Loon Flight Data

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This data set contains flight data from Loon, a Google project and later an Alphabet subsidiary that provided wireless internet access to rural areas using high-altitude balloons. The data set includes GPS and sensor data from all 2,131 flights across the project's entire nine-and-a-half year history, from the first sounding balloon experiment in August 2011 through the last balloon landing in May 2021. In total the data set comprises over 218 flight-years of data (over 127 million telemetry points), the vast majority from altitudes between 50 and 110 hPa (approximately 15.5 to 21 km above sea level).

Data

The data is provided in both NetCDF and GZipped CSV (comma-separated values) format. The underlying data is identical in both. Data is split across multiple files (divided by time) for easier download.

The dataset contains the following fields:

- **flight_id:** unique identifier representing the flight.
- **time:** time measurements were taken, in UTC based on GPS.
- **latitude:** degrees latitude, in the range [-90, 90]. Uncertainty ±2.5 m based on GPS.
- **longitude:** degrees longitude, in the range [-180, 180). Uncertainty ±2.5 m based on GPS.
- **altitude:** geometric altitude, in meters above mean sea level. Measured at the payload (i.e. the bottom of the balloon). Uncertainty ±2.5 m based on GPS.
- **temperature:** ambient temperature, in degrees Kelvin. Uncertainty ±5 K during day, ±2 K during night.
- **pressure:** ambient atmospheric pressure, in hectopascals. Uncertainty ±1 hPa. Measured at the payload (i.e. the bottom of the balloon)
- **earth_ir:** upward long-wave radiative flux, in Watts per meter squared. See notes below.
- **earth_ir_sensor_config:** Denotes sensor configuration type (i.e. where located on the balloon). See notes below.
- **acs:** Altitude Control System state: 1 if ascending (increasing altitude), -1 if descending (decreasing altitude).
- **propeller_on:** 1 if a propeller is providing lateral thrust, otherwise 0. If 1 then velocity_u and velocity_v will not be computed.

The following derived fields are computed from the base fields listed above and are provided for convenience. See notes below for details on how they are computed.

- **velocity_u:** Zonal (west-to-east) component of balloon velocity, in meters per second.
- **velocity_v:** Meridional (south-to-north) component of balloon velocity, in meters per second.
- **omega:** Vertical velocity, in hectopascals/second.
- **acceleration:** Average change in horizontal velocity over the sliding window used to compute balloon velocity, in meters per second squared.
- **solar_elevation:** Angle of sun, in degrees relative to horizontal.
- **solar_azimuth:** Angle of sun, clockwise relative to North.
- **is_daytime:** 1 if the sun is visible from the balloon (i.e. not occluded by the horizon), otherwise 0.

Notes

Data is sampled at 1 Hz on the balloon, and the most recent telemetry sample is downlinked every 10 seconds to 20 minutes (typically 1 minute) depending on configuration. Some filtering is performed on the balloon.

flight_id

Flight ID is a unique identifier assigned to a particular flight, and comprises a balloon class (usually a single letter) followed by a dash and a number. Flights were usually flown in numerical order, though sometimes a number would be skipped if a launch was scrubbed. Balloon classes were as follows. The list does not include *Bluebird*, *Condor*, *Dodo*, *Eagle* and *Jay* designs, which were limited-run designs that were either never flown or brief flights with limited telemetry. Starting in 2013 (Ibis) most envelopes were manufactured by Raven Aerostar, though some experimental designs were still built in-house.

Height, radius and mass ranges are given below (where available). Height and radius are at float. *System mass* is the combined mass of payload and envelope mass. Starting with the Plover design, balloons also included between 5-25 kg of ballast that could be dropped to extend the life of the balloon, and any ballast kept after launch is included in system mass. *Lift-gas mass* is the mass of lift gas (Helium) at launch and does not account for leakage over time, nor does it include air pumped into the ballonette for altitude control.

- **Icarus:** Latex sounding balloons used at the start of the project to test balloon-to-ground and balloon-to-balloon networking. 12 flights, 2011.
- **Pterodactyl (PT):** Latex sounding balloons. 40 flights, 2012-2013.
- **Albatross (A):** Aluminized Mylar zero-pressure ("trash-bag shaped"), first Loon-manufactured envelope. System mass 7-17 kg. 22 flights, 2011-2012.

- **Falcon (F):** Cylindrical superpressure balloon from clear PET Mylar, first Loon-manufactured superpressure balloon. Height 34.8 m, radius 0.97 m, system mass 23-34 kg, lift-gas mass 5 kg. 9 flights, 2012.
- **Grackle (G):** Brief attempt at designing a solar Montgolfiere. System mass 48 kg, lift-gas mass 9 kg. 1 flight, 2014.
- **Ibis (I):** Pumpkin-shaped superpressure balloon using PE material, used for public launch over New Zealand in 2013. Height 7.4 m, radius 8.9 m, system mass 49-155 kg, lift-gas mass 12-24 kg. 430 flights, 2012-2016.
- **Kestel (K):** Zero pressure balloon built out of 0.8 mil PE material. System mass 7-20 kg, lift-gas mass 2-4 kg. 21 flights, 2013-2015.
- **Lark (L):** Updated pumpkin-shaped superpressure balloon (PE material). Height 8.5-8.8 m, radius 10.2-10.5 m, system mass 81-119 kg, lift-gas mass 13-20 kg. 42 flights, 2013-2015.
- **Merlin (M):** Pumpkin-shaped superpressure. Height 7.0 m, radius 8.4 m, system mass 56-79 kg, lift-gas mass 9-15 kg. 58 flights, 2014-2015.
- **Nighthawk (NG, NR):** Pumpkin-shaped superpressure. Height 7.6-7.7 m, radius 9.1-9.3 m, system mass 64-229 kg, lift-gas mass 11-22 kg. 434 flights, 2015-2016.
- **Osprey (O):** Pumpkin-shaped superpressure. Height 8.0 m, radius 9.6 m, system mass 92-113, lift-gas mass 19-25. 235 flights, 2016-2018.
- **Osprey Large (OL):** Pumpkin-shaped superpressure. Height 8.3 m, radius 9.9 m, system mass 89-119 kg, lift-gas mass 17-26 kg. 159 flights, 2016-2018.
- **Plover (P, PG):** Pumpkin-shaped superpressure design with "reverse ballonet" that pumped air into the outer-layer gas bag. Also flown as "LN". Height 8.7 m, radius 10.4 m, system mass 75-177 kg, lift-gas mass 16-32 kg. 370 flights, 2017-2021.
- **Quail (Q):** Larger pumpkin-shaped superpressure with reverse-ballonet design. Also flown as "LN". Height 10.1 m, radius 12.2 m, system mass 173 kg, lift-gas mass 37 kg. 1 flight, 2017-2021.
- **Loon (LN):** Plover and Quail flights launched after mid-2019 were designated as "LN" class regardless of envelope design. LN-001, 6, 7, 24-27, 33, 82-89, 106-111, 117-120, 134-135, 143-154, 238, 267-269 used the larger Quail envelope, all others used Plover envelope designs. 280 flights, 2019-2021.
- **Experimental (EXP, MI, V1, VG):** Various experimental one-off designs. 13 flights.

time, latitude, longitude, altitude

Timestamp, latitude, longitude, and geometric altitude were all collected using a NovAtel OEM7 receiver, which processes signals collected by the standard dual GPS paddle antennas located on either side of the avionics bus. The avionics bus is located between 1.5 and 3 meters below the base of the balloon envelope.

Time is the time data was collected on the balloon. Most (~95%) of times are rounded to the nearest second, but time is still reported to millisecond accuracy to ensure that [flight_id, time] uniquely labels a single telemetry. In CSV files time is represented as an RFC3339-formatted UTC timestamp of the form `YYYY-mm-ddTHH:MM:SS.fffZ`.

temperature

Ambient temperature of environment around sensor. This is not corrected for daytime effects of solar radiation on the sensor itself, and we suspect this leads to biased readings (higher than ambient air temperature) during daylight hours.

earth_ir, earth_ir_sensor_config

Upwelling IR was measured as temperature using a Melexis MLX90614ESF-BAA-000-TU infrared thermometer, which reports object temperature in degrees Kelvin. Uncertainty of raw data depends on both measured temperature and the sensor's self-temperature (see linked-to spec sheet), but a rough guide is ±6 degrees C. Raw reported values were lightly filtered on-balloon before being reported, and then converted to flux using the formula:
$ir\_flux = 0.000000056704 \cdot (temperature\_kelvin)^4$

The sensor points straight down (with an uncertainty of about ±2 degrees), but was placed in different locations throughout the project. The earth_ir_sensor_config parameter groups observations with similar configurations of the IR sensor on the payload. For analyses sensitive to the overall IR flux bias, these groups of observations should be treated separately or used to assess systematic biases in results.

acs

Most loon balloons could change altitude through use of an Altitude Control System (ACS), which would pump air into a separate gas bag (called a ballonet) to cause the balloon to descend, and vent air from the ballonet to cause the balloon to ascend again. Balloons would then be "steered" to a target by catching winds at different altitudes.

This field reports 1 if the ACS was trying to ascend (that is, venting air from the ballonet), -1 if the ACS was trying to descend (pumping air into the ballonet), and 0 otherwise. Note that balloon altitude or pressure may still change even when ACS is off (e.g. due to loss of superpressure, turbulence and vertical winds, or deliberate ballast drop), and in some instances may not change even if ACS is on (e.g. if trying to ascend when the ballonet is already completely vented).

propeller_on

A handful of Loon flights (12 in all) experimented with a propeller, which would produce lateral propulsion in addition to that provided by the surrounding winds. This parameter reports 1 if the propeller was on at the time, 0 otherwise. Wind velocity should not be computed from GPS location when propeller_on is non-zero, as the balloon's velocity includes both ambient wind velocity and thrust from the propeller.

velocity_u, velocity_v

Together these fields represent balloon velocity computed using a 6-minute (± 2 minutes on each side) sliding window centered at the given time. velocity_u represents the zonal (west-to-east) velocity component, while velocity_v represents the meridional (south-to-north) velocity component, both in meters per second. Both values are computed entirely from the GPS location fixes across a short time window, and are provided for convenience.

The velocity at a telemetry point P at time t is computed as follows:

1. Set P_p to the point with timestamp t_p closest to (t - 3 minutes) and P_n to the point with timestamp t_n closest to (t + 3 minutes). If a point cannot be found within 3 ± 2 minutes on either side of P then the point is skipped (velocity_u and velocity_v will not be set).

2. Compute distance vector D_p = distance(P_p, P) and D_n = distance(P, P_n). Distance vectors are in meters (u, v) and computed assuming the WSG84 ellipsoid. Altitude is assumed to be at the midpoint geometric height.

3. Compute velocities for the segments on either side of the current point:
   $V_1 = D_p / (t - t_p)$
   $V_2 = D_n / (t_n - t)$

4. If $V_1 > 110$ m/s, $V_2 > 110$ m/s, or $\|V_1 - V_2\| > 50$ m/s then the point is skipped. This is intended to reject outliers that are likely due to GPS error rather than actual motion.

5. Set balloon velocity vector [velocity_u, velocity_v] to the weighted mean of V_1 and V_2:
   $V = w_1 \cdot V_1 + w_2 \cdot V_2$
   where $w_1 = (t_n - t) / (t_n - t_p)$ and $w_2 = (t - t_p) / (t_n - t_p)$

Loon balloons are driven by the surrounding air, and in constant wind a balloon's velocity is a good proxy of the average velocity of the surrounding winds over the time window. (The one exception is when propeller_on is non-zero; velocity_u and velocity_v are both set to NaN for those points.) When local wind velocity changes it can take a few minutes for the balloon to "catch up" to the surrounding winds.

It should be noted that pressure and geometric altitude are measured at the payload attached to the bottom of the balloon, so the winds contributing to the overall velocity will typically include altitudes up to 10 meters higher depending on the class of balloon. The range of altitudes contributing to the computed velocity can be even higher if the balloon is changing altitude during the six-minute smoothing window.

omega

Vertical velocity in hectopascals/second, computed using the same sliding window and weighted averaging as balloon velocity. A positive value indicates the balloon is descending (lower altitude, higher pressure). High absolute omega for a given point means balloon velocity was integrated over a larger range of altitudes.

acceleration

Average change in horizontal velocity over the sliding window used to compute balloon velocity, reported in meters per second squared:

$$A = \|V_2 - V_1\| / [0.5 \cdot (t_n - t_p)]$$

where V_1, V_2, t_n and t_p are the same as when computing balloon velocity.

Note that the change in velocity is divided by *half* the total window width. This is because V_1 and V_2 are computed across the range $(t - t_p)$ and $(t_n - t)$ respectively, and so represent velocity at the midpoint of their respective segments.

solar_elevation, solar_azimuth, is_daytime

Calculations are based on the algorithm used by the NOAA Solar Calculator (https://www.esrl.noaa.gov/gmd/grad/solcalc/index.html), and includes atmospheric refraction effects. Solar elevation is relative to horizontal, so is_daytime can still be true (1) even if solar_elevation is slightly negative.