R028-A

Application of Solar Soaring Power Manager (Phase III)
Submitted by Packet Digital, LLC

Response to Reviewers
Prepared by Packet Digital and Dr. Robert Walters of the Naval Research Lab

1. Objectives

Response to Reviewer 2A:

Regarding long-term job opportunities, Packet Digital intends to continue R&D and productization in the UAS space, Packet Digital will continue working with NRL and other partners to increase UAS endurance through solar and innovative power systems, while keeping as much of the future manufacturing as possible within North Dakota. The UAS space is a rapidly growing field in which both Packet Digital and the state of North Dakota are well-positioned.

The intended outcome of this proposal is to help further develop the UAS industry in North Dakota and that jobs created with this proposal will be long-term positions. It is expected that these will be high-paying, technically rewarding jobs that will help retain some of the talent that comes out of the North Dakota university system. Since this proposal was originally submitted (in June 2015), Packet Digital has formed a joint venture with Aerobotic Innovations, known as Botlink for the commercialization of UAV products. Botlink has created 18 full-time, permanent engineering/development positions. In addition, we currently have at least 20 employees working on the initiative which we also expect to be long term. We expect the headcount to go to 100 in the next two years.

This project addresses North Dakota's goals of advancing renewable energies and establishing a leading role in the UAS commercial sector.

Based on the results of Phase I and II, we have produced an analysis showing that with the current airframe and battery capacity, 22% efficient solar cells will provide **"through-the-day" flight** endurance of roughly 18 hours depending on flight conditions. This is roughly a **4-5 times improvement.** Such endurance capability has the potential to establish a huge commercial market for a wide range of applications. Moreover, this can be achieved with the high-performance, commercial solar cells from a third party, obtained via a strategic collaboration. Thus, our proposed project is poised to place North Dakota at the forefront of this commercial market and to have the first mover advantage.

This will be achieved by establishing the UAS solar wing manufacturing in North Dakota, as part of the overall UAS assembly. It is important to note that while the 22% efficient Si solar cells can be obtained through this collaboration, the array manufacturing capability does not exist. The process for interconnecting the solar cells, assembling them into strings, and laminating them into flexible sheets is presently being performed by NRL and Packet Digital with support from space solar array manufacturers and North Dakota-based composite experts acting as subcontractors. Furthermore, the process of integrating these flexible sheets as the face-skin of

the UAS wing is presently being done by NRL, Packet Digital and North Dakota-based composite experts. These activities must be transitioned to a commercial manufacturer, and we propose this manufacturer be in North Dakota. We consider this to be the first generation of our solar-UAS product that will create unprecedented capability to the SUAS commercial space and place North Dakota clearly in the lead. This first generation system will establish a renewable energy-powered system manufactured in North Dakota that addresses the goals of both the North Dakota REC and the North Dakota goals for UAS manufacturing.

By participating in the photovoltaic technology development at NRL, this North Dakota REC project stands to gain immediate access to the next generation solar cells. When available, these solar cells can be directly inserted into the UAS solar-wing manufacturing, enabling a second-generation UAS system, manufactured in North Dakota, with revolutionary capability. This enhanced capability will expand the commercial UAS space.

Thus, this project can be seen as a two-stage process. In the first stage, we will place North Dakota in the position of manufacturing flexible solar arrays using existing solar cells and rapidly breaking into the UAS commercial market. As commercialization and manufacturing continues, NRL will interject the advanced solar cell technologies to enhance the system performance and thereby expand the market base even further and allowing North Dakota to be in the position of dominating the UAS commercial space with this advanced renewable energy technology. Further, since the solar technology being transitioned from NRL to Packet Digital is applicable to a wide variety of terrestrial power applications, North Dakota will be positioned as a possible solar manufacturing state.

The cost-competitive nature and commercial viability of the 40% efficient cells should be clarified. The state-of-the-art, 40% efficient cells will be available to commercial customers as a premium product line. Like most commercial producers, however, Packet Digital aims to provide premium, mid-level, and economy product lines to capture the widest possible audience and expects the majority of customers will settle on the mid-level price point. As such, the 40% efficient cells are not going away. We are instead adding additional product lines to generate broader demand as the 40% efficient cells become available.

Packet Digital and NRL will continue development and commercialization of several levels of high-efficiency, multi-junction solar cells to deliver better technology at a more affordable cost to more customers. The 40% efficient cells will have widespread value in a variety of applications, albeit at a premium price, which may not provide a suitable entry point for some clients.

The primary cost driver for the high efficiency solar cells, specifically the GaAs based multijunction (MJ) cells, is the manufacturing methodology. The MJ solar cells are grown via metal-organic chemical vapor deposition (MOCVD). MOCVD is a excellent tool to create highly sophisticated, multi-layered semiconductor devices consisting of many elements stacked in regular matrices. While MOCVD has allowed us to produce astounding results for our MJ solar cells on a small scale, the tool is inherently expensive for making solar cells as large area devices. To address this, NRL is working on with laboratories developing solar cells, in particular the National Renewable Energy Laboratory (NREL), to develop a grow tool specially designed for solar cell growth. Once we reach a solution for large-scale cell growth, production costs of the high-efficiency MJ cells will be reduced considerably.

Response to Reviewer 3A:

Packet Digital agrees that the market for extended endurance UASs will not be limited to N.D. However, there is still a very significant market within N.D., such as the agriculture and oil and gas industries.

Packet Digital also intends to keep as much of the new manufacturing as possible within N.D. As mentioned in the Phase III objectives, Packet Digital will be working with ND-based companies Chiptronics, c2renew, and ComDel Innovations for solar UAS manufacturing.

See also response to reviewer 2A.

2. Achievability

Response to Reviewer 1A:

In phase III, Packet Digital will design a fixed-wing, extended endurance UAS built using thin, flexible Si solar cells and an optical camera as a payload. This UAS will enable 8 hour or day shift flight times using 22% and 27% solar cells. The payload will be interchangeable, but it is anticipated that a camera such as the Sony QX1 will cover a wide variety applications. Cameras modified to capture NDVI data are also available. This entire system will be available to customers for <$100k. Based on discussions with potential customers, there is market potential for a UAS of this price and performance.

Regarding payloads, current systems use optical and infrared image sensors. Numerous other payloads are possible, such as RF transmitter/receivers, gas detectors, multispectral imaging, etc. It is correct that payload will impact aircraft endurance due to the additional weight and required power. The payload capacity of the current airframe configuration is approximately 3.5kg. However, Packet Digital plans to work closely with customers to offer engineering services and optimization based on their specific payload needs.

Response to Reviewer 2A:

The reviewer has expressed concern whether Si solar cells can meet the goals of this project due to the rigidity and the lower efficiency. The rigidity issue is resolved by a number of solar cell manufacturers offering Si solar cells which are thinner and more flexible than traditional Si cells. While not as flexible as thin film solar cells, the are flexible enough to conform the the UAS wing without sacrificing aerodynamic efficiency.

Regarding the lower efficiencies of Si solar cells, Packet Digital agrees that current Si efficiencies may not enable an endless endurance UAS. However, current analysis estimates 22% efficiency will enable up to 18 hour flight times during a summer day in Fargo. While not endless, it enables UAS applications that are not feasible with current flight durations and an entire day shift UAS to fly pipelines and power lines.

Response to Reviewer 3A:

The reviewer is correct that the development of high efficiency (~40%) solar cells is extremely difficult and that transferring the technology from R&D to cost-efficient commercial manufacturing is not a one-year project. Packet Digital and NRL will continue to invest in high-efficiency solar cells for UAS beyond the term of this ND REC project. A UAS has been

outfitted with high-efficiency (27%) solar cells, which are currently available, albeit at a higher price point, for customers that require the high-efficiency and can tolerate the cost.

3. Methodology

Response to Reviewer 1A:

Regarding the UAS functionality, a long-endurance UAS could have a variety of uses depending on customer needs, which would then determine the type of payload installed. A UAS used to inspect longer stretches of highway could use simple optical sensors, while aircraft used to inspect an extension of oil pipeline could implement multispectral or gas detection technology. Packet Digital will work with customers to determine their payload needs and optimize the aircraft accordingly for size, weight and power.

Please see the payload response in section 2 for more information.

Regarding design attention to FAA requirements, Packet Digital keeps up-to-date on the FAA regulations for UAS, including the upcoming Part 107. Packet Digital's aircraft meets the FAA part 107 requirements in terms of weight (<55lbs), max ground speed (87 knots), and max altitude (400 ft).

Response to Reviewer 2A:

Significant progress has been made during the project to improve solar wing level efficiencies. The NRL solar development team has achieved 33% efficiencies and we will continue to work on increased efficiencies enabled by this project. Note that this was the initial manufacture of these wings and there is still much optimization to be done in terms of solar array assembly and lamination which will increase efficiencies.

Packet Digital apologizes that this was not made clearer in the Phase I proposal. Solar cells with 2x the efficiency of current commercial solar cells will have a significant price premium. This issue was presented and discussed with the ND REC previously (See July 20, 2015 proposal presentation). Please also note that Packet Digital is not abandoning the MJ solar cells. They will still be used for any customers that require that performance, and R&D will continue to improve production methods and ultimately decrease the purchase cost. The Si solar cells selected for Phase III along with the enabling solar electronics developed during this project will bring new levels of endurance to a broader market.

The Si-based solar cells selected are flexible and significantly thinner than traditional Si cells. Packet Digital and NRL have assembled and ground-tested a UAS with commercially available Si cell wings in Phase II. Flight tests will be conducted with this configuration in between Phase II and III. Ground testing with the first set of assembled solar wings has shown that the Si cells are flexible enough to conform to the aerodynamic surface without degradation. Simulation models show predicted flight times of up to 18 hours with the Si cell arrays and initial tests show that the simulation model matches real-world performance fairly well.

4. Contribution

Response to Reviewer 2A:

While the current FAA limitation is 400ft for standard commercial UAS aircraft, it is expected that this limitation will be relaxed in the future. When it is relaxed, Packet Digital will be ready to offer a commercial solution. In the meantime, the military and countries other than the US will benefit from the use of the soaring algorithms.

The purpose of switching to Si solar cells is to enable a manufacturing-ready UAS within the time frame of this project. Phase III will combine knowledge gained from NRL's solar UAS with N.D. molding experts (c2renew, ComDel Innovations) to produce a manufacturable UAS. It is anticipated that a commercial UAS will be the outcome of phase III.

5. Awareness

Response to Reviewers 1A and 2A:

Packet Digital and NRL have meet with world solar experts and ten solar manufacturing companies to select the most lightweight, efficient and cost effective solar cells for this projects.

Please see the following external references to the NRL's work with MJ solar cells:

- Yakes, et al. "Evaluation of strained InAlAs as a window layer for wide bandgap materials lattice matched to InP", Proc. 42nd IEEE Photovoltaic Specialist Conference, New Orleans, LA, June 2015.
- Lumb, et al. "Transfer-printing for the next generation of multi-junction solar cells", Proc. 42nd IEEE Photovoltaic Specialist Conference, New Orleans, LA, June 2015.
- Lumb et al. "Double quantum-well tunnel junctions with high peak tunnel currents and low absorption for InP multi-junction solar cells", Appl. Phys. Lett. 100, 213907 (2012); doi: 10.1063/1.4722890
- Lumb, et. al, "Quantum wells and superlattices for III-V photovoltaics and photodetectors". Presented at the SPIE Solar Energy + Technology, SPIE. (Vol. 8471, pp. 84710A–84710A–10). doi:10.1117/12.964654
- Schmieder, et al. "Analysis of GaAs Solar Cells at High MOCVD Growth Rates." Proc. 40th IEEE Photovoltaic Specialist Conference, Denver, CO, June 2014.

6. Background

No comments

7. Project Management

Response to Reviewer 1A:

Regarding the relation of the system integration and low-cost solar wing integration tasks, it was originally decided that the high-efficiency solar arrays would take priority over

Response to Reviewer 2A:

The Gantt Chart was small due to the length constraints of the proposal. Please see more details below. Milestones:

Objective 1: Solar Wing Development

Task 1: GaAs solar wing integration - NRL -
At the end of month 5, a MJ solar cell wing will be integrated with the entire UAS. The array stackup process will be identified and the wing level performance will be characterized.

Task 2: Lower cost Si solar wing integration - Packet Digital/NRL -
At the end of month 8, Si solar cells from a specific manufacturer will be selected based on efficiency/cost/flexibility and a Si solar cell wing will be integrated with the entire UAS. The array stackup process will be identified and the wing level performance will be characterized. This aircraft will serve as a prototype for broad-scale production/manufacturing at the end of Phase III.

Objective 2: System Integration

Task 1: Full system integration - Packet Digital/NRL -
At the end of month 7, the full solar system (MJ solar cell wings, MPPT, smart battery, PMAD, and ESC) will be integrated into the ER-1 airframe. Installation and test procedures will be created.

Objective 3: System Testing

Task 1: NRL Flight Testing - Packet Digital/NRL -
With the exception of the winter months, monthly flight tests will be conducted at NRL facilities. Flight reports including the performance of the power system will be delivered. Any issues with the power system will be addressed.

Task 2: ND Flight Testing - Packet Digital/ NPUASTS -
With the exception of the winter months, monthly flight tests will also be conducted in N.D. Flight reports including the performance of the power system will be compared to NRL data. Any issues with the power system or airframe will be addressed.

Objective 4: Manufacturing Plan for Commercial UAS

Task 1: Solar wing manufacturing process - Packet Digital/c2renew -
Molds and laminate/composite manufacturing process will be established for the ER-1 solar wings. Prototype wings using this process will be delivered by month 8.

Task 2: UAS manufacturing plan - Packet Digital/Chiptronics/ComDel -
An electronics and UAS assembly process will be identified at Chiptronics. If the need for a custom UAS fuselage is needed, ComDel will be the leading candidate to perform that work. A manufacturing plan will be in place by month 12.

Regarding a majority of the Phase III budget being provided by NRL, this is due to NRL driving the MJ high cost solar cell wing development. In addition, we would like to stress that the

matching effort brought by NRL is highly leveraging, as the NRL effort builds on extensive experience and expertise in SUAS flight projects of just this nature.

As discussed in the section 1 response, a major focus of the NRL, and the DOD as a whole, is executing several R&D programs to specially address the affordability of the high efficiency, MJ solar cells. We expect the results from these projects to bring a new solar cell manufacturing capability to the market within the next 2-3 years. This will make the high efficiency solar cells available as a drop in replacement for this UASs we are currently producing.

8. Equipment Purchases

No comments

9. Facilities

No comments

10. Budget

No comments

Overall Comments and Recommendation

Response to Reviewer 1A:

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Response to Reviewer 2A:

Regarding the disappointment that the MJ cells are not being used for the commercial UAS, we would like to reiterate that the solar cells are not being abandoned altogether. Development will continue, including development of a lower cost manufacturing process as mentioned

previously. MJ cells will also be available for customers that require the high efficiency, but it is anticipated that a majority of customer's needs will be met with the Si solar cells.

Regarding the doubts whether Si solar cells are suitable for UAS applications, initial work with commercially available Si solar cells has shown that they are flexible enough to apply to UAS wings. This work was done with cells with >20% efficiency and a cost of <$3 per cell.

As previously described, the FAA height restrictions do limit the applicability of soaring to many customers, but it is still available to military and customers from other countries. Additionally, it is anticipated that the FAA will increase the UAS flight ceiling.

Regarding long term jobs, it is anticipated that skilled manufacturing jobs will be created and sustained by the manufacturing launch of a commercially viable UAS as will be defined in this phase. The work done in phases I and II (MPPT, PMAD, smart battery) has been very well received by NRL and Packet Digital has been subcontracted for an additional DOD contract. It is expected that more government funding will continue as Packet Digital becomes a recognized leader in the UAS power space. This will create and sustain additional engineering jobs in ND.

All reviewers:

Please see responses to specific topics.

Appendix A: NRL Research Team

Proposed NRL Team

Rob Walters

Education
- University of Maryland Baltimore County, Ph.D. Applied Physics

Research Interests and Experience
- Has performed research at NRL since 1990 focused on advanced photovoltaic power sources for space and terrestrial applications
- Successfully executed a large number of R&D efforts, including three space-based solar cell experiments on board the ISS
- Co-inventor of a novel multijunction solar cell technology
- Currently manages a 40-person branch at the NRL, consisting of ~$12 million of R&D efforts with ~$6 million in photovoltaic research
- Has over 130 publications to his name with over 100 conference presentations

Phil Jenkins

Education
- Cleveland State University, MS Electrical Engineering

Research Interests and Experience
- Has expert knowledge in solid-state device physics and semiconductor applications including, solar cells, thermo-photovoltaics, etc.
- Has authored technical papers and patents and has over 600 citations of his published work.
- Has experience designing, building and executing complex experiments in a variety of environments to include Mars, ISS, underwater, etc.
- Has received awards, including the NASA Group Achievement Award and a couple NASA Glenn Technology Awards.

Woojun Yoon

Education
- The Ohio State University, Ph.D. Electrical Engineering

Research Interests and Experience
- Has performed experimental, analytical, and simulation-based investigations of fundamental optoelectronic properties of semiconductor materials
- Has experience with fabrication of both organic and Si-based photovoltaic devices
- Has over 30 publications with over 30 conference proceedings

NRL Solar Team Continued

Solid State Electronics Branch

Maria Gonzalez

Education

- The Ohio State University, M.S and Ph.D. Electrical and Computer Engineering

Research Interests and Experience

- Has expert knowledge in solid-state device physics and semiconductor applications with a focus on photovoltaics
- Internationally recognized expert in high efficiency solar cell development
- Has experience in managing complex solar cell design and fabrication efforts
- Has over 20 publications with over 40 conference proceedings.

Ken Schmeider

Education

- University of Delaware, Ph.D. Electrical Engineering

Research Interests and Experience

- Has extensive research experience with epitaxial growth of III-V based solar cells
- Has skills with modeling photovoltaic device design/fabrication and optical/mechanical/electrical characterization of materials
- Has over 30 publications with over 30 conference proceedings