An Instrumented, Balloon-supported Tether for Early Space Elevator Research and Revenue

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1. Introduction

An instrumented, balloon-supported tether could provide an organisation such as the International Space Elevator Consortium (ISEC) or the Japan Space Elevator Association (JSEA) with essential upper atmosphere data as well as the necessary revenue stream and apparatus to begin preliminary research into the operation of a space elevator. It is well understood that a successful space elevator could provide a sustainable and cheap way to cater for the ever-growing demand for satellite and spacecraft launch services. Unfortunately, the concept of a space elevator has been written off by many academics and industry experts as science fiction. Groups such as ISEC and JSEA aim to prove that a thoroughly researched proposal for a space elevator can be made and eventually put into action, but currently rely primarily on academics volunteering their time. There is currently a gap in the market for research conducted on a balloon-supported tether at high altitudes. Previously deemed unviable due to winds at high altitude and the difficulty of operating such a long tether, the dawn of Ultra High Molecular Weight Polyethylene (UHMWP) has made these research stations possible. Research and operations that have previously relied exclusively on satellites could be done at a fraction of the price, allowing the stations to be rented out to research teams and provide the revenue required to continue space elevator research. As a corollary, the apparatus could also provide a platform for early tests of space elevator climber systems.

2. System Specifications

The most recent technical study into a tethered balloon system was conducted by Daisuke Akita in 2012. To decrease the risk of hazards presented by the wind, Akita's report suggested launching the balloon with the tether wound up on a reel, before releasing it when the floating altitude had been reached by the balloon and allowing it to unwind under its own weight (Akita, 2012). In order for this system to work effectively, the balloon system would have to be anchored to the sea with a drogue chute attached to the end of the tether (Akita, 2012). Furthermore, a sea-anchored system allows the balloon-supported tether to be deployed easily in a number of global locations without the need to construct a ground station.

Two main scenarios were considered for the wind which had previously cast doubt on the idea. The limiting scenario, in which the wind was weak at the floating altitude of the balloon, but strong in the Jetstream during its ascent, was analysed numerically (Akita, 2012). It was found that by utilising a tether constructed of the commercially available UHMWP Dyneema, a tethered balloon would not only be able to withstand high winds, but survive under the tension created by its own weight (Akita, 2012). Dyneema has a tensile strength of 2.84kN/mm^2 and a density of 970kg/m^3, which far outperforms the nearest rival, a carbon fiber named Torayca (Akita, 2012). Torayca offers a tensile strength of only 2.4kN/mm^2, and a higher density of 1600kg/m^3 (Toray, n.d.). In order to maintain a safety factor greater than 2, the balloon would be limited to an altitude of 25km and be 30m in radius. The tether would be of length 25km and diameter 4mm, and the drogue chute 4m in diameter (Akita, 2012). Other configurations at different altitudes and tether diameters were considered, but gave inadequate safety factors. With the configuration selected, the point of highest tension at the connection between the tether and balloon would be in the region of 2.7kN, giving a safety factor of 2.6. This leaves a payload mass limit of 89kg (Akita, 2012).

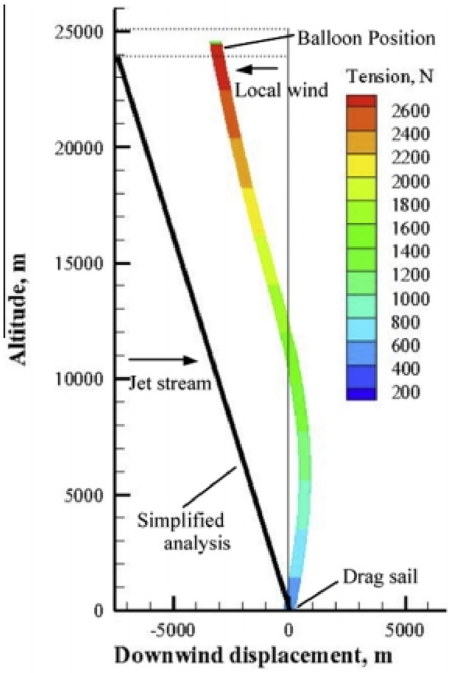

Figure 1 – Tether shape and tension when drag sail is in the sea in case 2 wind distribution (Akita, 2012)

However, a safety factor of 1.5 is the aerospace industry standard. According to Akita's calculations, a number of configurations allow for this. At an altitude of 36km, the maximum altitude Akita analyses, a balloon of diameter 100m could support a payload of approximately 250kg with a tether 7mm in diameter (Akita, 2012). Also at 36km, a balloon of diameter 120m could either hold a payload with an approximate mass of approximately 1000kg if a tether of 9mm is used (Akita, 2012). At 30km altitude, a balloon of diameter 40m with a tether diameter of 3mm could hold a payload of approximately 100kg (Akita, 2012). At the same altitude, a balloon of diameter 60m with a tether diameter of 5mm could support instrumentation of approximate mass approximately 700kg (Akita, 2012). Finally, if the altitude were reduced to 20km, a much larger payload could be supported. A balloon of diameter 40m with a tether of a 10mm dimeter at this altitude could allow a payload of up to approximately 1050kg (Akita, 2012). Furthermore, if the balloon diameter were increased to 50m and the tether diameter to 12mm, a payload of approximately 2900kg could be supported at 20km altitude (Akita, 2012).

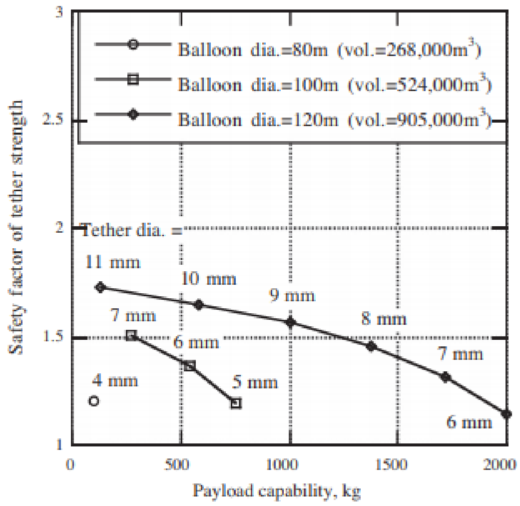

Figure 2 – Payload capability and safety factor (36 km altitude) (Akita, 2012)

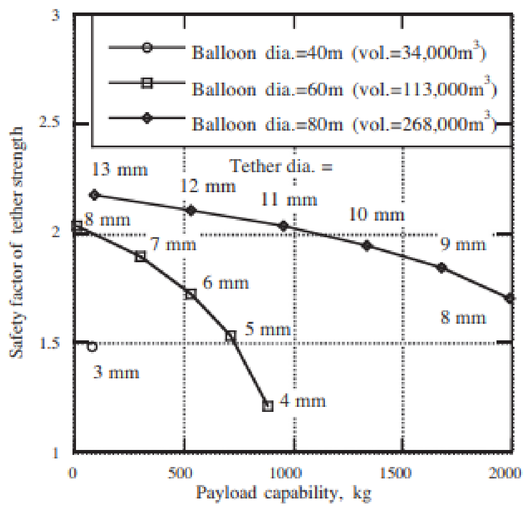

Figure 3 – Payload capability and safety factor (30 km altitude) (Akita, 2012)

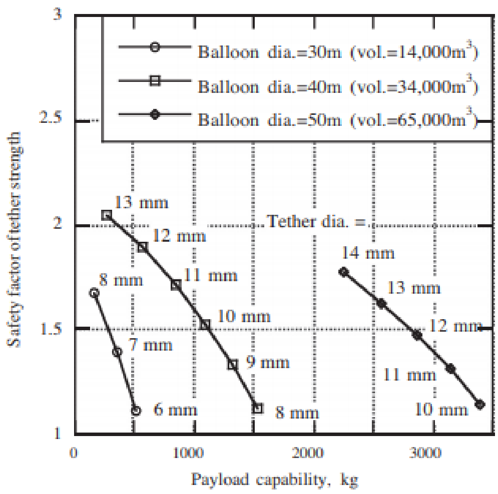

Figure 4 - – Payload capability and safety factor (20 km altitude) (Akita, 2012)

Akita also looked at the limitations that the Jetstream would put on the viable locations for the system. The limiting case that had been analysed to give the configuration above was created using the wind speeds of the Jetstream during the months of May and September, when it is strongest, above Sanriku, Japan (Akita, 2012). Sanriku lies at a latitude of 39 degrees north; wind speeds would be similar at locations of a similar latitude. These balloon-supported tethers could therefore be placed off the coasts of Japan, the continental United States (excluding Alaska), Northern Africa, and Southern Europe.

3. Early Space Elevator Research

The primary purpose of the balloon-supported tether within the space elevator research framework would be to test potential climber concepts, year-round readings of the tension in the tether, as well as the atmospheric conditions and radiation dosages at high altitude.

Although much climber research is focused around the large climbers that would ascend a space elevator, research has been done on smaller, lighter climbers as a proof of concept. These could be used in conjunction with the balloon-supported tether to test further concepts on a small scale. For example Powerlight Technologies', then LaserMotive, climber Otis won NASA's 2009 Power Beaming Challenge at the Dryden Flight Research Center (NASA, 2009). The climber weighed 5.22kg, moved at an average speed of 3.9 m/s up the 1km test cable, and was powered exclusively by wireless transmission (NASA, 2009).

A similar climber to this one could be constructed for use with the balloon system and could offer tests for climber mechanics such as tether interface equipment and drive apparatus, how to power the climber and climber energy management, cargo carrying, communications with a ground station, environmental controls, and attitude control (Swan, Swan, Penny, Knapman, & Glaskowsky, 2013).

Powering the prototype climbers using Powerlight's wireless transmission technology may not be possible for a tether anchored at sea. For the test in 2009, a large truck containing a TRUMPF TruDisk Laser generating 8000 Watts of energy was needed to power the beam transmitter's optics (The Spaceward Foundation, 2009). This is only for a climb only 1/25 of the length offered by the balloon-supported tether. Undoubtedly, a climb that is higher would need a more powerful laser. As well as this, atmospheric conditions would interfere with a line-of-sight connection to a climber, and the movement of a drone ship due to waves would make maintaining a connection even more difficult. The method of powering a test climber must therefore be considered further.

Figure 5 - TRUMPF's TruDisc Laser generating power for NASA's 2009 Power Beaming Challenge (The Spaceward Foundation, 2009)

Instrumentation for measuring tension, weather, and radiation are available commercially, as they are already common place on short-flight weather balloons. The advantage of having the instrument mounted on the balloon-supported tether is constant readings for the purpose of space elevator research. The readings could also be sold as an extra stream of revenue.

4. Instrumentation for Revenue Generation

In order for research conducted on an instrumented, balloon-supported tether to generate enough revenue to fund space elevator research it would have to offer an advantage over ground-based or space-based research methods. One method of doing this would be a telescope mounted on the tether for dark-sky astronomical observing. NASA already utilises balloons in the polar region to conduct research on heliophysics, x-rays, gamma-rays, infrared, and particle astrophysics, but very few if any high altitude balloons for dark-sky observation exist (Fesen & Brown, 2015).

A paper by Fesen and Brown originally suggested a high-altitude telescope be carried by a powered aerostat (Fesen & Brown, 2015), but the balloon-supported tether offers a cheaper and easier method of doing this. At an altitude of 25km a telescope would not be subject to the difficulties of ground-based telescopes. For the balloon-supported telescope, there would be no weather interference, no dust or other particulates, only 2.5% of the atmosphere to observe through, and the sky would always be clear allowing for constant imaging (Fesen & Brown, 2015). As a corollary, the telescopes could be launched and operate at a fraction of the price of space-based ones.

With all these advantages taken into account, a telescope with a mirror of 0.5m diameter supported by the tether could have a resolution of 0.25 arcseconds per pixel at a wavelength of 500nm (Fesen & Brown, 2015). By comparison the median resolution of the Paranal Observatory, which is the largest optical-infrared observatory in the Southern Hemisphere, from 1999-2006 was 0.83 arcseconds (European Southern Observatory, 2006). This is much less than the theoretical angular resolution of the telescope due to atmospheric effects. Therefore, if observing optical and infrared, this would make the balloon station competitive with space-based telescopes for imaging quality (Fesen & Brown, 2015).

The SuperBIT telescope is an already existing balloon-borne visible-to-near-UV telescope collaborated on by NASA's Jet Propulsion Laboratory and a number of universities internationally. It also has an effective resolution of 0.25 arcseconds, but only flies for 7-8 hours at a time (Romualdez, Benton, Brown, Clark, & Damaren, 2018). Furthermore, access to its capabilities is limited to the groups collaborating on it. The tether-supported telescope could potentially be hired out at an hourly rate to researchers, similar to current ground-based telescopes and observatories.

iTelescope, a website that allows researchers to remotely hire time on their telescopes, charges $88 per hour for dark-sky observation with their largest telescope (iTelescope, n.d.). Located in California, this telescope has a theoretical resolution of 0.62 arcseconds per pixel before atmospheric seeing is taken into account (iTelescope, n.d.). Performing better than both this telescope and the Paranal Observatory, the tether-supported telescope could be hired out at a much greater rate.

SuperBIT and its apparatus, however, have a combined mass of 1000kg (Romualdez, Benton, Brown, Clark, & Damaren, 2018). This is greater than ten times the carrying capability of the balloon-supported tether. According to the configurations researched by Akita it would be possible to construct a system to support a telescope at a similar mass whilst still having a safety factor in the range of 2. Using a balloon of diameter 80m at 30km altitude, compared to the 30m diameter balloon at 25km altitude previously specified, Dyneema tethers of 10mm and 11mm in diameter would have payload capabilities of 950kg and 1300kg respectively as well as safety factors of 2.05 and 1.95 respectively (Akita, 2012).

Alternately, if the safety factor were reduced to 1.5 as discussed earlier, a number of the configurations outlined in section 2 could be used to support a high-altitude telescope with a mass similar to that of SuperBIT.

Such a configuration would undoubtedly come with increased costs, and must be subject to further consideration.

5. Regulations and Health and Safety

As expressed earlier in Akita's study, health and safety risks can be mitigated to those already known about high altitude balloons during launch by deploying the tether once floating altitude has been reached. The legalities and necessary procedures surrounding the balloon whilst it is tethered are less clear.

The General Technical Administration of the United States Federal Aviation Administration offers some advice for operating tethered balloons within the territorial waters of the United States of America. However, this legislation is not all-encompassing and more specificities should be sought regarding a tethered balloon at such a great altitude.

Firstly, any tethered balloon must be operated "in compliance with all construction, certification, airworthiness, registration, and operating regulations applicable to aircraft." Furthermore, as the balloon is unmanned, it does not require the vertical controls required of a manned, free-floating balloon. Consideration should be given to a lighted tether for night operations, although this may not be possible with the payload limitations presented by the balloon-supported tether. As a corollary, local air traffic control must be advised on the presence of the tether and balloons; this must be the case in class D airspace (Federal Aviation Authority, 2015).

The UK Civil Aviation Authority was contacted for advice, but there was no response.

The situation is less clear for operation in international waters, and must be subject to further investigation.

6. Cost Estimate

Some elements of the tether-supported balloon system can be purchased easily through commercial routes. The anchor chute is available from www.seaanchor.com for $1,000 (Para-Tech Engineering Co., 2019). Marlow Ropes, a client of Dyneema, provided a quote of $12,500 for a tether of length 25km and diameter 4mm. Unfortunately, readily-available commercial high altitude balloons are not manufactured with a diameter of 30m. These would have to be sourced separately, and the cost of the balloon system would most likely comprise of this expense. For a system aimed at generating revenue, the same is the case for the tether-mounted telescope.

7. Conclusion

An instrumented, balloon-supported tether has been made possible by advances in materials that can withstand the tension put on a tether at high altitudes. By constructing such a system, it could be instrumented to test early space elevator climber prototypes at mid-to-high latitudes. If used to generate revenue, a telescope mounted on the tether would be able to provide a profitable, high resolution platform for researches that rivals space-based telescopes. Consideration would have to be made as for adapting the configuration of the system to support a telescope similar to NASA's SuperBIT. As such a system has not been constructed before, legislation that already exists surrounding the situation is unclear. It has not been written with such a private venture in mind. The same is the case for cost of the actual balloon and the telescope that it would be used to field.

References

Akita, D. (2012, August 15). Feasibility study of a sea-anchored stratospheric balloon for long-duration flights. *Articles in Space Research*, 50.

European Southern Observatory. (2006). *Astroclimatology of Paranal*. Retrieved from European Southern Observatory Web Site: https://www.eso.org/gen-fac/pubs/astclim/paranal/seeing/adaptive-optics/statfwhm.html#2006plot

Federal Aviation Authority. (2015, July 7). *Volume 3, General Technical Administration, Chapter 12, Introduction to 14 CFR, Part 91, Related Tasks, Section 2: Balloons.* Retrieved from Federal Aviation Authority Web Site: http://fsims.faa.gov/wdocs/8900.1/v03%20tech%20admin/chapter%2012/03_012_002.htm

Fesen, R., & Brown, Y. (2015, May 23). A Method for Establishing a Station-Keeping, Stratospheric Platform for Astronomical Research. *Experimental Astronomy*, 39.

iTelescope. (n.d.). *iTelescope Membership and Education Plans*. Retrieved from iTelescope Web Site: https://go.itelescope.net/info.aspx

iTelescope. (n.d.). *Telescope 24*. Retrieved from iTelescope Support: https://support.itelescope.net/support/solutions/articles/231907-telescope-24

NASA. (2009, October 11). *LaserMotive LLC Wins Prize in Power Beaming Challenge*. Retrieved from NASA Web Site: https://www.nasa.gov/offices/oct/early_stage_innovation/centennial_challenges/cc_pb_feature_11_10_09.html

Para-Tech Engineering Co. (2019). *Boat Accessory Pricing*. Retrieved from Sea Ancor Web Site: https://www.seaanchor.com/prices/

Romualdez, L. J., Benton, S. J., Brown, A. M., Clark, P., & Damaren, C. J. (2018). Overview, design, and flight results from SuperBIT: a high-resolution, wide-field, visible-to-near-UV balloon-borne astronomical telescope. *Proceedings of SPIE*, *10702.* Austin.

Swan, P. A., Swan, C. W., Penny, R. E., Knapman, J. M., & Glaskowsky, P. N. (2013). *Design Considerations for Space Elevator Tether Climbers.* International Space Elevator Consortium. Lulu.com.

The Spaceward Foundation. (2009). *2009 Power Beaming Archive*. Retrieved from The Spaceward Foundation Web Site: http://www.spaceward.org/games-pb2009

Toray. (n.d.). *TORAYCA laminate method - Specifications/performance*. Retrieved from Torayca Web Site: http://www.torayca.com/en/lineup/industrial/ind_006.html