UniSat Educational Mission: Measurements of Pollution in the Stratosphere with CubeSat and High-Altitude Balloon Flight

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Abstract

UNICEF Satellite (UniSat) is an educational initiative of UNICEF, Tech4Impact and Ministry of Innovative development of the Republic of Uzbekistan to attract more girls and women to STEM and space-related fields. The crew of 20 girls conducted an actual practical project. It took place in Uzbekistan on 8 May 2022. This project aimed to study pollution in the Karmanin region of Navoiy province using CubeSat as an installation for sensors and a high-altitude balloon for lifting it to the stratosphere. Besides, we checked the performance of various sensors at high altitudes and low temperatures. Nanosatellite reached an altitude of about 12 km and collected almost all intended data about pressure, pollution, and humidity during a three-hour flight. We also inspected how these data correlate according to each other. Using the results of this flight, we analyze the air quality in a specific region and propose improvements for subsequent flights. This research paper intends to describe the system design and process of the mission, discuss the data collected and present the main results of the flight.

Keywords— CubeSat, nanosatellite, pollution, high-altitude balloon, altitude, stratosphere, UniSat.

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1 Introduction

CubeSat is the term used for nanosatellite that has a basic unit form of a 10 cm edge cube. It became very popular for its small and simple structure in educational, academic, and research missions [NPE19]. A combination of CubeSat and a high-altitude balloon is usually used before the actual space launch to test all systems and subsystems working correctly under harsh conditions very close to the space ones. CubeSat Design Specification includes all the needed information, specifications, and requirements about it. Our team constructed a nanosatellite ourselves when participating in 10-day-long Al-Farabi Kazakh National University workshops. The guide for the CubeSat first-time builders can be found in Reference [NU17]. We used a nanosatellite to imitate an actual space launch with various sensors. The attached sensors list includes humidity sensor-HDC1080 Low Power[Ins16]; pressure sensor-LPS22HB[ST17a]; accelerometer, gyroscope-LSM6DS3TR-C[ST17b]; PM2.5 and PM10 sensor-SDS011[NFC15];

As an elevatory mechanism, we used a high-altitude balloon filled with helium. It has also become a popular method primarily because of the low cost and the altitude of around 30 km it can reach. Thus, the instruments used (in our case, sensors and batteries) undergo the test with a possible temperature under -40 degrees and low pressure.

Generally, there were two goals of this UniSat project. The first is to allow girls to build their nanosatellite from the very start. The second aimed to measure PM2.5 and PM10 particle pollution in the Karmanin region of Navoiy province. Both of these we successfully achieved and concluded that the air in that region is pretty well. We also analyzed the work of sensors, batteries, and camera under low temperature and pressure conditions. It will significantly help future program launches because the problems faced could be overcome by changing particular parts or insulating them from harmful impacts.

2 Mission Design

The structure of the construction is quite common and straightforward. It consists of the high-altitude balloon, parachute, CubeSat, resistor with nano thread, and camera. You can see the general structure of the mechanism on the Figure 1.

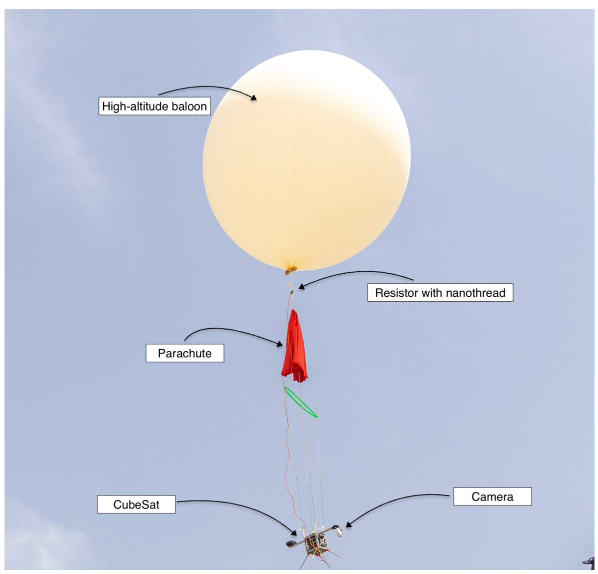

Figure 1: The structure of UniSat in the flight.

A high-altitude balloon plays a key role in the success of the experiment. Generally, it is filled with the appropriate amount of helium to have a safe and stable construction lift. If the amount of helium is insufficient, the construction will get down soon after the launch. Such a balloon can reach the stratosphere at an altitude of up to 40 km, where under the harsh conditions of temperature and pressure, it expands up to a specific maximum size and bursts. In our case, we wanted altitude to be controlled. Thus, we added a resistor with nano thread between the balloon and parachute. When sending a signal of undocking from the ground station at an altitude of around 8 km, the resistor gets hot and melts nano thread which leads the balloon to dump its payload. It starts a free-falling for a while.

Here comes the parachute role that helps the payload land successfully on the Earth. When the parachute becomes fully open, it helps lower the speed of our payload depending on the size of parachute. We used particular round red tissue along with a plastic circle to make it work. It was attached with threads to the satellite.

Our CubeSat construction is very complex. Looking at the Figure 2 on the left is a GPS tracker; on the right is a camera.

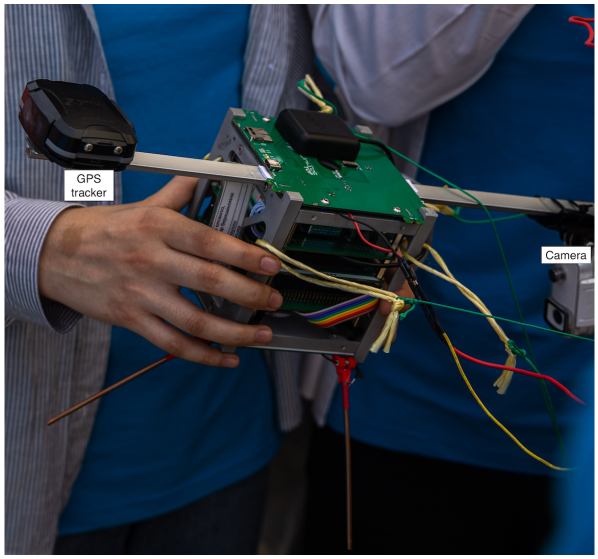

Figure 2: The camera and GPS tracker installed on CubeSat.

Structured parts of CubeSat can be seen in Table 1. In the Figure 3, there are different parts of CubeSat itself. The UniSat Antenna board is mounted at the bottom of the satellite and has four antennas for communication with the Earth. Next comes the UniSat EPS system consisting of four batteries; it provides the power supply for our satellite. UniSat Main Board contains an onboard computer from the ATmega Microcontroller family and other chips and sensors. Next, a separate board for its large dimensions is used for Nova PM sensor SDS011. The last closing board is UniSat Top Board with minor required elements. We constructed the

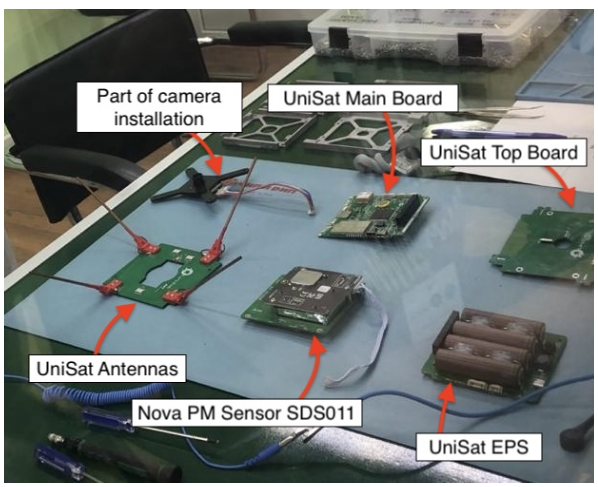

Figure 3: The detailed parts of CubeSat.

CubeSat using the abovementioned parts in the clear room at the Figure 4 that looks like an aquarium with a low dust particle content. This room is not hermetic, but the temperature of it is always kept low, and the pressure - is high, so filtered air is constantly pumped in.

№	From bottom to top
1	UniSat Antenna
2	UniSat EPS
3	UniSat Main Board
4	Nova PM Sensor SDS011
5	UniSat Top Board

Table 1: The table of CubeSat parts.

Figure 4: The clear room.

3 Mission Process and Analysis

3.1 Mission Process

On 8 May, we went to the estimated launch location in the Karmanin region of Navoiy province. The place was chosen for its ecological condition and good landscape for launch. We set up a scientific camp, established a ground station, and started to test all systems and subsystems of our CubeSat.

Our construction was ready to implement its mission when everything was tested and fixed. We launched the CubeSat twice. According to our data analysis, the first launch started at 13:23:31 and ended at 13:24:03. The change in the speed is depicted in the Figure 5.

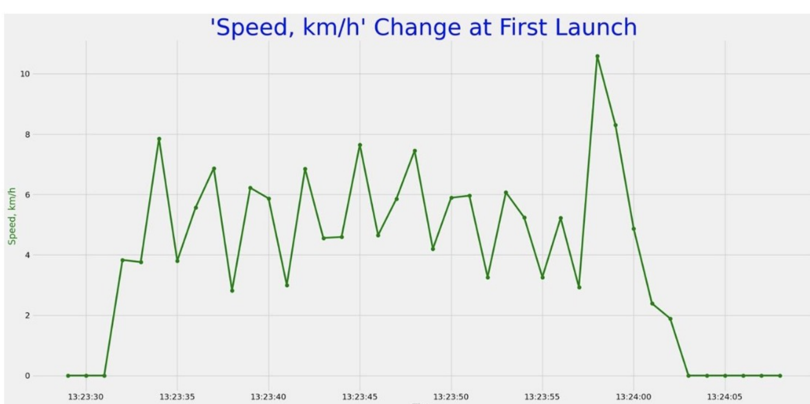

Figure 5: The speed change over first flight.

We failed first time because of our mistake with the balloon, which was not enough filled with helium. After addressing this issue, we again launched our satellite at 13:34:14 successfully this time. At the ground station, our team received data about the location and altitude in hexadecimal format and translated it into meaningful values. The graph off altitude change is on the Figure 6.

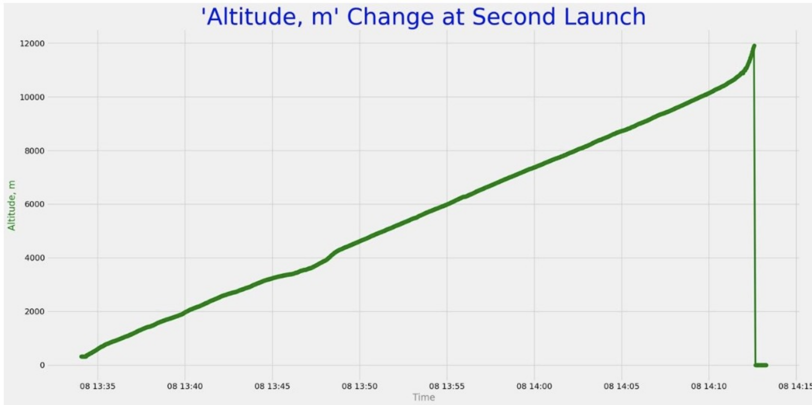

Figure 6: The altitude change over second flight.

When the construction reached the height of 6-7 km, we sent a signal of undocking, but it did not work, and our satellite continued to climb up. At 14:12:35 nanosatellite reached an altitude of 11,914 meters and stopped transmitting signal; we lost a connection with it. As it turned out later, our CubeSat turned off under the external stimuli of temperature and pressure. The search team went to the last received location to find a satellite. Unfortunately, they failed, and we announced to the people of that region that we had lost a satellite. After several days it was found in the Nur-Ota region and transferred to Tashkent. After analyzing the data, we could reconstruct the path of CubeSat in the Figure 7. Adding to this, we also could estimate the time of landing approximately near 15:59:58.

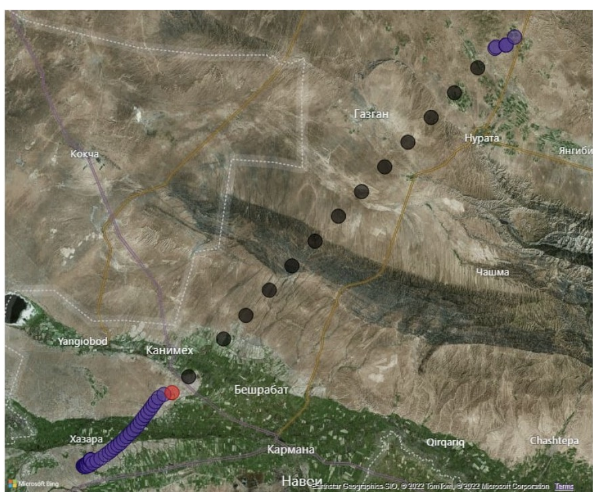

Figure 7: The reconstructed path of CubeSat.

3.2 Data Analysis

Our nanosatellite gathered two types of data: geodata (Figure 8) and sensor values (Figure 9).

We elaborated on the data using the pandas library of the Python programming language. Initially, the data collected from GPS and sensors needed to be merged into one table. Data was stored in an unordered way, so the next thing we did was to sort them according to the time value. As it can be seen from the Figure 10, all data is stored in an object dtype. It should be converted to numerical values for easy analysis and graph visualization.

For the time value, it was the internal time of the nanosatellite and the time stored from the GPS tracker. The internal was stored according to the Almaty region and GPS time according to UTC +0. We believe that

	No	Datetime, dd/mm/yyyy hh:mm:ss	GPS Time, hhmmssddmmyy	Status	Antenna	Longitude	Latitude	Altitude, m	Speed, km/h	Course
57669	2425	'05/08/2022 17:23:46	'112408080522	FIX	OK	65,7290878	40,68353	466.3	0,00	154,4
57670	2426	'05/08/2022 17:23:47	'112409080522	FIX	OK	65,7290878	40,68353	466.4	0,00	154,4
57671	2427	'05/08/2022 17:23:48	'112410080522	FIX	OK	65,7290878	40,68353	466.5	0,00	154,4

Figure 8: The geodata collected.

Datetime, dd/mm/yyyy hh:mm:ss	HDC TEMP, \`C	HDC HUM, %	LPS PRESS, hPa	LPS TEMP, \`C	LSM TEMP, \`C	LSM AX, mg	LSM AY, mg	LSM AZ, mg	LSM GX	LSM GY	LSM GZ	PM2.5	PM10	EXT_TEMP, \`C	BATT, V	VSYS, V
'05/08/2022 15:24:23	-26,0	0	15,6	635,3	-33,2	88,4	-22,9	853,5	420,0	2310,0	-420,0	0,0	0,0	-100,0	2,95	0,01
'05/08/2022 15:24:24	-26,0	0	15,6	635,3	-33,2	88,4	-22,9	853,5	420,0	2310,0	-420,0	0,0	0,0	-100,0	2,86	0,01

Figure 9: The sensors data collected.

```
result.info()

<class 'pandas.core.frame.DataFrame'>
Int64Index: 38040 entries, 0 to 38039
Data columns (total 26 columns):
 #   Column                         Non-Null Count  Dtype
---  ------                         --------------  -----
 0   No                             38040 non-null  int64
 1   Datetime, dd/mm/yyyy hh:mm:ss  38040 non-null  object
 2   GPS Time, hhmmssddmmyy         38040 non-null  object
 3   Status                         38040 non-null  object
 4   Antenna                        38015 non-null  object
 5   Longitude                      38040 non-null  object
 6   Latitude                       38040 non-null  object
 7   Altitude, m                    38040 non-null  float64
 8   Speed, km/h                    38040 non-null  object
 9   Course                         38040 non-null  object
 10  HDC TEMP, `C                   38040 non-null  object
 11  HDC HUM, %                     38040 non-null  int64
 12  LPS PRESS, hPa                 38040 non-null  object
 13  LPS TEMP, `C                   38040 non-null  object
 14  LSM TEMP, `C                   38040 non-null  object
 15  LSM AX, mg                     38040 non-null  object
 16  LSM AY, mg                     38040 non-null  object
 17  LSM AZ, mg                     38040 non-null  object
 18  LSM GX                         38040 non-null  object
 19  LSM GY                         38040 non-null  object
 20  LSM GZ                         38040 non-null  object
 21  PM2.5                          38040 non-null  object
 22  PM10                           38040 non-null  object
 23  EXT_TEMP, `C                   38040 non-null  object
 24  BATT, V                        38040 non-null  object
 25  VSYS, V                        38040 non-null  object
dtypes: float64(1), int64(2), object(23)
memory usage: 7.8+ MB
```

Figure 10: The data collected.

data obtained from the GPS tracker is more precise than the satellite; thus, we converted it to the Tashkent timezone UTC +5. Some empty fields needed to be deleted from the table entirely. Next, we segregated data at the flight's date and time to simplify the analysis. Later, we noticed that sensor "EXT_TEMP, 'C" was not installed in our construction because it showed -100 all the time. In clearing the data, we understood that sensors started to show abnormal values at some point. We had proposed several possible causes, but the most realistic one is connected with the temperature over a certain height. What we did was look through the documentation of the sensors and find their working temperature ranges. Thus, here is the list:

- LPS: pressure and temperature sensors from -40 to +85 degrees Celsius.
- HDC: temperature sensor -40 to +125 degrees Celsius.
- HDC: humidity sensor from -20 to +70 degrees Celsius.
- LSM: accelerometer and gyroscope from -40 to +85 degrees Celsius.
- PM: pollution sensors from -10 to +50 degrees Celsius.

This should be considered in the future analysis because sensors give unstable values outside these borders. First, we wanted to compare values from three temperature sensors in the Figure 11. We observed that the LPS sensor reaching the height with the temperature of 0 degrees started to give abnormal values; thus, we decided to rely on the LSM temperature sensor for future analysis. Let us visualize the values of each sensor:

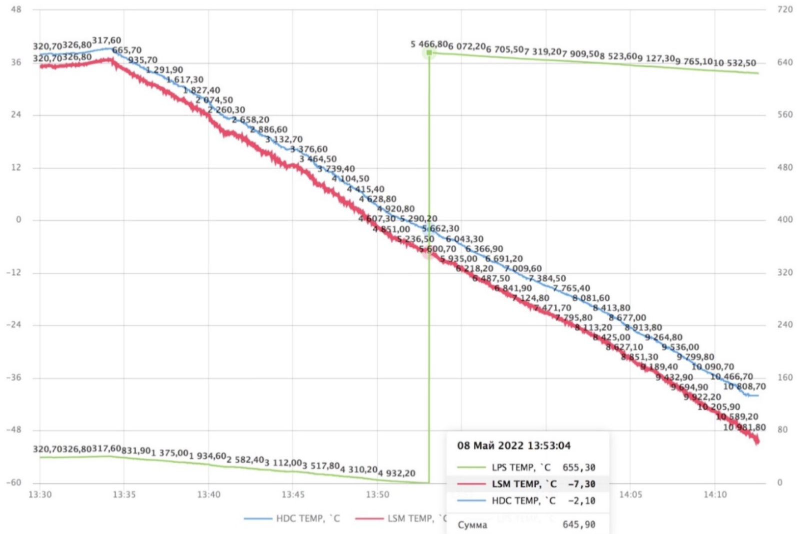

Figure 11: Values of three temperature sensors.

3.2.1 Atmospheric pressure sensor

In the Figure 12, there is LPS sensor values change over time. In this case, we used a color division to show

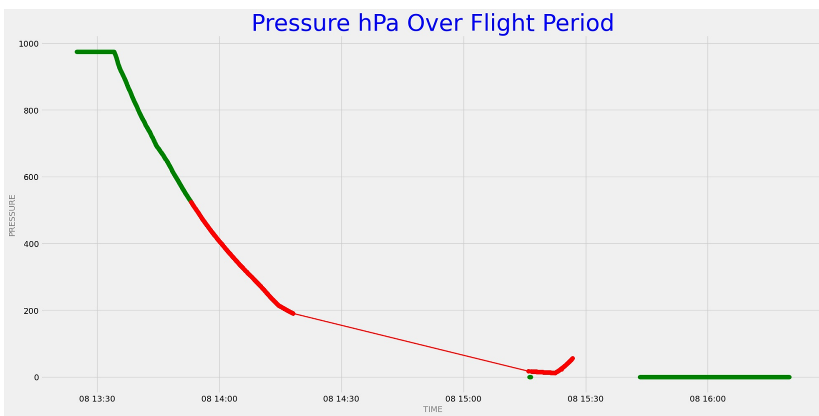

Figure 12: Pressure change over time.

the abnormal temperature - red; and normal temperature - green. For this sensor, we used its temperature sensor, which, after 0 degrees, stopped working correctly; thus lower temperature limit is 0 degrees. Normal atmospheric pressure is 1013,25 hPa, and as we see at the launch, it was close to 1000 hPa. With the increase in altitude, the pressure goes down in the Figure 13. As seen on this graph, the pressure equals zero in the second half of the flight (with a parachute). That happened because after recovering, the pressure sensor broke down. We assume that because of pressure drops, a specific membrane inside this sensor could burst and tank the work of the sensor.

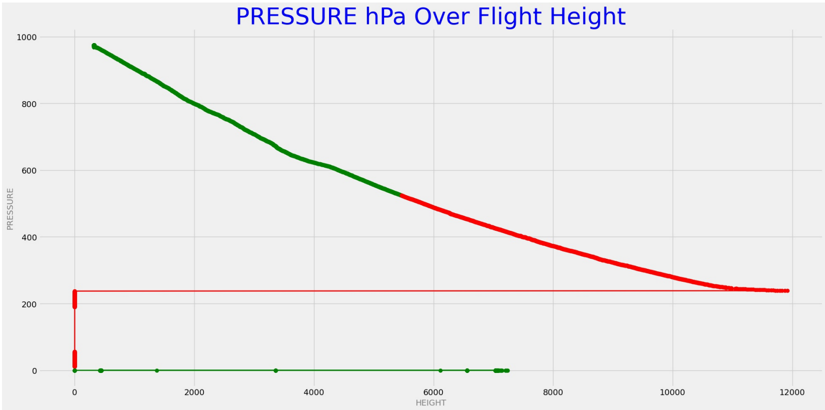

Figure 13: Pressure change over height.

3.2.2 Humidity sensor

We can notice how the humidity changed over time in the Figure 14. We should consider that this humidity

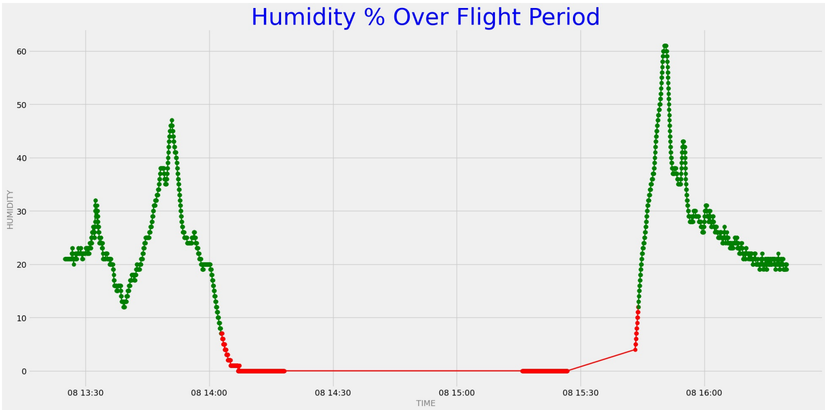

Figure 14: Humidity change over time.

is taken at different altitudes and over different regions. We can conclude from the Figure 15, where we see humidity change over the first half of the flight over height, that there is maximum humidity at the altitude of 5 km. This is connected with the possible clouds occurring at this height, like Altostratus and Nimbostratus,

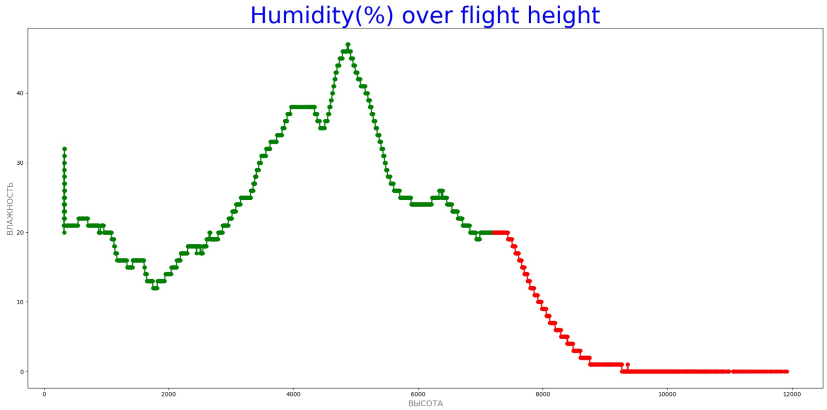

Figure 15: Humidity change over height.

which can bring rain and snow.

3.2.3 Pollution sensors PM2.5

This sensor is the most vulnerable to the temperature because its lower limit is only -10 degrees. So we can see that the graph starts to show abnormal values in the middle of the Figure 16, noted in red. The norm of

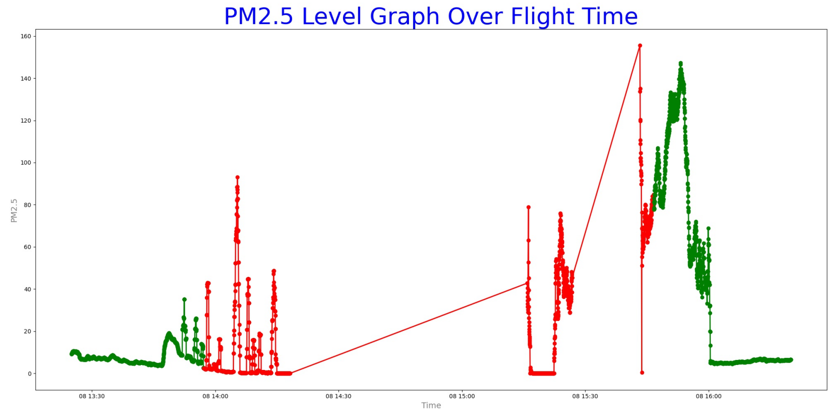

Figure 16: PM2.5 level change over time.

PM2.5 fine suspended particulates is 25 micro-grams per cubic meter, according to WHO. In the Figure 17, we can see that a significant part of the values is within normal parameters under an altitude of 7 km. According

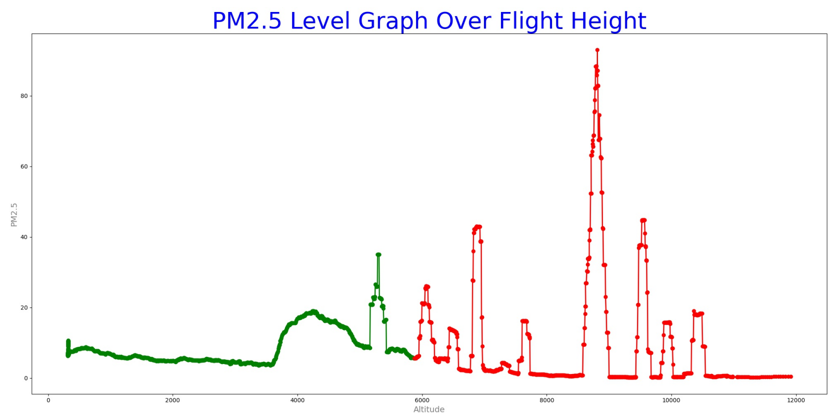

Figure 17: PM2.5 level change over height.

to the European air quality index, we have 1 grade(Very good) within 1 km height with an average value of 7.30 micro-grams per cubic meter.

3.2.4 Pollution sensors PM10

The values of PM10, similar to PM2.5, are skewed by low temperature 18. The norm of PM10 fine suspended particulates is 50 micro-grams per cubic meter, according to WHO. In the Figure 19, we can see that a significant part of the values is within normal parameters under an altitude of 7 km. According to the European air quality index, we have 2 grade (Good) within 1 km height with an average value of 29.82 micro-grams per cubic meter.

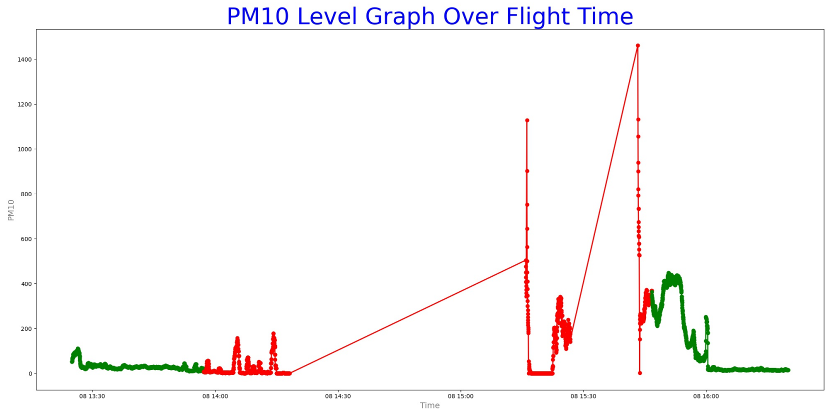

Figure 18: PM10 level change over height.

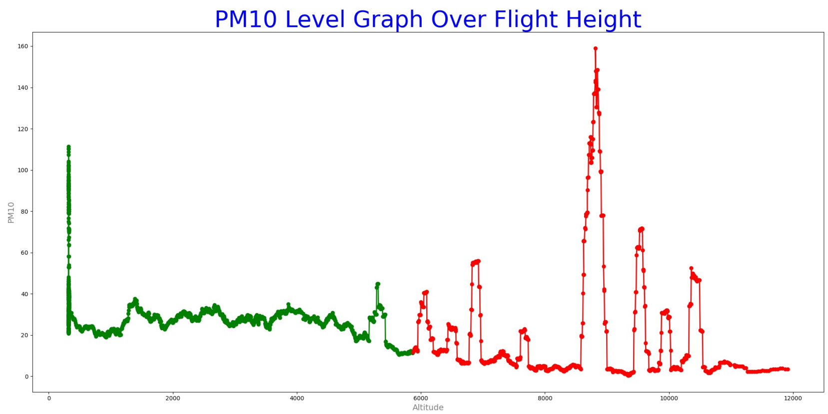

Figure 19: PM10 level change over height.

3.2.5 Accelerometer and Gyroscope

An accelerometer helps to fully understand the direction and the magnitude of the object's acceleration regarding Earth (Figure 20). A gyroscope measures the angular velocity of the object. In our case, we have

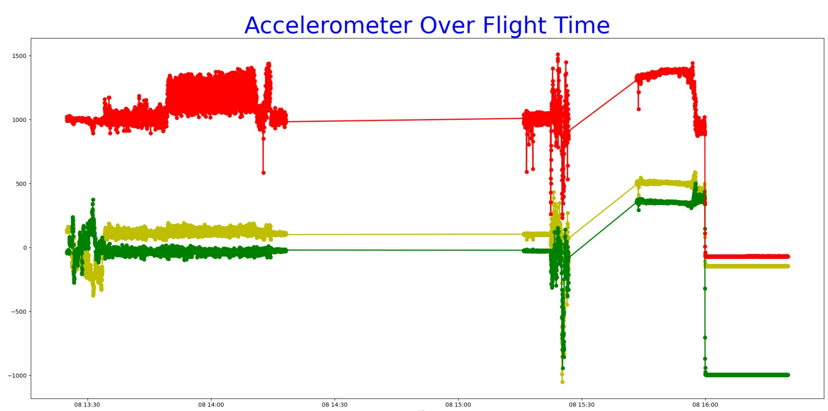

Figure 20: Accelerometer values change over time.

analyzed the possible landing time of our CubeSat based on both values. For example, when all three values of the gyroscope become 0, the object is in a dormant state. Thus as seen in the Figure 21, at around 16:00, our CubeSat landed. When the CubeSat recovered in the second half of the flight, it was flighting with the parachute and thus fluctuated a lot.

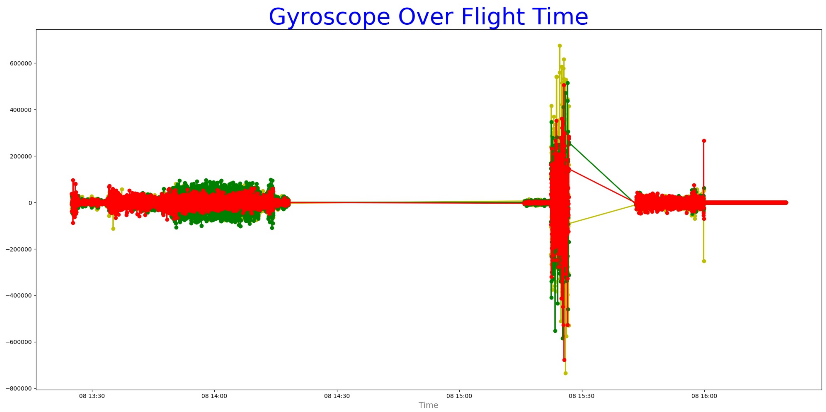

Figure 21: Gyroscope values change over time.

3.2.6 Battery power and voltage

Battery power and voltage The normal battery temperature range, usually at a lower limit, is -20 degrees. Considering this, we constructed a graph and noticed that temperature significantly influences these indicators. When returning to normal temperatures, the power of CubeSat batteries recovers in the Figure 22.

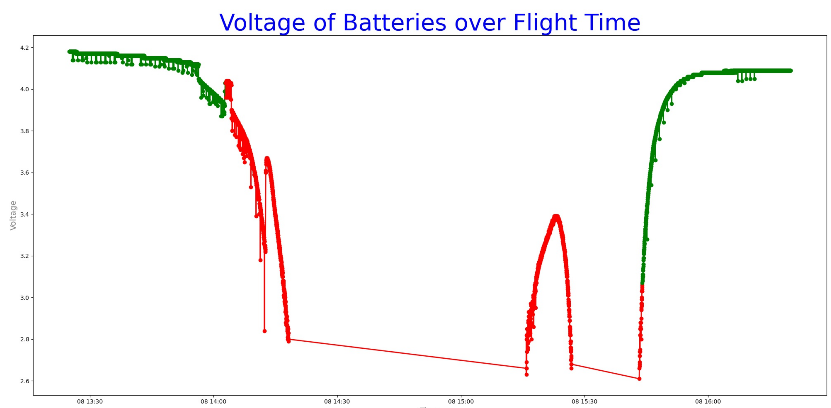

Figure 22: Voltage change over time.

3.3 Experiment with atmospheric pressure and altitude

We decided to conduct a small experiment with obtained data. From the physics course, we all know that pressure depends on the object's altitude over Earth. Because we have altitude data from the GPS tracker and pressure from the LPS sensor, we calculated height alternatively. Doing this, we compared it to the actual altitude to prove the validity of our data.

The air weighs approximately 1,229 kg on a cubic meter at standard temperature and pressure. The weight of the air in the column of air creates atmospheric pressure. That is why pressure goes down as we climb up to the mountain: the higher you climb, the less air is above you. At sea level upon ascent to 10.5 meters, pressure changes to around 1mm or more precisely according to the following expression

$$h - h_0 = 18400 \log \frac{p_0}{p}(1 + \frac{t}{273})$$

Using it, data was filtered, so no parameter equals zero. We constructed the Figure 23 to show the deviation of the calculated altitude from the actual altitude of GPS. The higher the altitude, the higher the deviation. This may be connected with minor errors in sensor accuracy.The Figure 24 shows the deviation in percentage over the height.

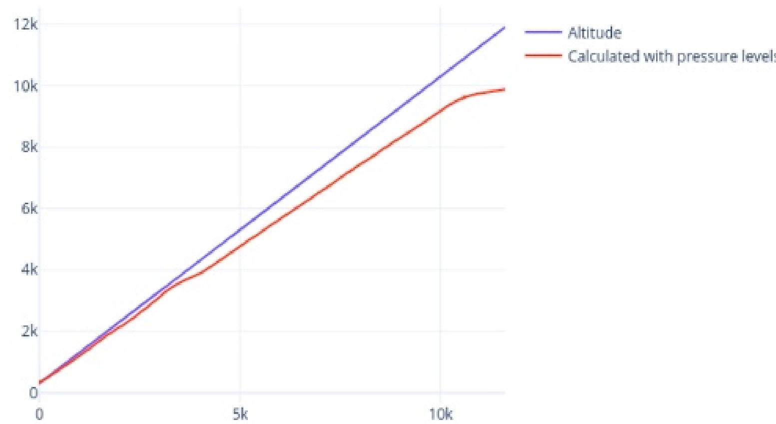

Figure 23: Comparison of altitudes: calculated and measured by GPS.

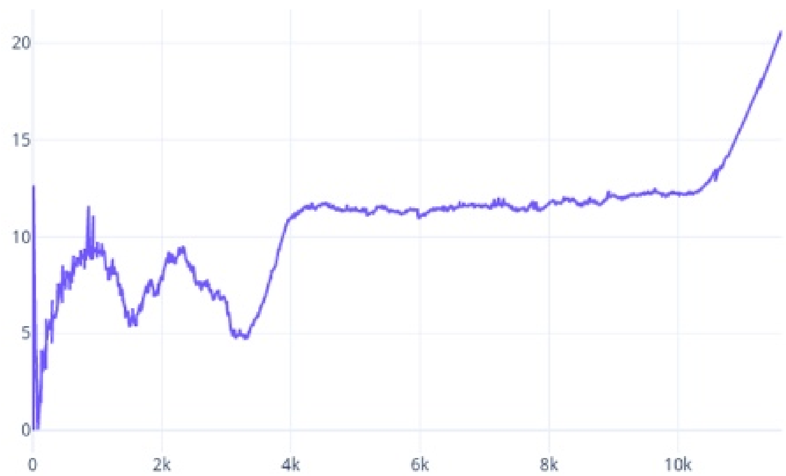

Figure 24: The deviation in percentage over the height.

4 Conclusion

This paper discussed the main observations noticed when achieving specific goals. We can conclude that the air quality in the Karmanin region of Navoiy province is good, with average pollution in the allowed range. We analyzed the work of several sensors in conditions close to the stratospheric ones and now know that some of them should be replaced by others less vulnerable to the temperature or should be insulated with other materials. The results of this paper were presented at the closing ceremony of the UniSat project to the representatives of UNICEF, the US Embassy, and other international organizations; all girls were awarded certificates of participation.

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