8. Klas Andersson, Issac Kaminer, and Kevin Jones, "Autonomous Soaring: Flight Test Results of a Thermal Centering Controller," presented at the AIAA Guidance, Navigation, and Control Conference, 2010.
9. Cathrine Antal, Oleg Granichin, and Sergey Levi, "Adaptive Autonomous Soaring of Multiple UAVs using Simultaneous Perturbation Stochastic Approximation," presented at the 49th IEEE Conference on Decision and Control, 2010.

10. José Antonio Cobano, et al. "Thermal Detection and Generation of Collision-free Trajectories for Cooperative Soaring UAVs," presented at the IEEE/RSJ International Conference on Intelligent Robots and Systems, 2013.
11. Andrew T. Klesh, Pierre T. Kabamba, and Anouck R. Girard, "Optimal Cooperative Thermalling of Unmanned Aerial Vehicles," Proceedings of the 8<sup>th</sup> International Conference on Cooperative Control and Optimization, M. Hirsch, C. Commander, P. Pardalos, and R. Murphey, eds., January 30–February 1, 2008, Gainesville, FL, pp. 355-369.
12. Klas Andersson, et al. "Thermal Highs and Pitfall Lows: Notes on the Journey to the First Cooperative Autonomous Soaring Flight," presented at the 51st IEEE Annual Conference on Decision and Control, 2012.
13. Nathan Depenbusch and Jack Langelaan, "Coordinated Mapping and Exploration for Autonomous Soaring," Proceedings of Infotech@Aerospace, March 29–31, 2011, St. Louis, MO, <https://doi.org/10.2514/6.2011-1436>.
14. Daniel J. Edwards, "Integrating Hydrogen Fuel Cell Propulsion and Autonomous Soaring Techniques," presented at the AIAA Guidance, Navigation, and Control Conference, 2018.
15. Daniel Parry, "NRL Tests Autonomous 'Soaring with Solar' Concept," Naval Research Laboratory, Washington, DC, [<https://www.nrl.navy.mil/news/releases/nrl-tests-autonomous-soaring-solar-concept>] accessed 2018-12-14.
16. David Scheiman, et al. "A Path toward Enhanced Endurance of a UAV using IMM Solar Cells," presented at the 43rd IEEE Photovoltaic Specialists Conference, 2016.
17. David Scheiman, et al. "A Path toward Enhanced Endurance of a UAV using IMM Solar Cells," presented at the 44th IEEE Photovoltaic Specialists Conference, 2017.
18. David Scheiman, et al. "Solar Technology Comparison for Wing Integration in Unmanned Aerial Vehicles," presented at the 7th IEEE World Conference on Photovoltaic Energy Conversion (a joint conference of the 45th IEEE PVSC, 28th PVSEC, and 34th EU PVSEC), 2018.
19. Daniel J. Edwards, "Autonomous Locator of Thermals (ALOFT) Autonomous Soaring Algorithm," NRL Formal Report 10,272, Apr. 2015.
20. IRARS Committee. *Civil NIIRS Reference Guide*, 1996.