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Perpetual flight with a small solar-powered UAV: Flight results, performance analysis and model validation

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Abstract— **This paper presents the design of the small-scale hand-launchable solar-powered AtlantikSolar UAV, summarizes flight results of a continuous 28-hour solar-powered flight that demonstrated AtlantikSolar's capability for energetically** *perpetual flight***, and offers a model-based verification of flight performance and an outlook on the energetic margins that can be provided towards perpetual flight given today's solar-powered UAV technology. AtlantikSolar is a 5.6m-wingspan and 6.9kg mass low-altitude long-endurance UAV that was designed to provide perpetual endurance at a geographic latitude of 45N in a 4-month window centered around June 21st. A specific design emphasis is robust perpetual endurance with respect to local meteorological disturbances (e.g. clouds, winds, downdrafts). Providing the necessary energetic safety margins is a significant challenge on small-scale solar-powered UAVs. This paper thus describes the design optimizations undertaken on the AtlantikSolar UAV for maximum energetic safety margins. In addition, this paper presents the flight test results, analysis and performance verification of AtlantikSolar's first** *perpetual endurance* **continuous 28-hour flight. The flight results show a minimum state-of-charge of 40% or excess time of 7 hours during the night. In addition, the charge margin of 5.9 hours indicates sufficiently-fast battery charging during the day. Both margins exceed the performance of previously demonstrated solar-powered LALE UAVs. Another centerpiece of the paper is the verification of these flight results with the theoretical structural-, aerodynamics- and power-models that were developed and used to conceptually design the UAV. The solar-power income model is extended to take into account solar-panel temperature effects, the exact aircraft geometry and the current orientation and is compared against flight results. Finally, the paper provides an analysis and overview into under what conditions and with which energetic margins** *perpetual flight* **is possible with today's battery- and solar-cell technology. A perpetual endurance window of up to 6 months around June 21st is predicted at northern latitudes for the AtlantikSolar UAV configuration without payload. A final outlook into first perpetual endurance applications shows that perpetual flight with miniaturized sensing payloads (small optical and infrared cameras) is possible with a perpetual flight window of 4-5 months.**

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1. INTRODUCTION

Solar-electrically powered fixed-wing Unmanned Aerial Vehicles (UAVs) promise significantly increased flight endurance over purely-electrically or even gas-powered aerial vehicles. A solar-powered UAV uses excess solar energy gathered during the day to recharge its batteries. Typical UAV applications such as industrial and agricultural sensing and mapping clearly benefit from this increased flight endurance. However, given an appropriate design and suitable environmental conditions, the stored energy may even be enough to continuously keep the UAV airborne during the night and, potentially, subsequent day-night cycles. This so called *perpetual flight* capability makes solar-powered UAVs great candidates for applications in which data needs to be collected or distributed either continuously or on a large scale. Applications such as large-scale disaster relief support, meteorological surveys in remote areas and continuous border or maritime patrol would benefit in particular from this multi-day continuous flight capability [1].

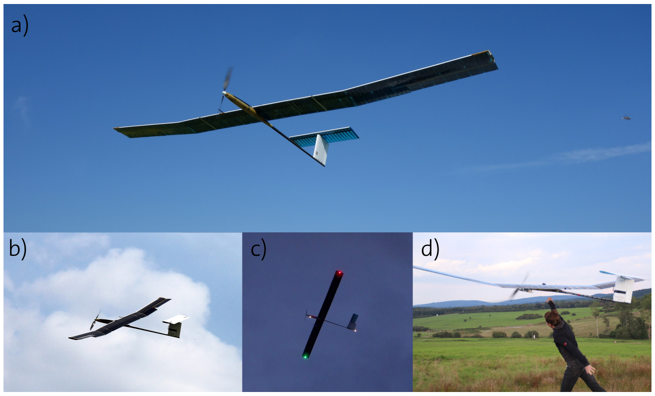

Figure 1. The AtlantikSolar solar-powered low-altitude long-endurance (LALE) UAV: a) After take-off b) exposing the solar-cells and engaged spoilers c) after a night flight d) during hand-launch in a Search-and-Rescue research mission with the sensing and processing pod attached below the left wing. Images a) and c) are from the continuous 28-hour *perpetual endurance* demonstration flight on June 30th 2015.

Recently, interest in employing large-scale (wingspan above 20m), solar-powered High-Altitude Long-Endurance

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(HALE) UAVs as *atmospheric satellites* - i.e. stationary/loitering platforms e.g. for telecommunications relay - has peaked. Notable examples of this trend are *Solara* [2] and *Zephyr*, which has already demonstrated a continuous flight of 14 days [3]. In contrast, smaller scale solar-powered UAVs are mostly designed for Low-Altitude Long-Endurance (LALE) applications. Though faced with the more challenging meteorological phenomena of the lower atmosphere (clouds, rain, wind gusts or thermals), low-altitude UAVs provide the advantages of higher resolution imaging with reduced cloud obstruction, lower complexity and cost and simplified handling (e.g. through hand-launchability). As a result, solar-powered non-perpetual-flight capable LALE UAVs aiming to reach flight times up to 14 hours are currently being intensely studied in the industry [4], [5]. On the other hand, research targeting perpetual endurance in small-scale solar UAVs has been relatively sparse. Most research has been focusing on conceptual design studies without extensive flight experience, e.g. [6]. Projects that have demonstrated *perpetual flight* are Cocconi's *SoLong* [7], which performed a continuous 48-hour flight using solar power while actively seeking out thermal updrafts, and SkySailor [8], which demonstrated a 27-hour solar-powered continuous flight without the use of thermals in 2008. However, these UAS were mainly developed to demonstrate the *feasibility* of perpetual flight for the first time, and do neither provide sufficient robustness against deteriorated meteorological conditions (e.g. clouds or downwinds) nor the capability to fly perpetually with common sensing payloads. For example, the SkySailor UAV crossed the night with only 5.8% of remaining battery energy.

Given the recent advances in solar-cell, battery- and sensing-technologies, this paper aims to provide an overview over what improvements in *perpetual flight* robustness and payload-carrying capacity can and have already been achieved today, and what applications this may open up for solar-powered *perpetual flight*-capable UAVs in the near future. We extend the work of [7], [8] by presenting the design and analyzing flight results of *AtlantikSolar* (Figure 1), a solar-powered LALE-UAV designed in [9] for robust multi-day autonomous operation that still allows the use of on-board optical and infrared sensor systems. More specifically, we will extend our previous work with

- a summary of incremental technical improvements integrated into the second AtlantikSolar (*AS-2*) in comparison to our previous work.
- a discussion and analysis of flight results from AtlantikSolar's *AS-2* first *perpetual endurance* flight of 28-hours. These results validate the design in our previous work and indicate significantly improved energetic safety margins (*perpetual flight* with up to 40% remaining battery energy).
- an extension of the models and conceptual design tools presented in [8], [9] with more precise solar power input models, which are crucial to accurately assess the *perpetual flight* capability of a solar-powered UAV.
- an outlook into what sensing payloads today's technology allows solar-powered UAVs to carry in *perpetual flight* missions.

2. SYSTEM OVERVIEW

The solar-powered UAV considered in this paper is the AtlantikSolar UAV (Figure 1), a small-size low-altitude long-endurance (LALE) UAV developed to allow multi-day continuous flight in a 4-month window centered around June21st at a geographical latitude of 45°N. A special design emphasis was to provide sufficient energetic margins to deviations from the nominal operating point as well as to local meteorological deteriorations such as clouds or vertical winds. The aerial vehicle is targeted towards large-scale operations including meteorological observations, aerial mapping or search-and-rescue support, and as such can be hand-launched for quick on-field deployment. Three AtlantikSolar aircraft have been developed and constructed at ETH Zurich so far. The complete system design approach, and specifically the design characteristics of the first AtlantikSolar aircraft (*AS-1*), are summarized in our previous work [9]. However, this paper deals with the second revision of the AtlantikSolar aircraft (*AS-2*). The aircrafts are equal except for a set of technical optimizations that will be described below.

UAV Platform Design

All AtlantikSolar UAV airframes are of a conventional glider-like T-tail configuration with two ailerons, an all-moving elevator and a rudder. At a wingspan of 5.6m, the aircraft total mass for AtlantikSolar *AS-2* is now $m_{total} = 6.93kg$ due to structural optimizations and a redesign and thus decrease in battery-mass. More specifically, 60 high energy density lithium-ion battery cells (Panasonic NCR18650b, 243Wh/kg) are integrated into the wing spars for optimal weight distribution and provide $E_{bat}^{max} = 705Wh$. The wings also house 88 SunPower solar cells, which have been upgraded to SunPower E60 cells with a $\eta_{sm} = 23.7\%$ module-level efficiency. The aircraft is driven by a RS-E Strecker 260.20 brushless DC motor with $k_V = 400RPM/V$ that works at up to 450W electrical input power. It drives an all-steel planetary gearbox with four pinion gears and a 5:1 reduction ratio and a foldable custom-built carbon-fiber propeller with diameter $D = 0.66m$ and pitch $H = 0.60m$. The gearbox had to be upgraded from previous designs to increase propulsion system reliability during multi-day flights. The characteristics of AtlantikSolar *AS-2* are summarized in Table 2.

Table 1. AtlantikSolar AS-2 design characteristics

Parameter	Value
Wing span	5.65m
Wing chord	0.305m
Length	2.03m
Height	0.45m
Total mass*	6.93kg
Battery mass	2.92kg
Max. payload mass	1.0kg
Stall speed	7.9m/s

*No payload

The avionics are centered around the *Pixhawk* PX4 Autopilot [10] - an open source and open hardware project initiated at ETH Zurich. An ADIS16448 10-Degrees of Freedom (DoF) Inertial Measurement Unit (IMU), a u-blox LEA-6H GPS receiver, and a Sensirion SDP600 differential pressure sensor are used to estimate the aircraft attitude. The main 433MHz medium-range telemetry link is complemented by an optional IRIDIUM-based satellite communication backup link. The custom-made Maximum Power Point Trackers (MPPTs) and battery monitoring circuits provide detailed energy flow information including solar power income P_{solar}, outgoing power P_{out} and battery charging power P_{bat} and in addition monitor the overall and cell-level charge states to increase system safety. Four high-power indicator LEDs are installed to allow night operation. The low-level avionics framework can be complemented by a sensor and processing unit - comprising an optical camera, an infrared camera, and an Intel Atom-based on-board computer running Ubuntu and the Robot Operating System (ROS) - that was developed at the Autonomous Systems Lab (ASL) and has been demonstrated in multiple Search-and-Rescue research applications [11].

State Estimation and Control

State estimation is based on an Extended Kalman Filter (EKF) design that fuses data from the 10-DoF IMU, the GPS and the airspeed sensor to estimate position, velocity, orientation (attitude and heading), QFF (pressure at sea level), gyroscope biases, accelerometer biases and the wind vector [12]. Sideslip angle and Angle of Attack (AoA) can subsequently be derived from these estimates. The estimator can cope with prolonged GPS outage scenarios through an implemented airspeed sensor fallback mode and is optimized to run efficiently on the on-board Pixhawk flight controller.

The underlying on-board control system employs cascaded PID controllers for rate and attitude control and a combination of Total Energy Control System (TECS) and L_1-nonlinear guidance for position and altitude control [9]. This approach offers the advantage of easy integration into the on-board Pixhawk flight controller due to the low computational demands. The control framework supports features such as coordinated-turn control and passive use of energy from thermal updrafts to increase flight-performance and -efficiency, and the automatic deployment of spoilers in excessively strong thermal updrafts to increase flight safety.

3. SYSTEM MODELING

The first comprehensive energetic models to assess and design for performance and *perpetual flight* capability of solar-powered UAVs were developed by [8], [13]. In our previous work [9], these models were extended and used to conceptually design the AtlantikSolar UAV. Figure 2 shows a typical model output. The sections below provide a summary of these energy-based models, present the extensions to the solar power income model that were implemented in this paper, and summarize the main performance metrics that arise during simulation and will later be used for performance analysis.

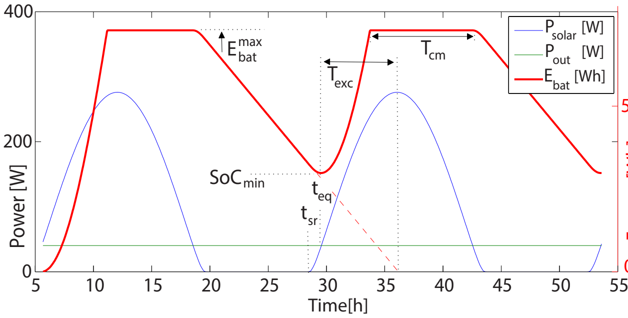

Figure 2. Exemplary results and major performance metrics as obtained for an energetic simulation of a 48-hour solar-powered UAV flight.

Energetic models for solar-powered UAVs

The simple quasi-static energy input/output-models used for solar-powered UAVs typically neglect the UAV's kinetic energy and only model the electric energy E_{bat} in the aircraft batteries and the altitude h as a representation of the potential energy E_{pot}. These two state equations are forward-integrated to assess the energy flows and the energetic safety margins that a solar-powered UAV provides with respect to *perpetual flight*. The combined state equation may be written as

$$\begin{aligned} \frac{dE_{bat}}{dt} &= P_{solar} - P_{out} \\ \frac{dh}{dt} &= \frac{1}{m_{tot} g} \cdot (\eta_{prop} \cdot P_{prop} - P_{level}) \end{aligned} \tag{1}$$

In the special case of fully charged batteries($E_{bat} = E_{bat}^{max}$), we enforce ${}^{dE_{bat}}/_{dt} \leq 0$, and for level flight, we have ${}^{dh}/_{dt} = 0$. The total required electric output power in equation (1) is

$$P_{out} = P_{prop} + P_{av} + P_{pld}. \tag{2}$$

P_{av} and P_{pld} represent the required avionics and payload power respectively, but the main contribution usually comes from the required electric propulsion power P_{prop}. In the important case of level-flight, $P_{prop} = {}^{P_{level}}/_{\eta_{prop}}$, where η_{prop} includes propeller, gearbox, motor, and motor-controller efficiency. Using the assumption that the UAV operates at the airspeed requiring minimum aerodynamic level-flight power, we can state

$$P_{level} = \left(\frac{C_D}{C_L^{\frac{3}{2}}}\right)_{min} \sqrt{\frac{2(m_{tot} g)^3}{\rho(h) A_{wing}}}. \tag{3}$$

Here, $m_{tot} = m_{bat} + m_{struct} + m_{prop} + m_{sm} + m_{av} + m_{pld}$ is the total airplane mass, where battery, structure, propulsion and solar module masses m_{bat}, m_{struct}, m_{prop}, m_{sm} are automatically sized according to [9] and m_{av}, m_{pld} are user choices. The local earth gravity is g, A_{wing} is the wing area, and $\rho(h)$ is the local air density. The airplane lift and drag coefficients C_L and C_D are retrieved from 2-D airfoil simulations using XFoil [14], with C_D being combined with parasitic drag from the airplane fuselage and stabilizers and the induced drag

$$C_{D,ind} = \frac{C_L^2}{\pi \cdot e_0 \cdot \lambda}. \tag{4}$$

Here, $e_0 \approx 0.92$ is the Oswald efficiency and λ the wing aspect ratio. The power income through solar radiation is modeled as

$$P_{solar}^{nom} = I \cdot A_{sm} \cdot \eta_{sm} \cdot \eta_{mppt}, \tag{5}$$

where our previous work [9] considers the exposed solar module area A_{sm} as a horizontally-oriented and thus aircraft-attitude independent area $A_{sm} = f_{sm} \cdot A_{wing}$ with relative fill-factor f_{sm}, module efficiency η_{sm}, and Maximum Power Point Tracker (MPPT) efficiency η_{mppt}. The solar radiation $I = I(\varphi, h, t)$ is assumed to be a function of the geographical latitude φ, the altitude h, and the current date and local time t, and is modeled as in [15]. This model is extended in the section below.

Extension of solar-power income model

Instead of modeling the aircraft's solar modules as one single horizontal surface, this paper takes the current orientation of the aircraft (roll, pitch and yaw) into account and uses a more elaborate geometric representation of the aircraft as depicted in Figure 3. The set of N solar module-covered areas A_{sm}^i each contains the cell configuration and relative orientation of the surface with respect to the airplane as a property. In lateral direction, this is the wing dihedral angle $\Delta\phi_{dih}$.

In longitudinal direction, every solar module area A^i_{sm} is mounted at an additional solar cell pitch angle $\Delta\theta_{A^i}$ with respect to the wing chord line due to the wing upper surface profile. The relative pitch orientation between the aircraft's longitudinal or x-axis (which is approximately aligned with the IMU longitudinal axis) and the wing chord line is added on top and is designated as $\Delta\theta_{wing}$. Using the specific number of solar cells on each surface, $n_{A^i_{sm}}$, the geometric properties above, and the global aircraft attitude in the form of the Euler-angles roll ϕ, pitch θ and yaw ψ we retrieve a representation for the sun-exposed area of each surface as

$$A^i_{sm} = f(\phi, \theta, \psi, \Delta\phi_{dih}, \Delta\theta_{wing}, \Delta\theta_{A^i_{sm}}, n_{A^i_{sm}}). \tag{6}$$

Combining the individual exposed surface areas via the simple sum

$$A_{sm} = \sum_i^N (A^i_{sm}) \tag{7}$$

returns the sun-exposed surface area of the whole aircraft as required for equation (5). The exact model parameters used in this paper are given in table 2.

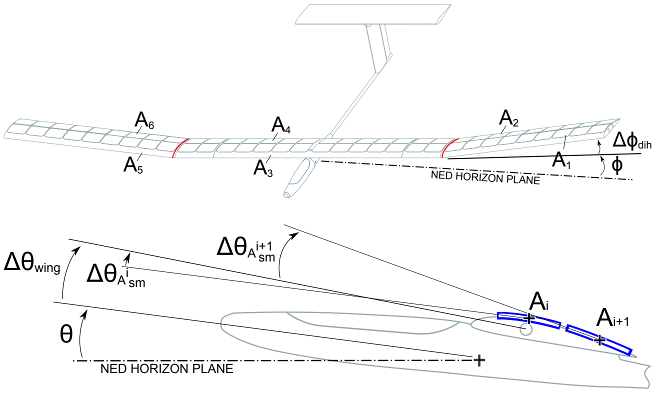

Figure 3. Geometric representation of AtlantikSolar within the solar power model. The set of sub-surfaces and their respective orientation to each other and to the North-East-Down horizontal plane in lateral direction (top) and arrangement in longitudinal direction(bottom)

In addition to geometric considerations, this paper also models the solar module efficiency losses occurring at temperatures above the Standard Test Conditions (STC) of T_{STC}=25°C using the simple linear relationship

$$\eta_{sm} = \eta^{STC}_{sm} \cdot \big(1 - c_l \cdot (T_{sm} - T_{STC})\big). \tag{8}$$

An initial value for the solar module efficiency under STC is given in table 2. The loss factor $c_l = 0.3\%/K$ is extracted from datasheets. The instantaneous solar module temperature is approximated using the linear relationship

$$T_{sm} = T_{amb} + \Delta T_{max} \cdot \frac{P_{solar}}{P^{max}_{solar}}. \tag{9}$$

Here, T_{amb} is the ambient temperature measured by the airplane, and ΔT_{max} is the temperature difference between solar module and ambient temperature that was measured in flight approximately at maximum insolation (i.e. at $P^{max}_{solar} \approx 260W$). Note that further effects such as shading of the solar modules e.g. by the horizontal tail plane, the influence of cell-cell interaction and the protection diodes, the influence of movements of the solar-cell covered ailerons, and changes in the efficiency of the MPPTs as well as the solar modules with respect to the insolation level and angle of incidence are not modeled yet but are considered candidates for following research.

Table 2. Solar model parameters (AtlantikSolar *AS-2*)

Parameter	Value	Source
$\Delta\phi_{dih}$	6.0°	Aircraft specs
$\Delta\theta_{wing}$	5.7°	Aircraft specs
$\Delta\theta_{A^i_{sm}}$	$\Delta\theta_{A^1,A^3,A^5} = -0.5°$ $\Delta\theta_{A^2,A^4,A^6} = 9.4°$	Measured
$n_{A^i_{sm}}$	$n_{A^1,A^3,A^4,A^6} = 12$ $n_{A^2,A^5} = 20$	Aircraft specs
η^{STC}_{sm}	23.7%	Measured in lab [16]
η_{mppt}	95%	Estimated

Performance metrics for solar-powered UAVs

A typical simulation result from a forward integration of the model described in the sections above, together with performance parameters that can be retrieved from it, can be seen in Figure 2. The battery energy E_{bat} and the equivalent measure state of charge (SoC) show the expected behavior that the batteries are charged during the day, remain at a plateau while $P_{solar} > P_{out}$, and are discharged during the night. The relevant performance metrics that can be extracted from such a simulation are:

- Minimum state-of-charge SoC_{min}, expected at $t = t_{eq}$ in the morning, and defined as $SoC_{min} = \min(SoC(t))$
- Excess time T_{exc}, a safety margin indicating for how much longer the aircraft could stay airborne after a successful day/night cycle if $P_{solar} = 0$ on the second day, i.e. defined as

$$T_{exc} = \frac{E_{bat}(t = t_{eq})}{P^{nom}_{out}}\bigg|_{P_{solar}(t>t_{eq})=0}. \tag{10}$$

- Charge margin T_{cm}, a safety margin indicating how much unused charging time the aircraft has available after fully charging its batteries before the discharge begins, i.e. defined as

$$T_{cm} = T(E_{bat} = E^{max}_{bat}). \tag{11}$$

4. MODEL VERIFICATION AND TRAINING

The power output and power income models used for performance prediction were verified in flight tests with the AtlantikSolar *AS-2* UAV. A second step involves training the model parameters based on that flight test data to allow more accurate performance predictions.

Required Output Power

The required power for level flight in equation (2) is determined as in [9], i.e. through direct measurement of the $P_{out} = f(v_{air})$ relationship. The airplane is set into autonomous loitering mode and performs an airspeed sweep from $v_{air} = 7.4...13.5 m/s$ at constant altitude. The measured power curve is depicted in Figure 4. The minimum required total electric power for level flight is $P_{out} = 39.7W$ at an airspeed of $v_{air} = 8.3 m/s$. This power curve is a direct input for the *perpetual flight* simulation.

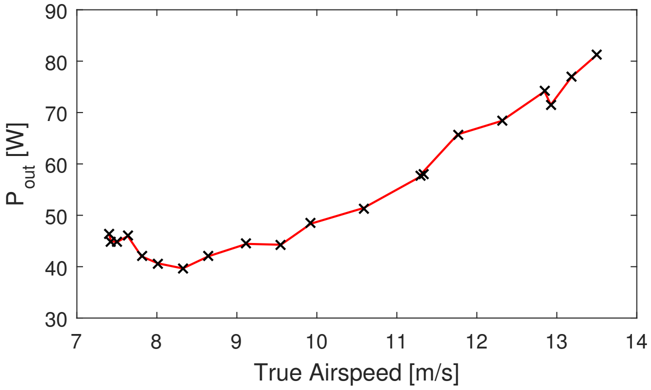

Figure 4. Power curve, i.e. the required level power P_{out} vs. airspeed, measured in constant-altitude loiter mode and averaged over T=200s intervals for each plotted data point.

Received Solar Power

To provide reliable results on the charging performance of a UAV, the solar power income models of section 3 need to be verified against the measured power income during flight. Figure 5 shows such a direct comparison from the early morning to shortly before noon for one AtlantikSolar *AS-2* autonomous loitering test flight. The comparison showed that deviations of up to 5% in the of total amount of solar energy collected throughout the day exist when assuming the modeling parameters of table 2. The total amount of collected solar power, however, needs to be modeled as accurately as possible to correctly predict the aircraft battery charge state. To train the used model, the model parameters of table 2 were therefore adapted. More specifically, the solar module efficiency η_{sm}^{STC} - which was only known from lab tests done on the raw modules without them being installed on the AtlantikSolar AS-2 wings - was adapted to $\eta_{sm}^{STC} = 22.53\%$ to fully align the measured and modeled accumulated solar power income.

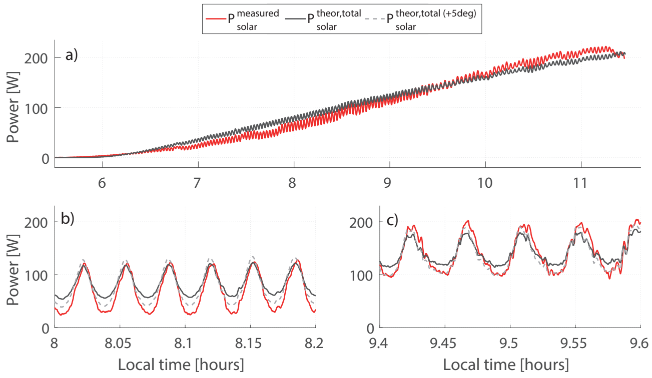

Figure 5. Theoretically expected vs. measured solar power income for the early morning to the early noon of an AtlantikSolar AS-2 test flight. For better readability, the original flight data has been filtered with a two-sided moving average filter with semi-window length $n_f = 200$ points.

The achieved fit of the power income is visible in Figure 5a. Although the accumulated solar power income is correct, the measured power income is slightly lower than the theoretical one at low income power, and higher than the theoretical one at high income power. Excerpts from the curve in Figure 5a are shown in Figure 5b (early morning) and Figure 5c (later morning). Figure 5a clearly indicates that the average measured power income at that time is below the theoretically expected one. One reason for this behaviour can be inferred from the flight logs. These show that, especially in low radiation conditions, the MPPTs exhibit sub-optimal maximum power point (MPP) tracking behavior. The MPPT efficiency η_{mppt} is also known to decrease at lower income power. A third explanation is related to the solar module efficiency η_{sm}, which decreases in weak irradiation conditions [17]. Of course, all other effects described in section 3 have not been modeled, which can also contribute to model/measurement discrepancies. Integrating precise models for all these factors is a research target for the final solar power income model.

In addition, visible in Figure 5b and Figure 5c, the amplitude of the oscillations due to the aircraft loitering is larger for the measured power income. One reason are the uncertainties in determining the exact current pitch attitude of the solar module surfaces, which may be falsified by errors in the measurement of $\Delta\theta_{wing}$ and $\Delta\theta_{A^i_{sm}}$, but also by attitude estimation errors of the aircraft pitch angle θ itself. Figures 5b and 5c therefore both include a theoretically expected power income for an additional $\Delta\Theta_{add} = 5^\circ$, which already provides an excellent fit. Note that in general, the model captures small-scale changes e.g. due to instantaneous roll-angle and pitch-angle changes very well. It remains to be investigated what specific error in the total pitch angle estimation might be the reason for the amplitude differences.

Overall, the quality of the fit means that the theoretical power income model is a very good quantitative fit for flights in similar - i.e. very good - irradiation conditions. However, if large deviations from this *training point* arise, for example caused by significant cloud cover that decreases the power income over the full day and results in the battery not even being fully charged, then the model will overestimate the actual solar power income. This is one reason why - until further research has been undertaken - our conceptual design and simulation environment applies additional safety margins on the minimum SoC under which we assume that perpetual flight is possible (section 5).

5. FLIGHT RESULTS

A total of 60 test flights with a flight duration of 225 hours have been completed with the three versions of AtlantikSolar produced at ETH Zurich so far. The flight test program has recently culminated in the first completely solar-powered day/night flight of 28 hours and 18 minutes with AtlantikSolar *AS-2*. The flight set a new Swiss endurance record for solar-powered UAVs and proved AtlantikSolar's *perpetual endurance* capability. This *perpetual endurance* capability has only been shown by one smaller (in terms of mass) solar-powered UAV [8] before.

Flight results from 28-hour continuous solar-powered flight

The 28-hour continuous solar-powered flight was performed on June 30th and July 1st 2015 at a geographical latitude of $\phi_{lat} = 47.6^\circ$ in Rafz, Switzerland. Flight conditions throughout the whole flight proved to be excellent, with only occasional and very marginal high-altitude cloud cover and moderate winds up to $4\,{}^{m}\!/_{s}$. Figure 6 shows an excerpt of logged flight data. The airplane was launched at 11:14am on June 30th at 58% state of charge. While launch and landing were performed in manual RC-control, overall 98% of the flight were performed in autonomous mode. As common for LALE-UAVs aiming for perpetual endurance, the flight strategy was to fly low at constant altitude for as much time as possible to reduce power consumption, and ascend only when the batteries are fully charged at the end of the day to store potential energy in altitude.

The analysis of the required output power P_{out} in Figure 6 shows strong fluctuations for both P_{out} and the aircraft altitude h after launch- and from late morning to early evening in general. This is caused by significant time-varying thermal up- and downdraft activity. As described in [9], in this case the UAV will passively gain altitude and thus energy from thermal updrafts until it reaches the maximum user-specified altitude $h_{max} = 720m$ AMSL. However, the average power consumption over the sections with strong thermal activity (e.g. until $t = 20h$ on the first day) is still $P_{out}^{avrg} = 67.8W$ and thus around 50% more than measured in calm air (Figure 4). The effect of thermal downdrafts therefore exceeds that of thermal updrafts. The resulting slower charge process needs to be considered as a function of location and time when analyzing solar-powered UAV performance flights and was thus included as a parameter in our modeling environment. During the night, the air is naturally calmer, and we retrieve $P_{out}^{avrg} = 41.8W$ - mostly taken from the battery - from 9pm to 6am. This represents less than 5% error with respect to the measured data in Figure 4.

The overall validation and training of the solar power models has been performed in section 4, and the direct comparison with flight test data from the 28-hour flight confirms the findings: The generated solar power P_{solar} is slightly lower than the theoretically expected value at low power income (morning and evening), and slightly higher at high power income (around noon). Figure 6 also shows the actual battery charging power P_{bat}, and when the batteries are fully charged ($t = 13.73h$ on day 1, $t = 12.33h$ on day 2), it is evident that the MPPTs limit the effective P_{solar} to reduce battery wear by charging slowly at high state of charge. This is in compliance with the standard CC/CV charging method for Li-Ion batteries, which suggests an exponentially decreasing charge power similar to Figure 6. It can also be seen that while the MPPTs limit the battery charge power P_{bat}, they will still supply the full output power P_{out} if available. The plots in addition show that $SoC(t = t_{launch} + 24h) > SoC(t = t_{launch})$, and thus the *perpetual flight* capability is proven.

The exact performance metrics achieved during the 28-hour flight are determined from the data in Figure 6 and are summarized in Table 3. The minimum state of charge during the whole flight is $SoC_{min} = 41\%$. This is a significant improvement over previous solar-powered UAS designs such as SkySailor, which reached $SoC_{min} = 5.8\%$ [8]. The minimum state of charge translates to an excess time of $T_{exc} = 7.04h$. The charge margin T_{cm} is 5.9 hours, and thereby provides significant margin against e.g. decreased solar power input caused by clouds. Note that the time until the batteries are at $SoC = 90\%$ - which would still allow perpetual flight in these conditions - is much lower because the charge rate is decreased after that to decrease battery wear. The resulting charge margin until $SoC = 90\%$ is thus also increased. The measured performance metrics correspond well with the performance metrics predicted during the initial conceptual design of AtlantikSolar [9]. However, note the initial design was carried out for AtlantikSolar *AS-1* and with slightly different flight data.

The performance metrics predicted by our conceptual design and simulation tools agree very well with the measured data. We retrieve $SoC_{min} = 39\%$ and $T_{exc} = 6.28h$, i.e. errors of 4.8% and 10.8% respectively. This close agreement is found primarily because the state of charge and excess time are - given that $P_{solar} = 0$ during the night - nearly exclusively a function of power consumption P_{out} and maximum battery energy E_{bat}^{max}, where we learned the former parameter from extensive flight testing and have a rather precise estimate of the latter. The relative errors regarding the charge margins T_{cm} and $T_{cm}^{90\%}$ are 16.7% and 9.2% respectively. In addition to being harder to measure from flight test data, the charge margin is also harder to model, as it is prone to both local deviations in input and output power as well as to modeling errors in both.

Table 3. Comparison of performance metrics for the 28 hour flight test and the corresponding simulation.

Metric	Flight	Sim.	Comment
SoC_{min}	41%	39%	
T_{exc}	7.04h	6.28h	(with t_{eq}^1=7.59h
T_{cm}	5.9h	6.89h	(t_{eq}^2=19.67h, t_{fc}=13.77h
$T_{cm}^{90\%}$	8.18h	8.93h	(t_{eq}^2=19.67h, $t_{fc}^{90\%}$=11.49h

Overall, and especially compared to previous designs such as [8], the flight results show significantly improved energetic margins both with respect to local deteriorations in power income (e.g. clouds) as well as power consumption (e.g. horizontal and vertical winds). Given that the performance metrics T_{exc} and T_{cm} from [9] were largely confirmed, the robustness analysis for perpetual flight in these local meteorological deteriorations is still valid with only minor modifications. As a last step, the improved energetic margins motivate an outlook into multi-day flight applications of such *perpetual flight* capable low-altitude solar-powered UAVs. Figure 7 provides an overview over the minimum state of charge versus the day of year DoY assuming flight at a northern latitude of $\phi_{lat} = 47.6°N$. Perfect conditions both with respect to solar power income (i.e. clearness $CLR = 1.0$, or equivalently $P_{solar} = P_{solar}^{nom}$) and required output ($P_{out} = P_{out}^{nom}$) are assumed for the calculation.

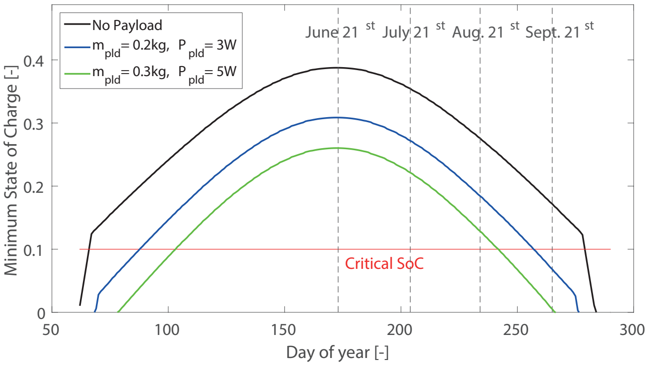

Figure 7. Predicted minimum state-of-charge (SoC) as a function of the day of the year for AtlantikSolar *AS-2* at a latitude of $\phi_{lat} = 47.6°N$. The critical SoC is an experience-based limit below which the batteries should not be discharged for safety reasons.

It is shown that without payload, perpetual flight is possible in a six-month window around June 21st assuming that the

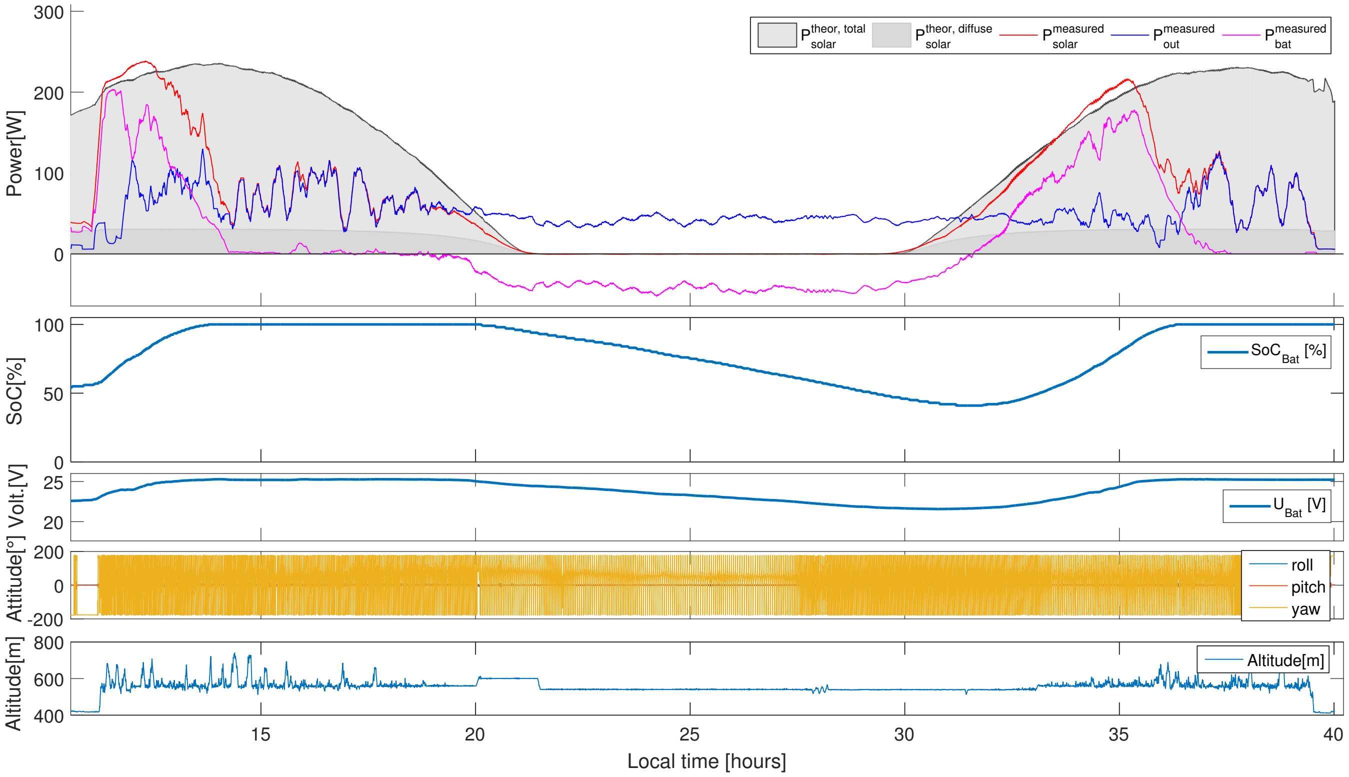

Figure 6. Flight log data for the AtlantikSolar *AS-2* 28-hour *perpetual endurance* flight on June 30th 2015. The recorded power income and output data is recorded at 2Hz and was time averaged with a two-sided moving average filter with semi-window size 1000 samples to reduce the effects of aircraft attitude-induced oscillations.

aircraft shall not discharge its batteries below a certain critical SoC level SoC_{crit}. This safety margin is crucial, first, to account for remaining uncertainties in the modeling process (sections 3 and 4), but on the other hand to allow for sufficient remaining battery energy and, thus, propulsion power e.g. if a go-around during landing is required. Initial applications of multi-day solar-powered low-altitude flight may involve long-endurance aerial sensing, observation and mapping missions. For that purpose, Figure 7 also considers two miniaturized sensing payloads: A simple optical camera with integrated on-board image recording or, alternatively, an atmospheric sensing payload ($m_{pld} = 200g$, $P_{pld} = 3W$) and a small-scale infrared camera such as described in [11] with either on-board recording or additional live-image downlink ($m_{pld} = 300g$, $P_{pld} = 5W$). The first application allows continuous multi-day flight in up to a window of 5 months and the latter in a 4 month window around June 21st. Note that the endurance provided by such solar-powered UAVs even when perpetual flight is not possible is still sufficient to provide full daylight-flight capability and is thus sufficient for most large-scale mapping tasks [11].

6. CONCLUSION

This paper has presented design improvements of the small-scale hand-launchable solar-powered AtlantikSolar UAV, has summarized flight results of a continuous 28-hour solar-powered flight that demonstrated AtlantikSolar's capability for energetically *perpetual flight*, and has offered a model-based verification of flight performance and an outlook on the energetic margins that can be provided towards perpetual flight given today's solar-powered UAV technology. The flight results show that a significant increase in the *perpetual flight* energetic margins has been achieved with respect to earlier low-altitude *perpetual flight*-capable UAVs. This increase in energetic margins comes from the progress in battery- and solar-cell technology, but also from the thorough design optimization and testing performed for the AtlantikSolar UAV. The improved performance is the basis for more robust *perpetual flight* in solar-powered LALE UAVs. However, it should be noted that even the high achieved energetic margins of $T_{exc} = 7.04$ hours and $T_{cm} = 5.9$ hours are not enough to sustain *perpetual flight* in severe meteorological conditions such as strong winds or cloud cover. Nevertheless, the results motivate a look into first applications of solar-powered low-altitude *perpetual flight*. While *perpetual flight* without payload is possible in a 6-month window around June 21st for AtlantikSolar AS-2, applications with a 200g optical camera or atmospheric sensing payload or a 300g infrared camera system would still provide a four and five months *perpetual flight* window in optimal conditions. These applications for *perpetual flight*-capable solar-powered UAVs could be of significant importance in simple monitoring, mapping or sensing tasks including border and maritime patrol or meteorological sensing in the medium future.

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Philipp Oettershagen *received a M.Sc. in Aerospace Engineering from California Institute of Technology in 2010 and a Diploma (Dipl.-Ing.) in Aerospace Engineering from University of Stuttgart, Germany, in 2011. He is currently a research assistant and PhD-student at ETH Zurichs Autonomous Systems Lab, where he is leading the AtlantikSolar Unmanned Aerial Vehicle (UAV) project. Besides the conceptual design and system engineering of high-performance solar-powered UAVs, he is interested in using in-flight estimations of the often highly cluttered and dynamic meteorological environment for trajectory planning and UAV decision making.*