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Multi-mission Ultra-long Duration Stratosphere Platform: Potential, Capacity and Limitation Study

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Abstract: The purpose of this study is to evaluate the potential capacities and limitations on using multi-mission ultra-long duration stratosphere platforms. Stratosphere flight provides a unique vantage point for scientific exploration as well as for Earth observation and surveillance. The ability to fly for an extended duration of time several months to years) at near space altitudes is an elusive goal. However, in recent years. Renewable energy technology has progressed to the point where ultra-long duration multi-mission stratosphere platforms can be considered. This platform is one type of long endurance air vehicle that has significant potential. The proposed platform, unlike aircraft, generate lift through the buoyancy effect instead of through aerodynamics lift. So, such platforms do not need to stay in motion to remain aloft; it also has the ability to carry heavy payloads with considerable volume constraints. These characteristics, compared to other conventional conditions make it unique candidate for long endurance high altitude flight. The analysis shows high investment potentials and huge capacities in stratosphere flights. It also proves that building such platforms is feasible and promising. Also, it may help the third world countries in growing and sustaining their development plans.

1. INTRODUCTION

The stratosphere is defined as the region between 18 and 50km above the Earth surface. It was a cultural blind spot, too high up for conventional aircrafts flight path, but too low for Low Earth orbits satellites. Stratosphere flight provides a unique vantage point for scientific exploration as well as for observation and surveillance. The ability to fly for an extended duration of time (several months to years) at stratosphere altitudes has been an elusive goal. However, in recent decades, electronics and solar energy equipment technologies have progressed to the point where long duration stratosphere lighter than air, buoyant, platforms can be considered.

Air buoyant vehicles properly known as balloons, airships, aerostat, and any novel buoyant air vehicles are being developed from new materials and/or technologies. Air buoyant vehicles can be classified based on hull configuration, the way of producing vertical force, and payload capability [1-9]. Classification based on their hull configuration can be rigid, semi-rigid, and flexible. In contrast, a rigid shape can be maintained independent of envelope pressure because the envelope is usually supported by rigid framework. Semi-rigid shapes, have some characteristics of rigid and flexible airships. Flexible airships sustain their shape profile by a pressure difference between the lifting gas in the hull and the atmospheric environment. An envelope of the gas containment membrane encloses the lifting gas. Ballonets permit the envelope pressure to be controlled, and the relative fullness of fore and aft ballonets is associated with pitch control. NASA from early in the twentieth century funded a lot of interesting balloon projects known as flexible structure airships. Balloons play an important role in NASA's current scientific investigations, including upper atmosphere research, high energy astrophysics, stratospheric composition, meteorology, and astronomy [10-12].

This work will study and evaluate the stratosphere potential, capacity, and limitations for operating buoyant platforms for ultra-long endurance missions. To evaluate the potential, capacity, and limitations of the stratosphere, some assessment of basic parameters will be executed in some of this context. The stratosphere platform system can be broken down into three main entities: carrying platform, payload, and ground stations. The design analysis of the carrying platform can be divided into four main subsystems: structure and subsystem accommodation, power generation and distribution management subsystem, navigation and control subsystem, lifting force generation and mobility subsystem. The launching, landing, and payload safe recovery subsystem can be considered but after platform design verification. Payload conceptual design can also be divided into three main subsystems: imaging, communications, and command and data handling. The ground segment is composed of two entities, mobile control and data reception station and mission operation and management center.

In this study, we will consider a semi-rigid stratosphere buoyant winged platform. The main issue in stratosphere flight is generating lift within a low atmospheric density environment. The concept of winged hull platform body design considerations takes advantage of the lift force generated by density difference between the buoyant body and the environment. The proposed stratosphere buoyant platform shown in Figure 1 has the shape of a bird with two wings carrying propellers that generate thrust when it has to move. On the top of these wings a set of solar cell arrays will be fixed to generate needed power. The generated power will be stored in batteries to be available for use any time. The wings can provide natural stability under normal flight conditions, increase platform payload capacity, and decrease drag [23].

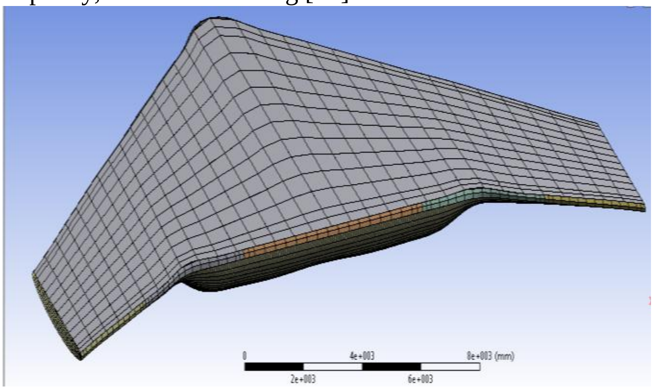

Figure 1. Stratosphere platform general configuration

2. MISSION PARAMETERS CALCULATION

The Earth atmosphere is composed of many layers. Each layer has its own characteristics and very dynamic environment with great fluctuations in wind speed, solar flux intensity, temperature, density, pressure, and cosmic radiation. The stratosphere environment is where the platform will operate. It has a large influence on the platform performance, design, and capabilities. The main physical parameters of the Earth's atmosphere and environment are presented in Table 1 and the atmospheric construction is shown in Figure 2.

Wind Speed

The assessment of stratosphere potential, capacity, and limitations for operating an ultra-long duration platform require evaluation of some basic parameters affecting the desired mission. Because of the stratosphere characteristics the platform design will not be an easy task. It will be very sensitive to windspeed, air density, environmental pressure and temperature, and the available incident solar flux radiation. The platform can potentially operate at any location that has sufficient solar flux intensity to generate the required power and atmospheric density to maintain it aloft.

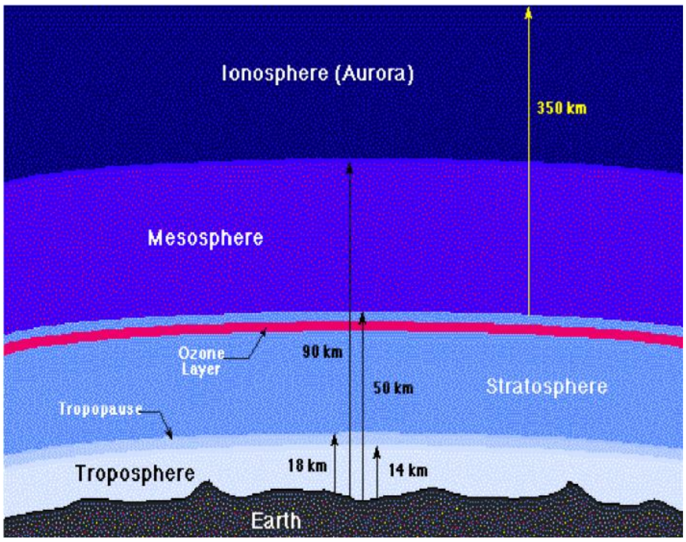

Figure 2. Profile of Earth's Atmosphere [13]

Table 1. Earth's Physical Properties [14]

Inclination of Equatorial Orbit	23.45°□
Earth Orbit Eccentricity	0.01673
Day Period	23 h 57.8 m
Mean Solar Radiation Intensity	1352 W/m2
Albedo	30%
Gravitational Field	9.81 m/s^2
Sidereal Year	365.26 Earth day
Surface Temperature Extremes	130 – 300 °k
Earth Diameter	12 756 km

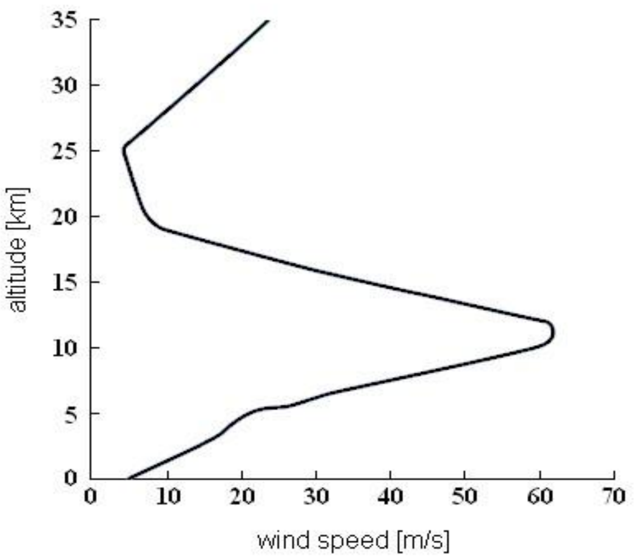

Figure 3. General average wind speed profile versus altitude [15]

The wind speed that the platform must overcome to move to the target area or to maintain its location is highly dependent on the time of year, latitude, and altitude. Although the wind does not affect the power generation capability of the platform, it has a significant effect on drag force resisting its movement and therefore power consumption. So, flying in locations that have high winds could pose a significant challenge to the power system design. A generalized average wind speed profile is presented in Figure 3.
Figure 3shows that the optimal operational altitude for the platform is between 19 and 25km at which the average wind velocity is approximately 5 m/s. The superiority of this altitude is because the average wind velocity is minimal.

Temperature and Pressure

The environmental temperature is one of the major parameters directly affecting the platform design process. Design of a good thermal control subsystem depends mainly on the operation altitude and the on-board equipment operational conditions. The external pressure depends mainly on the altitude. External pressure has direct effect on the hull design. Figure 4 presents the temperature and pressure variation against altitude [18].

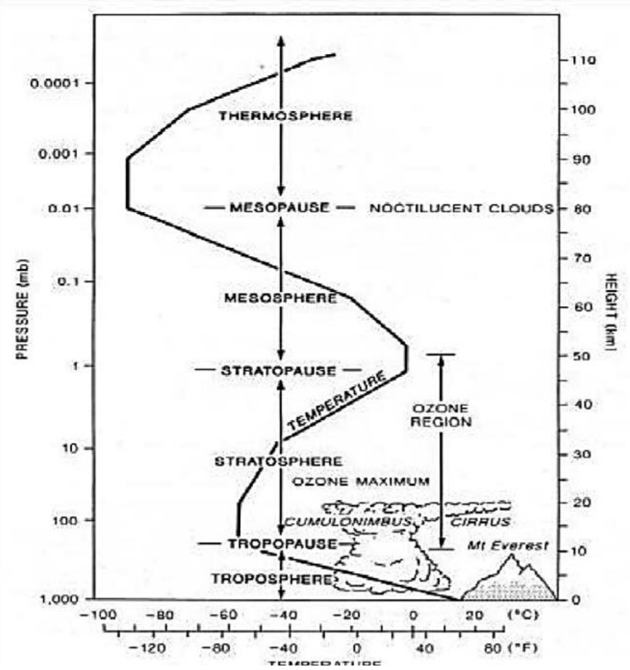

Figure 4. The pressure variation versus altitude

Radiation Environment

The radiation environment in the stratosphere is a result of the interaction of charged particles of solar and galactic origin with the magnetosphere and the atmosphere of the Earth. The intensities and the composition of the radiation field change with latitude and altitude and solar activity were studied in many articles such as [19-22]. Charged particles of galactic and solar origin with high energies are able to penetrate the magnetic field of the Earth and to enter the atmosphere.

The quantity of its penetration ability is called the magnetic rigidity and is given by the cosmic ray's momentum divided through interactions of predominantly very high energy protons with the atmosphere secondary particles are produced, such as alpha particles, protons, ions, muons, electrons, positrons and neutrons, as well as gamma radiation. A number of these secondary particles have a great effect on the onboard electronic components depending on its intensity. The galactic cosmic radiation arises from sources outside the solar system. The cosmic ray has to penetrate theEarth magnetic field in order to enter the atmosphere by its charge. The atmosphere resistance to penetration by cosmic rays is called magnetic cutoff. The magnetic cut-off is defined as the threshold value of magnetic rigidity blows it the cosmic rays are not able to penetrate. The magnetic cut-off values distribution over the Earth's atmosphere depends on the altitude and latitude. Smart and Shea [20] calculated the vertical cut-off at 20 km latitude and presented calculation results in Figure 5. Van Allen, J.A. and Tatel, H.E.[22] measured the ionized particles intensity across the atmosphere from sea level to 161 km altitude. The measured data presented in Figure 6. Schaefer, H.J.[21] presented different altitude dependencies of the charged particles in Figure 7.

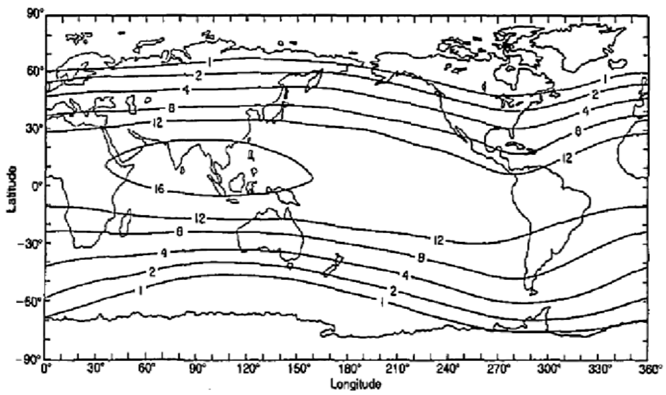

Figure 5. Vertical cut-off rigidity calculated for20 km altitude [20].

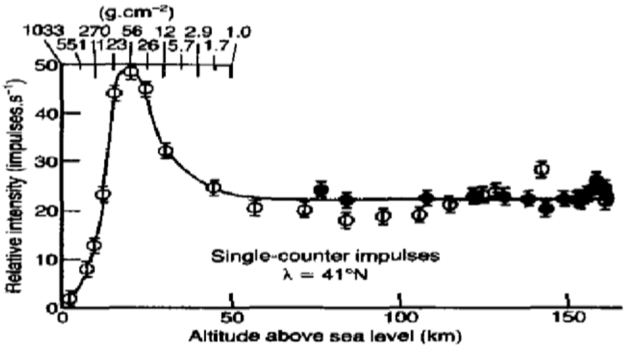

Figure 6. Intensity of charged particles dependence on altitude [22].

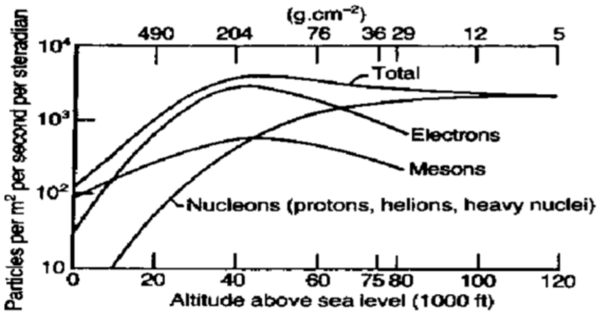

Figure 7. Altitude profile of charged particles in the atmosphere [21].

Coverage

An ultra-long duration stratosphere platform provides a vantage point and capability that is presently not available with conventional air vehicles or satellites. A number of potential applications can be executed both civilian and military according to the mission objectives. Examples of civilian missions are communications andwide area surveillance.

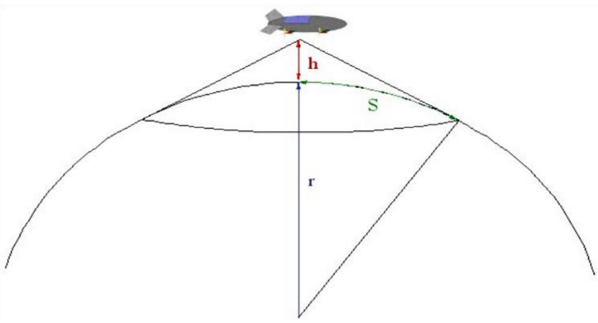

Figure 8. Coverage area as seen from the platform altitude

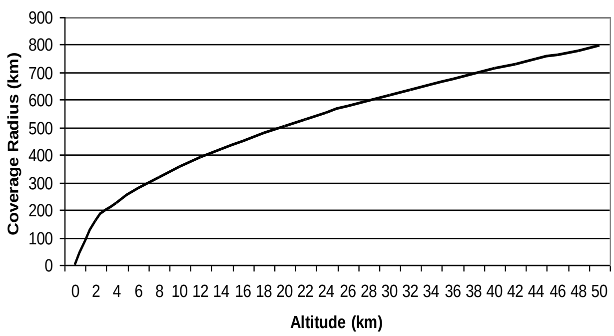

Figure 9. Coverage area radius versus platform altitude

Each mission has its own peculiarity. Radar and Laser imaging systems, as well as short wave thermal infrared and visible light bands imagery scanners, are examples of Earth observation payloads that benefit from the stratosphere platform operation. The range these devices can see will depend on the altitude of the platform. Therefore, the higher up in the atmosphere you can position the platform the greater the coverage area. The coverage area of the platform is determined by calculating the distance to the horizon from the platform. It is given by equation 1 and presented in Figure 9.

$$S = r\left[\cos^{-1}\left(\frac{r}{r+h}\right)\right] \qquad (1)$$

where S is the radius of the coverage circle assuming Earth is a sphere, h is the platform altitude, and r is the Earth radius as shown in Figure 8.

Drag Calculation

The key to minimize the required platform size or to maximize the performance of a given size is to operate it under minimum drag conditions. For an Earth observation mission where the platform is non-stationary most of the day, minimum drag will be the main objective of the configuration design. In such a case drag is a combination of the mean relative velocity, platform size necessary to lift the desired payload, and the air density at the operational altitude.

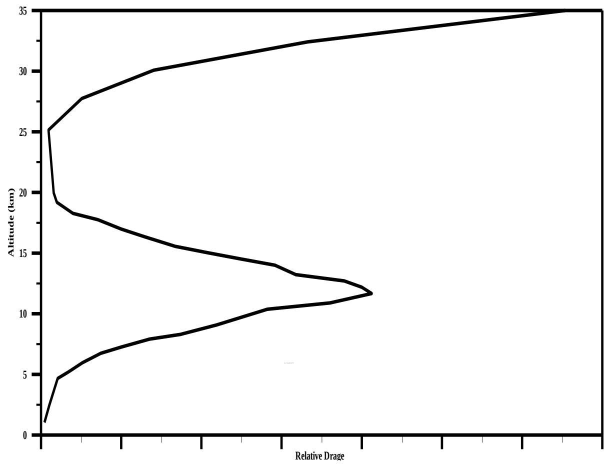

Figure 10. Relative drag on a platform sized to carry a fixed payload

The drag (D) on the platform is proportional to the wind velocity (V) and air density (ρ). It is based on an estimate of the scaling of the platform in a mass point. This proportionality is given in equation 2 and presented in Figure 10.

$$D \propto \frac{V^2}{\rho^{2/3}} \qquad (2)$$

Figure 10 illustrates the relative minimum drag is at an altitude between 19 and 25 km which indicates the optimal operation altitude for the platform. It is based on the efficiencies of the various components that make up the system and the thrust level needed to overcome the drag on the lighter than air platform. From an energy standpoint, the power consumption based on mean wind speed is used to determine the required movement energy over the day period. The platform drag (*D*) is based on a volumetric drag coefficient (C_{dv}) and the platform volume (V_p). For this analysis, it was assumed that the platform was to maintain position and sometimes to move. Therefore, the movement velocity (V) at which it is operating is the relative wind speed,

$$D = \frac{1}{2}\rho\, C_{dv} V_p^{2/3} V^2 \qquad (3)$$

The drag coefficient is based on the fineness ratio of the platform. The fineness ratio (f) is the ratio of the length (l) of the platform to its diameter (d) or width as given by $f = \frac{l}{d}$. The drag coefficient, given by equation 3, will decrease significantly as the shape moves from a sphere to an elongated cylinder and begins to level off at a fineness ratio of about 4.

$$C_{dv} = 0.23175 - 0.15757f + 0.04744\, f^2 - 7.0412 * 10^{-3} f^3 + 5.1534 * 10^{-3} f^4 - 1.4835 * 10^{-3} f^{-5} \qquad (4)$$

Equation 4 is valid for a fineness ratio up to 10 for a cylindrical shape with hemispherical end [16]. This drag is what has to be overcome by the thrust from the propeller.

For f = 4.0, C_{dv} = *0.0266*, V = *40 m/s, and* V_{pl}= *3300* $m^3$the calculated drag based on this given values is D = 3000 N.

Calculation of Incident Radiation Solar Flux

In addition to the wind, the solar flux radiation environment is the second significant environmental factor that drives the design and capabilities of the platform. The incident solar flux radiation is very predictable and can be modeled with significant accuracy.

The solar radiation environment is constantly changing. As the solar elevation angle changes throughout the day and the solar intensity also changes throughout the year due to slight variations in the distance of the Earth from the sun, the available output power from the solar array will vary. The environmental factors that influence the solar array produced power are shown in Figure 11.

The solar flux at Earth's orbit is on average 1352 W/m^2 (SI_m). The actual flux will vary throughout the year as the Earth orbits the sun. The variation in Earth's orbital radius (r_{orb}) from the mean orbital radius (r_{orbm}) is represented by the eccentricity (ε) of Earth orbit which has a value of 0.017. The actual solar flux (or intensity, SI) in W/m^2 for a specific day of the year is determined by the following equations:

$$SI = SI_m \left(\frac{r_{orbm}^2}{r_{orb}^2}\right) \quad (5)$$

$$r_{orb.} = R_m^{(1-\varepsilon^2)} / (1 + \varepsilon \cos(\alpha)) \quad (6)$$

where R_m is the mean orbital radius of the Earth is (1.496 E8 km), and (α) is defined as 0 on January 4 and increases by 0.98° per day.

The power incident on the solar array cells is given by the normal component of the incident flux given in equation 5. Due to the operation maneuvers of the airship and the variation in the sun elevation angle and position throughout the day this incident angle will vary throughout the day. Determining this incident angle is a critical factor in modeling the produced output power from the solar array. The airship configuration is presented in figure 1.

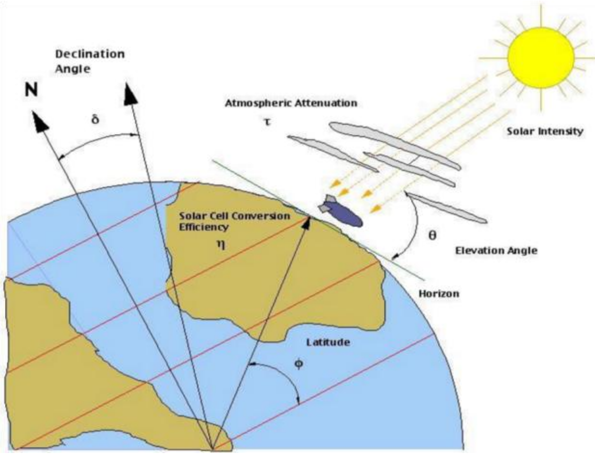

Figure 11. Factors that affect the airship's power production capabilities.

The solar array cells are proposed to be on the upper surface of the platform. There is no solar array in other places of the platform. The platform is assumed to be oriented horizontal (parallel to the Earth surface) with no pitching of the nose upward or downward.

To calculate the power harvested from the array cells the incident flux (component normal to the array surface) must be determined. The incident power (Pn) on a unit area of the solar array in W/m2 for a specific time during the day is given by equation (7)

$$P_n = SI(1 - \tau) \sin \theta_l \quad (7)$$

where τ is the attenuation of the solar flux due to the atmosphere, θ_l is the local sun elevation angle as seen from a specific segment of thesolar array and an orientation angle of γ. The orientation angle is represented by the position of the platform. For this analysis, the atmospheric attenuation was assumed to be 15% ($\tau = 0.15$). The local solar elevation angle is also based on the solar elevation angle (θ) relative to the solar cells surface (or horizontal), the latitude (ϕ) of the airship location, the declination angle (δ) of the Earth (which is based on the time of year is being zero at 21st March) and the geometry and orientation of the platform. The local solar elevation angle can be derived based on the position of the sun and the inclination angle (β) of a solar array plane segment mounted on the platform body upper side relative to the horizontal. From figure 12 the following relationships can be derived.

$$\theta_l = \sin^{-1}[\sin\theta \cos\beta - \sin\omega_l \sin\beta \cos\theta] \quad (8)$$

$$\theta = \frac{\pi}{2} - \cos^{-1}(C - D\cos\omega) \quad (9)$$

$C = \sin \phi \sin \delta$ (10)

$D = \cos \phi \cos \delta$ (11)

The solar angle ω is a function of the time ofday and is given by equation 12, where the time of day in hours (t) is based on a 24-hour clock. The solar hour angle is defined as being zero at midnight.

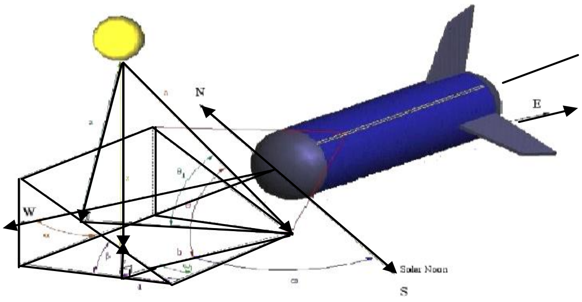

Figure 12. Solar array incident flux geometry

$$\omega = -\frac{2\pi t}{24} \quad (12)$$

The local hour angle (ω_l) is based on the position of the sun as well as the orientation angle (γ) of the airship. The local hour angle is given by the following equation 13:

$$\omega_l = \alpha + \frac{\pi}{2} - \frac{2\pi t}{24} \quad (13)$$

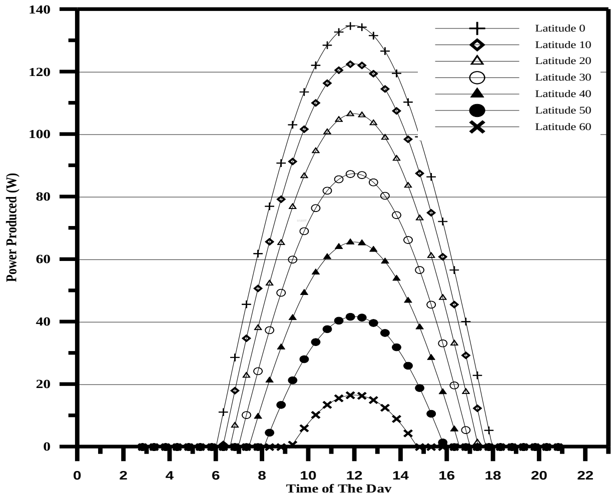

Figure 13 Winter solstice solar incident power at different latitude

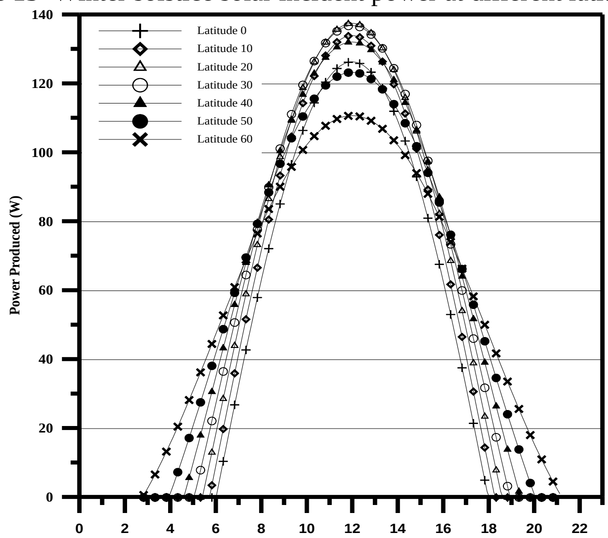

Figure 14 Summer solstice solar incident power at different latitude

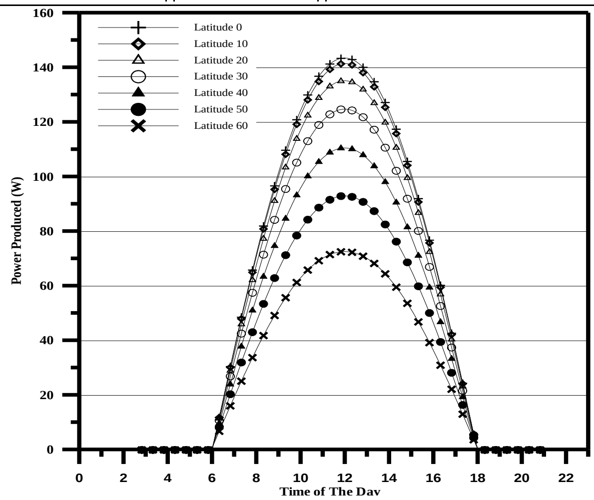

Figure 15 Vernal equinox solar incident power at different latitude

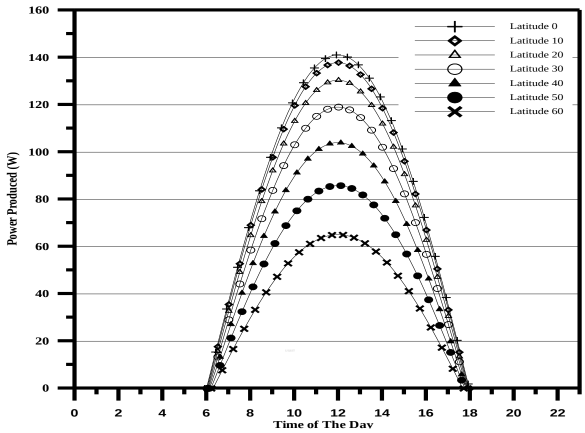

Figure 16 Autumnal equinox solar incident power at different latitude

The incident powers on the platform solar array are shown in Figures 13 through 16. These figures show the incident solar power on a unit area of the solar cells array for various times of the year for solar array inclination angles of $\beta = 0°$ at different latitudes.

Lifting Gas Volume Calculation

Assuming the high altitude lighter than air platform total weight is 2000 kg, including platform structure, power equipment, and remote sensing system equipment, in addition to the buoyant system equipment. Archimedes' buoyant principal states "buoyant force equal to the difference in weight of the displaced air and the lifting gas" can easily be applied to the platform in the atmosphere. Assume B is the buoyant force equals 2000 kg, m_a is the mass of displaced air, m_g is the mass of lifting gas, and g is the gravity acceleration, then

$$B = g(m_a - m_g) \qquad (14\text{-a})$$

$$B = gV(\rho_a - \rho_g) \qquad (14\text{-b})$$

Where ρ_a is the air mass density (1.28 kg/m^3) and ρ_g is the lifting gas mass density; (if the lifting is Helium then $\rho_h = 0.1785\ \mathrm{kg/m^3}$ at sea level attitude; while the high altitude lighter than air platform shall operate at the altitude 21.5 km approximately (70000 ft), the air density is about 0.0645 kg/m^3 and Helium density is about 0.00269 kg/m^3. Then substitute into equation 14-b the platform volume shall be $V_p = 3300\ \mathrm{m^3}$.

Propeller

Propellers used to move the platform from its location tothe targeted area not to generate the aerodynamic lift. So, the operation of the propeller is the most important and critical element to satisfy one of the major mission requirements. The majority of the power produced is consumed for thrust production by propellers. When considered from this perspective one can see why propeller performance have a great impact on the platform sizing design. The environmental conditions should be highly considered. The platform will need to be controllable and therefore produce thrust from the surface up to its design altitude. The variation in wind velocity (V), as well as the atmospheric density (ρ) and viscosity (μ) as the platform ascends or descends would result a wide aerodynamic operational range.The propeller mustbe capable to operate in such range and produce the necessary thrust. The combination of the environment and the operational conditions in addition to thepropeller design parameters, can be expressed in Reynolds number for the propeller. The Reynolds number (Re) for the propeller is given in equation 15:

$$R_e = \frac{\rho c \sqrt{V^2 + \left(\frac{\pi d n}{60}\right)^2}}{\mu} \qquad (15)$$

To size the propellers for a given platform configuration and operational location, more intensive study will be needed for mapping propellers utilizing vortex theory analysis code [17] for a propeller with a different number of blades.

3. PLATFORM SYSTEM DESCRIPTION

The proposed platform system diagram is divided into two segments separated by a dashed line the ground segment lies below the dashed line and the aerial segment lies above, as illustrated in Figure 17. At the ground segment, the remote operators interface with a Mission Control Center (MCC) and a platform flight simulator. The MCC performs two functions: 1) enables the operators to monitor the health of the platform and its equipment, and 2) provides the flight task command and control capability over the platform. Commands issued by the operators are sent to the platform from the MCC through an established Data Reception and Transmission Facility (DRTF) or to the Guidance, Navigation and Control (GN&C) subsystem in the flight simulator center.

The proposed platform is powered by solar energy only during the daylight and by stored power in batteries when it carries out night missions. Platform mass will be optimum and minimum with respect to the mission and satisfy the payload requirements. The aerial segment platform is composed of these major components: optics; image sensor and front-end electronics; GPS and inertial measuring unit (IMU); command and data handling unit including guidance, navigation and control(GN&C), data communication subsystem, and platform structure which mounting and accommodating platform equipment. The lower stratosphere's environment is characterized by low air pressure (100 mBar), the environmental ambient temperature is low, but has a variation between -50 and -70 °C, but inside the instruments low temperature gradients are expected between the electronics compartment and the optical part. Typical wind speed profiles show a minimum at altitudes between 20 and 25 km. Turbulence is expected to be limited, but this will have to be confirmed during flight trials.

GPS and IMU will be integrated for obvious reasons. They will allow for approximate geo-referencing in near real time data processing, and support automatic tie point extraction for high accuracy bundle block adjustment.

Thermal cycling may cause the IMU to exhibit time-dependent drifts; adding heaters near critical components should compensate for this. However, we will model this behavior after stratospheric flights and acquiring image series with stable geometric configurations above well-known ground control so that we can generate a reference with bundle block adjustment.

The command and data handling unit C&DHU is the heart of the instrument integrated with GN&C. It triggers other subsystems, collects their data and adjusts settings as required (e.g., integration time of the image sensor, which is based on a histogram analysis of the previous image). Furthermore, it performs data compression on the images used on a dedicated chip and it formats the data stream that is sent to the communication unit.

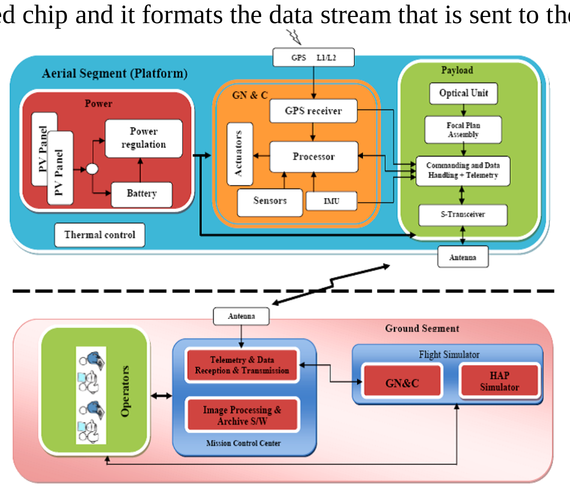

Figure 17Comprehensive system configuration

The C&DHU is programmable, so its functionality can be adapted to the needs that appear during flight trials. The platform will be designed to operate for months to years in a totally autonomous way, but if its payload has malfunctions or does not produce data as expected, the platform can be brought to land and the payload can be modified.

All image and ancillary data will be delivered to the data communication unit and then down linked via transmitter to the ground reception station in real time. Data rates up to 20 Mbit/s are achievable, but only to a dish antenna that is within about 150 km of the platform. Receiving command from the MCC will be via S-band or a UHF receiver which would of course be an important asset, but the required power to achieve this with a non-directional antenna should simply be taken into consideration.

The GN&C subsystem provides an autopilot capability to the platform so that its flight path meets the high-level objectives commanded by the MCC operators. This subsystem also gathers state and health information from itself and all other onboard subsystems andthen deliver it to the onboard command and data handling subsystem for packing.It transmits that data in a telemetry stream back to the ground station. When the telemetry data are received by the MCC, it is displayed immediately to the operator via user-configurable, customized displays. This feedback loop enables the operator to monitor the overall health and performance of the platform, and then issue commands as necessary.

The system doubles as a virtual test bed by connecting the remote operators and the MCC to a flight simulator on a separate workstation. The simulator includes the same software designed to run onboard the platform, along with a simulation of the platform dynamics. Interfacing the MCC with the flight simulator can be extremely useful. It can provide a mechanism for pre-flight validation of the GN&C subsystem with an operator or pilot in-the-loop. It also can be used as a training tool to instruct operators how to properly command and monitor the platform. Finally, it can be used before and during the mission as a prediction tool to evaluate the expected performance of the vehicle in specific scenarios or as a software test bed.

The system will be a customizable design. The flight simulator will be designed to accommodate easy plug-and-play of different dynamic models. The Mission Control Center will provide a flexible user interface such that the operator can design and configure his own telemetry pages, and robustly interface with other third party software. The GN&C subsystem will be implemented in a generic, modular architecture so that algorithms may be quickly swapped and parameters easily changed to facilitate an ongoing design. These features will enable the system to be used throughout the complete mission cycle from design to flight-test to operations.

4. CONCLUSION

This analysis presented in this paper is an initiallook at the feasibility of operating a stratosphere platform for long endurance mission. The goal of the analysis was to establish the feasibility and potential of the concept and point out any limitations or restrictions if they existed. The analysis used conservative values for most of the parametersnot yet available. With the environmental models used, the component scaling values and the assumptions made, it was shown that continuous operation of a stratosphere platform for long endurance mission is feasible using present day technology.

Since this was an initial study there are numerous areas that could benefit from more detailed modeling and analysis. These include a more detailed stratosphere platform design and a more refined wind data model providing statistical averages of monthly, weekly, or even daily wind velocity and wind direction data that could lead to an accurate design of the platform. The addition of some or all of these items could have an effect on the results and the size of the airship necessary to carry out the desired missions. However, since the results of this analysis are based on some assumed environmental data and seasonal fluctuations in the available solar energy, the general conclusion on the overall feasibility of the concept produced in this analysis should remain valid. The platform operation will face severe shortage in power generation for the latitudes over 40° in winter season as shown in the power analysis.

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