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A LOW-COST, SUSTAINABLE ALTERNATIVE TO SATELLITES: THE CASE FOR HIGH-ALTITUDE BALLOONS

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Abstract
"In today's rapidly evolving world, space exploration remains one of the most intriguing yet most expensive domains we humans have expanded. Traditional satellites cost billions of dollars, whereas high-altitude balloons can achieve the same results at just 1.5% of that cost, with net-zero carbon production and 0% space junk. In this study, we have simulated a high-altitude balloon under suitable conditions using NOAA HYSPLIT and MATLAB software. We have also compared the cost with Geostationary Operational Environmental Satellite - R Series (GOES-R), a geostationary satellite that functions in Geostationary Earth orbit (GEO). This study aims to reduce orbital congestion, as we have seen that there are more than 6,000 tons of space debris in Low Earth orbit (LEO). For developing countries that cannot afford satellite development, High-Altitude Balloon (HAB) networks can be designed to carry out scientific research. This research ultimately aims to enable scientific discoveries at the cheapest cost."

1. INTRODUCTION

If we go sixty-seven years before this year then on Oct. 4, 1957, we humans finally unlocked the space world and transformed the human race beyond the horizon, when the Soviet Union launched Sputnik the first artificial satellite launched into space [1], and then we humans touched the Earth's Natural satellite, the Moon, since then more than five-thousand launches have occurred into the space and approximately 40 thousand objects are in space [2]. For space exploration tons of money is being used like NASA whose budget for the year 2025 is 25.4 billion dollars [3], this shows us that space exploration is expensive and the truth is it is, the things we have achieved due to the investment in space technology is resourceful like the Google maps navigation system or the climate change, hurricane, solar coronal mass ejection, solar radiation detection by National Oceanic and Atmospheric Administration (NOAA) [4], but also there are some countries whose Gross Domestic Product (GDP) is less than NASA yearly budget like Albania whose GDP is $ 23.5 billion or Afghanistan with $17.23 billion according to 2023 World bank report [5], this shows us two things that space exploration is critical that is why countries our investing so much but at the same time some countries who
can not afford it what should do, for that we need to find a solution and for that, our High Altitude air balloon are the answer.

This paper focused on how to make aerospace research feasible for everyone and also how to find Satellite alternatives most cheaply and promote the green aerospace idea with zero space junk projects, currently, there are 6000 tons of space debris in LEO which is a huge threat to future space missions [6] like the Iridium-Cosmos collision in 2009 have made this issue urgent as we see approximately 70% increment in space congestion [7], as in 2024 a piece of space garbage passes through the International space station (ISI) if the Russian space-craft did not fire for five-minutes then that shard could have passed with the distance of 4-kilometers [8] which could destroy the ISI in few moments which is the worst scenario, So we have to find an alternative and for that, the High Altitude Air Balloon is our best alternative as it is the cheapest and environmentally friendly and promotes zero-percent space junk idea.

These balloons can do everything that the satellites can do like measuring the weather data like the NASA GOES satellite network it can also serve for surveillance purposes and telecommunication purposes [9], Due to this high-altitude air balloon system we will be able to make developing countries to launch their own missions like GOES has the coverage of the whole North-South American continent and also some parts Africa and also the cost for GOES mission is about $11,700.1 million from FY2001 to FY2036 [10], but what about the other half of the world for that HABs are a low-cost alternative for just 1.5% of a satellite cost, hence this paper main objective is to make space research cheaper and accessible.

In order to achieve this we are going to design a theoretical model for our balloon it will be an alternative to a satellite here we are considering the (GOES-R) satellite, in our design the balloon can harness solar power for 12 hours and some other parameters like wind speed is considered to be constant for convenience of balloon simulation, we have also not restricted our balloon for better coverage of area as we want the maximum area to be cover as we are working for the satellite alternative this scientific balloon can utilize solar energy and achieve SDG-7 also due to high altitude balloon we are also achieving SDG-1 that is no poverty means if we save the cost on space missions we can utilize it on the development of the people, moreover we will include a lithium-ion battery in the payload so that it could function 24-hours [11], it will also have a parachute due to which we can get the payload back in the 100km of the launch radius [12], due to which we promote the recycling and we can reuse the payload for future HABs launch making it sustainable, the approach that we are following consists of the balloon design, the solar model and the comparative-cost analysis of High altitude air balloon with GOES-R satellite. .

2. Balloon design

In order to design our High altitude air balloon we have taken a theoretical approach in which we have utilize existing research paper data and then utilizing the NOAA HYSPLIT software through this we were able to create a trajectory for the high altitude air balloon and understand how we can control and how much area it covers, so we are following the model developed by the Chinese researchers [11] in it our scientific balloon can go up to 30 km and can stay up-to fifty days [13] but in some scenario can go up-to 37 km and can stay for fifty-seven days [14], we are considering two launch location first the Alaska Fairbanks USA and also the University of Mississippi in USA, the reason is that Alaska is actually a site that is used for launching scientific balloons in space by NASA [14] that is why we are using it to simulate our first path of balloon to see how it will propagate in space, Alaska Fairbanks relative wind speed is very low and also variation is negligible so we have considered the wind speed throughout to be 15m/s, and for our second location that is Mississippi we have selected that
location because this region in covered by GOES-R so we wanted to launch the balloon from a place that can actually replace the satellite.

In order to stabilize the balloon in one respective area we can use the wind data in this Chinese research paper [11], they have developed model ACS altitude control system, whose main goal is to study wind patterns and change the course of the high altitude balloon, in the balloon design we have a helium balloon and due to the buoyancy effect our balloon ascends in the sky as helium is

lighter than air, ballonet that is filled with air that is connected with a pump and valve through this mechanism we can control the amount air inside the ballonet through which we can control the ascend and descend of the balloon and through which we can propagate our balloon according to the wind pattern if the upper layer wind is more so we pump in air so our balloon gets heavy and it descends and vice versa, but here in our research paper we are going to use these weather pattern to propagate our high altitude balloon for longer distances through which they can cover the maximum area because we are developing an alternative to satellite , in it we have used the NOAA HYSPLIT software to conduct the trajectory analysis our HAB both in Alaska Fairbanks and also Mississippi.

As again we are developing an alternative to the Geo stationary satellite GOES-16 the high-altitude air balloon payload will include solar panels and a battery to be self-efficient and harness clean energy, and the payload will have the following sensors similar to the one that GOES-16 has, that is the Advanced Baseline Imager (ABI), the Extreme Ultraviolet and X-ray Irradiance Sensors (EXIS), which includes an Extreme Ultraviolet Sensor (EUVS), X-Ray Sensor (XRS), EUVS/XRS Electrical Box (EXEB), Sun Positioning Sensor (SPS), Geostationary Lightning Mapper (GLM), Magnetometer (MAG), Space Environment In-Situ Suite (SEISS), which includes an Energetic Heavy Ion Sensor (EHIS), Solar Ultraviolet Imager (SUVI), and Data Processing Unit (DPU) all of these sensors will on the payload along with that a parachute and also the pump and exhaust valve with additional thrusters if needed.

Here the payload will have all the sensors that any satellite has as the consumption of the sensor is very low and can be under 400 watts, whereas the ACS will take around 350 watts [11], so here we have selected laminated latex as the material due to its property to work in high internal pressure, it at the ground level will have a volume of 50 m^3 and in space it can reach up to 5065 m^3 except that the balloon can handle the payload of 2000lb easily so all the sensors and solar panel can be carried easily also we will indulge a parachute [15] so when the balloon burst after 50-days, and after the bursting, we can recover the payload due to the parachute, and then we can reuse the payload for our mission by just integrating the latex balloon and parachute for just 10% of the whole HAB project and do countless mission, hence we are achieving our goal of sustainable low cost space exploration.

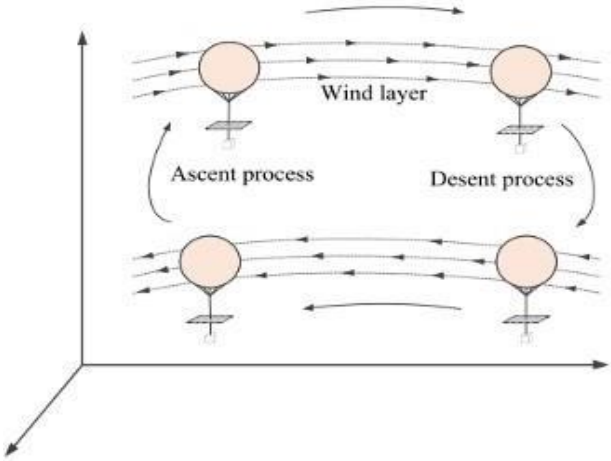


Fig. 1. Schematic of the station-keeping mechanism of the balloon.

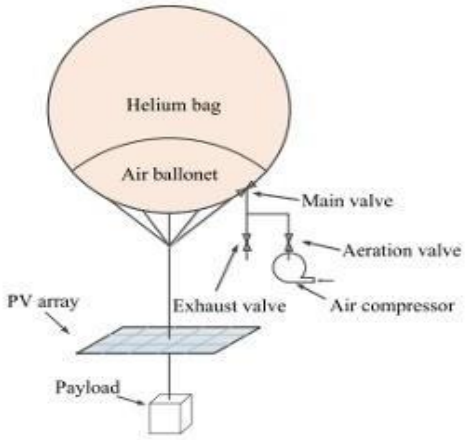


Fig. 2. Sketch of the altitude adjustment mechanism of the balloon.

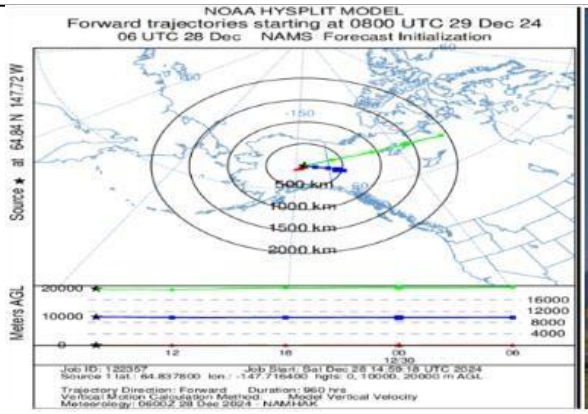


Fig. 3a. Depicts Trajectory model.



Fig. 4a. Real life image of high altitude balloon.

So from the above-generated trajectory model, we understood that the high altitude air balloon will propagate and it is going up to 200km forward from Fairbanks Alaska USA, to Canada this shows us that these HABs can be an alternative to the satellite as they can also propagate to longer distance providing us with longer coverage, whereas we have this real life image of high altitude balloon which showcase the balloon at ground level and also the payload with it.

3. Solar Harvesting Model

Now, here we will be finding solar power production and how it is utilized by our High Altitude air balloon. For that first, we find the solar power harness by the solar panel, the power generated by a solar panel is given by:

$P_{solar} = A \times I \times \eta$

Where,

- A = Solar panel area (m) = 1.5 m^2
- I = Solar irradiance (W/m) = 800 W/m^2
- η = Solar panel efficiency = 0.20

$Psolar, HAB = 1.5 \times 800 \times 0.20 = 240W$

For 12 daylight hours:

$Eday, HAB = Psolar, HAB \times 12 = 240 \times 12 = 2880Wh$ $(2.88kWh)$

Now, for the GOES-R satellite solar power model:

- A= 5 m^2
- I= 1361 W/m^2
- η= 0.28

$Psolar, GOES = 5 \times 1361 \times 0.28 = 1905W$

For 12 daylight hours:

$Eday, GOES = 1905 \times 12 = 22860Wh$ $(22.86kWh)$

HAB Power Consumption:

- Payload Power = 50 W
- Station-Keeping Power (Altitude Control) = 54 W
- Daily station-keeping energy: 1296 Wh

Total Power Consumption per Hour

$Ptotal, HAB = 50 + 54 = 104W$

Total Energy in 24 Hours: Etotal,HAB=104×24=2496Wh (2.5kWh)

GOES-R satellite power consumption:

Payload Power = 400 W

Station-Keeping Power = 350 W Total Power Consumption per Hour:

Ptotal, GOES = 400 + 350 = 750W

Total Energy in 24 Hours:

Etotal, GOES=750×24=18000Wh (18kWh)

HAB Battery Storage Nighttime demand:

Enight, HAB = Ptotal, HAB × 12 = 104 × 12 = 1248Wh

Battery efficiency = 85% (η charging = 0.85)

Sbattery, HAB = 0.851248 = 1469Wh

Chosen Battery: 2577 Wh, enough for night operation. GOES-R Battery Storage:

Nighttime demand:

Enight, GOES = Ptotal, GOES × 12 = 750 × 12 = 9000Wh

Battery efficiency = 90% (η charging = 0.90)

Required battery capacity:

Sbattery, GOES = 0.909000 = 10000Wh

Chosen Battery: 51000 Wh, more than enough.

Hence, we can conclude that our high-altitude air balloon can replace the GOES-R satellite in the technical department as it is able to produce

enough power, to perform all actions that a GOES-R satellite can perform.

Table 1 Power consumption comparative analysis.

PARAMETER	HAB	GOES-R
Solar Panel Area (m')	1.5	5
Solar Panel Efficiency	20%	28%
Solar lrradiance (W/m')	800	1361
Total Energy in 12 Hours (Wh)	2880	22860
Solar Power Generation (W)	240	1905
Payload Power (W)	50	400
Station-Keeping Power (W)	54	350
Total Power Consumption (W)	104	750
Total Daily Energy Need (Wh)	2496	18000
Night Battery Requirement (Wh)	1248	9000
Actual Battery Capacity (Wh)	2877	51000

It is evident from the above table that the High altitude balloon has the potential to carry space mission at a much lower power consumption level.

Table 2 High-Altitude Balloon Payload Table GOES-R.

Payload Type	**GOES-R Equivalent Sensor**	**Purpose**	**Proposed HAB Instruments**
Imaging System	Advanced Baseline Imager (ABI)	Earth observation, monitoring atmospheric conditions	Raspberry Pi Camera, IR Sensors
Solar Irradiance Monitoring	EXIS (EUVS + XRS), EXEB, SPS	Monitoring extreme ultraviolet and X-ray solar activity	Mini solar radiation sensors, X-ray photodiodes, sun trackers
Lightning Detection	Geostationary Lightning Mapper (GLM)	Detection and mapping of lightning activity	Optical lightning sensor modules
Magnetic Field Sensing	Magnetometer (MAG)	Monitoring geomagnetic field variations	Miniature 3-axis magnetometers
Space Weather Monitoring	SEISS (incl. EHIS)	Monitoring of charged particles and solar radiation	Radiation counters, Geiger-Müller tubes
Solar Observation	Solar Ultraviolet Imager (SUVI)	Capturing full-disk solar images in the ultraviolet spectrum	UV-sensitive miniature imaging sensor

The table 2 showcases us that we can use different kind of sensors as our payloads to perform different kind of operation according to our need, also HABs can carry all the instrument as it can handle up-to 2000 pounds according to NASA scientific balloon missions data, but even NASA carries specific high altitude air balloon projects therefore we can perform two or three operations simultaneously by the use of high altitude balloons.

	FY 2024 & Prior	FY 2025	FY 2026	FY 2027	FY 2028	FY 2029	CTC	Total LCC
GOES-R	**10,423.5**	**134.8**	**129.9**	**129.9**	**129.9**	**129.9**	**622.1**	**11,700.1**
Development	**9,294.3**	**17.8**	-	-	-	-	-	**9,312.1**
Flight	5,892.0	0.3	-	-	-	-	-	5,892.2
Instruments	2,088.7	-	-	-	-	-	-	2,088.7
Spacecraft	2,045.6	-	-	-	-	-	-	2,045.6
Launch Services	791.2	-	-	-	-	-	-	791.2
Other	966.5	0.3	-	-	-	-	-	966.8
Ground	1,869.6	-	-	-	-	-	-	1,869.6
Program Support	1,532.8	17.5	-	-	-	-	-	1,550.3
Operations, Maintenance, Sustainment**	**1,129.3**	**117.0**	**129.9**	**129.9**	**129.9**	**129.9**	**622.1**	**2,388.0**
Operations and Maintenance	271.2	40.9	40.9	40.9	40.9	40.9	286.3	762.0
Sustainment	858.1	76.1	89.0	89.0	89.0	89.0	335.8	1,626.0

Fig. 4. Shows the budget of GOES-program.

4. Comparative Analysis Satellite and HAB system

To perform the comparative cost analysis we should first see how much the GOES-satellites program costs.

According to this report, we can understand that the NOAA has spent around $11,700 million, until now out of which approximately $400 million to $1.5 million is spent on GOES-16 only, as this budget also includes GOES-14, GOES-15, GOES-17, GOES-18, and GOES-19, hence we can understand that how much money is invested in space research whereas, if we see a lowest level High altitude balloon then t can be made at $1000 [16], for this we are considering an actual experiment conducted by University students was a high altitude air balloon which just costed$1000 it is not a replacement for GOES-16, but still this balloon experiment performed perfectly with a variety of instrument located on it shows that we do not need rockets or heavy equipment and with less, we can accomplish greater tasks, hence from this experiment it validates us that we can make an alternative to GOES-16 satellite by using the exact equipment and increasing the budget to some greater extent.

Part	Function	Cost
Arduino mega	Microcontroller	$40
microSD card (16 GB)	Data storage	$10
Razor 9DOF	Inertial measurement unit	$75
GPS	Navigation	$50
GPS antenna	Antenna	$15
Spot tracker	Back-up tracker	$75
MicroTrak	APRS tacker/radio	$250
Connectors/cables	Misc	$20
Parachute	Impact reduction	$15
Subtotal	(One time cost)	$550
Balloon	Lifting vehicle	$90
Helium	Lifting gas	$200
$LiSO_2$ batteries (x4)	Power	$70
Total		<$1000

Fig. 5. Arduino Megaproject cost breakdown, from Avionics and Power Management paper.

4.1 Development and Launch Costs

- Single HAB production: $40,000
- Launch and deployment cost: $5,000-$15,000.
- Total cost per HAB:50,000.

4.2 Operational Costs

- Single HAB lifespan: 50 days.
- Total HABs needed over 10 year

NHAB=Single HAB Lifetime (50 days) Satellite Lifetime (10 years)=503650≈73. CHAB=73× 50,000=3.65 million USD

The whole GOES program can cost up to $11.7 billion, a GOES satellite can work for 10 years including orbital storage time hence we are replacing it with one HAB $3.65 million USD I order to make data continuous we will have three-HABs model so two in space at time, so we will have $10.95 million which is 0.73% of GOES-R satellite.

Table 3 High altitude air balloon cost analytics.

Components	Cost Estimate
High-Altitude Balloon (HAB) Material	$500 - $2,000
Solar Panels (300W, 1.Sm^2, 20% efficiency)	$750 - $966
Battery Storage (2.577 kWh Li-ion Battery)	$2,574
Electronics & Payload (Sensors, GPS, Comms)	$5,000 - $20,000
Helium or Hydrogen Gas for Lift	$500 - $2,000
Ground Station Setup	$5,000 - $15,000
Total Estimated HAB Cost	$10,000 - $40,000

Hence, by the above calculations, we can interpret that High altitude air balloon system can be a low-cost alternative to GOES satellites.

5. Results and discussion

Now, we are going to discuss the results that we have calibrated, in this study we have extensively used the publicly available data and research papers, we also used the NOAA HYSPLIT software for trajectory, and MATLAB for analyzing solar model, here first we interpreted the result of NOAA HYSPLIT software, due to this

program we are able to calculate the actual trajectory of the HAB if it is launch from that particular site.

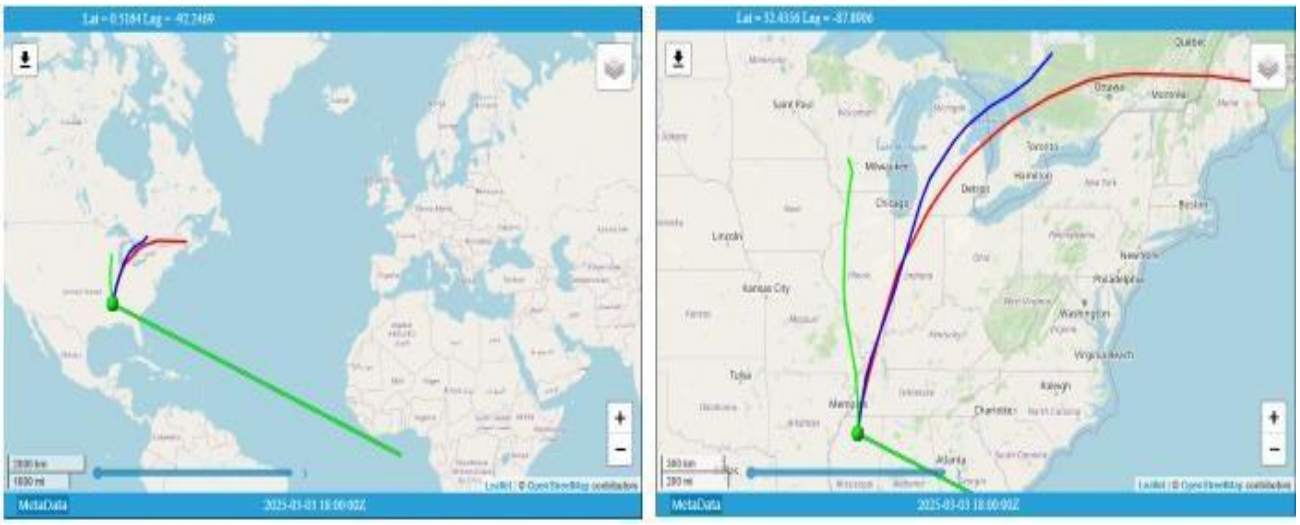


Fig. 6. Trajectory of High altitude balloon at Mississippi at different altitudes.

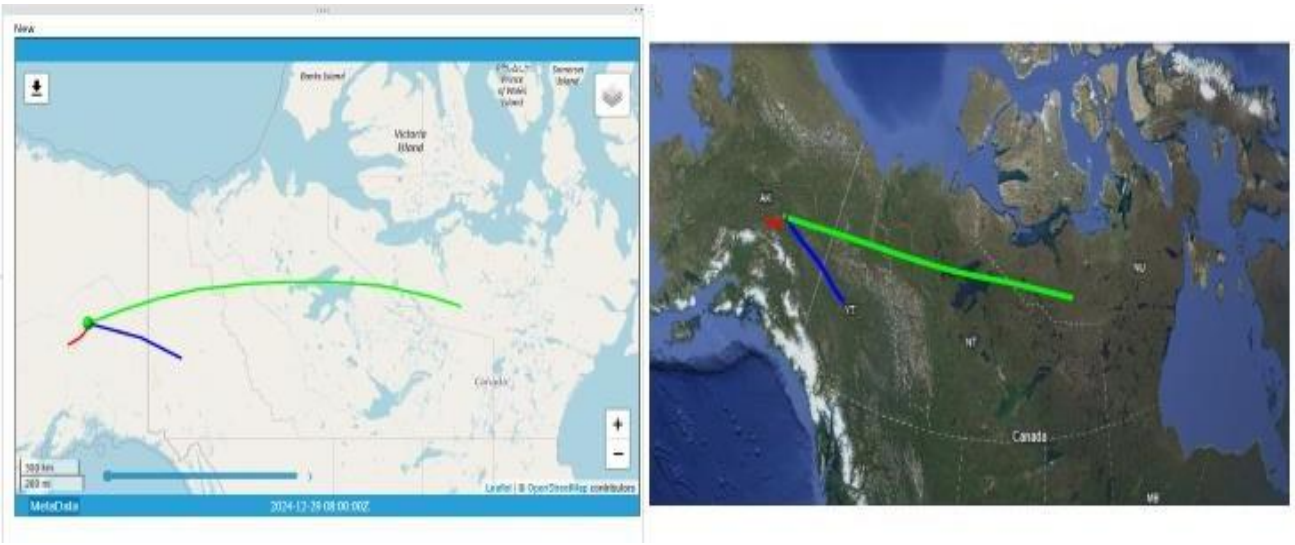


Fig. 7. Depicts the trajectory of high altitude balloon at Alaska Fairbanks at different altitudes.

From these trajectories graphs we understand that if we want to cover the Alaskan region to Canada the upper half of the American continent then we have to deploy the High-altitude air balloon at Alaska Fairbanks, but if you want to cover the East-Southern coast of North America and also cover the Atlantic ocean than we should launch our HAB at the University of Mississippi, which will cover these regions and also is the impeccable alternative to GOES-16 as it covers the East part of the North- American Continent.

Also, by deploying HABs at two locations we can cover the whole North American Continent and also the Atlantic Ocean hence we can get the whole data of the United States of America and Canada by the simultaneously functioning of these HABs we will also have a third HAB in standby, so as soon as one HAB burst we can deploy another one and in that way we can continuously have the data, hence in just 0.73% cost of the traditional GOES-16 satellite with also payload recovery making it an environmental friendly alternative

too.

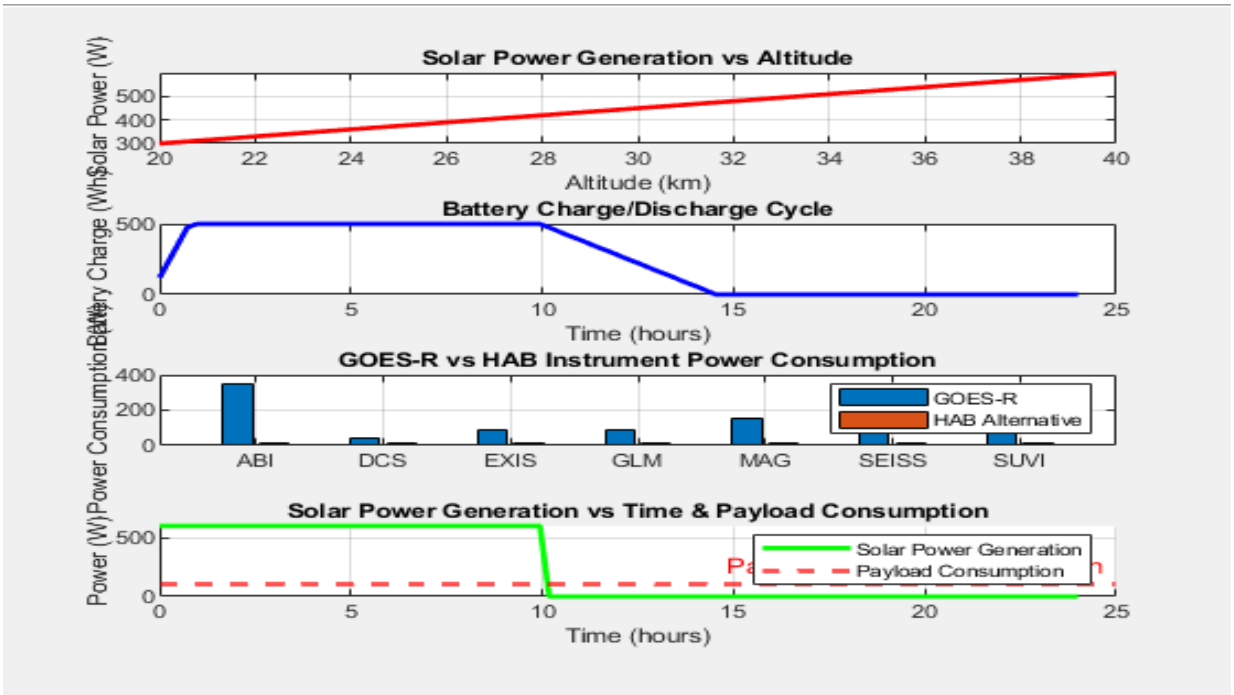


Fig. 8. Simulation of the Energy management of High Altitude air Balloon.

With the help of MATLAB software, we have developed a theoretical-based solar harvesting model, according to this graph we understand how we get solar power energy generation, like with an increase in Altitude we are also witnessing a rise in solar power production. After that we can see how the battery dissipates energy like when it is the night the system is fully dependent on the battery here we have considered 12 hours of the night so we can see how the battery is working, then we have the power consumption of payload between GOES-R and HAB in which we can see that HAB is the best alternative in every scenario, and in the last one we can understand that the payload will require a constant supply of power to run it, and also that the solar power generation occurs for the 12 hours daylight cycle which is again considered here for the sake of simplicity, hence by the MATLAB software we can easily simulate how our High Altitude Air Balloon utilize solar power.

6. Limitation

It is also essential to highlight the limitation of the high-altitude air balloon as it can reduce the cost massively and enables developing countries to have a cost-effective space research option; it also comes with its disadvantages. The HAB can stay in orbit for about 55 days in the case of NASA balloon projects, so it faces a real problem as GOES-R is a 5-year active satellite mission. So, due to the balloon burst problem, the data will be discontinuous.

Also the foot print area that the HAB covers will be less than the area covered by the GOES-R satellite due to which we cannot perform all the applications at a wider spectrum, so by using the National Oceanic and Atmospheric Administration (NOOA), National Environmental Satellite, Data, and Information Services (NESDIS) software we have the actual foot print area that the GOES-R satellite which shows that the satellite covers the whole South America, Central America and most of North America where as HAB cannot achieve it.

6.1. Calculating HAB foot print area

For a spherical Earth, we have the approximate coverage radius R (in km) from altitude h (in km) is,

1Coverage Radius (d) = $(2Rh + h2)^2$
So, we are considering.
h=30km (HAB Altitude) R=6371km (Earth's Radius)
1d = $(2 \times 6371 \times 30 + 302^2)2$
1d = $(382{,}260 + 900) = (383{,}160)^2$ =≈ 619km
So the coverage radius is ~619 km. Now, to find the footprint area:
A = $\pi \times d2 = \pi \times (619)2 \approx 1{,}203{,}000km2$



Fig. 9a. Shows the view of HAB from sky.

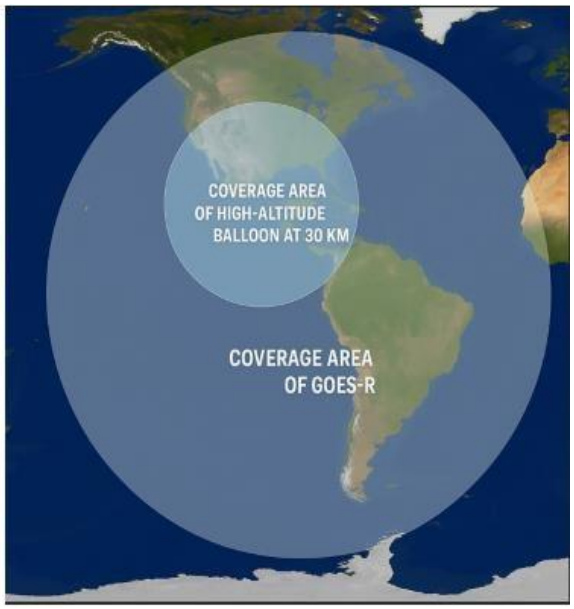


Fig. 9b. The foot print area.

So, by performing the calculation we get that the HAB can only cover the 1/6th of what the GOES-R satellite can cover which shows us a major limitation of the High Altitude air balloon also we have shown the real view of an HAB from above the sky which is an experiment conducted by the Indian Institute of Astrophysics [17] so from all this we can understand that the high altitude air balloon do have advantages but due to its less working time and coverage area the possibilities to perform large level of operations will be limited.

7. Conclusion

Hence, through this paper we have elaborated why the High-Altitude air balloon promotes sustainability, green aerospace, low-cost alternatives, and decrement in orbital congestion due to these HAB alternatives we can minimize space debris and achieve less orbital junk in space [18], this scientific balloon has the capability of carrying experiment in space for 50-days, after that it will burst for that a HAB system needs to be ready so that data is not discrete, through this paper we have discussed how a HAB can be an alternative to a Geostationary satellite and can perform all task with less than 1% of its cost.
Through this, research we can finally understand that there is a way to make space exploration cheaper and accessible to all the nations of the world, hence by the use of high-altitude air balloons we can perform all kinds of tasks from navigation to understanding climate change pattern to coronal mass ejection from the sun, in a fraction of the cost of the making of satellites.

8. Future Recommendation

So, we would like to recommend that a more diverse HAB system should be developed that covers the whole Earth, and also how to make the air balloon material biodegradable to achieve net zero pollution, and also need to work on how to increase the coverage of high altitude air balloon.

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