

Pico-Balloons

Around the world in 14 days.

50,000 FT
(9.46 MI)

OWL Community STEM Program

- Dan Welch – KC9LGR
- BS – Applied Physics, MS - EE
- Optical Wavelength Laboratories
- Space-Hobbies.com Seminars
- MTU Science/Technology Outreach

PicoBalloon Project Goals

- Have fun building, launching, and tracking the progress of our low-cost (\$30) balloon satellite as it circumnavigates the Earth.
- Learn about high-altitude balloon physics, electronics, amateur radio, GPS, embedded programming, solar power, weather, and the atmosphere.



Pico Balloon Topics

- Balloon Physics
- Atmosphere and Weather
- Tracker Payload Design
- RF Communications and Tracking
- Building and Launching

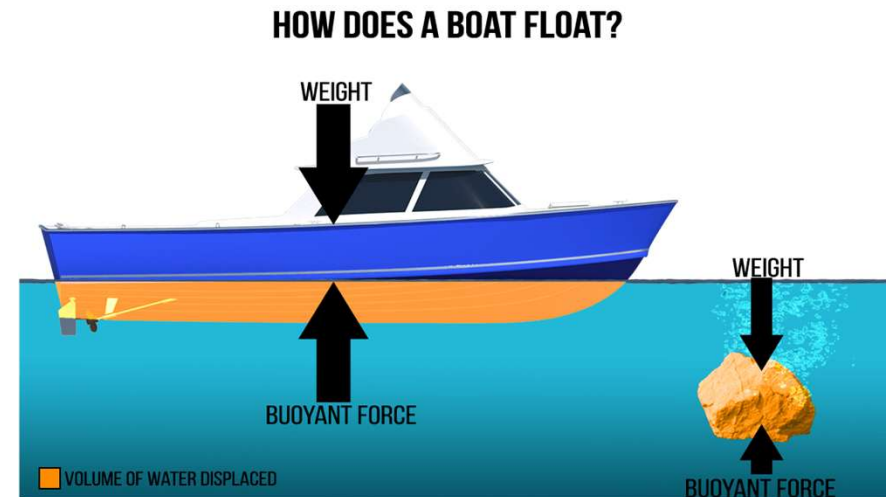
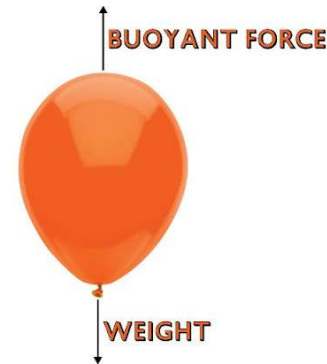
Balloon Physics

How High Can They Go



Archimedes' Principle

- The upward force on a body within a fluid is equal to the weight of the fluid that the body displaces.
- A fluid is a liquid or gas
- The amount of fluid displaced equals the volume of the body that is within the fluid.
- **Rising** – The body weighs less than the displaced fluid. The difference in weight is the amount of lift.
- **Floating** – If the body weighs the same as the displaced fluid, there is no vertical motion.
- **Sinking** – The body weighs more than the fluid displaced.



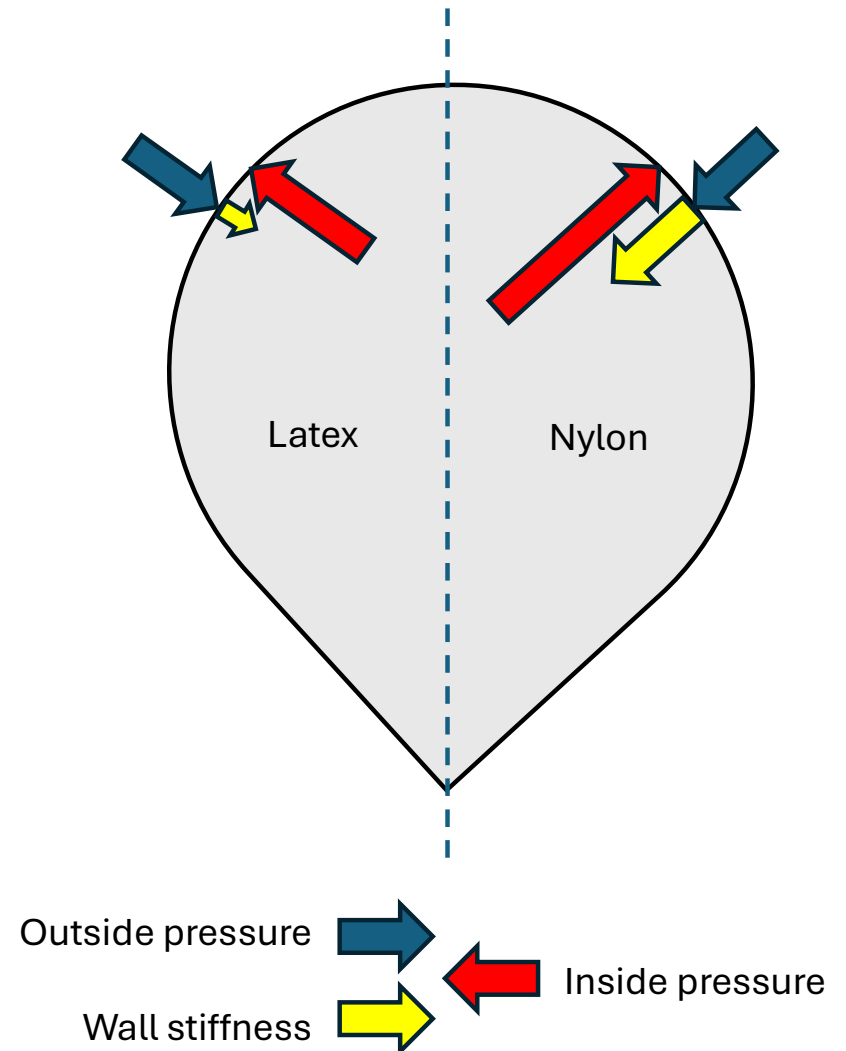
<http://wordpress.mrreid.org/2010/07/18/advert-of-the-year/>
<https://aceboater.com/how-does-a-boat-float>

Ideal Gas Law

- Law of confined gases **$PV = RnT$**
- **P** = pressure, **V** = volume, **R** = ideal gas constant, **n** = amount of gas molecules in moles, **T** = temperature
- Solving for P: **$P = RnT/V$**
- Pressure is inversely proportional to volume
- Pressure is directly proportional to the number of gas molecules and temperature
- It does not depend on the type or weight of the gas molecules
- All gas molecules have the same kinetic energy at a specific temperature so (**nT**) is the total kinetic energy of the gas.

Balloon Types

- The balloon's volume determines the amount of air displaced and the lift.
- Because Latex stretches, the balloon's volume keeps increasing with altitude, which preserves the lift, but they eventually burst. Good for short high-altitude flights with heavier payloads.
- Nylon balloons are inelastic and difficult to stretch. At full volume, they don't expand and will float at a fixed altitude. Good for long duration flights.



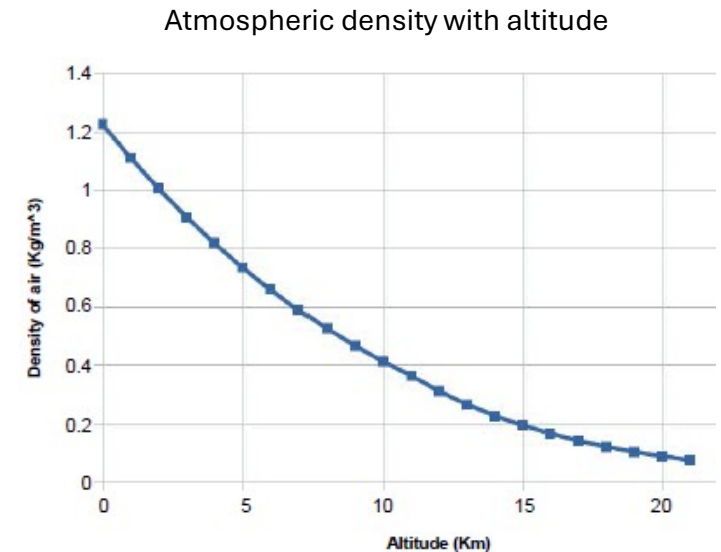
Super-Pressure Balloons

- Once at full volume, the balloon will continue to rise until its weight equals the weight of the surrounding atmosphere displaced by the balloon's volume. At float altitude, the internal pressure is much higher than the surrounding atmosphere. Because the volume no longer changes, the altitude remains stable.
- Because pressure is inversely proportional to volume, the gas will expand inside the balloon to match the lower outside pressure, causing the balloon volume to increase. This increased volume displaces more atmosphere and preserves the free lift.
- As the balloon rises, the outside atmospheric pressure decreases.
- At launch, the balloon is only partially filled



Float Altitude

- To find our final float altitude we need
 - The weight of the balloon
 - The weight of the payload
 - The fully expanded volume of the balloon
 - The amount of additional lift we desire
 - More lift requires more initial volume and therefore more gas at launch
 - More lift means the balloon will rise faster
 - More gas means more weight and a lower float altitude
 - Free lift and gas type gives the weight of gas loaded at launch. Final density is total weight / maximum balloon volume.
- When this density matches the surrounding air density the balloon will no longer rise.



An experimental study of Wind Data of a Wind Farm in Kosovo - Scientific Figure on ResearchGate. Available from: https://www.researchgate.net/figure/Change-of-air-density-to-altitude_fig1_326209923 [accessed 23 Apr 2025]

Float Altitude Calculator (Tropopause ~10km altitude)

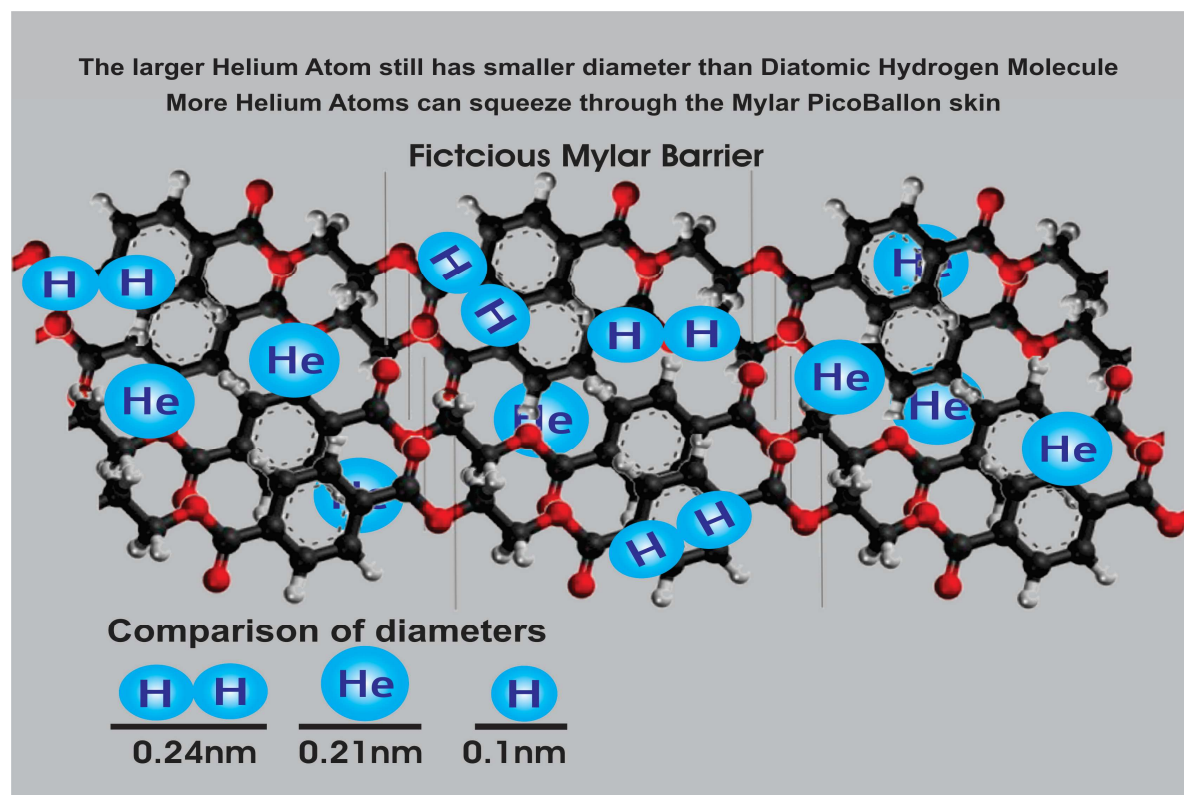
B	C	D	E	F	G	H	I	J	K	L	M	N	O	P	
SuperPressure Balloon float calculator (by Steve Randall)										Version 1g – 17/11/2020		Gas Density Table in Kg/cu m			
												at 101.325kPa at MSL 0 deg C 15 deg C			
Gas	Chosen Gas	Free Lift	SP balloon		Payload	Gas	Total		Neck	Launch					
	Density	(g)	vol (cu m)	weight (g)	Weight (g)	Mass (g)	Mass (Kg)		Lift (g)	Gas Fill (cu m)					
Hydrogen	0.0852	5.00	0.250	72.40	10.00	6.5362782	0.0889	>>>	15.0000	0.0767	<<<				
				36.2											
System Density at float (Kg/cu m)			K		Float						Atmospheric				
0.3557			0.026992		Internal Pressure (kPa)		External Pressure (kPa)		Temp (deg C)		Altitude (m)		Pressure (kPa)		
					23.375687		22.08503		-56.46		11180		101.325		
free lift ratio (see [1])			K/V								(36670.4 ft)				
0.05622			0.107967		Differential Pressure at float						Superpressure				
					(kPa)		(psi)				Onset (m)		Altitude at whi		
					1.2907		0.1872		<<<		10770		full, superpres		
											>>>		down into floa		
					Super Pressure by [1]						(35325.6 ft)				
Use:					(kPa)		(psi)								
Inputs in green cells					1.2416		0.1801		<<<						
Results in arrowed pink cells															
Inputs:															
Gas – drop-down of the the type of gas you will use to fill the balloon (Hydrogen/Helium)															
Free Lift – desired free lift – sets the amount of gas needed, float differential pressure and altitude															
SP balloon vol. – the volume of the balloon (or total volume if multiple balloons) that you will be using															
SP balloon weight – the weight of the balloon envelope (or total weight if multiple balloons)															
Payload weight – weight should include everything that is not included in the balloon weight (so line, tape etc).															
References:															
[1] Superpressure Balloons for Horizontal Sc															

Hydrogen .vs. Helium

Weight

Hydrogen molecule 2.016g/mole

Helium atom 4.002g/mole



Lifting Gas Choices

- Hydrogen
 - + Best Lift and least leakage
 - - Requires a regulator
 - - Explosive
- Helium
 - + Good lift and inert
 - + Can use a balloon regulator
 - - Hard to purchase
- Party Helium
 - + Cheap and easily available
 - + Includes a balloon regulator
 - - Poor lift (contains nitrogen)



Quality Mylar(Nylon) Balloons

- Large mylar balloons (> \$150)
 - Scientific Balloon Solutions (SBS)
- Low-cost nylon party balloons
 - Minimal leakage
 - Bigger is better (30" or more)
 - 30"-36" Types known to work:
 - Orbs clear spherical (\$11)
 - Party Woo spherical (\$3-5)



SBS Mylar Balloon

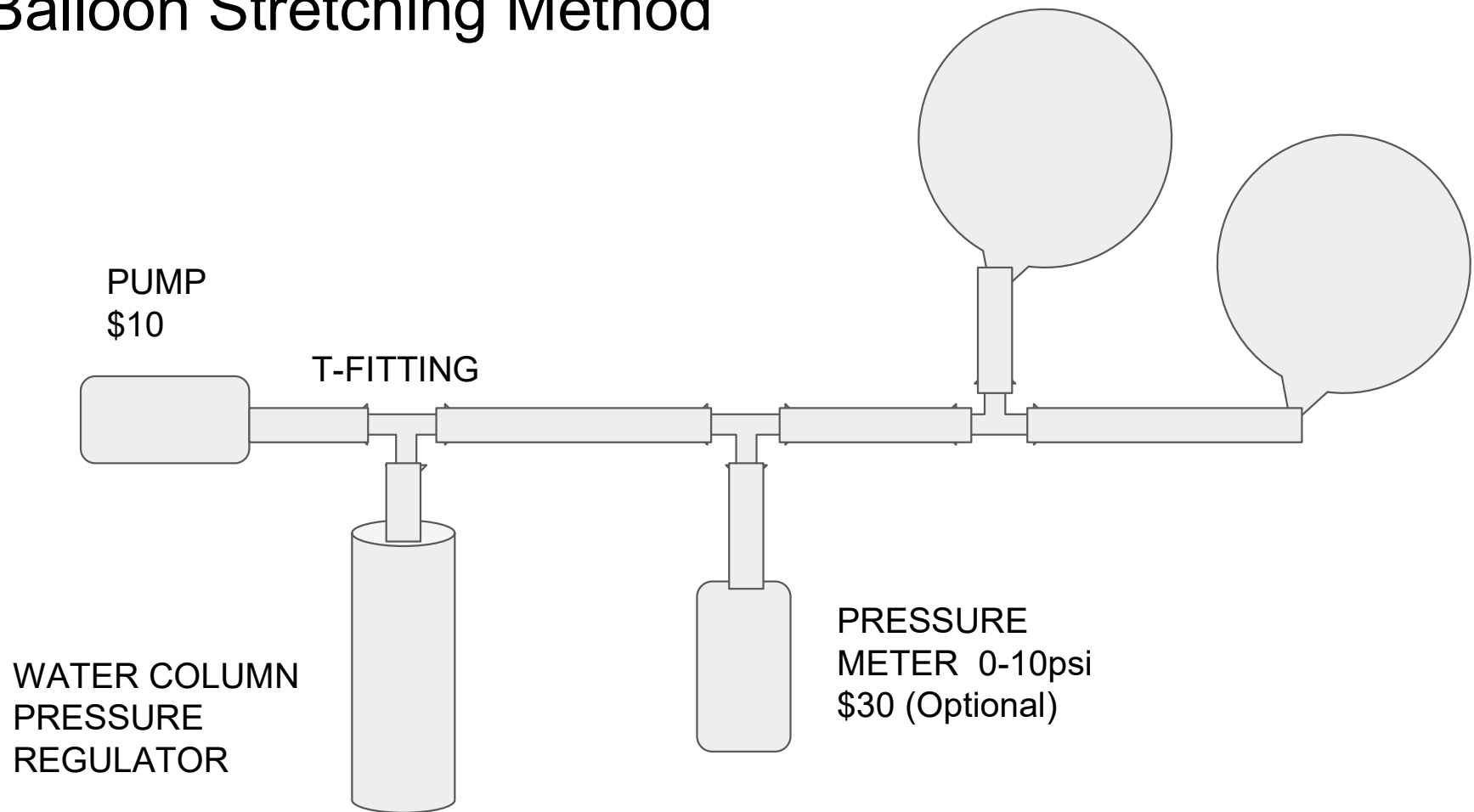


Orbs 32" Nylon Spherical Balloon



Party Woo Nylon Foil Balloon

Balloon Stretching Method



Stretching Party Balloons

- Increase volume
 - Higher altitude
- Detect leaks before launch
- Equipment
 - Aquarium pump \$10
 - 1/4" aquarium hose and T-fittings
 - 2' long PVC pipe with bottom capped
 - Rubber bands
 - 10psi pressure meter \$30 (optional)
 - Humidifier (optional)





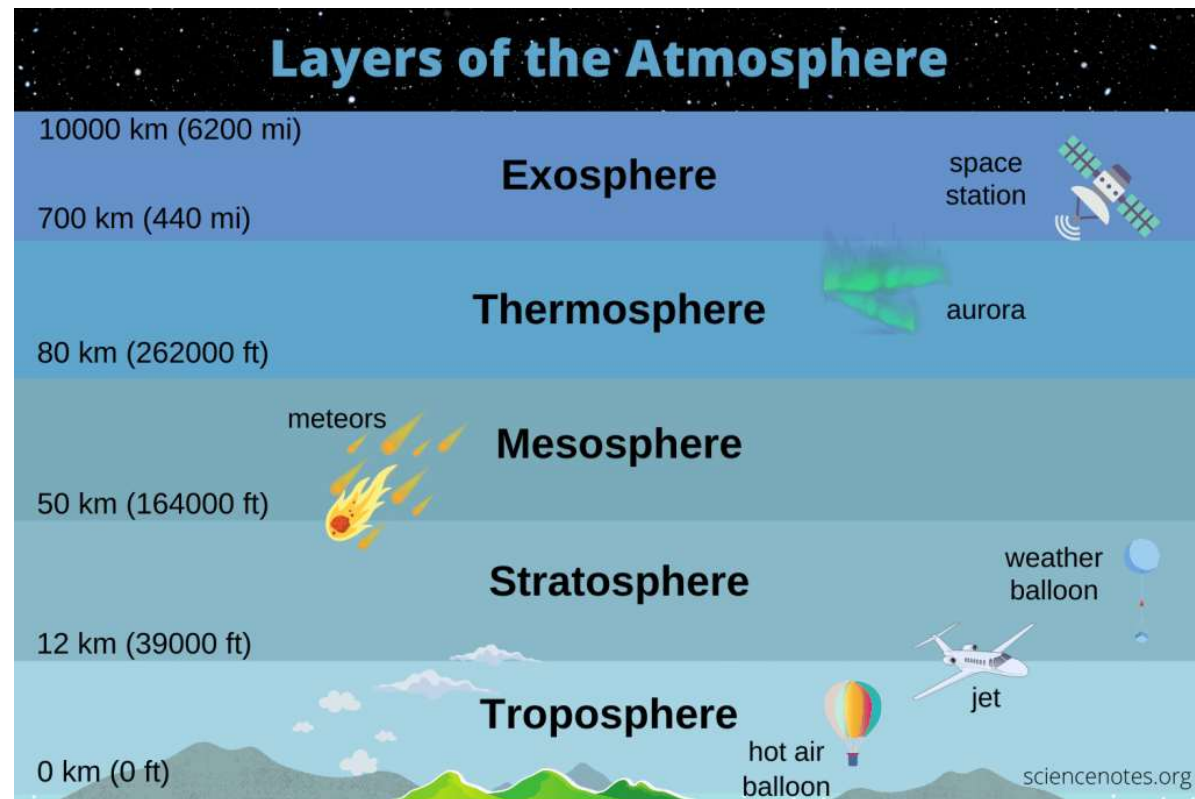
Earth's Atmosphere

And Pico-Balloons

<https://images.squarespace-cdn.com/content/v1/6123aa4da7d85907b823dc29/1646063669874-SKXA5SWVYES9QIB01OHI/clouds.jpg>

Atmospheric Layers

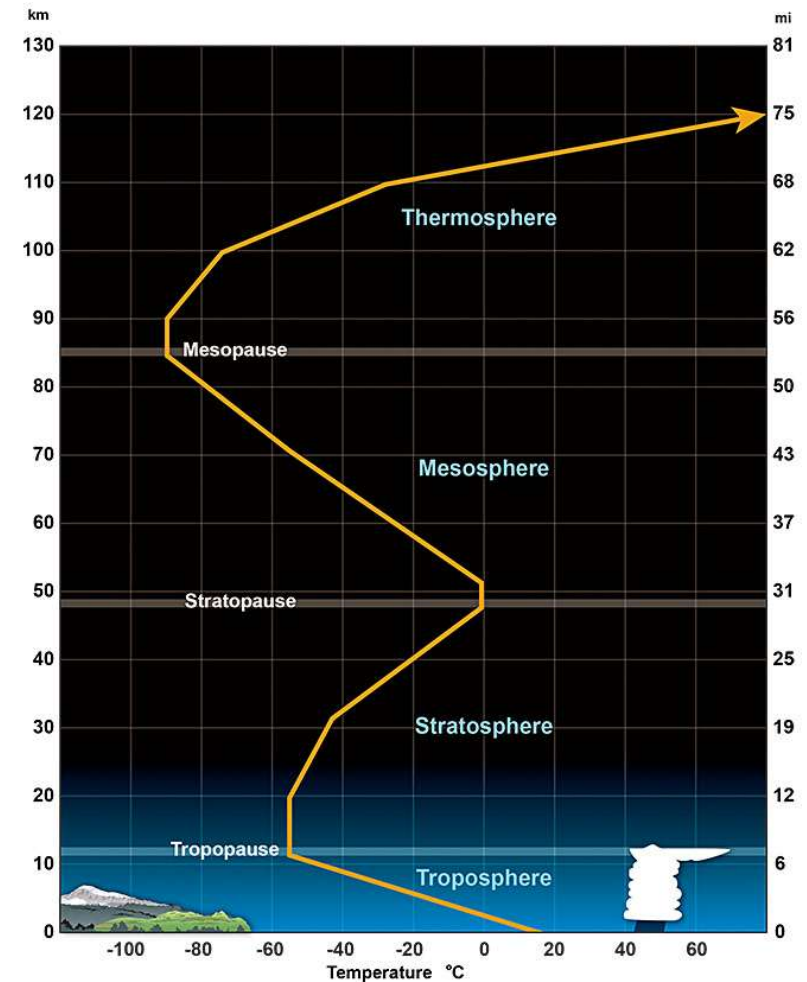
- Pressure decreases exponentially with altitude
- Temperature initially decreases with altitude but begins to increase in the stratosphere
- Pico-balloons fly at the top of the troposphere or near the bottom of the stratosphere
- We will see why this is the best altitude in the coming slides



<https://sciencenotes.org/wp-content/uploads/2022/05/Layers-of-the-Atmosphere-1024x683.png>

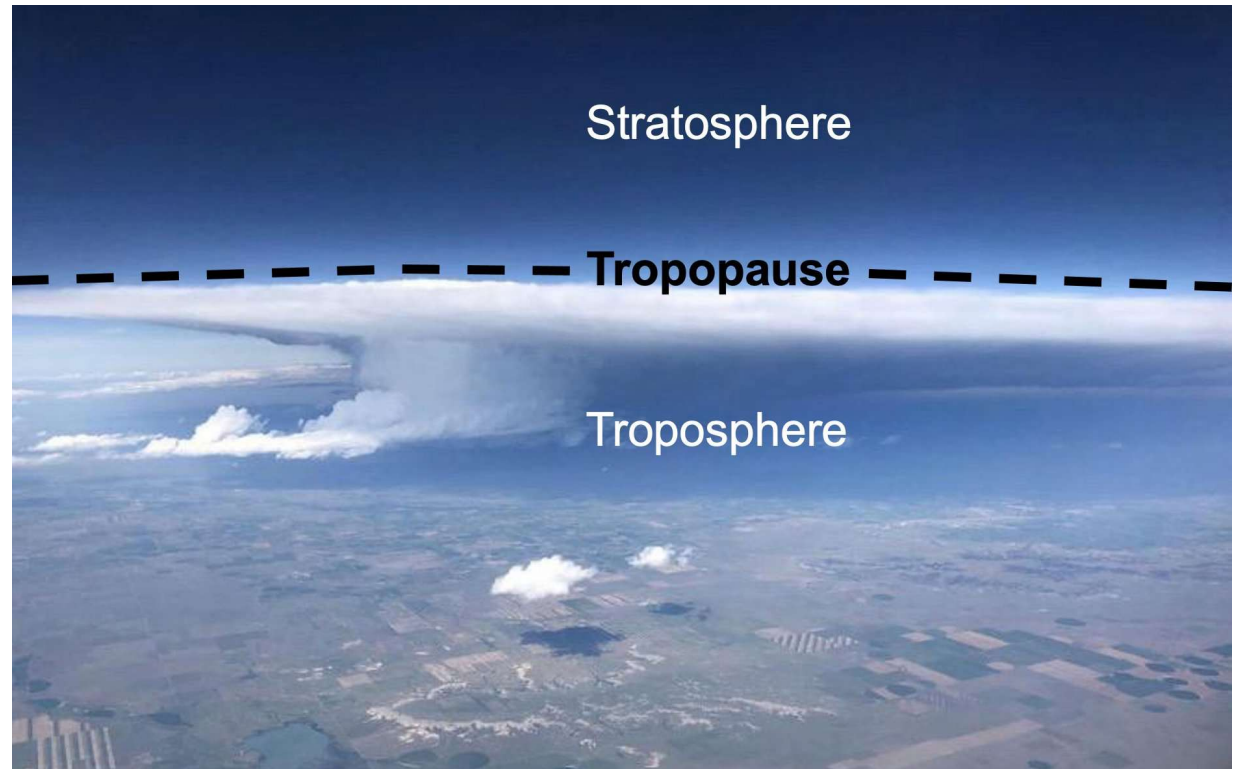
Atmospheric Temperatures

- Pico-balloons fly in the coldest part of the lower atmosphere
- Temperatures are around -57°C or -70°F
- This can cause problems for electrical components and must be considered in the design



NOAA.gov

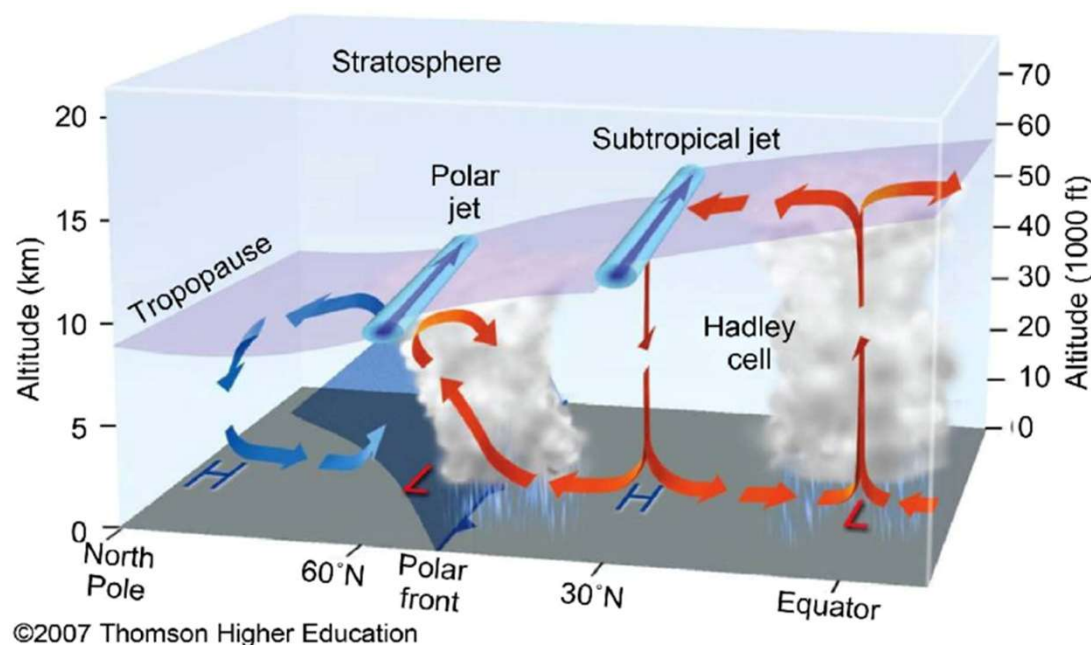
Tropopause



- Temperature Inversion layer – temperature stops decreasing with altitude as it does in the troposphere and it may even start increasing
- Rising warm air and clouds can rarely penetrate this inversion layer
- To avoid cloud tops we try to fly above the tropopause

Cloud Tops

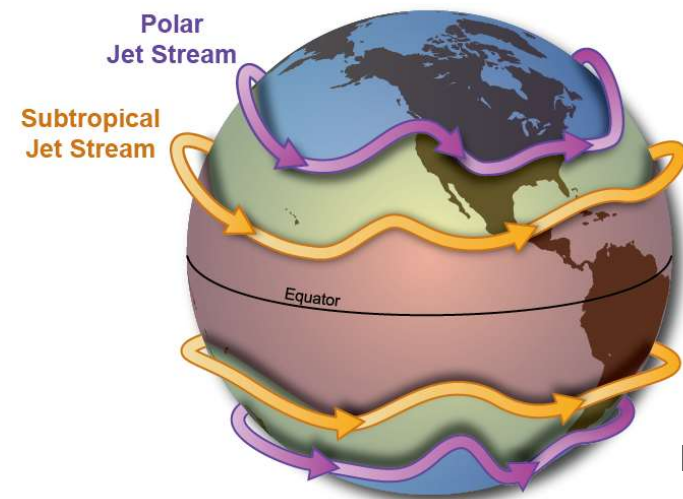
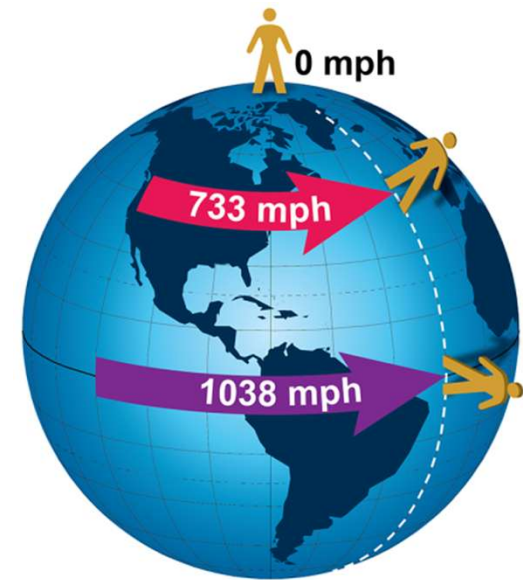
- The atmosphere is thicker near the equator and the altitude of the tropopause almost doubles from pole to equator.
- It is difficult to get a pico-balloon above the tropopause near the equator.
- The altitude limit of a low-cost pico-balloon with a payload is around 50,000 ft
- Large thunderstorm cloud tops near the equator can be high enough to bring down a pico-balloon.
- In a cloud, condensation or ice crystals forming on the balloon can add enough weight to bring the balloon down into the storm and to the ground.



https://atoc.colorado.edu/~cassano/atoc3050/lecture_notes/chapter11.pdf

Coriolis Effect / Jet Stream

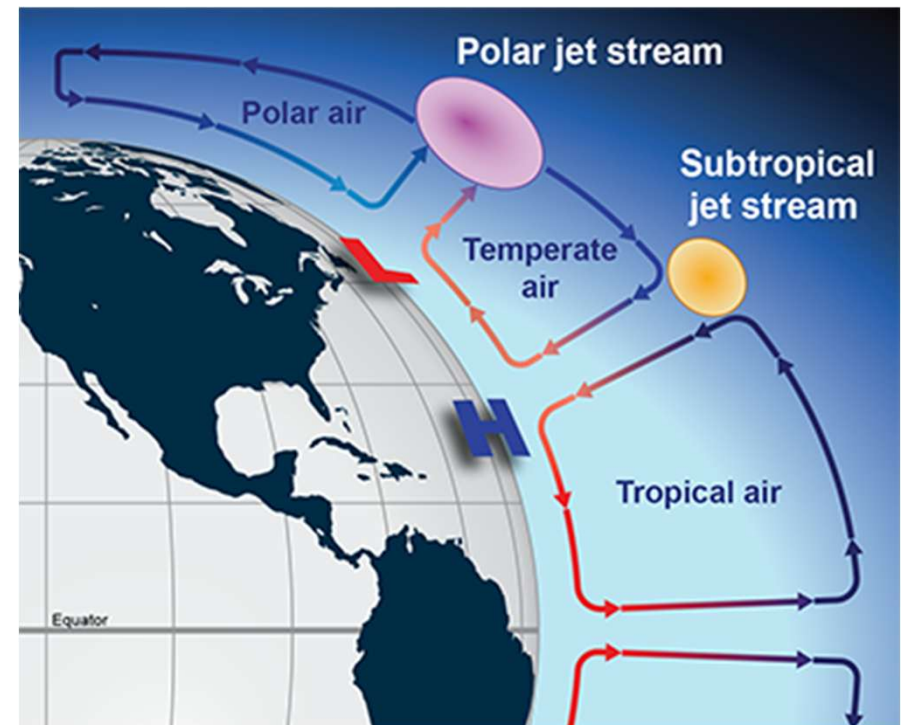
- Earth's atmosphere is rotating at 1038mph at the equator but is not rotating at all at the poles.
- Warm air rises high in the atmosphere near the equator and then flows down toward the cooler poles where it cools and falls back down
- This means air high in the atmosphere is moving from the equator toward the poles. Due to the Earth's rotation, this air has extra eastward velocity as it moves toward the pole.
- This results in an eastward upper atmospheric winds of up to 200mph called the jet stream
- This wind flows around other atmospheric weather systems like a winding river.



NOAA.gov

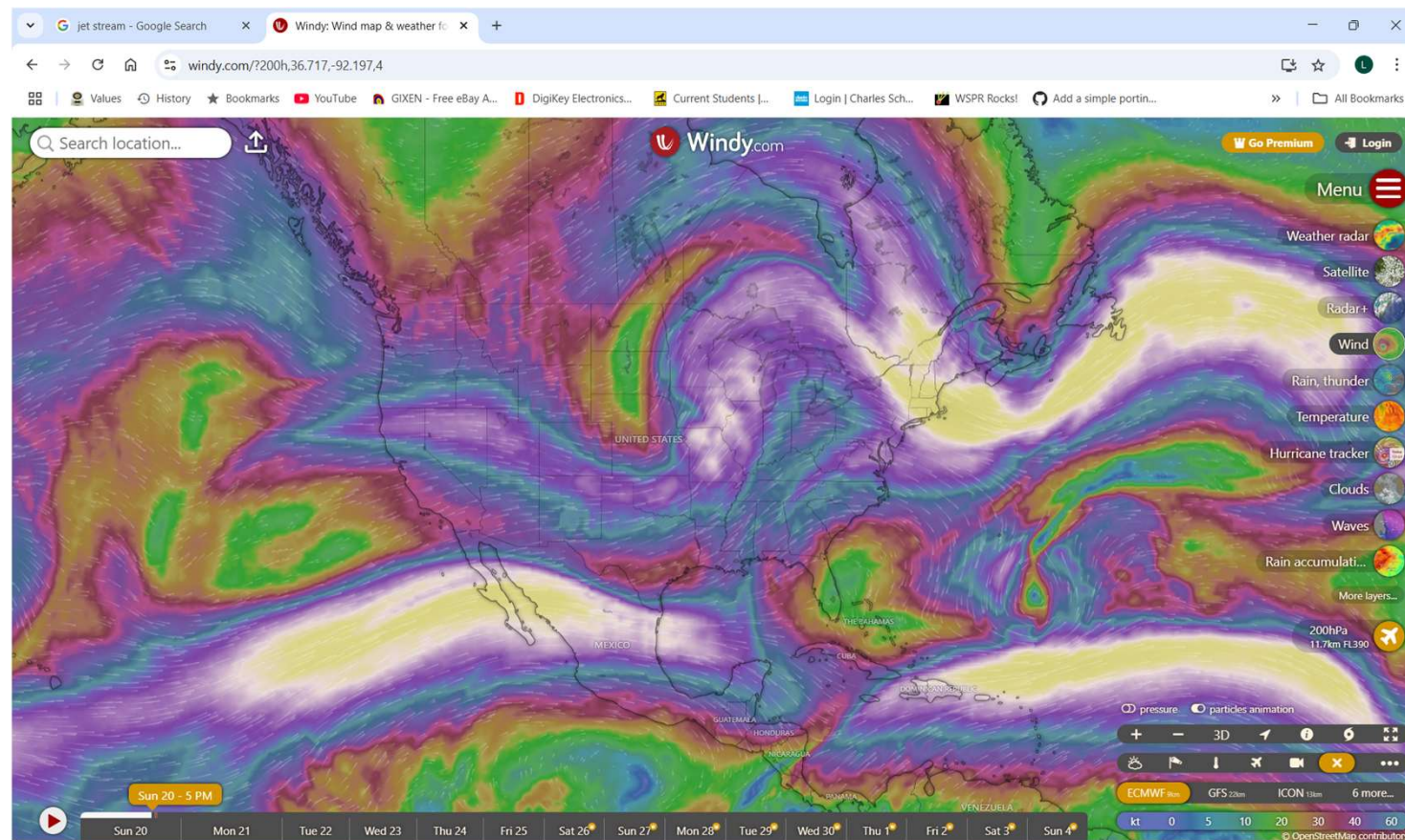
Jet Stream

- Pico-balloons use the Jet Stream to move around the Earth
- We want to fly at the upper altitude of the jet stream around 45,000 ft to avoid clouds.
- Going higher can avoid more clouds, but the balloon will not travel as fast in the lighter winds.



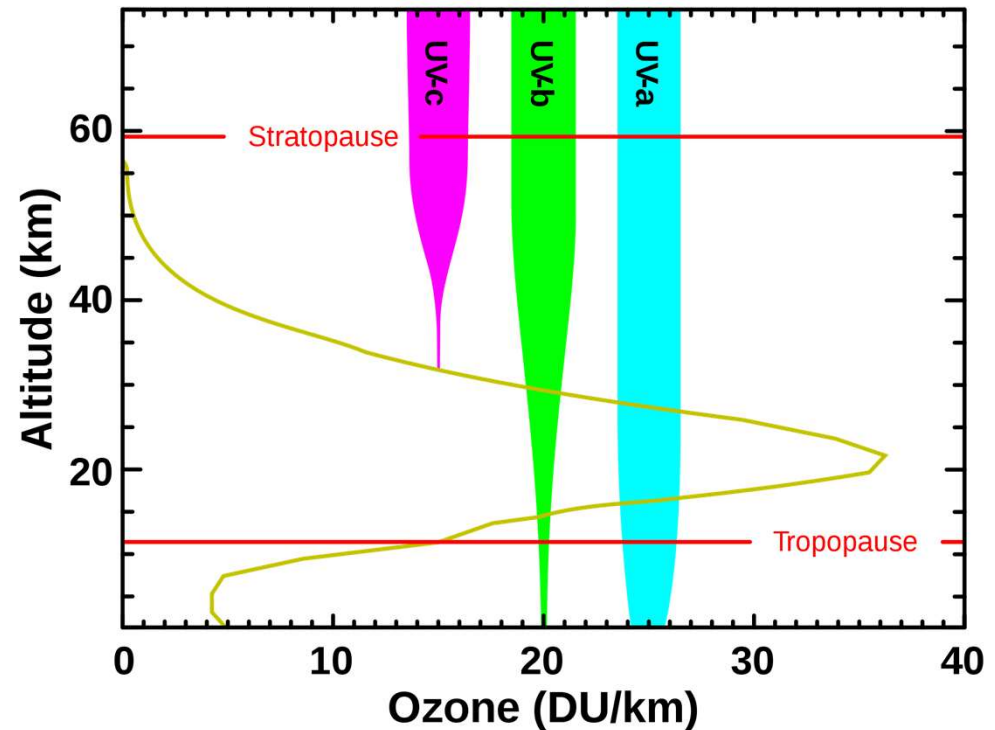
NOAA.gov

Windy.com – Monitors and Predicts Winds



UV Exposure

- Higher UV light exposure at 50,000ft will eventually degrade the balloon material and the solar cell
 - This may cause the balloon to start leaking or burst
 - Reduces power output from the solar panels



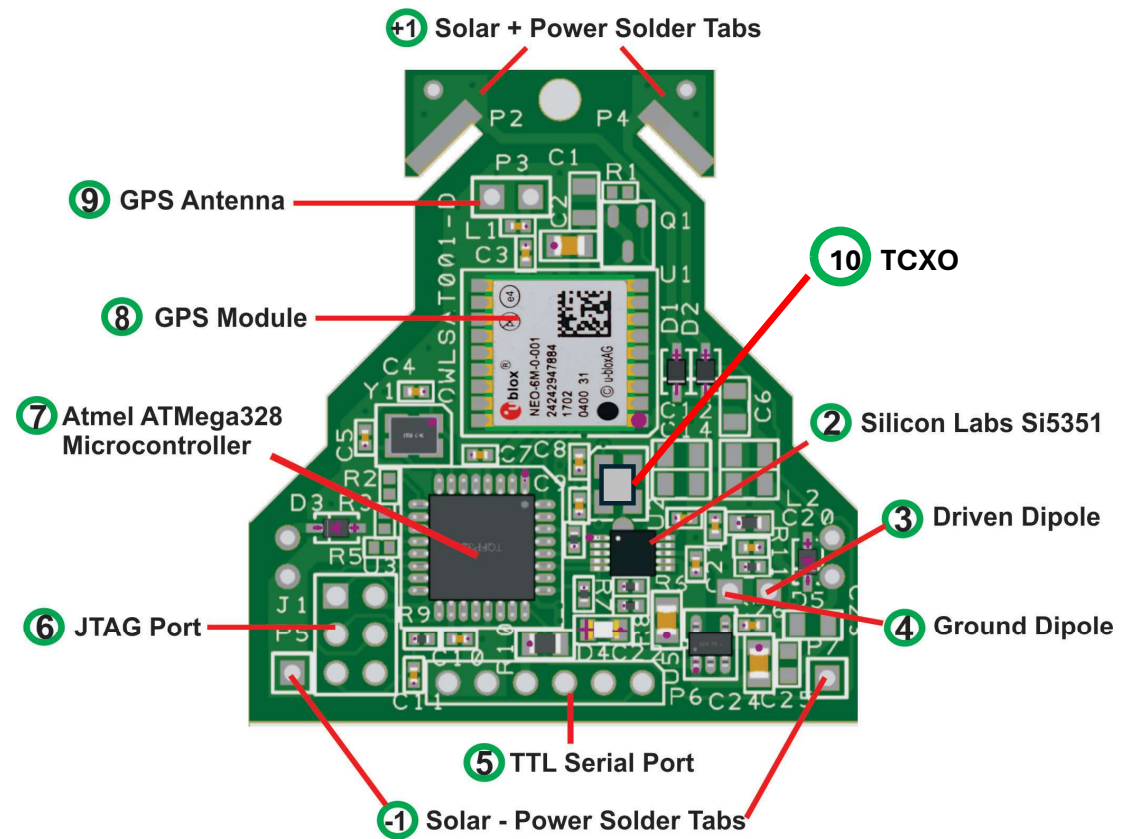
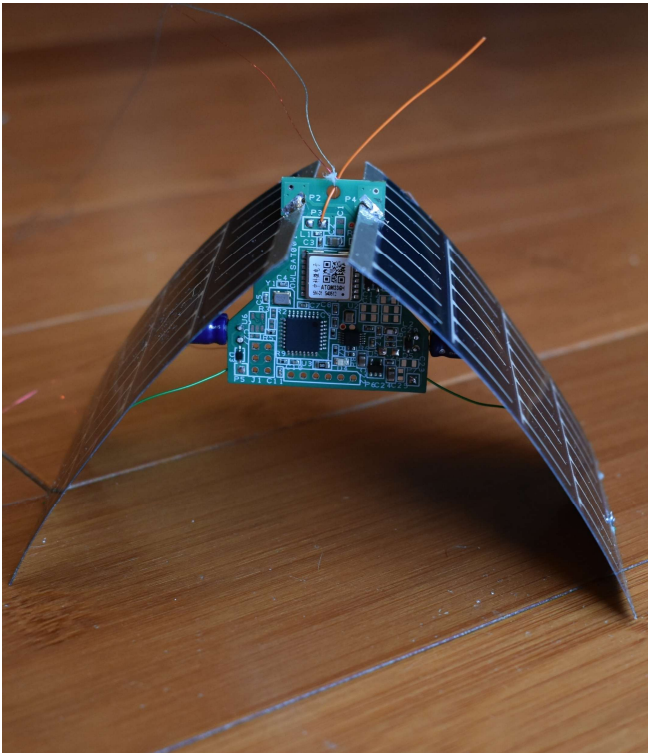
Flight Termination

- Early balloon failure
 - Overfilling
 - Defective seals
- Encountering tall cloud tops that cause icing
- Electrical component or wiring connection failures
- UV damage
 - Balloon leakage
 - Solar panel failure
- Supercapacitor failure from low temperatures
- Missile from F-16 Fighter Jet

Pico-Tracker Electronics

Embedded Programming

Pico-Tracker PCB Components



Small Size – Low Power

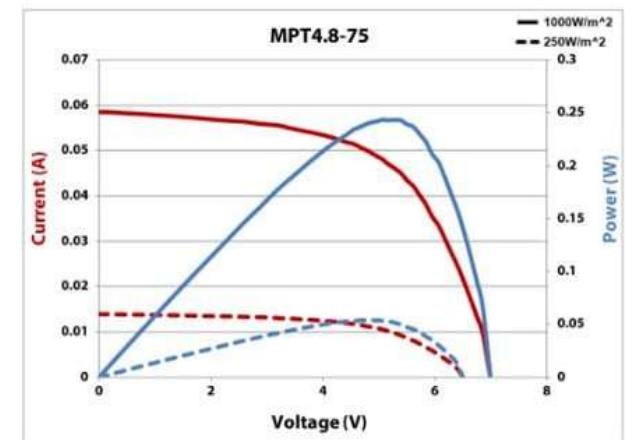
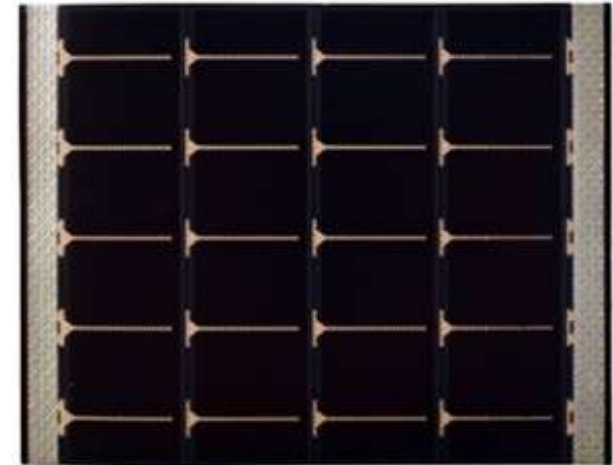
- The payload must be light weight to achieve the required altitude
- Batteries are too heavy
- Small light weight solar panels and a small PCB (8 to 10 grams total weight) are the best option
- Small solar panels necessitate low power consumption and low power RF transmissions

Cold Temperatures

- At 45,000 feet temperatures are around -70°F (-57°C)
- The electrical components, tape, and glue must work in very cold temperatures
- Some ICs are not rated for these temperatures
- Supercapacitors become much less efficient at -55°C
- The heat of sunshine on the parts can help

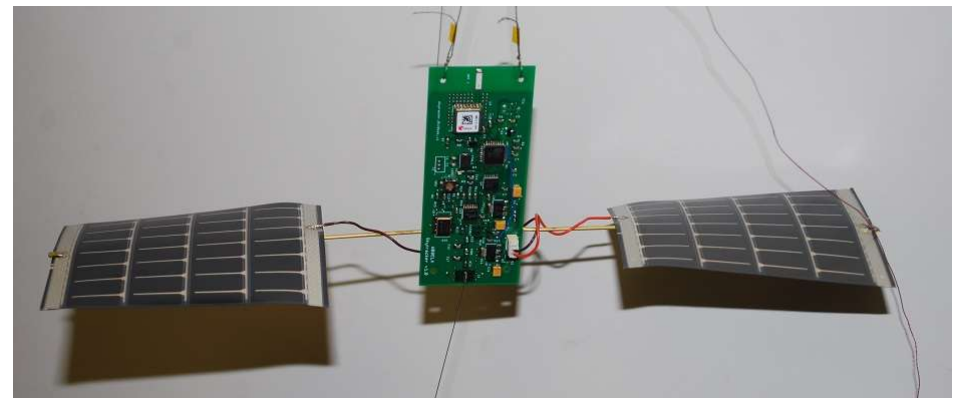
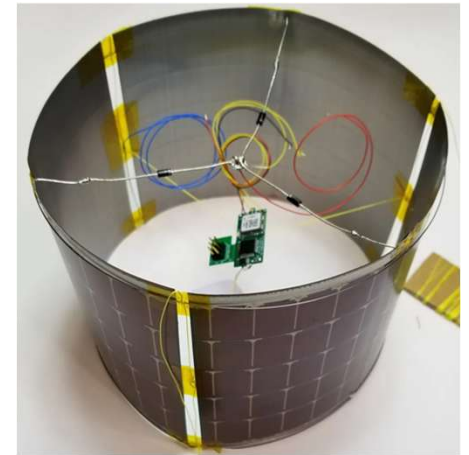
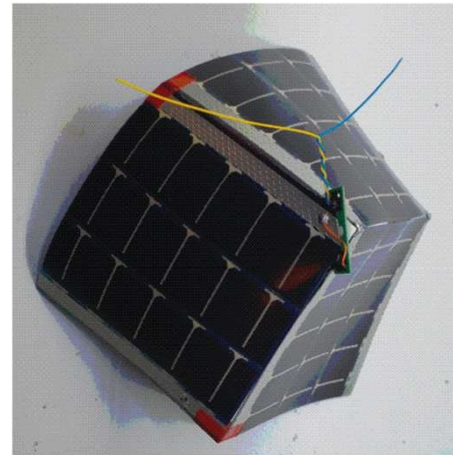
Solar Power

- Solar Cells convert light to electricity by the photovoltaic effect
- Silicon Solar Cell types
 - Single crystal – best efficiency 20-22% but expensive and delicate unless encapsulated
 - Polycrystalline – good efficiency 15-17% but delicate unless encapsulated (most common)
 - Amorphous thin film – rugged, flexible, and light weight but less efficient 7-13% and more expensive than polycrystalline
- Encapsulation adds too much weight



Sun Angle and Power

- Sun angles vary with time of day, season, and latitude.
- Output power depends on the amount of light hitting the panel and its efficiency
- Get maximum light when the panel is perpendicular to the Sun direction
- Our goal is to stay powered for as long as possible
- A 45° panel orientation works best for all situations



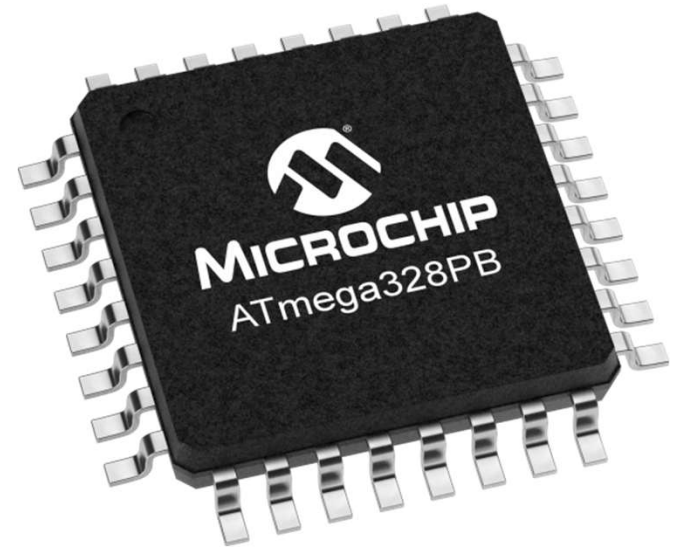
Super Capacitors

- The solar panels may not always point toward the Sun, so we need to store energy to prevent restarting the microcontroller.
- Super capacitors are a good lightweight solution
- 100X capacity of the same size standard capacitor
- Electrostatic double-layer capacitors (EDLCs)
 - Activated carbon electrodes for large surface area
 - Mobile charges are cations and anions in solution
 - Double layer charge separation of under 0.5nm



Microcontroller

- Very low power microprocessor with output ports that generate signals to control the other devices on the tracker.
- The software that runs the tracker is programmed into the chip and is not lost when powered down.
- The software receives GPS data and converts the location to WSPR protocol then controls the Clock Generator to transmit the WSPR packet.



GPS Module

- Module containing the GPS RF receiver and a microprocessor to convert the received satellite information into position information.
- The microprocessor sends the position information to the tracker microprocessor using standard NEMA serial data strings.
- National Electrical Manufacturers Association (NEMA) creates industry standards.



Clock Generator and TCXO

- The clock generator needs a stable input clock that will not drift with temperature. (TCXO) Temperature compensated crystal oscillator.
- The tracker microcontroller communicates with the clock generator over a serial bus.
- The microcontroller sets the output frequency of the clock produced by the clock generator.
- This frequency is changed between four different values to generate the final WSPR tones used to transmit the data.
- The receiver uses these tones to reconstruct the data bits in the WSPR packet.



RF Communications

Tracking the Balloon



GPS – Global Positioning System

- Constellation of satellites send time and position information to receivers.
- The receiver uses the received satellite positions and times to determine its own position.
- This requires having a good connection to a minimum of four separate satellites
- The initial process can take a few minutes.
- Transmissions are at a frequency around 1.5GHz
- The pico-balloon uses a 2-inch $\frac{1}{4}$ wavelength monopole antenna to receive GPS satellite signals



GPS Jamming and Spoofing

- When flying over war zones, the balloon may have the GPS signal jammed causing the balloon not to report its position for a day or two.
- GPS spoofing may cause the balloon to report an inaccurate position and altitude
- When the balloon leaves the jamming or spoofing area it will continue working normally.

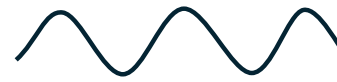
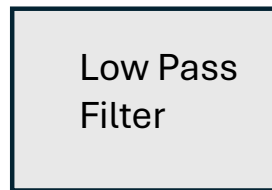
Restricted Transmission Areas

- Some countries do not allow areal HF transmissions within their airspace
- The software in the Pico-Tracker will not transmit when it is located over these countries
 - England
 - North Korea
 - Yemen

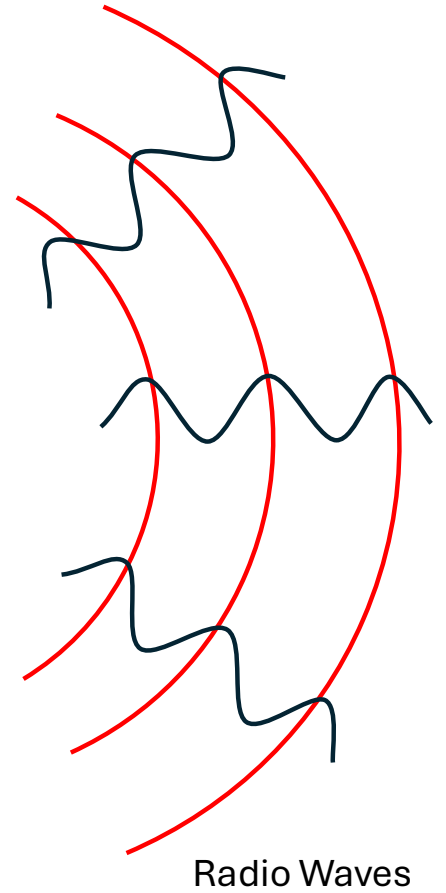
Pico-Tracker Transmitter



Clock Generator



Antenna

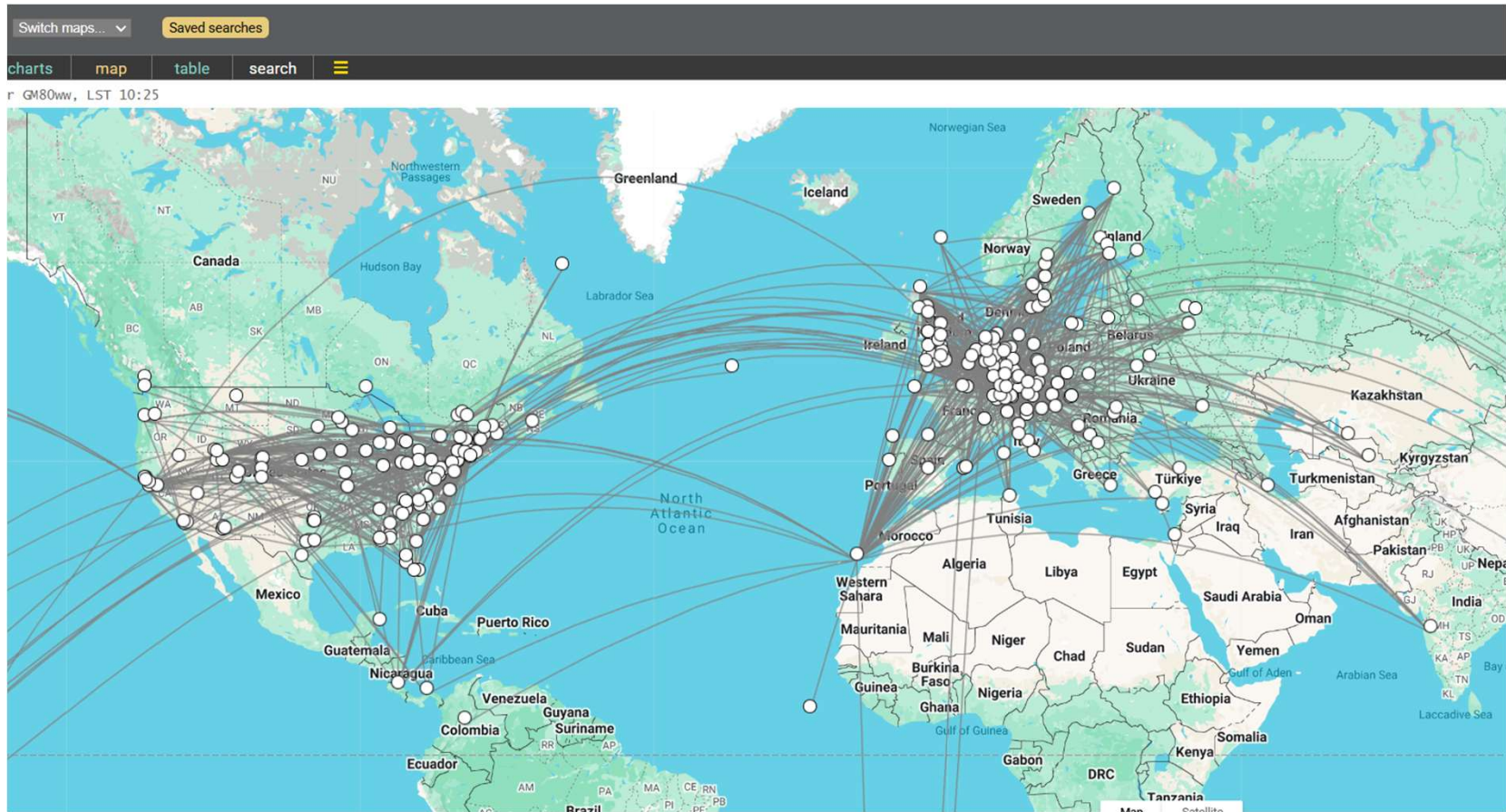


Radio Waves

WSPR – Weak Signal Propagation Report

- The amount of skip can change as the charge and height of the ionosphere change from day to night and with solar conditions.
- Amateur radio hobbyists dedicate weak transmitters to send data about the transmitting station on HF bands.
- Stations that receive the data report it to a database that shows which bands and areas are currently good for long transmission.
- Pico-balloons piggyback on this system to report their position and altitude
- WSPR protocol was designed to receive very weak signals and allows our 15mW signal to be received over great distances

WSPR Mapping Website – wspr.rocks



WSPR protocol

Sends Date/Time, Callsign, Grid Locator, and Xmit Power (Altitude)

50 data bits/2 minutes = 0.42 bps

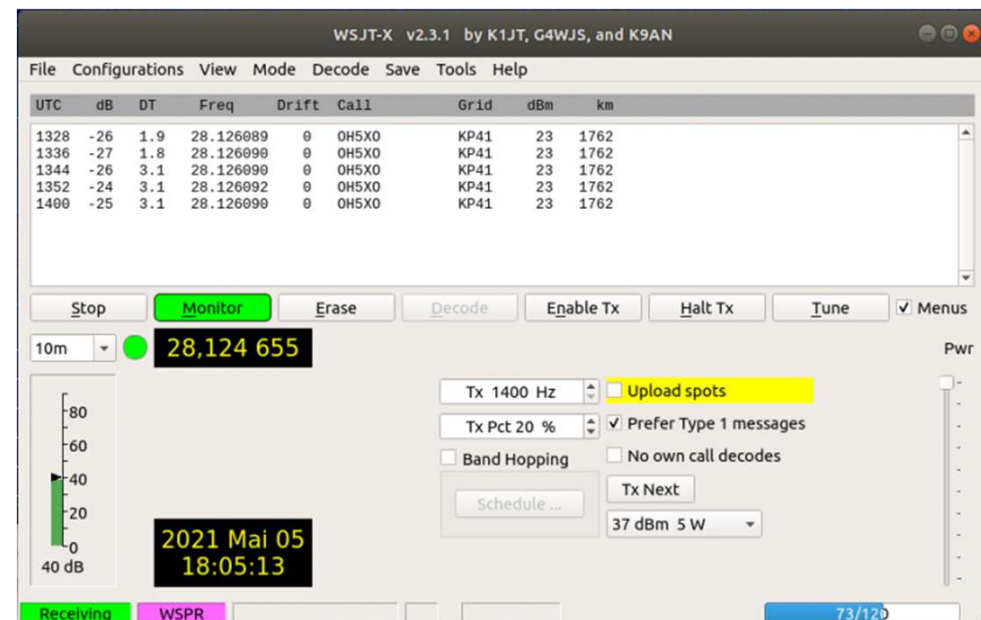
Also sends sync and FEC bits

4 frequency CPFSK , 1.5Hz separation

Transmission only occupies 6Hz bandwidth

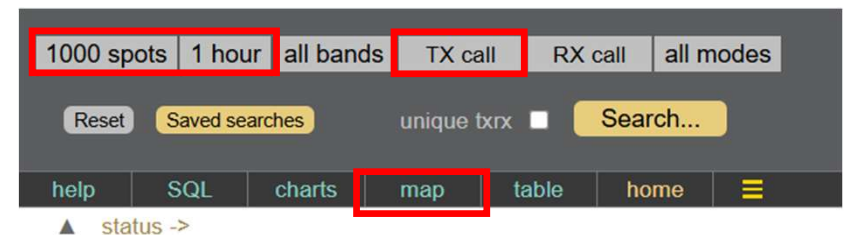
Pico-Tracker output power of 15mw on 20/30m amateur bands

WSJT-X Software weak signal communications



Finding Your Balloon

- On wspr.rocks search tab, type your call sign into the TX call box
- Select the duration from the time box
- Increase the total number of spots if choosing a long duration
- Press the search button
- Then select the map tab



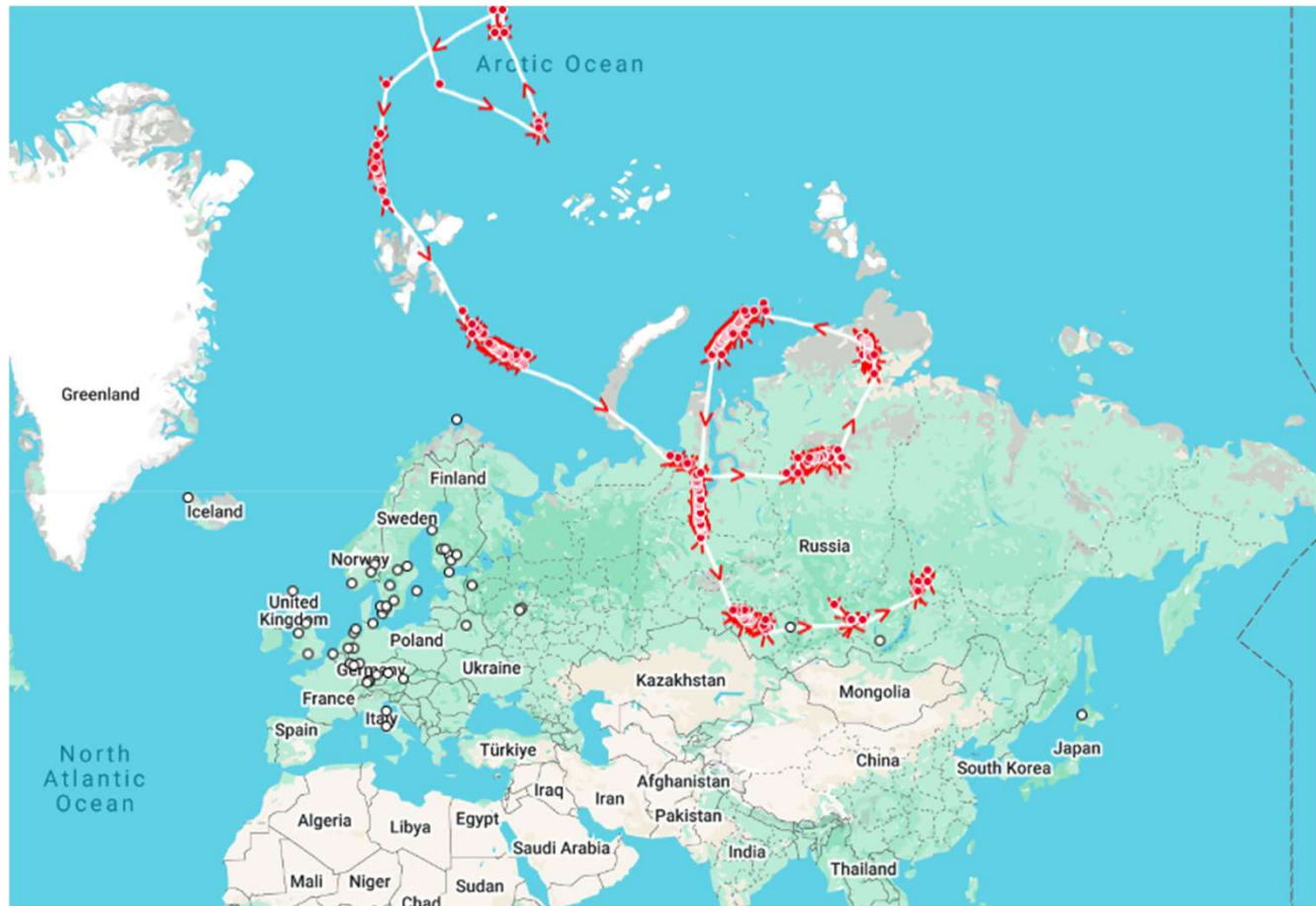
Quick start

Click the Search button and have a look around.

- use the help page if you get stuck
- the hamburger ☰ sets preferences

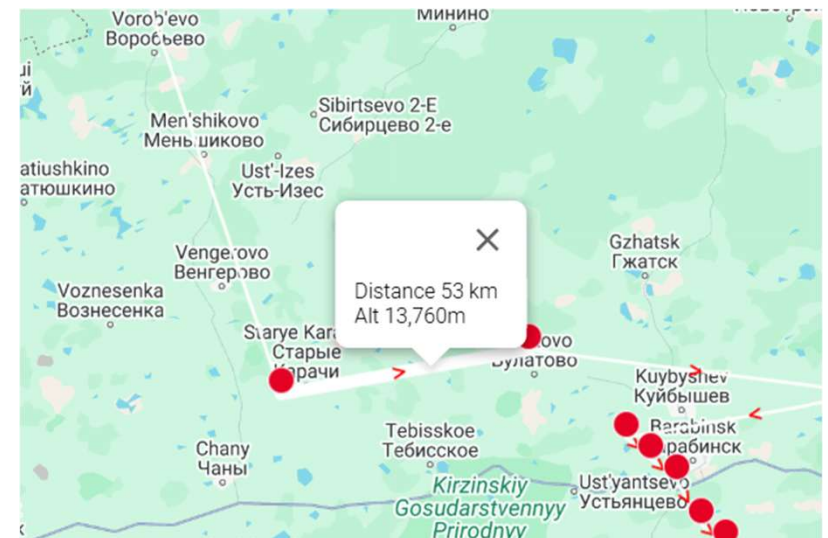
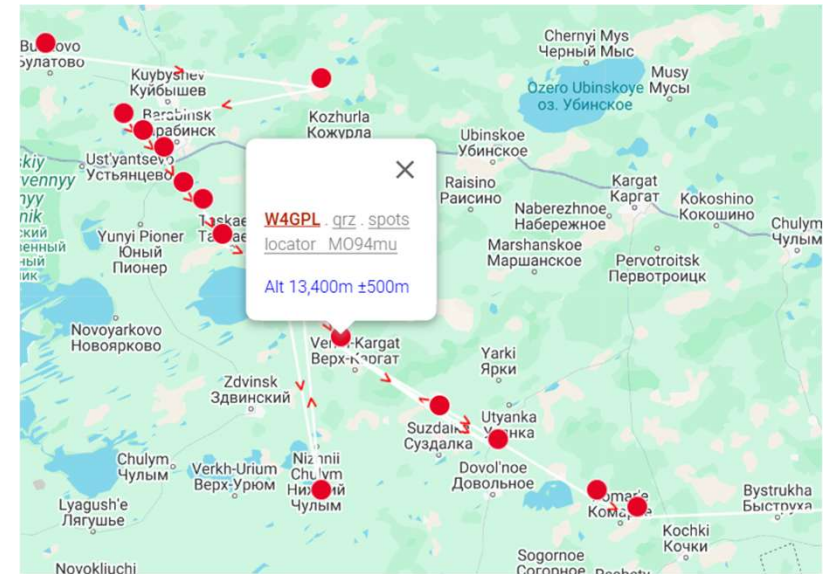
Map of Pico Balloon Flight on wspr.rocks

- Shows track and altitude at each point
- Solar power – only transmits during daylight
- This balloon went over the north pole



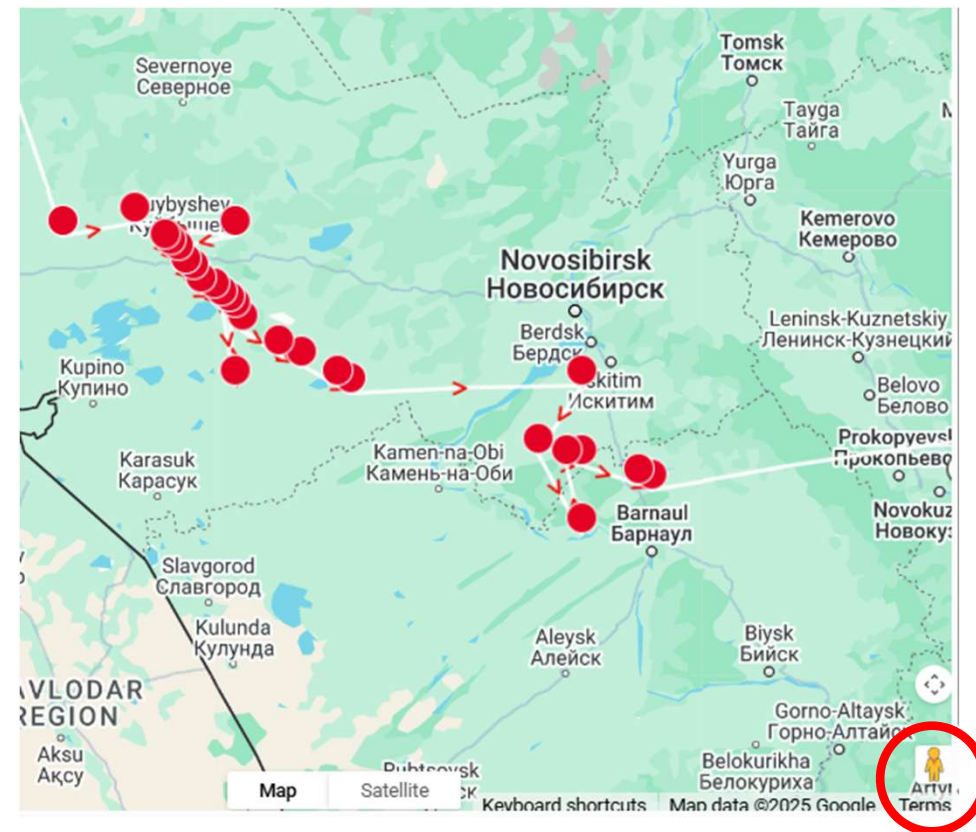
Balloon Altitude

- Click on any balloon position to display the grid locator and altitude
- Click on any connecting line to get the distance

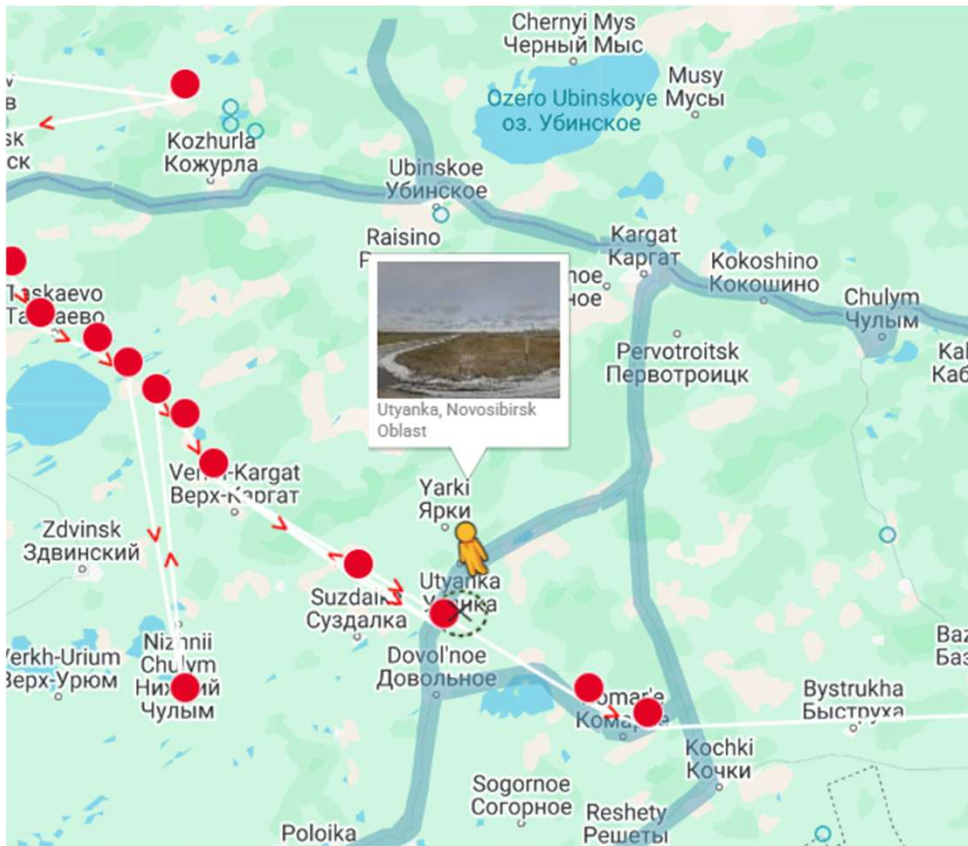


Geography

- Google Maps – Street View
- Use “orange man” to get street view from wspr.rocks
- Click and drag him on top of your location and drop him on any highlighted object to see the geography and architecture

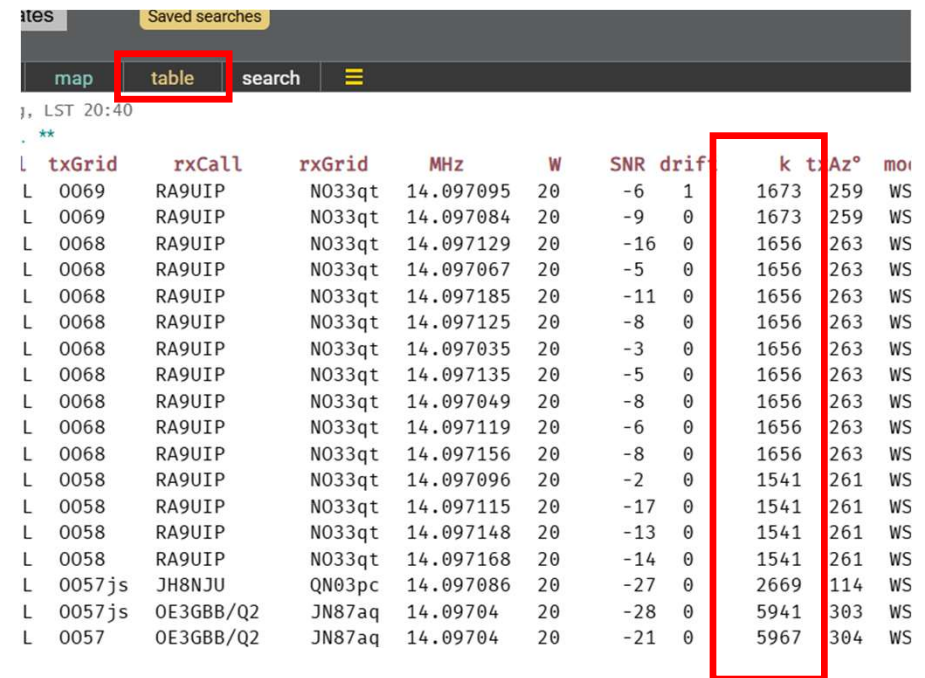


Street View from wspr.rocks



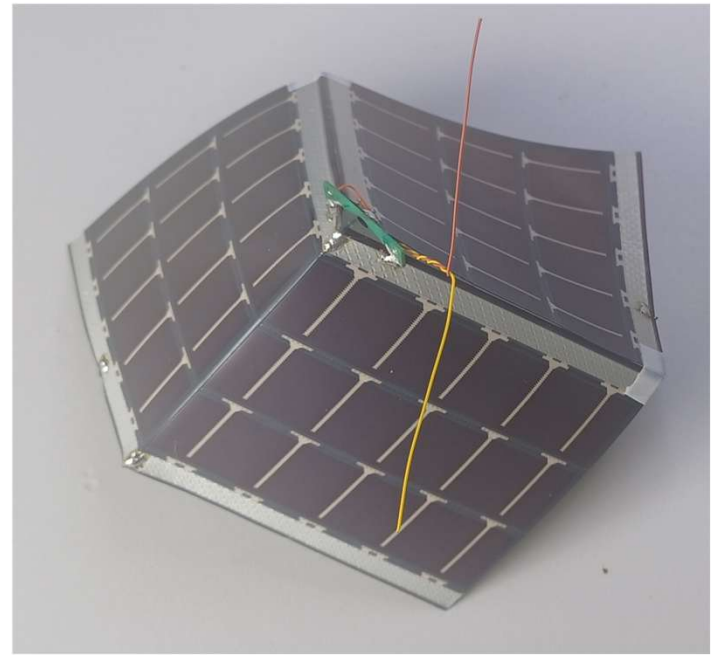
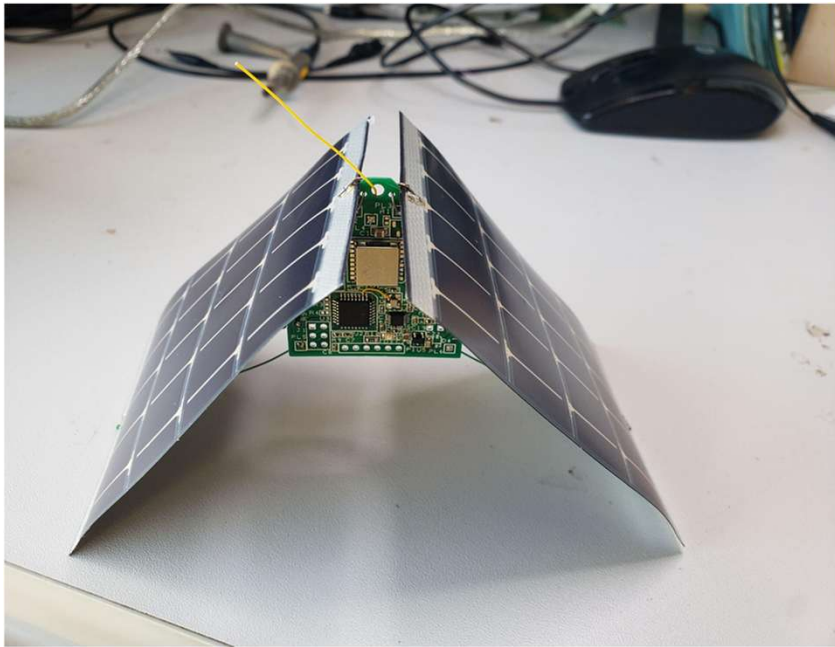
Transmission Distance

- wspr.rocks shows the receiving stations distance from the balloon in the table view
- It also shows the call sign of the receiver under “rxCall”. Whose personal details can be viewed at QRZ.com



	txGrid	rxCall	rxGrid	MHz	W	SNR	drift	k	tx	Az°	mo
L	0069	RA9UIP	N033qt	14.097095	20	-6	1	1673	259	WS	
L	0069	RA9UIP	N033qt	14.097084	20	-9	0	1673	259	WS	
L	0068	RA9UIP	N033qt	14.097129	20	-16	0	1656	263	WS	
L	0068	RA9UIP	N033qt	14.097067	20	-5	0	1656	263	WS	
L	0068	RA9UIP	N033qt	14.097185	20	-11	0	1656	263	WS	
L	0068	RA9UIP	N033qt	14.097125	20	-8	0	1656	263	WS	
L	0068	RA9UIP	N033qt	14.097035	20	-3	0	1656	263	WS	
L	0068	RA9UIP	N033qt	14.097135	20	-5	0	1656	263	WS	
L	0068	RA9UIP	N033qt	14.097049	20	-8	0	1656	263	WS	
L	0068	RA9UIP	N033qt	14.097119	20	-6	0	1656	263	WS	
L	0068	RA9UIP	N033qt	14.097156	20	-8	0	1656	263	WS	
L	0058	RA9UIP	N033qt	14.097096	20	-2	0	1541	261	WS	
L	0058	RA9UIP	N033qt	14.097115	20	-17	0	1541	261	WS	
L	0058	RA9UIP	N033qt	14.097148	20	-13	0	1541	261	WS	
L	0058	RA9UIP	N033qt	14.097168	20	-14	0	1541	261	WS	
L	0057js	JH8NJU	QN03pc	14.097086	20	-27	0	2669	114	WS	
L	0057js	OE3GBB/Q2	JN87aq	14.09704	20	-28	0	5941	303	WS	
L	0057	OE3GBB/Q2	JN87aq	14.09704	20	-21	0	5967	304	WS	

Assemble and Launch the Tracker



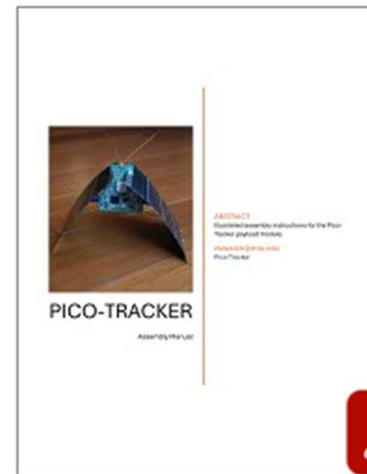
Detailed Pico Tracker Assembly and Launch Procedures



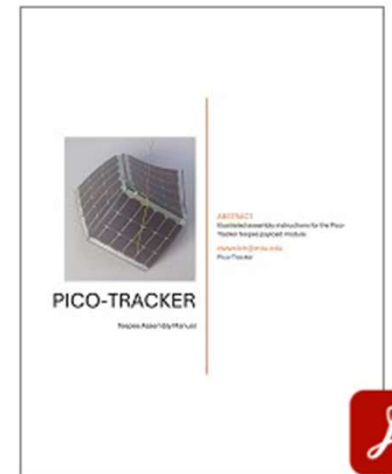
PICO BALLOON LAUNCH
PROCEDURE.pdf



PICO BALLOON STRETCHING
PROCEDURE.pdf



SUPERCAP TRACKER ASSEMBLY.pdf

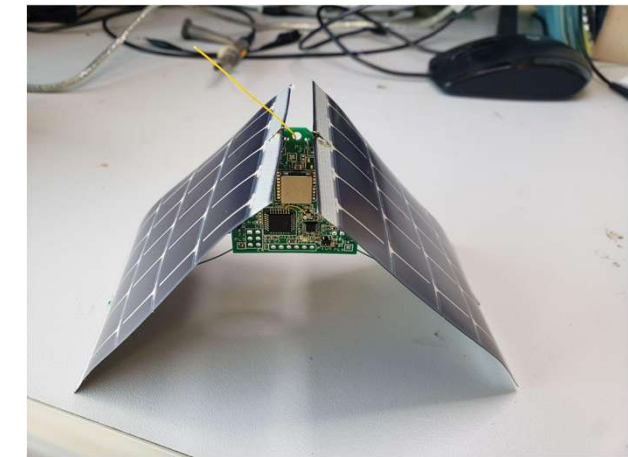
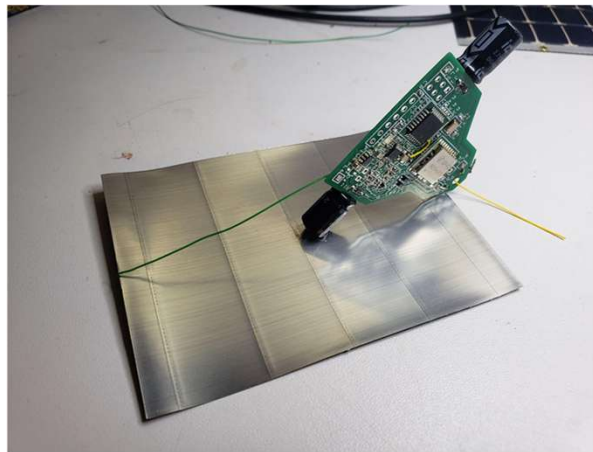
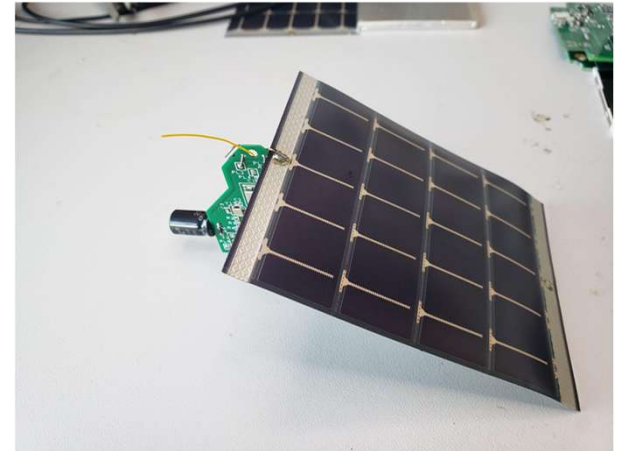
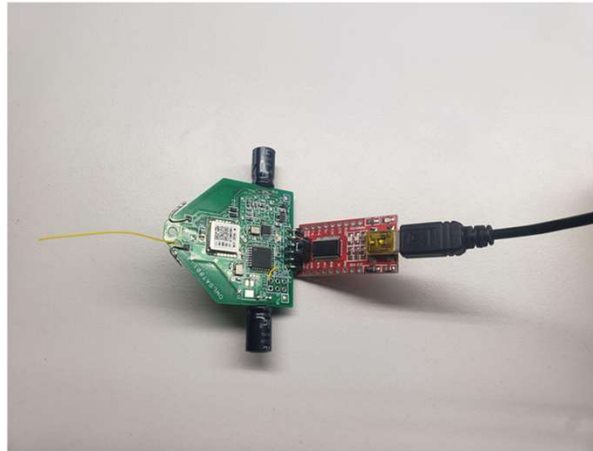


TEE-PEE TRACKER ASSEMBLY.pdf

Download from: SPACE-HOBBIES.COM PICO BALLOONS WEB PAGE

Assemble Tracker

- Configure transmitter
 - USB-to-TTL serial adapter
 - Amateur Radio Callsign
 - Xmit Bands and schedule
 - Transmit altitude
- Add GPS antenna
- Add solar panels
 - Solder +/- connections
 - Glue to SuperCap
- Electrical test
 - Power
 - GPS



Configure WSPR transmitter

ZachTek WSPR Transmitter Configuration Version 1 - Revision 16

Device name
WSPR TX

WSPR Beacon | Signal Generator | Boot Configuration | Serial Port

WSPR Configuration

Call Sign
☐ Prefix Call Sign Suffix ☒
KC9LGS / 7

Band selection

LP	Band	Progress
☐	2190m	
☐	630m	
☐	160m	
☐	80m	
☐	40m	
☒	30m	
☒	20m	
☐	17m	
☐	15m	
☐	12m	
☐	10m	
☐	6m	
☐	4m	

Pause after last band (optional).
400

Transmit Schedule, transmit every ...
☐ 2 minutes (Default)
☒ 10 minutes Schedule 00,10,20,30,40
☐ 20 minutes
☐ Band coordinated schedule
☐ Only when moving (Tracker)

Location
☒ Auto (GPS)
☐ Manual
☒ Send a more precise location

Reported power
☐ Normal mode 10 dBm
☒ Encode Altitude as power

Start Stop

Device Status

Hardware 1:5
Firmware 1:14
Restart

Current output frequency
000 000 000.00
MHz kHz Hz

Transmitter Output
☐ On
☒ Off

Program running
☐ WSPR Beacon
☐ Signal Generator
☒ Idle

GPS Information

Signal Quality
0%

No Position Lock

UTC Time 00:00:00 Position 000000

Az/EI plot of GPS Satellites

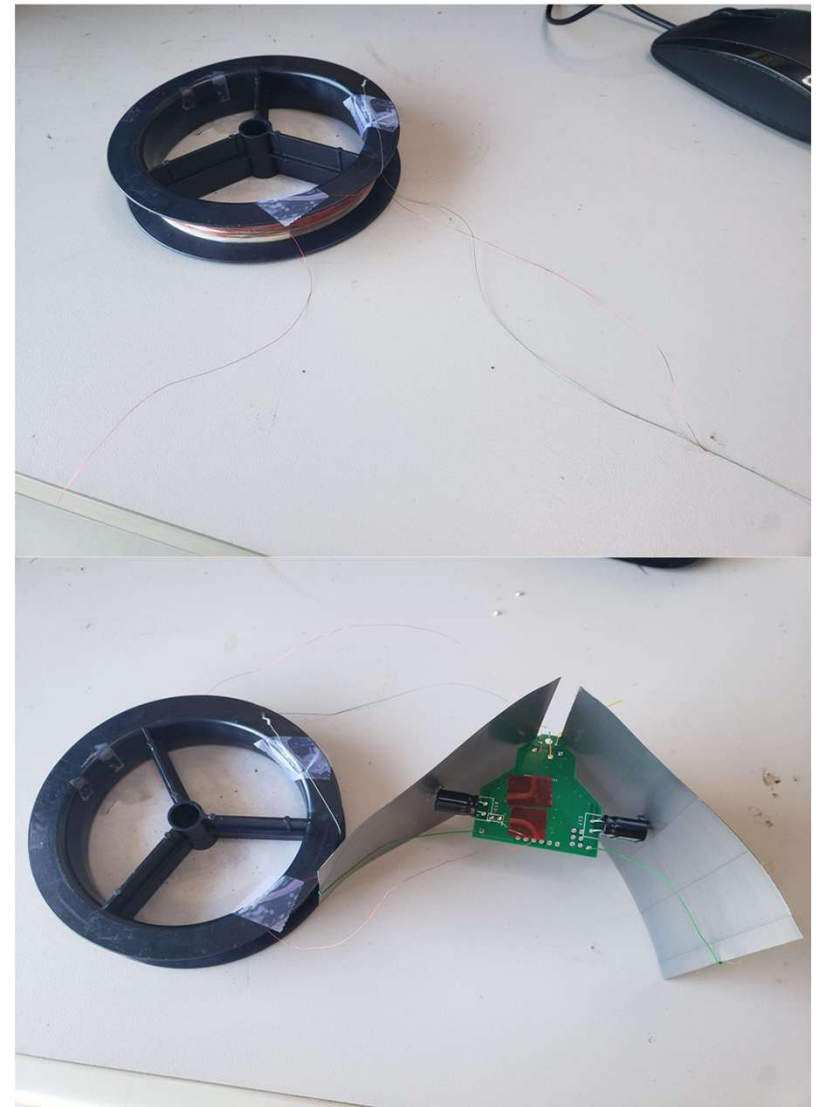
You need to run factory setup to complete the configuration
No user data was found, setting default values
ZachTek WSPR Pico transmitter
Firmware version 1:14
Configuration saved
Configuration saved

Read progress 100% (Re)Read Settings Save Settings

Debug view

Build and Attach HF Antenna

- 20 m Amateur band
 - Half-wave vertical dipole
 - 17.5ft segments of 36 AWG magnet wire
 - One 19ft segment of braided fishing line
- Attach one antenna wire to the braid
 - String lines on the floor or workbench
 - Use glue (E6000) every 3 feet
 - Spool the wires
- Attach to PCB
 - Tie braid and solder wires to the PCB
 - Leave slack in the wire attached to the braid
 - Tape (Tyvek) the wire to the PCB for strength
 - Test transmission with a radio receiver



Balloon Neutral Weight

- Neutral weight for calibrating the balloon lift
- Weigh payload on postage scale (minus spool)
- Balloon neutral weight = payload + free lift
- Add 5 to 8 grams of free lift
 - Less gives greater final altitude
 - More rises faster but could burst
- Various-sized binder clips make good adjustable weights



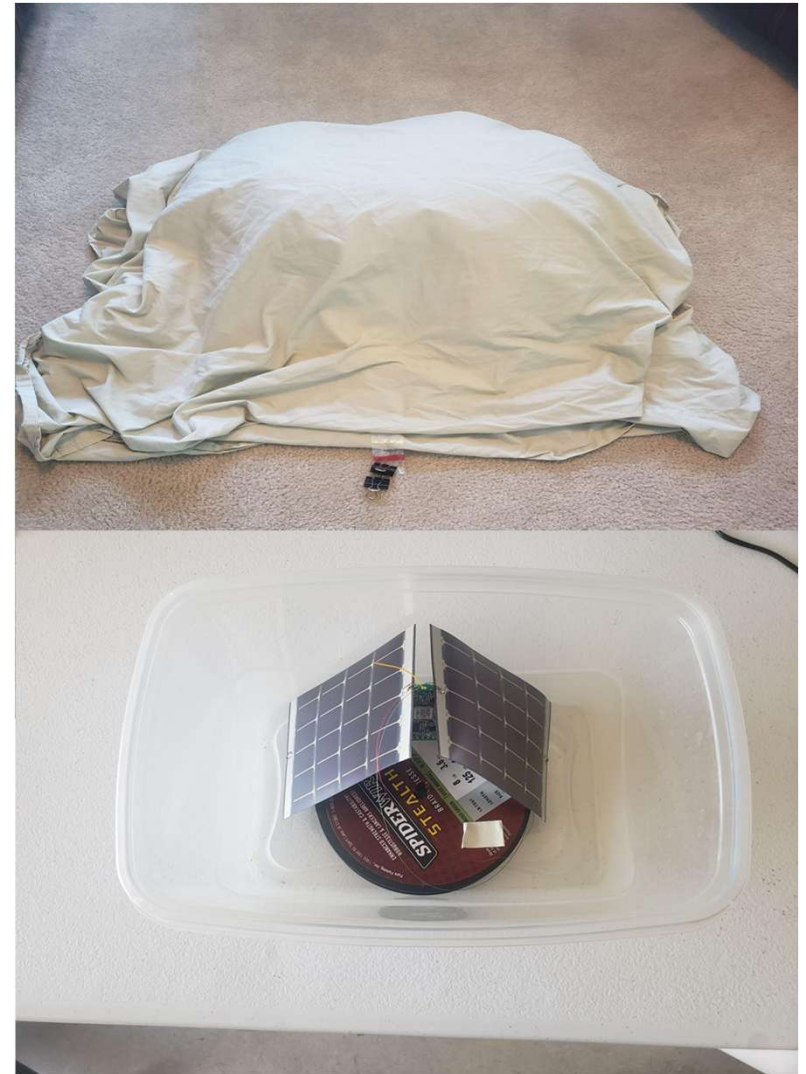
Inflate Balloons Just Before Launch

- Vacuum air from the stretched balloon using an aquarium pump
- Add Hydrogen or Helium until the balloon starts to rise
- Attach a neutral test weight to the fill port
- Inflated balloon + neutral weight should make the balloon hover
- When correctly inflated, seal with glue and/or a heat sealer
- Tie on a piece of braided fishing line
- Reinforce with Tyvek tape
- Attach weights to hold balloons down during transport



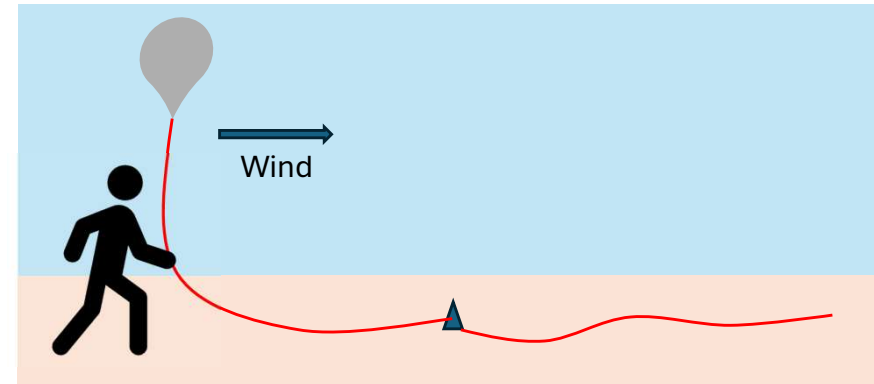
Launch Day

- Conditions
 - No clouds
 - Light winds
- Location
 - Downwind is clear of tall obstacles
 - Clear surface - no plants, sticks, or stones. Blacktop, gravel, or sand is best
- Transport
 - Balloons inside a sheet with weights attached
 - Transmitter with antennas in a box or tub



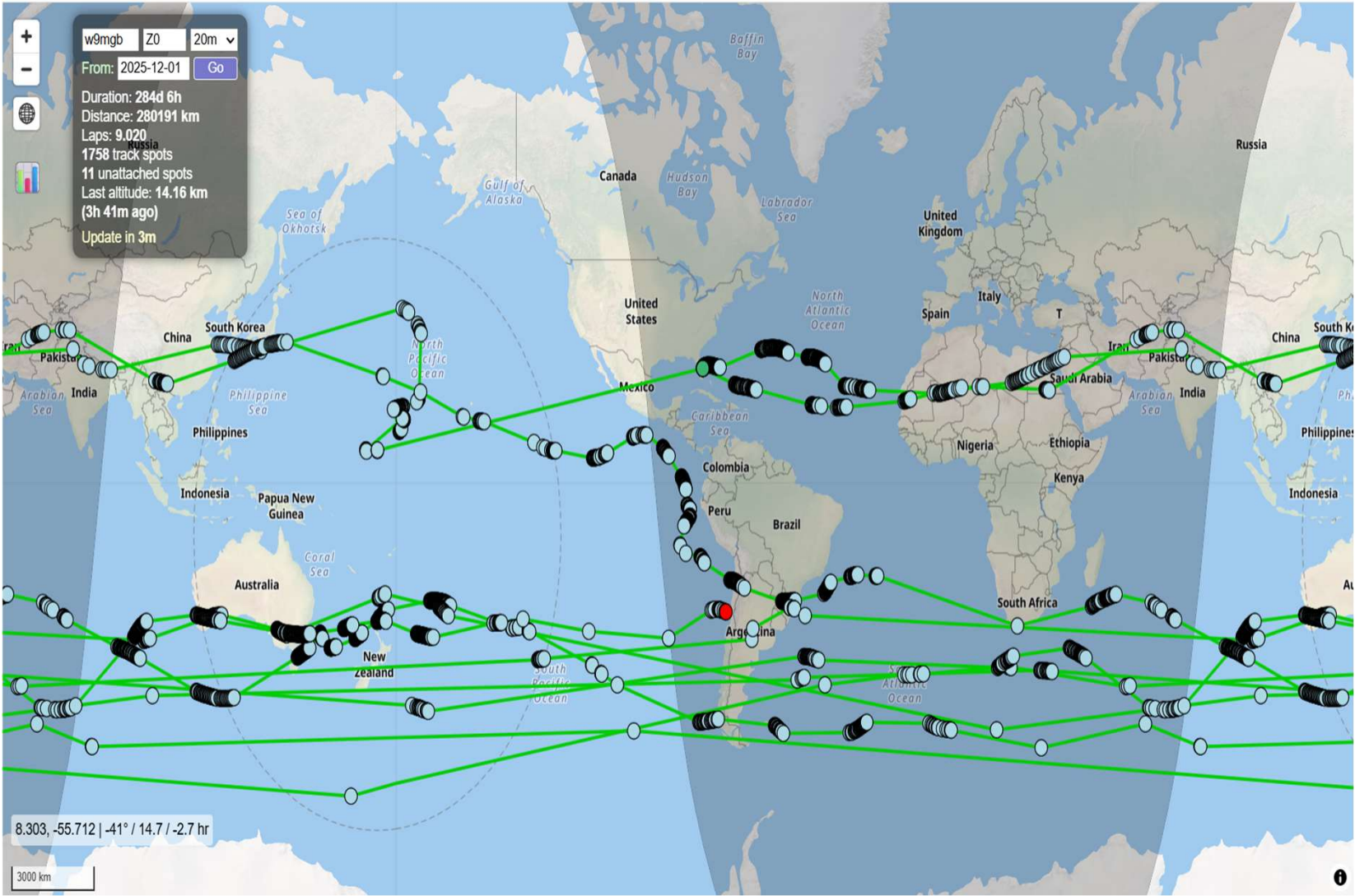
Launching the Balloon

- Lay out the transmitter and antenna
 - Determine wind direction
 - Lay the balloon antenna wire and line upwind
 - Place the sheet containing the balloon at the end of the line
 - Tie the balloon lines together
 - Remove balloon weights
 - Hold the balloon and remove it from the sheet
- Launch at the lowest wind speed
 - Feed line out as you walk toward the transmitter, letting the balloon rise straight up
 - If the balloon is less than 30 degrees from vertical, let go when the transmitter is at head level



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TELEMETRY
VIEWER



BALLOON LAWS

- A few states prohibit releasing balloons
- Almost all have exemptions for single balloons launched for scientific or educational purposes
- Florida is the most restrictive
 - Only government agencies
 - 1600 weather balloons a day
 - Threw out the baby with the bath water



THAT'S

ALL

FOLKS