Thermal Zones on Project Loon - Artifact

The thermal environment of our system in the stratosphere is challenging and can be difficult to even measure or specify. Even a seemingly simple question such as “What temperature is it up there?” doesn’t have a straightforward answer since there are different temperatures for air and radiation and the extent to which they matter is based on object geometry and surface finishes. This document is an attempt to clarify what to expect for common scenarios on different parts of the balloon system, traps to avoid, and how to optimize designs.

Everything specified below applies to the Loon system at float altitude (15.24 km to 20.3 km and latitudes ± 20°. It should be noted that most of the data here is derived from sources in tropical latitudes, and that this represents thermal worst-cases in terms of the most critical variables: cold DWIR and highest albedo.

Questions this document answers:
“What is the thermal environment that we expect?”
“If I put a thing on this one part of the balloon, what temperature will it get to?”
“I have a component that consumes X amount of power. Where should it go?”

General Thermal Environment for Loon

In the stratosphere, considerations must be given to the air temperature, air density, radiation boundary conditions, solar input and other factors. While this can vary somewhat between thermal zones as discussed below, nominal conditions are given here.

Property	**Minimum**	**Maximum**	**Notes**
Air density	0.0885 kg/m^3	0.203 kg/m^3	Directly driven by balloon design; pressure and altitude ranges are consequences
	~20.3 km	~15.2 km	
Air temperature	-90C	-50C	CNES data in all months in the tropics (where it is coldest) from 50 to 70 HPa.
Solar loading	0	1414 W/m^2	Varies by season; edge cases noted
DWIR (heat from Earth)	96 W/m^2	364 W/m^2	-70C to +10C blackbody; takes up 0.48 of the total surroundings view
UWIR (heat from space)	10 W/m^2	20 W/m^2	15 W/m^2 can be used as a single value. Takes up 0.52 of the total surroundings view
Albedo	0	1000 W/m^2	Do not use maximum in combination with maximum DWIR

Air density

The V1 Loon flight vehicle is designed to achieve float at ambient air densities of 0.203 kg/m^3 to 0.0885 kg/m^3.
Rationale: Correlates with Internet Access Service Minimum Altitude of 15.24 km and Flight Vehicle Float Altitude of 20.3 km.

Altitude

Loon V1 nominal float operations occur between 15 km to 20.3 km.

Air temperature

Ambient air temperature for our nominal float operating range is between -50C to -90C. This is based on CNES data[2] saying that these temperatures are outside of the 3σ range in all months in the tropics (where it is coldest) from 50 to 70 HPa. Additionally, we have not seen temperatures outside of this range over the United States so it is a safe range to use.

Note that it is possible to be outside of this range in the stratosphere. CNES has detected air as cold as -97C but the range given is considered to be a safe +/- 3σ range.

Solar loading

In the daytime, the sun is largely unfiltered by the atmosphere and varies by season from 1322 W/m^2 to 1414 W/m^2 based on the Earth's distance from the sun. A value of 1400 W/m^2 is a conservative single value to use when concerned about heating.

Albedo is the degree to which solar wavelengths are reflected from Earth and it is known to affect space vehicles as well as Loon. Fortunately, the highest albedo areas are also the physically coldest (ice, snow, clouds)[1] so albedo must be spec'ed as a function of downward IR. Designing according to the worst case of both wavelengths at the same time leads to unrealistic overdesign[1].

- Solar energy reflected from the ground is up to 350 W/m^2 for a DWIR flux of 364 W/m^2 (10C)
- As the DWIR flux decreases to its minimum of 96 W/m^2 (effective temperature of -70C), the maximum solar energy reflected increases linearly to 1000 W/m^2.

"Solar snap" is a phenomenon in satellites in which a spacecraft going from an eclipse state to a sun-exposed state will experience a very rapid change in temperature that may impact component reliability. While this doesn't impact Loon from a planet-shading standpoint since our system is not as fast as satellites, components above the despin mechanism (Zones 1 and 2) may spin into the sun in an unpredictable and sudden way. The effects are strongly dependent on the geometry, thermal mass, and surface finishes of the components but it should be taken into account when placing components in Zone 1 and Zone 2.

Thermal radiation boundary conditions:

Unlike most indoor terrestrial problems that have a single radiation surrounding temperature, an object in the stratosphere has an "upward IR" and "downward IR" condition. The boundary between them is an interesting question. The view factor between the balloon in our altitude range and the Earth can readily be calculated to vary between 0.460 and 0.465, but this assumes that the Earth is a sphere with no atmosphere. In fact the atmosphere also participates in radiation and curve-fitting to data implies that a view factor of 0.48 is a good approximation for our altitude range. The number has to be between 0.460 and 0.500, so the error introduced by this approximation has to be less than 4% and sharpening it further would require more detailed dependencies on atmospheric variables that we can't measure directly.

The downward IR condition is specified to be between -70C to +10C. As shown in this plot, different sensors agree on the same general trend though there is some variation. Our DWIR sensor is not believed to be accurate as we're usually running it out of spec, so the high readings are not believed and 10C is the number used. Note that these temperatures are *effective blackbody* temperatures: to get an infrared heat flux in W/m^2, use the Stefan-Boltzmann law by calculating σT^4, where σ is 5.67×10^{-8} W/m^{2}K^4 and T is the absolute temperature, in Kelvins.

There is little consistent data available on upward IR conditions; multiple papers on ballooning suggest different values. What they do agree on is the *magnitude* of these values, which is small: between 10-20 W/m^2 (-158C to -136C), so without much error we can use the value of 15 W/m^2 which corresponds to -145C.

Gravity:

Gravity is only slightly less than on the Earth's surface, as it reaches a low of 9.74 m/s^2 at the top of Loon's altitude range.

Zone 1: On or atop the balloon

Includes the apex electronics, top-plate assembly and ACS - mechanical hardware. These assemblies feel the full effect of the sun in the daytime, particularly in the tropics where the sun can be directly overhead. The balloon partly blocks their line-of-sight to the ground and above they only have the cold nothingness of the stratosphere, so their effective radiation boundary conditions will tend to be low. Objects in this location are typically subjected to the most extreme temperature swings of any components on our system.

If you put something in this zone with no thermal protection that doesn't generate heat:

Lowest possible temperature: -100C

High temperature: surface-dependent. Up to 70C for black surface facing the sun.

Zone 1 is an unattractive place for any equipment that is sensitive to temperature swings or that burns much power because the boundary conditions have such a large diurnal difference. The Apex board consumes about 1 Watt so it fits into the territory of "Just insulate it and maintain temperature at night"

For electronics in this area with a normal temperature sensitivity range (-40C to 85C), as a rule of thumb 1 Watt per 100 cm^2 on the board enables one to still insulate to strike a balance between night heating and daytime power-burning. If the power is higher then one may need to not insulate and this could result in one of:

- Burning excessive power at night
- Allowing components to get out-of-spec cold at night
- Needing a more complicated thermal solution which might require moving parts

Zone 2: Under the balloon and not in an enclosure

This is similar to Zone 1 in its air temperature extremes, though it has some shading from the balloon itself.

If you put something in this zone with no thermal protection that doesn't generate heat:

Low temperature: -90C. This is especially important for components like despin which have moving parts that must be designed for this temperature.

High temperature: surface-dependent. Up to 70C for black surface facing the sun.

The maximum solar loading is reduced by 40% for a horizontal surface because of balloon shading. Assuming two layers of shell and two layers of ballonet film and geometry that is non planar, and short down connect (provides for envelope shadow on the payload). In general this will depend on film properties and ballonet geometry and must be determined anew for each balloon iteration, but 40% is a good starting point and is true for Nighthawk-Raven balloons.

Zone 2 doesn't have quite as harsh of swings as Zone 1 due to having at least some shading for horizontal surfaces and more exposure to the Earth IR, but it's also hard to say very much about how calculation should happen in this zone without more specifics. Things one must keep in mind are:

- If something is above the despin unit, its orientation with respect to the sun is not constant.
- Radiation boundary conditions will vary depending on how close an object is to the Nav payload, which generally reflects IR radiation.
- Convection boundary conditions will vary based on how close an object is to the Nav payload and solar panels: it is typical for solar panels to reach temperatures of 50-60C in the daytime so components above them will have an air temperature elevated above ambient.
- ACS airflow is generally too low to significantly impact convection unless the object is very close to the ACS

Zone 3: Anything thermally coupled to a photon harvester

Photon-harvesting is our way of regulating temperatures by coupling to the Earth's infrared radiation rather than the air around us, as well as minimizing the effects of the sun. It is a powerful tool for living with standard electronics in a difficult environment but it has limitations that should be considered. Additionally, it is unusual to call this a "zone" since it's more of a description of a packaging technique, but enough of the components on our truss system use this

Objects placed in a photon harvester enclosure will usually have tolerable temperatures at night (-40C to -20C is typical) but when passing over clouds in areas with cold air, temperatures might drop to -70C if not regulated with heaters. The good news is that this is mainly due to thermal radiation which is proportional to T^4 so it doesn't take as much heat to recover from this as it might in other devices: nevertheless, if there is no thermal control on the device it could get to -70C from time to time.

- Components on such devices are strongly recommended to ***all*** have a minimum temperature spec of -40C or less. If one component has a higher spec, it should be thermally isolated carefully (not by just taking out some copper on a PCB - this is much less effective than one might intuitively think). Please ask for help on this if you need to use a component that needs to always be at 0C, for example. Alternatively, ask a reliability engineer if it can be responsibly exposed to colder temperatures in the long-term.
- For devices that have a normal temperature range (-40C to 85C), one needs about 20cm^2 of photon harvester surface per steady-state Watts of heat dissipated on the device. This is a rough rule of thumb and will also be dependent on heat distribution, geometry, and component specs but it does give a starting point.

- If the device is expected to maintain -40C temperatures on the coldest of nights, one should include heaters that can supply 1 Watt of heat per 40 cm^2 of photon harvester area at low battery voltage. This is a very conservative number using a combination of many worst cases and it is quite rare that the heaters will use more than 60% of this much power for more than ~1 hour at night.
- If possible, heat generating components should all be on one side of the board which will face downward (i.e., toward Earth) and contact the photon harvester. Ideally, no components taller than heat generating components will be on this side to avoid cutting holes for them. The Wooten board for an example of a job well done on this.
- Notes for mechanical engineers involved:
    - Interface material is important.
    - The bottom of the aluminum should be painted with our standard coating. The top is ideally painted as well, except for parts where gap pads touch (which should be masked in painting)

The maximum temperature for an unpowered object in Zone 3 is less studied since it is less of a concern. Basic and conservative reasoning (using the spec at the knee of the DWIR/Albedo curve and assuming no convection) points to a maximum unpowered temperature of 300K but in practice (including convection effects) the maximum is 0C.

Zone 4: The electronics bay section of the Nav payload

The electronics bay is designed for low-power electronics with a relatively constant load. It is fully insulated and near the battery bay so one can expect warmer temperatures than what they might get in other zones, but the power dissipation for this area is limited. Zone 4 electronics shall dissipate less than 12 Watts (TBR) of heat.

The ambient temperature of this zone with the allocated heat dissipation varies between -10C and 40C and is dependent on diurnal cycle, hardware configuration, and nighttime heater setpoints.

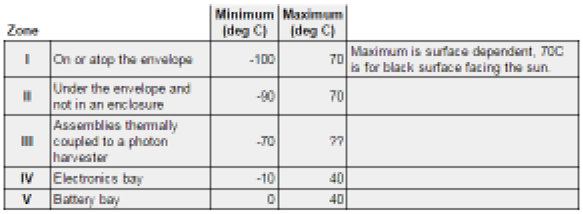
Please do not choose parts that generate significant amounts of heat based on a maximum ambient temperature spec on a data sheet since this is calibrated toward sea-level air density.

Zone 5: In the battery bays

Battery bays in the Nav payload were designed for holding batteries. Nevertheless, in a pinch we've put *very* low-power components in this region. It should be noted that empty bays can be used for auxiliary batteries (e.g., Snowth) to good effect as they'll share heat from other batteries and do not generate much heat of their own. However, please do not put something in battery bays without carefully thinking about it just because it mechanically fits and you can't figure out where else to put it - this zone is highly insulated and cannot support components that generate much heat.

For components that generate heat during normal operation, a heat flux per unit area of the PCB of no more than 1 Watt per 50 cm^2 of footprint is preferred for a typical PCB

The battery's setpoint shall be maintained at 15C. Zone 5 temperature shall be 0C to 40C in empty bays (varying by diurnal cycle and battery configuration).



Zone		Minimum (deg C)	Maximum (deg C)	
I	On or atop the envelope	-100	70	Maximum is surface dependent, 70C is for black surface facing the sun.
II	Under the envelope and not in an enclosure	-90	70	
III	Assemblies thermally coupled to a photon harvester	-70	??	
IV	Electronics bay	-10	40	
V	Battery bay	0	40	

Temperatures define the minimum and maximum thermal environments for Loon hardware assuming no thermal protection or heat generation.

Table source

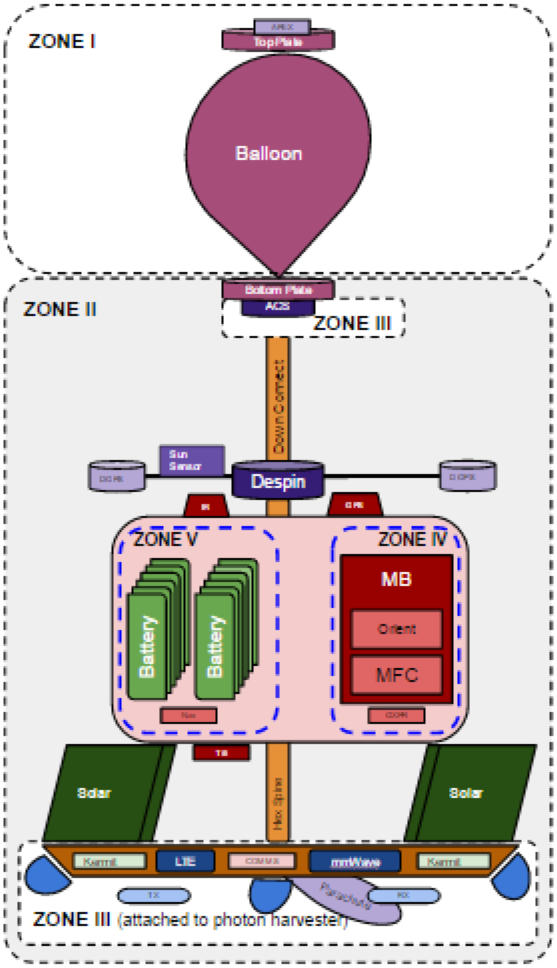


Figure not to scale'

Note: Associated temperatures for each assembly by zone documented in this table. Temperatures provided describe the environment for an assembly with no insulation or power. Each assembly is responsible for providing thermal control within the power budget allocated for that assembly.

Reference: Thermal Zones on Project Loon

Figure Loon Thermal Zones.

Ground Thermal Requirements

Equipment on Loon must also survive in some operational states while not flying. Primarily this is for just before launch and on ground stations.

The primary spec used is a slightly modified form of ETSI EN 300 019-1-4 V2.2.1, Class 4.1 (Non-weatherprotected locations). Our two launch sites as of 2016 do potentially capture the extremes of this spec, so it is to be taken seriously if one wants to ensure equipment functionality.

	Low	High
Shaded air temperature	-40C	+40C
Unshaded air temperature	-40C	+55C
Relative humidity	0%	100%
Direct solar loading	0 W/m^2	1200 W/m^2
Elevation, launch site	0 m	1310 m (elevation of WMC)
Elevation, ground station	0 m	5000 m (possible Peruvian installation?)

Test requirements for consideration:

Hot and Cold Start Demonstration

Hot restart at maximum voltage and cold start at minimum voltage shall demonstrate that the unit under test will turn "on" at the extreme temperatures that may occur during the mission and to demonstrate that when the unit is returned to the required test temperature (qualification or acceptance), that it fully meets its performance requirements.

Two (TBR) cold starts and two hot restarts shall be successfully demonstrated.

Heater Verification

Thermal testing shall demonstrate the ability of heaters to maintain units within survival (non-operating) temperature during work cold environments, minimum voltage and while the unit under test is off. (applicable for units that are powered off or may require a restart during flight)

Flight Temperature Sensor Verification

System-level thermal testing shall corroborate flight temperature sensors against test temperature sensors in at least the bounding hot and cold temperature conditions.

Mission Verified Temperatures

Flight vehicle temperature data (from flight aggregate data, post-processed and reported here) shall be used to establish assembly and component operating temperatures and non-operating Mission Temperatures.

If flight data is not available worst case thermal analysis plus 5°C (TBR) of temperature uncertainty shall establish assembly and component operating temperatures and non-operating.

Design qualification (EVT and DVT) and acceptance temperatures (PVT)

The qualification temperature shall be 10C (TBR) warmer than the maximum temperature and 10C (TBR) colder than the minimum temperature.

Acceptance temperature shall be 5C (TBR) warmer than the maximum temperature and 5C (TBR) colder than the minimum temperature.

Sources

1. Gilmore *et al* (2002) Spacecraft Thermal Control Handbook, Volume 1
2. CNES STR2-ST-0-7484-CN (2015) Specification d’environnement strateole-2