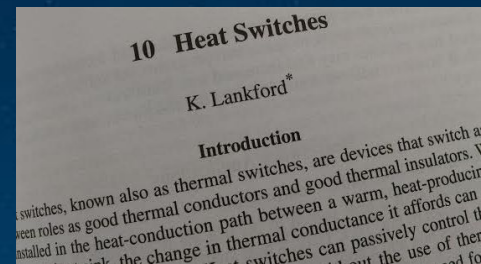


A white hot air balloon is positioned in the upper center of the frame, floating over a vast, rugged, mountainous landscape. The terrain is characterized by deep, winding valleys and steep, rocky slopes, all bathed in a soft, golden light that suggests either dawn or dusk. The sky is a clear, pale blue. The overall scene conveys a sense of vastness and tranquility.

The Deal with Photon Harvesting
15 July 2015
Loon LLC

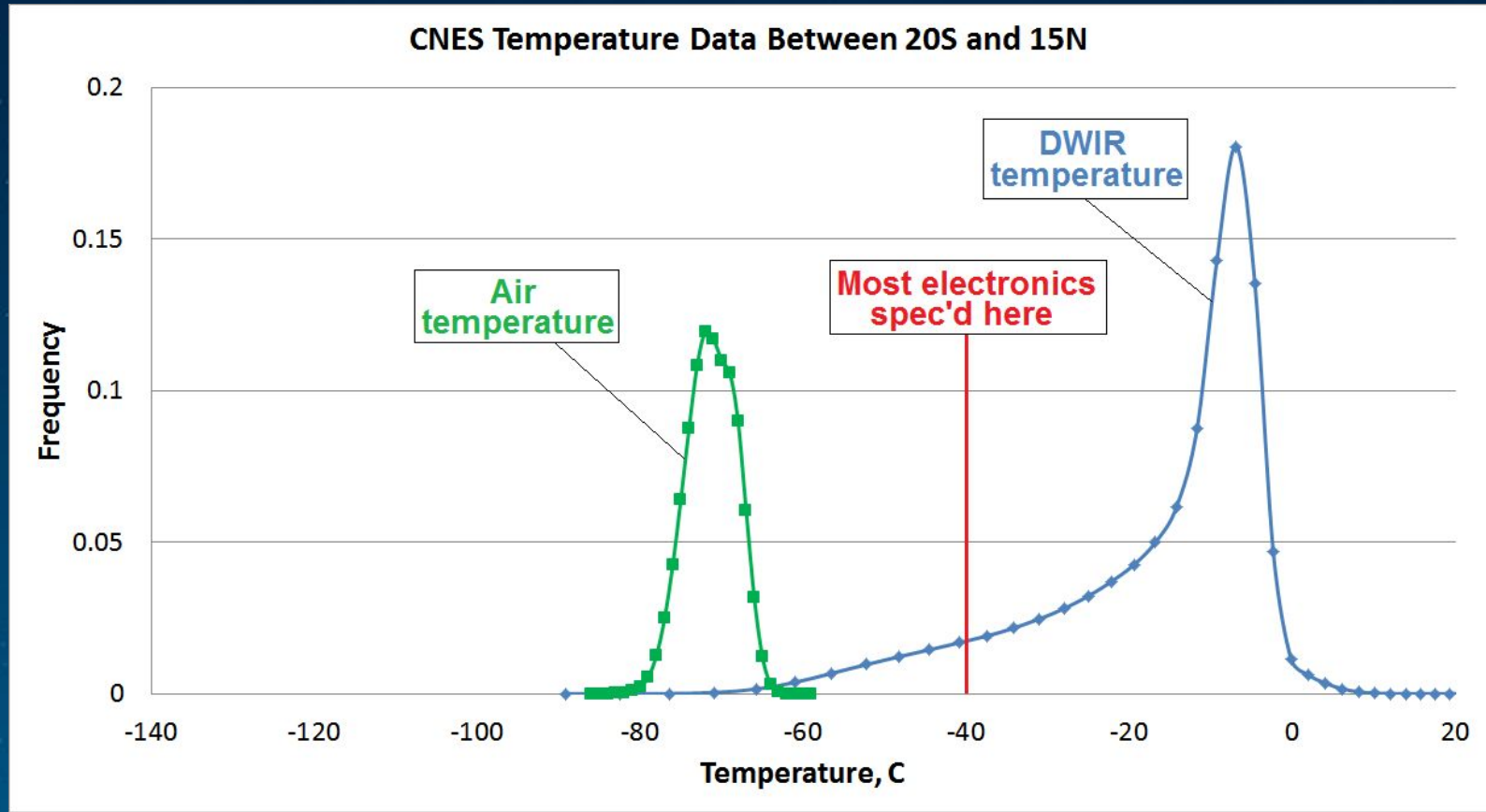
An Engineer's life, 2014-2015

- Sometimes: Electronics are **on** during the **day**
- Sometimes: Electronics are **off** at **night**
- Are we heating or cooling this stuff?
 - “Yes”
- Dealing with this in space has been a thing for decades
 - They also have space budgets...
 - ...and space reliability specs
- How do we do this for Project Loon?
 - Light, minimal power consumption
 - Cheaper + shorter design life than space
 - “Put it in the air and forget about it”



Our environment

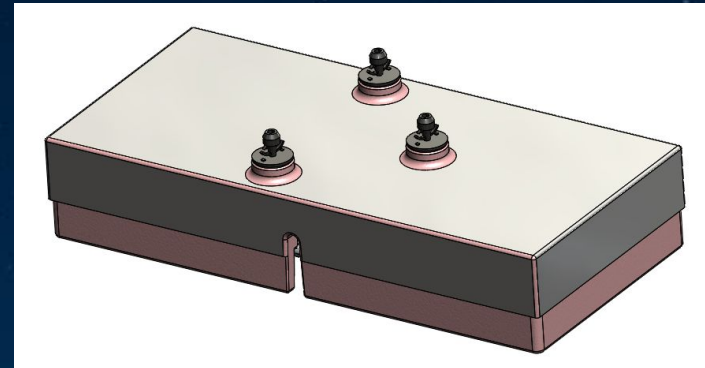
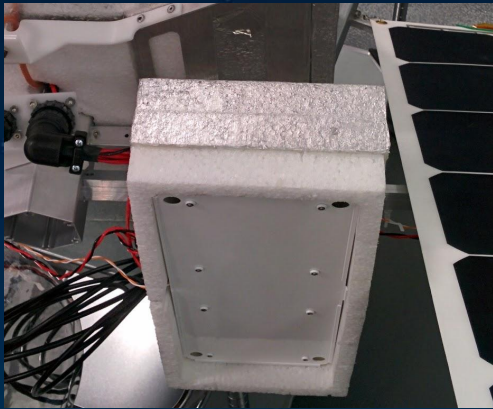
- Two good choices for heat leaving our system
 - Convection to air: almost always -80C to -50C
 - Radiating down: generally -60C to 5C, avg about -15C
- All potentially okay for cooling in the day
- Which is best for keeping warm at night?



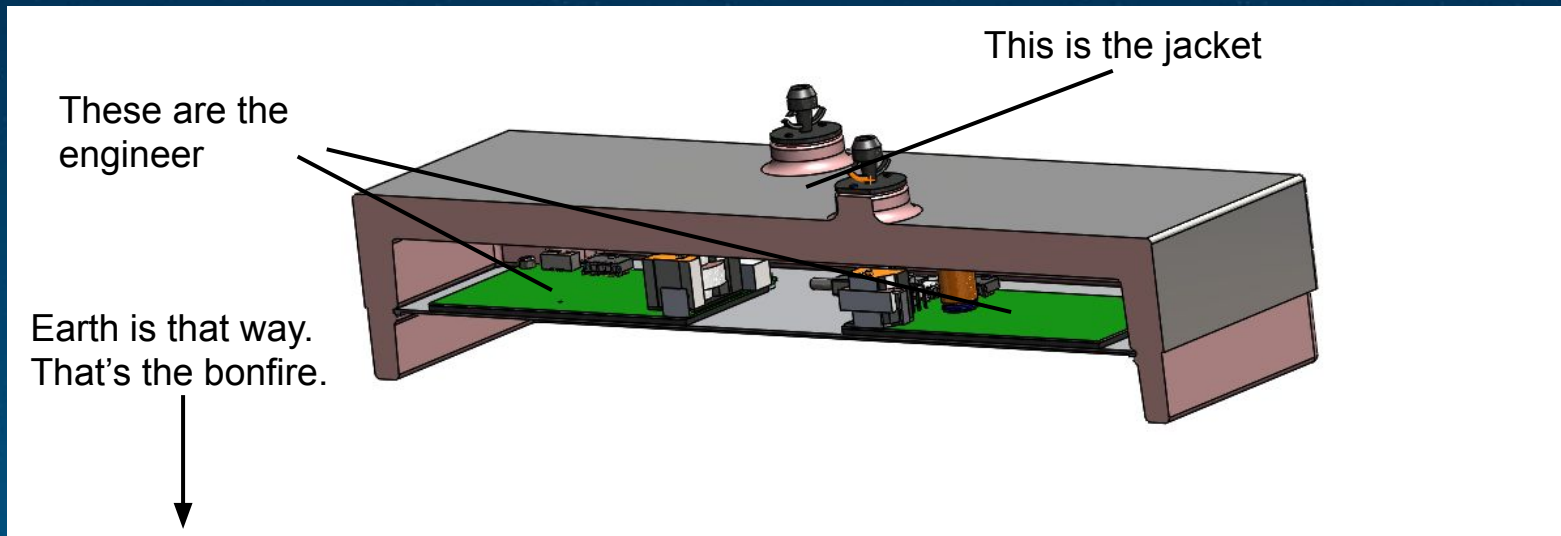
By way of analogy.....

- An engineer shows up in his usual shorts and T-shirt to a campout
- He thought the weather said 25C; it's actually 25F
- The engineer is a charismatic guy so his friends help out....
 - "Let's build a bonfire!"
 - "I have an extra jacket for you!"
- The jacket shields fearless leader from convection
- If he leaves it open in the front, he warms up by "harvesting photons" from the bonfire
- He becomes more like the temperature of the fire and less like the temperature of the air

So what does this look like?



Using the previous slide's analogy on this cross section:



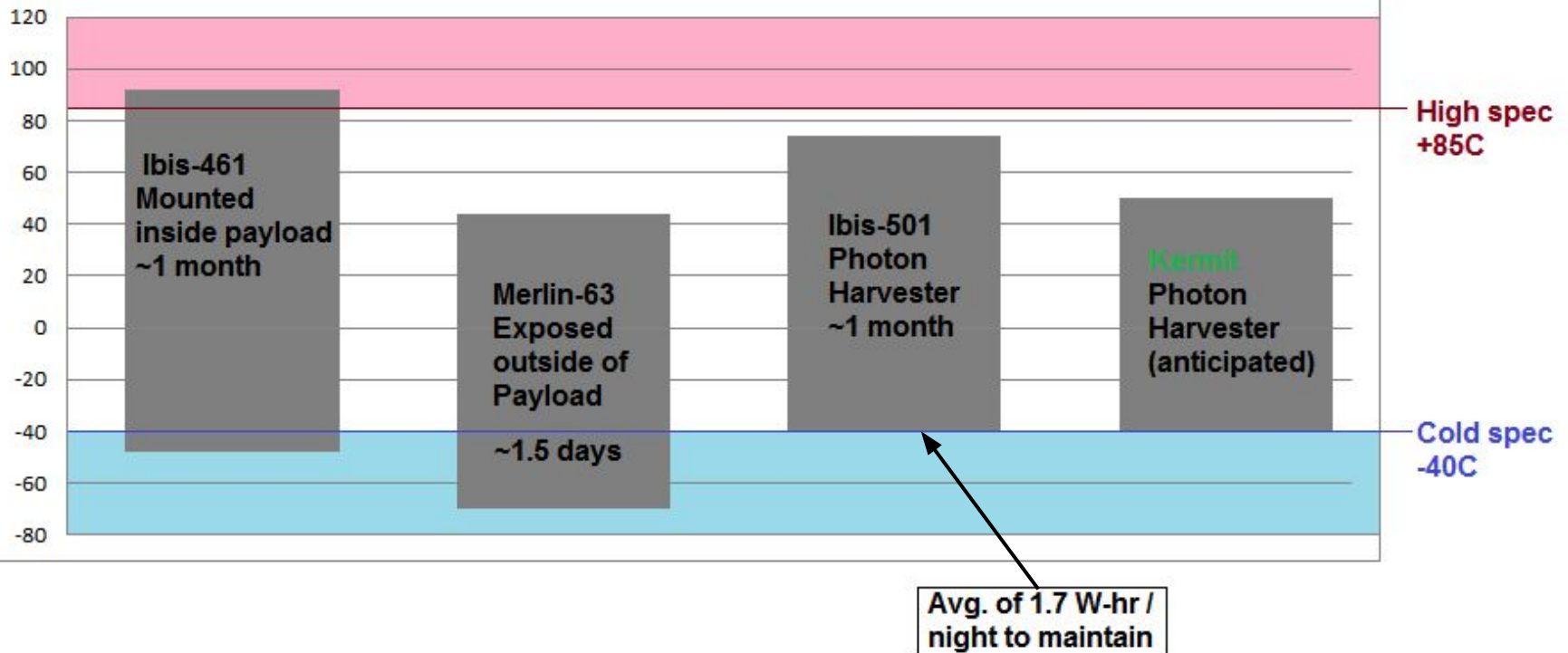
Ibis-466: Proof of Concept

- 400mm aluminum disks flown
- Earth-facing side is painted
- Metallized surface on top
- Flew 27 days, usually 20-40C warmer than air at night - *with no power added*
 - Wildly counterintuitive, even to thermal people
 - Former server and satellite guys' minds were blown
- The heat exchanger is just a plate now
 - No heat pipes
 - Radically simplified

Ibis-501: Actually doing something useful

- MPPT board is thermally awkward
- Not designed for a photon harvester but close enough to work with

MPPT Board Temperature Ranges

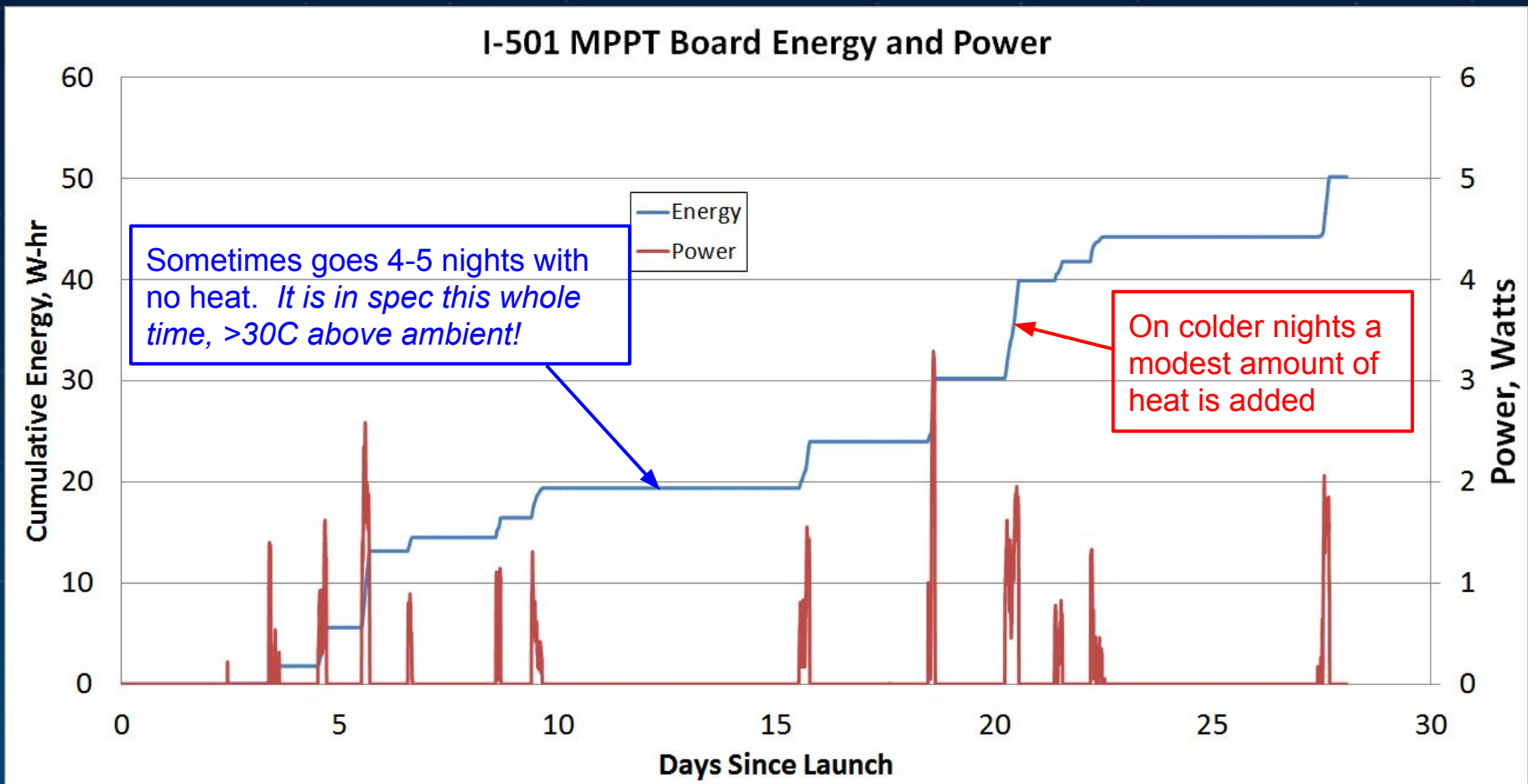


...what if the downward IR is cold?

- We have to burn power. There's not a good way around it.
- ...but photon harvesting yields one last trick
 - Convection heat transfer: $Q = C * A \rho^{1/2} (T - T_A)^{1.25}$
 - Radiation heat transfer: $Q = \epsilon \sigma A (T^4 - T_{DWIR}^4)$
- Radiation nonlinearity works in our favor
- Going from 40C to 60C takes 3x the power of going from -60C to -40C

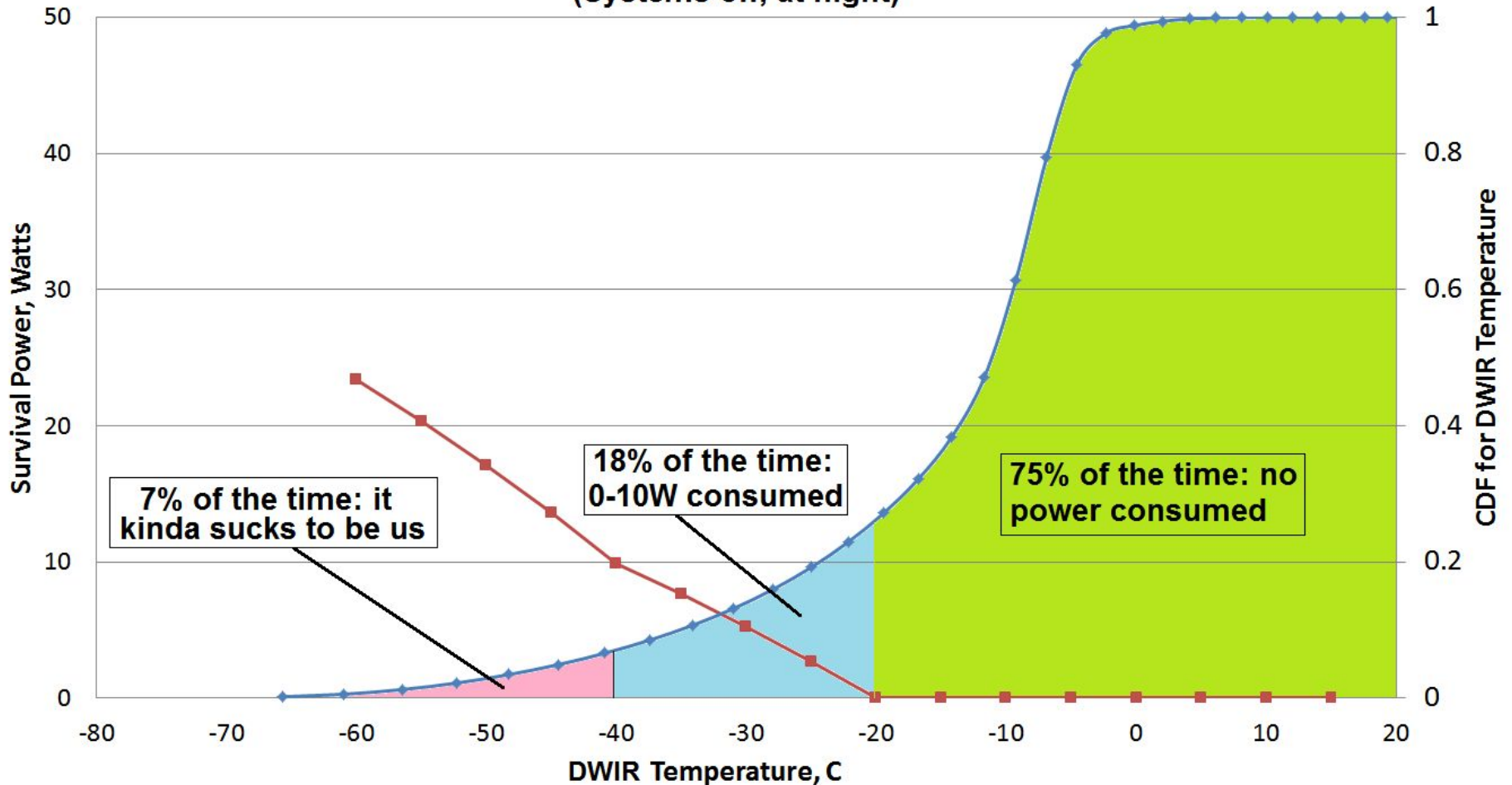
I-501 Nighttime Survival Energy & Power

...MPPT maintained at -40C



Survival Power Estimate for a Full LTE System

Energy Consumed and CDF of DWIR Temperature
(Systems off, at night)



4xKermits@-40C

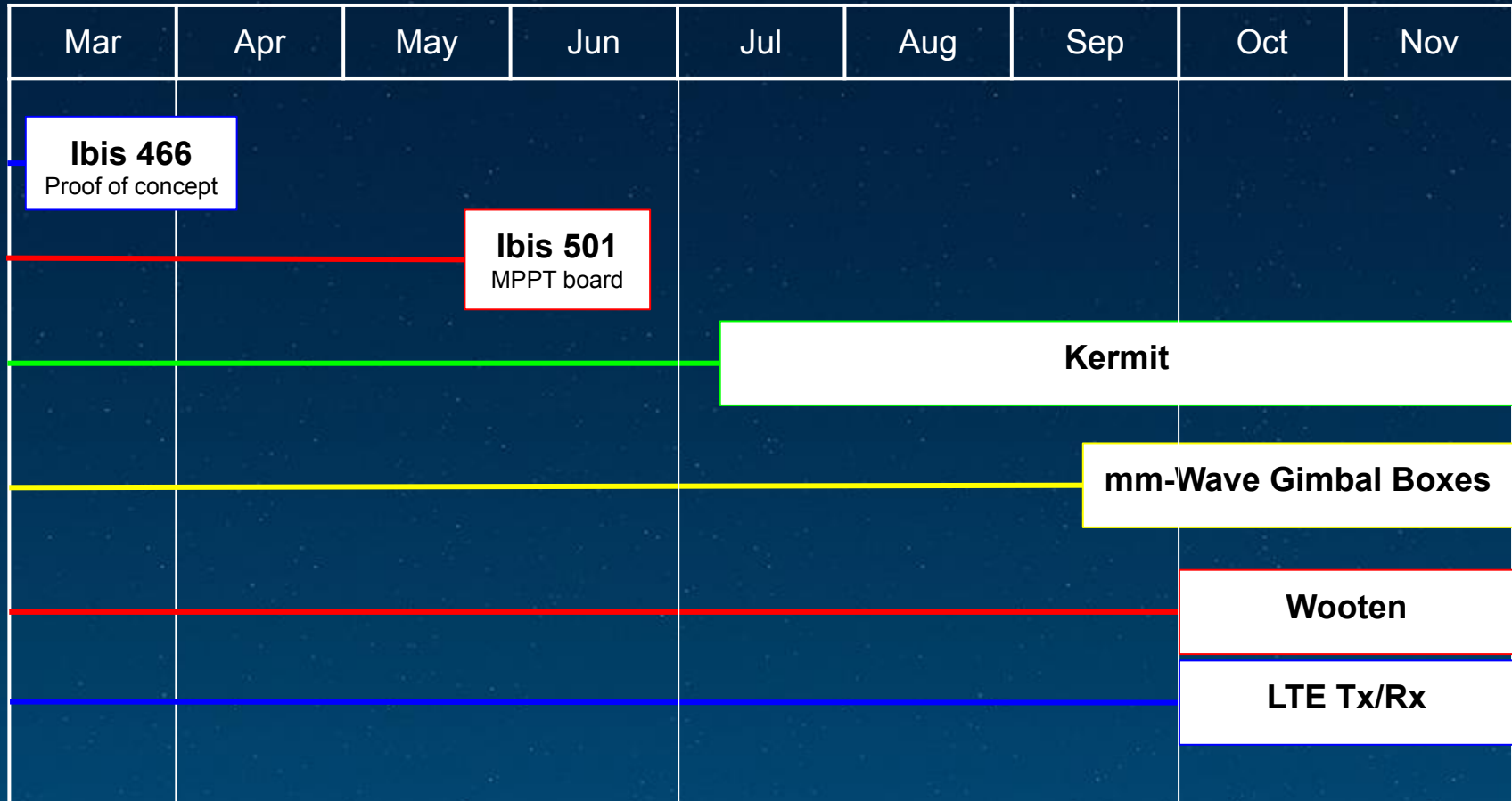
3xGimbal controllers@-40C

Wooten@-40C, 2xLTE antenna/boards@-60C

Cold DWIR Mitigators

- Reduce radiator plate size
 - Currently designed conservatively
 - Tradeoffs on high vs. low end
- Predict cold nights and conserve power beforehand
- Let some things run cold
 - Kermits are a good candidate
- Reduce pre-dawn service time after cold nights
- Run LTE at night: much of this becomes moot :)

Photon Harvester Roadmap

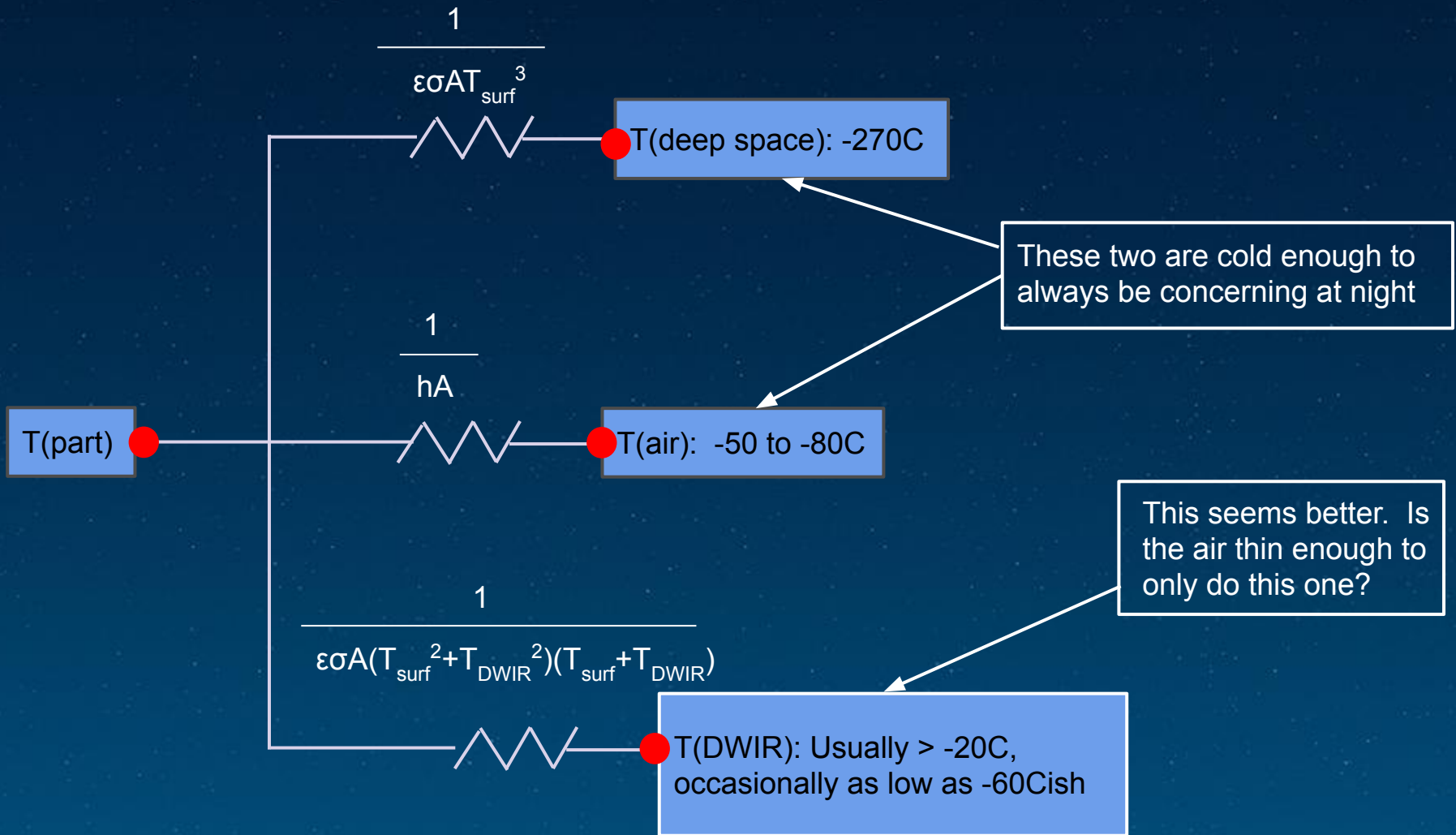


Backup

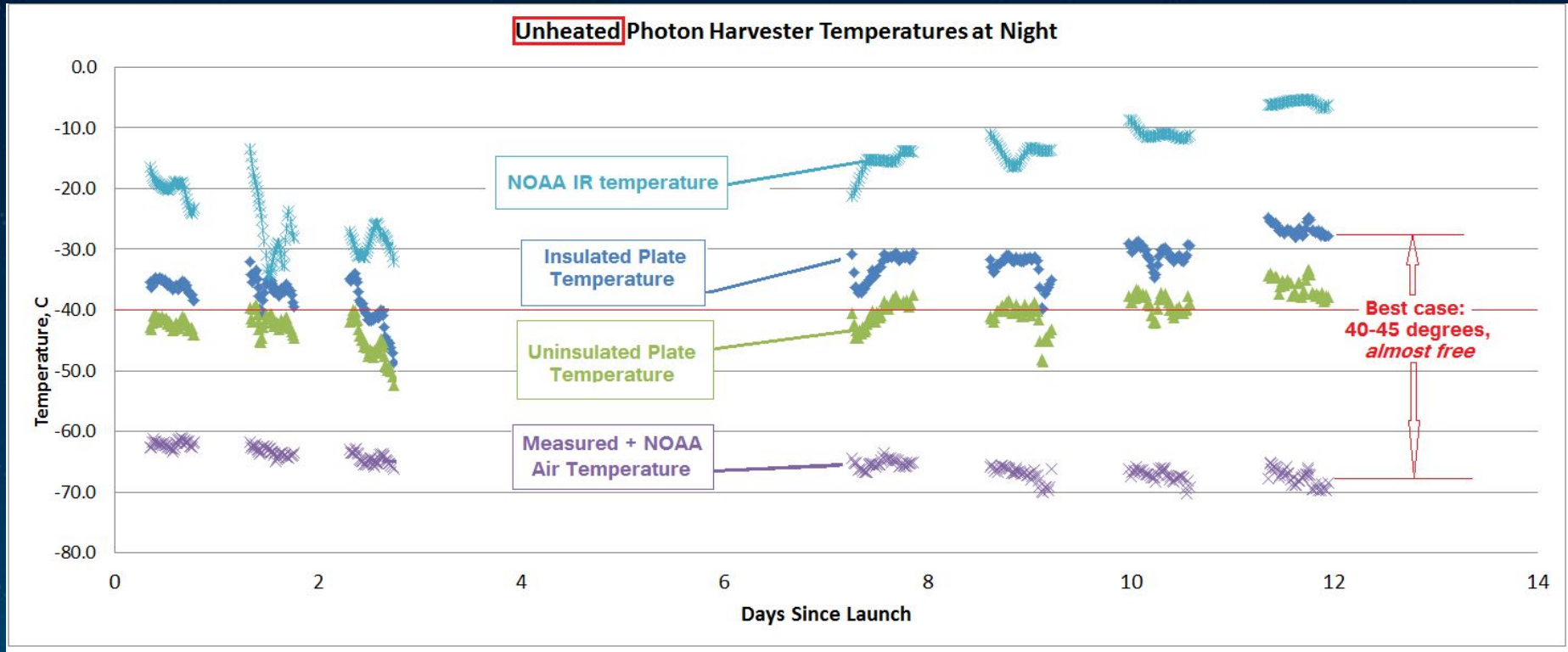
Someone wanted me to put this slide here

Method	Photon harvesters	Convection heat sinks	Convection heat sinks + heat switch
Avg. Survival Power for non-battery	2-3W	40W	12W
Worst survival power	25W, rarely	50W	20W
More control loops?	No	No	Yes
Hardware	Radically simple; <u>sometimes uses existing surfaces</u>	Specialized	Very specialized
Heat sink attach	Factory	Probably field	Probably field
Heat sink	Sometimes use existing HW	Always an extra component	Always an extra component

Three choices of ambients in the stratosphere

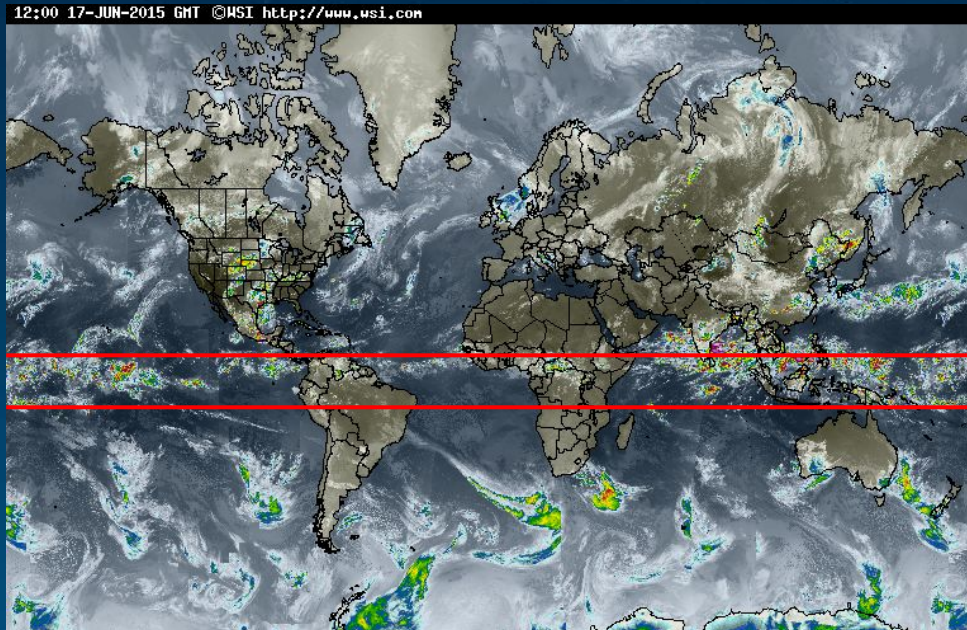
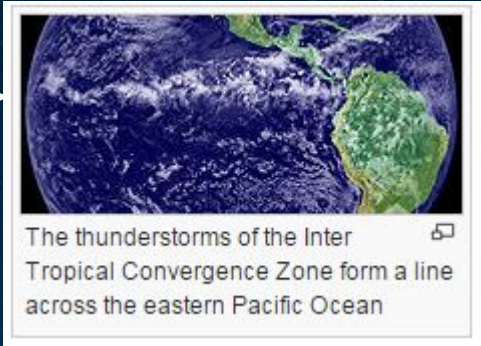


Plot of 7 nights of data



Seasonal Effects: Intertropical Convergence Zone

This is from the Wikipedia page



This actually happened a few weeks ago