The Flying Carpet: Aerodynamic High-Altitude Solar Reflector Design Study

Abstract

Our concept studies indicate that a set of reflectors floated in the upper atmosphere can efficiently reduce radiant forcing into the atmosphere. The cost of reducing the radiant forcing sufficiently to reverse the current rate of Global Warming, is well within reach of global financial resources. This paper summarizes the overall concept and focuses on one of the reflector concepts, the Flying Carpet. The basic element of this reflector array is a rigidized reflector sheet towed behind and above a solar-powered, distributed electric-propelled flying wing. The vehicle rises above 30,480 m (100,000 ft) in the daytime by solar power. At night, the very low wing loading of the sheets enables the system to stay well above the controlled airspace ceiling of 18,288 m (60,000 ft). The concept study results are summarized before going into technical issues in implementation. Flag instability is studied in initial wind tunnel experiments. This has forced evolution of the concept to one similar to a hang-glider, the sheet supporting the propelled wing at very low flight speed. Later designs may dispense with the wing altogether. Lift-induced drag can be minimized by joining several elements together in flight to create a large aspect ratio, and by staggering elements in flight as long-distance birds do, with swarm flight control. The primary parameter is the areal density that can be achieved for the reflector sheet under aerodynamic loads. Successful designs can be closed even with 2-mil Mylar sheets, but going to strengthened versions of solar sails would offer strong advantages. Mass-based cost estimation allows an upper bound on architecture cost by comparing equivalent number of launch masses of a well-known large space launch system. The next level of cost analysis shows that the manufacturing cost which is dominant, is best addressed through automotive industry techniques.

Introduction

A surprisingly viable solution to a major global problem is presented, and shown to be most appropriate for implementation by automotive industry approaches. Anthropogenic climate change is one of the most difficult problems of our time. The extraction and usage of primary energy resources is essential to advancing our economic well-being and standard of living. Billions of people wait at the sidelines, eager to access the benefits of modern lifestyles. At the same time, the release of heat and heat-absorbing Green House Gases (GHG), into the atmosphere is causing the temperature of the Earth's surface to rise at an alarming rate. The Intergovernmental Panel on Climate Change (IPCC) [1] in their Assessment Report 5 in 2014, reports that Earth's atmosphere is retaining heat at the net rate of radiant forcing of 2.29 Watts per square meter of the Earth's surface. Normalized to the disc area of Earth seen by the Sun, this gives 9.16 W/sq.m. compared to the 1350 W/sq m of solar energy, called Air Mass Zero or AM0 [2] falling on Earth's atmosphere. The prescribed remedies, even to prevent the rate of temperature rise from running out of control, are controversial as they hurt economies or prevent the advancement of subsistence economies. Island dwellers and people in low-lying coastal areas face rising sea levels because of the polar ice caps melting.

An obvious way to stop Global Warming is to reflect back a part of the sunlight that would otherwise reach the surface. Such a remedy has been proposed by six methods in the past:

1. Reflectors or bubbles in Space [3,4]
2. Chimneys removing CO2 and ejecting purified air.
3. Aerosol clouds released over Antarctica [5,6]
4. Reflective balloons released into the sky [7]
5. Reflective particles released along with industrial exhaust [8].
6. Wind turbines pumping Antarctic sea-water to the ice-cap [9,10].

General Features of the Glitter Belt Concept

Comparison with Space-based reflectors gives an obvious result. The average speed obtained for our aerodynamic flight concept is under 10m/s, compared to minimum low-earth orbit speed of 7500m/s. So Space flight requires 562,500 times the kinetic energy that ours requires. Our solution is to float reflective sheets in the upper atmosphere, nominally at 30,480m (100,000 ft), using means that ensure that they will not sink below 18,288m (60,000 ft or Flight Level FL60, the edge of controlled airspace) in the nighttime. Figure 1 highly exaggerates the sizes of individual reflectors for artistic effect; it also shows that reflectors will be concentrated in efficient bands rather than being uniformly spread over the globe. As seen later: the bands will probably follow the summer, and cross the Equator twice a year.

Reflective sheets of aluminized Mylar, for example, reflect 95 to 99% of broadband sunlight [11]. If made of solar sail material, these sheets can have extremely low areal mass, as low as 70 milligrams per square meter [12]. Assuming reflectivity of 90 percent to account for billowing and other imperfections, the actual reflector area used must be higher than the ideal. In comparison, the radiation level decreases from 1.35 kW/ m^2 (AM0 or Air Mass Zero) at the edge of Space down to 1 kW/ m^2 (AM1) at the ground, and that for only around 4 to 6 hours per day even in the tropics. Assuming a similar absorption ratio on the way back up, a reflector on the ground would thus manage to reflect only about half the incoming radiation out into Space even on clear days. Much of the remainder is absorbed in the troposphere [1], where density is high and the greenhouse gases are mostly present. Thus, high-altitude reflectors are roughly twice as effective per unit area as ground-based reflectors. They also do not need the landowner's permission and can float above the oceans and icecaps as well.

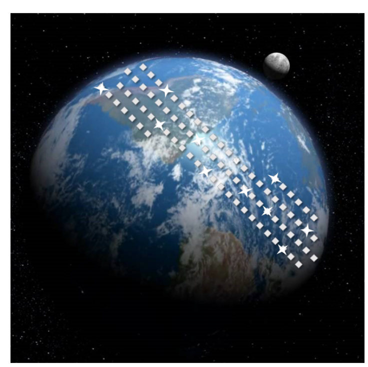

Figure 1. The Glitter Belt concept to cool the planet. An array of reflector sheets floated at high altitude reduces the amount of solar

radiation reaching the lower atmosphere and surface. Highly exaggerated sizes of individual reflectors.

Let us briefly consider the optical/cosmetic impact of this system in Figure 2. The sheets will reflect the sunlight falling on them, back out into Space. So that heat is definitely deflected away from the atmosphere. As shown in Figure 3, diffraction around the edges of the sheet, and the 33 kilometers of light-scattering atmosphere below, ensure that neither the sheets nor their shadows will be visible from the ground. From Space they will be visible as a swarm of bright dots: hence the term "Glitter Belt". At night, the black absorbent lower surfaces will absorb radiation coming from the surface, warming up the sheets. This heat will again be radiated out into Space from the upper surface as absorbed radiation warms the sheets. At night, the sheets might thus be visible in infrared, being warmer than the background temperature of the Earth as seen from Space.

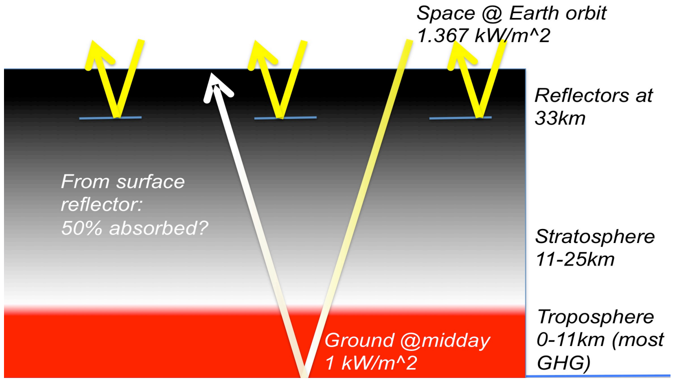

Figure 2. Comparison between high altitude reflectors and surface reflectors

The Numbers

As given in Table 1, the net radiative forcing [1] is 2.29 W/ m^2 of Earth's surface area. Translated to the projected disc area of sunlight falling on Earth, this is 9.16 W/ m^2. Table 2 considers what is needed to cool the Earth at twice this rate. We must reflect back 18.32 W/ m^2 of sunlight over the disc area. This requires 1.36 percent of the disc area. Projected back to the Earth's curvature, we must cover 1.36 percent of the illuminated hemisphere. Since the reflectors cannot keep pace with the Sun, twice as many reflectors are needed, with half being in nighttime at any given moment.

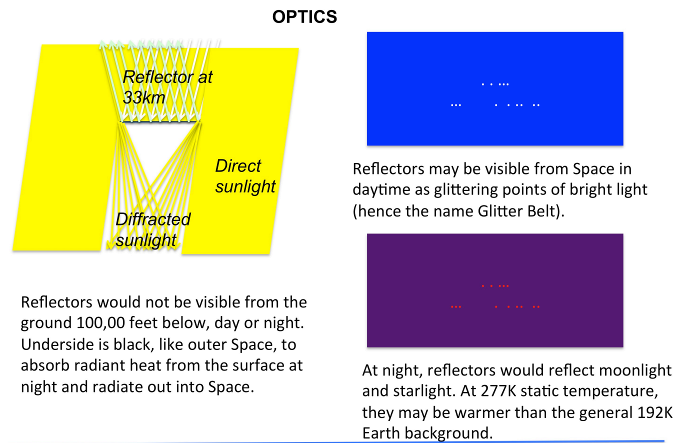

Figure 3. Diffraction around the edges making the sheets invisible from ground.

Table 1. Solar Parameters

Diameter of Earth, m	6347000
Disc area, m^2	3.164E+13
Solar intensity at Earth's orbit, W/ m^2	1.35E+03
Total solar flux W	4.26E+16
Net heat addition W/ m^2 of Earth surface per [1]	2.29
Net heat addition W/ m^2 if concentrated in solar disc area instead of Earth surface area	9.16

Thus, in effect, 2.72 percent of the Earth's surface must be shaded with reflector sheets oriented normal to sunlight, if we are to achieve a net cooling rate equal to today's warming rate. The total reflector area needed works out to be 1.78E12 sq.m., or roughly 1.8 million square kilometers. We imagine a standard 60m span, 30m chord sheet size, with 10 of these forming up spanwise once deployed at high altitude, into a standard high aspect-ratio unit. A total of 108 million such craft will be needed, distributed worldwide. In other words, essentially a billion of the 60m x 30m sheets, or equivalent area in whatever form.

Table 2: Global Cooling Parameters

% to be reflected back	1.36
Flux reflected, W	5.80E14
Reflector area at 90% efficiency converted and doubled to cover both hemispheres, m^2	1.89E12
Span of craft, m (10 joined side by side)	600
Length, m	30
Total 600m x 30m craft needed worldwide	1.08E+08

Several reductions are immediately apparent. We need not start cooling the Earth as fast as it is now heating: just stopping the heat increase will suffice, giving GHG-reduction and other "behavioral modifications" time to take effect. That earns a factor of 2. Another factor of 10 can surely come from intelligent prioritization of the reflector locations and distribution. For instance, a band of closely-spaced reflectors directly under the Sun's track would be much more effective than a uniform distribution over the Earth's surface, earning a factor of 2 or more because of the intensity gain. Following the summer sun should gain another significant factor. Prioritizing the peripheries of the ice caps (see Polar Necklace below) might stop the sea-level rise. In the following, we will ignore all these and estimate costs for 1 billion 60m x 30m reflector vehicles. Clearly this a conservative upper bound.

Upper Bound on Cost

The total area of reflector sheet derived above, certainly appears daunting. However, with solar sail material of areal density 70mg / m^2 (5E-5kg/m^2) for the Lattice Sail per [12] the mass to be floated is 132 million kilograms. We use two assumptions:

- Eventual system mass will be dominated by reflector mass.
- Aerospace system cost analyses simply scale cost by mass.

Thus the architecture cost is roughly bounded above by comparing the mass placed at altitude with the equivalent number of launch masses of a well-known large space launch system – although we are not launching to orbit, only to a very low-speed ascent to 1/10 of the altitude, and a tiny fraction of the kinetic energy, of Low Earth Orbit. Consider that a Space Shuttle at launch has a mass of roughly 2 million kilograms [13]. So the mass to be floated is close to that of 66 STS launch masses, if we succeed in going to solar sail areal density.

Solar sail material may not withstand aerodynamic forces. A conservative assumption of a practical effective areal density is 10 times what we stated above, or 0.7g/m^2. The total mass is now equivalent to that of 660 STS launches. At an estimated $1.5B per launch [14], the upper bound on cost is thus $990B, or rounded off to 1 trillion dollars. Real cost should be much less, since Space Shuttle is much more complex than that of floating millions of identical configurations at low speed. Even $1T spread over a decade is a bargain to bring the Earth rapidly back to the heat retention of 30 years ago. This need not cut into efforts to continue reducing atmospheric GHG. In fact it is surprisingly viable, which is what motivated the our work. As noted before, prioritization should cut costs much further.

Atmospheric Conditions

Table 3: Standard atmospheric conditions at 100,000 feet [15]

Altitude, m	30500
Temp K	227
Density, kg/m^3	1.67E-02
Viscosity	1.49E-05

Our initial calculations use standard atmosphere conditions at the selected daytime reflector altitude of 100,000 feet (30,480 m). Significant variations are possible. Winds are minimal over much of the planet at that altitude, but can be too strong over the Jet Stream [35] for the propulsion systems to keep station. Flight planning and control can avoid regions such as hurricanes, Jet Streams and polar vortices, and increase the concentration of reflector sheets at calm places.

Overview of Concepts

In this paper we will discuss three proposed implementations of the Glitter Belt, shown in Figure 4. The first is the Flying Carpet: a reflective lifting sheet pulled along by a solar-powered, propeller-driven set of flying wings. The second is the Quadrotor Beanie, where 4 centrifugally stabilized reflector sheets and solar-powered rotors hold up their own weight. The third is aerostatic: hydrogen balloons supporting the reflector sheet, again with rotors at the periphery providing control, transportation and station-keeping in wind when needed. Below we consider each concept in turn.

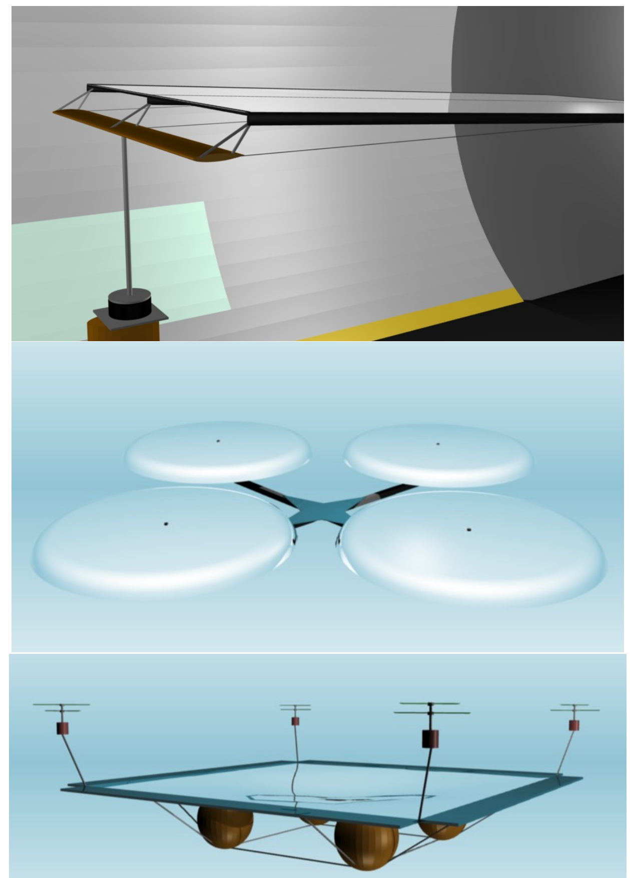

Figure 4. Three concepts to implement the Glitter Belt. Top: The Flying Carpet, an aerodynamically supported reflector. Middle: Quadrotor Beanie, Centrifugally stretched reflectors. Bottom: Balloon Beanie: Sheets supported by hydrogen balloons

Aerodynamic Solar Reflector: Flying Carpet

The basic element of the "Flying Carpet" reflector array is a rigidized sheet towed by a solar-powered, distributed electric-propelled fixed flying wing. The design point requires that night-time gliding descent must not come below 28,288 meters (60,000 feet or FL 60) density altitude. We set the daytime cruise altitude at 100,000 feet, reflecting essentially 1300 W/ m^2. Initial calculations conservatively use the sink rate at 100,000 feet, constant for 12 hours: actual sink rate will decrease as density increases. Unlike the NASA Pathfinder[16,17] and Helios[18] aircraft, we do not expect to need or provide any onboard energy storage except that of gravitational potential energy.

Low sink rate requires a high lift to drag ratio and low flight speed. The latter requires low wing loading to avoid extreme lift coefficients. The NASA Pathfinder and Helios solar-powered aircraft had difficulty exceeding 96,000 feet [19]. The Flying Carpet has an extremely low wing loading and thus needs minimal lift coefficient. The 30m chord was chosen because we expect laminar flow up to a chord Reynolds number of 1 million [20]. In later versions, active cambering of the sheet structure can ensure that the area aft of the nominal transition line is actually at incipient flow separation, hence ensuring a skin friction close to zero. Thus as the Flying Carpet evolves to to use much lighter solar sail material, the sheet size can be increased, perhaps by a factor of 10 to 100. The default presumption is that at takeoff from the ground, the Flying Carpet will be rolled up or stacked as broad sheet segments into the flying wing that tows it after deployment. In this case, wing and sheet span may be limited by runway width. An alternative is to use Origami techniques and pack the sheets into a wing of much lower span. A large span, ultralight ***aircraft could*** take off across a runway and climb fast enough to avoid obstacles. Deployment and recovery options are deferred beyond ensuring that there are viable and safe land-based launch and water-based force-down options.

While the reflector sheet easily supports its own weight with very small lift coefficient, the skin friction and induced drag components are large. The latter is easily minimized by joining several elements together in flight to create a large aspect ratio, and by staggering elements in flight as long-distance birds such as Canadian geese do [21-23]. Unlike birds, there is no flapping wing motion involved in this case, so it is feasible to position wingtips of perhaps 10 adjacent sheets contiguously to achieve a high effective aspect ratio. Thus we treat the basic aerodynamic component to be one of 600 m span by 30 m chord. The upwash effects of V-formation flight can then be achieved by positioning several (perhaps 25) such components in a closely spaced V formation. The primary parameter for this solution is the areal density that can be achieved for the reflector sheet without tearing due to aerodynamic loads: thus avoiding wind fluctuations and self-excited oscillations is of paramount importance.

Successful designs can be closed even with 2-mil Mylar sheets, but going to strengthened versions of solar sails would offer strong advantages. There is no anticipated need to stay aloft through nights longer than 12 hours, since the craft will migrate with the summer, North or South. There is not much point in reflecting the winter sun. The 12-hour requirement is imposed not because we want to deploy over the Equator much, but because the craft have to cross the Equator.

Centrifugally stretched aerodynamic reflector system

The second and third concepts are discussed and compared in a companion paper at this conference [24]. The second concept is a quad-rotor where each rotor consists of a slowly-spinning set of reflector blades at the edge of a large reflector hub. Energy storage is by a combination of altitude, rotational inertia, and tip-mounted batteries, possibly combined with slow edgewise flight similar to that of a helicopter or gyroplane in autorotation. The 50m diameter rotor has 15 to 24 blades and a hub extending to 50% of the radius.

Aerostatically Supported High-Altitude Reflector

The third concept is to support the reflective sheets above a set of hydrogen balloons. Some form of light, rigid structure will be required. The optimal form for the reflector sheet is probably a circle, stretched over an inflated ring or series of concentric inflated rings with radial supports. This concept avoids the need to provide continuous aerodynamic lift, and therefore breaks through the nighttime glide issue. Solar-powered rotors around the periphery provide trim, counter winds, and allow the twice-a-year migration. Some energy storage maybe added to provide emergency power at night. The issue of hydrogen leakage is addressed with a double-shell provided with an evacuation pump in between. The shell structure can be made with present materials, but in future may offer opportunities for advanced ultralight materials such as Silica AeroGel. The reflective coated Mylar membrane reduces the tilt needed to reflect evening, morning and polar summer sun. The size of the inner hydrogen-inflated shell can vary, constrained by the dimensions of the outer shell, so the risk bursting when exposed to direct sunlight is alleviated. Perhaps endurance will be limited by UV degradation, radiation hardening or tearing due to micrometeor impact. The standard temperature at 33,000 meters is a balmy 277K, but nighttime extremes are not yet known.

The Polar Necklace

Now we will discuss some concepts to improve the effectiveness of the first deployed systems. The most urgent visible symptom of Climate Change is the breakup of the Antarctic Ice Shelves [25]. These are large sheets of ice formed by the flow from glaciers coming off the higher elevations of Antarctica. Large portions of these are floating on the ocean. As ocean temperature increases, the sheets get thinner. Fractures appear. Large chunks drop into the ocean and float away. Their melting raises the mean sea level. Thus the problem is not so much the heating of the Antarctic plateau, but the rise in the sea level bordering Antarctica. By decreasing summer sunlight on the ocean at the coastline, melting may be reduced below winter freezing enough to reverse the present trend. A circular array of reflectors located south of 67 degrees Latitude (the Antarctic Circle) in summer should suffice. Kawai [26] has suggested ground-based reflectors at polar latitudes to assist this; however, installation costs and acceptability of such reflectors are not addressed. Even in summer, the polar sun is fairly shallow, and hence reflectors must incline at a steep angle to be normal to sunlight. The Flying Carpet may use symmetric, high-anhedral sheets. This may be an efficient short-term compromise. Quad-frisbees will also have trouble with large inclinations since they also depend on aerodynamic lift to balance gravity. However, the Balloon Beanies are well suited to this problem, since the lift needed from the balloons is the same at any inclination. The rotors on the system will help maintain trim and change direction to follow the Sun through each (long) day.

Semi-Annual Migration

The reflectors can be moved constantly to best reflect sunlight. Since the Flying Carpets are nominally horizontal, a long banking maneuver may be one option. Unlike birds that wait for late autumn and spring before undertaking long flights, the reflectors can be drifted slowly and continuously to track the midsummer Sun daily as the seasons change over the planet. The drift speed required is miniscule, well under 1 m/s.

Glacier Shading

Another concept is to locate reflectors above the mountain glaciers and tundra, to hinder summer melting. We considered whether the Balloon Beanies could be tethered above mountain glaciers, but does not compete with high-altitude reflectors. Glacier shading is best done by locating swarms of reflectors at 33km generally above the glaciers.

Who Will Pay For Global Cooling

While generally out of the scope of a technical paper, we must discuss this briefly because it is the only apparent "show-stopper" left. No one except perhaps the United Nations has any strong impetus to pay for the significant expense of global cooling. There is one quick and direct solution: this is for governments to recognize expenditure on the Glitter Belt by the amount of cooling achieved, converted to equivalent metric tons of CO_2 removed from the atmosphere. Such an equivalence can be obtained by inverting the calculation that gives the net radiant forcing rate from the number of tons of CO_2 already released into the atmosphere annually, converted to a continuous rate. References [27,28] from US Federal government labs propose such a generous equivalent for painting paved ground and roofs white.

Towards a Flying Carpet Demonstration

The biggest practical difficulty with a laboratory Flying Carpet demonstration so far is self-excited oscillations. Our objective here is to arrive at the simplest and least expensive configuration. The simplest concept was a sheet trailed behind a self-propelled, solar powered wing. Flag flutter instability is known to increase the mean drag by as much a factor of 7. Several wind tunnel tests with 7-MIL Mylar sheet all encountered flag instability.

The first test had sheets of different aspect ratios trailing behind a lifting wing in a wind tunnel. Each sheet was fixed under the leading edge, and allowed to trail back from there. This was to simulate a scheme where the sheet unrolled through a slit in the bottom surface of the fixed wing, the slit being located far upstream, close to the leading edge. This was done to enable a roll of sheet material to be located inside the torque box of the wing.

The large aspect ratio sheet did remain steady at low speeds as shown in Figure 5 (top); Reynolds number scaling makes this an adequate demonstration of stability at the high-altitude full-scale condition. However it exhibited large-amplitude waves in the spanwise direction at higher speeds, while the small aspect ratio case exhibited mostly chordwise waving. Next, a semi-rigid trailing edge was fixed to the sheet: a tube made of drinking straws, faired over with tape. This inhibited spanwise instability but allowed chordwise waving. The flutter was violent enough to rip off parts of the sheet, even at relatively gentle wind speeds of a few meters per second. Installing chordwise supports also made of drinking straws, was only partially successful.

Large spanwise slots were provided aft of the trailing edge to permit the disturbed flow over the wing to pass unhindered through the slots. This however did not stop the flag instability, as shown in Figure 5 (bottom). The rigidized sheets were also held above the wing. The packed and deployed configurations are shown schematically in Figure 6. This arrangement also exhibited instability, thereby proving that it was a self-excited instability of the sheet, not a disturbance propagating downstream from the wing.

Figure 5. 5:Wind tunnel tests of the Flying Carpet. Top: High aspect ratio sheet attached to the bottom of a flying wing, remaining steady at low wind speed. Bottom: Sheet exhibiting periodic flag flutter instability.

Tethered sail model of the first flight test system

When the overall concept was conveyed to several (friendly) reviewers, their main requirement beyond the initial questions, was about the flight test process. Our first concept design is for a system that can fly perhaps in 3 months from project start, using retail mass-market components. The key component is 1-MIL (25 micrometer) thick alumnized Mylar sheet, available in small rolls from mail-order suppliers. We can test this material in our lab and wind tunnels. Note that areal density of this sheet in Table 4 is roughly 500 times the ultimate solar sail material value. The deployed system will use much thinner and lighter sheets with ultralight structure.

Manufacturing Cost Estimate

Mylar is a polyester film made of Biaxially-oriented polyethylene terephthalate (BoPET) developed at the 3M company in the 1950s. The NASA ECHO-II launched in 1964 [29] was a 40m diameter hydrogen balloon made of 0.35MIL (9 micron) Mylar sandwiched and bonded between two layers of 0.18MIL (4.5 micron) aluminum foil. As discussed before, the sheet thickness of the flight test concept developed above, is 500 times that of the ultimate solar sail design considered. In addition, the weight per unit area comes out to be 3.3 times that of the sheet alone, which suggests that the design is terribly sub-optimal. This is mainly because we have no good way yet to estimate the structural mass needed to build the flying wing that is to support the solar cells and the motors and propellers. The estimation so far is over-conservative, and the mass addition to that of the sheet is quite small in the final design. The energy cost of manufacturing the film is estimated as follows. The Carbon Footprint of BoPET film manufacture is estimated at 5.6 kg equivalent of CO_2 per kg of the material by a modern competitor to BoPET [30]. Much of this is energy that comes in electric or thermal form. The US EPA [31] estimates that grid baseload energy is equivalent to 5.55E-04 kg of CO_2 per kWh as of 2012. For the 1MIL sheet of PET used in our model, this works out to a total energy cost of 2.23E12 kWh for the full system. Compare this to the solar energy reflected per year by the system in one year, which is 5.85E15 kWh. Thus the energy cost of the system is compensated within 4 hours! The energy cost of the aluminized layer is not included above, nor is the fact that in the present flight test design, the total mass is 3.3 times the sheet mass. Even allowing for a factor of 10 due to these errors, the energy cost is recovered inside two days. With the much-thinner sheets that we expect to achieve for mass production, there is thus considerable leeway for much more energy-consuming technologies to be used.

With the present system, the manufacturing cost dominates uncertainty. The material cost is relatively small, and the expected cost of operating a global traffic control system that will optimize the performance and ensure the safety of the constellation of deployed sheets, is under $60M/year. Combined with the Aerospace Learning Curve [32], the manufacturing still appears to be most similar, not to current aerospace examples in the civilian world such as the Goodyear Blimp [33] which is mostly hand-crafted in very small production runs, but to automobile manufacturing. The flying vehicles are not anywhere nearly as complicated as automobiles, but scaling off the weight of an automobile gives reasonable numbers for manufacturing cost. Based on the above, a first-cut cost estimation can be done for the Flying Carpet architecture, based on the flight test system proposed above. The mass per 600m x 30m unit is roughly 2100 kg. The retail price in the USA (Atlanta, Georgia) of the Toyota Camry family sedan [34] comes out at a cost per kilogram of $13.2. We assume that the Camry comes with a learning value corresponding to 1 million units, and
hence scaling to 108 million such units brings the per unit cost by another factor of 1.68 using the Aerospace Learning Curve.

At this stage the Flying Carpet is far sub-optimal. The ratio of total mass to reflector sheet mass is 3.3. Bringing this down close to 1.0 must wait until technical issues are resolved, and the tractor wing is reduced to the bare minimum. On the other hand, we expect this ratio to level out where further improvements are costly in technology investment.

Table 6: Night-time gliding characteristics

Total W/S	0.9988
Total Lift, N	20575
Total Drag,N	405
Total L/D of vehicle	51
Glideslope=ATAN(D/L)	0.01969
Sink Rate m/hr	890
Max altitude loss in 12 hrs, m	10679
Min Altitude reached in 12 hrs, m	19821

Table 4: Vehicle Design-Derived Figures: Reflective Sheet

Span,m	650.00
Chord:	4.00
Planform Area, m^2	2600.00
Aspect Ratio	162.50
Areal density of wing kg/ m^2 of planform	0.50
Cruise wing loading	1.00
Chord Reynolds # of wing	5.61E+04
CL	7.61E-01
CD Total of Wing	6.87E-03

Table 5: Tractor Aircraft Figures

Sheet Wing loading, Pascals	1.143
CL	8.70E-01
Speed, m/s	1.26E+01
Dynamic Pressure q	1.31E+00
Chord Reynolds Number	4.21E+05
CD viscous	4.09E-03
CD induced	1.20E-02
CD total	1.61E-02
Drag, N	3.82E+02
L/D	5.39E+01

As argued above, the mass of this Flight Test system concept is as much as 500 times that of what we believe can be achieved with solar sail technology. However, other costs may be incurred. The 1.73 trillion, spread over a decade, is still a cheap price to pay for a net cooling rate equal to today's global warming. A 100-fold cost reduction that appears possible, would reduce the full system cost to something quite surprisingly viable. That is the main point of this paper: *Reversing global warming entirely is well within our grasp*.

Looking ahead, such a project could be funded from industrial sources, particularly airlines, which have carbon quotas to meet. They would be funded as equivalent CO2 reductions. Investments in reducing the areal density and increasing the high-altitude longevity of reflector sheets have a direct and immediate payoff in architecture costs. Several different designs will be fielded initially at the highest-priority areas, with the production numbers expanding as the cost per unit reflected sunlight comes down. We expect that production will be distributed worldwide, with market consolidations depending on the funding sources and constraints.

Discussion

Winds can be too strong over the Jet Stream [35] for the propulsion systems to keep station. Flight experiments by NACA in 1940 [36,37] to study thunderstorms reported that only 13 out of 185 storms measured exceeded 15,240 m altitude, the average being about 9,100 m. Chances of lightning are almost nil because lightning forms as a result of a negative charge buildup in the bottom of cumulonimbus cloud, and a positive charge buildup on the ground. Typically clouds do not exist beyond 15,240 m [37]. Rarely, electrical discharges known as "sprites" occur above storm systems [38], which was attributed as a possible cause for a NASA balloon malfunction in 1989. Sprites are still not fully understood, and happen infrequently. Therefore, it is a safe assumption that flying above 60k ft would not put the flying carpet at risk of lightning strikes. If a few catch fire and disintegrate, the descent can be designed to be quite benign.

The amount of sunlight reflected, can be measured and accounted immediately. Once the system reaches several million reflectors, climate impact should become evident, assuming that today's climate change models are valid. Only about 50 to 100 million strategically positioned reflectors will be required, with costs collapsing to a small fraction of what we have projected for the flight test models.

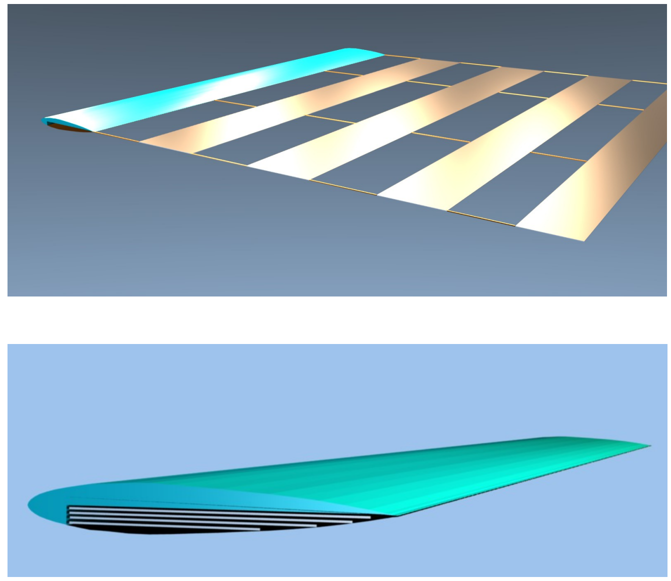

Figure 6. Slotted design for high-aspect ratio rigidized reflectors. Top: deployed form. Bottom: Launch configuration with reflectors packed into flying wing

Summary of Uncertainties

The development towards a global system of such massive payback potential, certainly opens many areas for research and development. For the first flight tests, very little new research is needed. However, huge improvements are possible in the following areas:

1. Learning to hold thinner sheets steady in aerodynamic flight at high altitude.
2. More refined models of upper atmosphere temperature variations and winds to guide vehicle design.
3. Studies of benign failure modes to ensure that any crashes do minimal damage.
4. Research to develop ultra-thin sheets that can withstand upper-atmosphere conditions for an extended period.
5. Manufacturing processes for this class of vehicles.

Conclusions

The development of the Glitter Belt concept is still at an early stage. Several points are seen to-date:

1. A set of reflectors at high altitude can reflect sunlight back into Space, reducing solar heating of the atmosphere.
2. While the number of such reflectors needed is several hundred millions, the overall cost over a decade is quite moderate.
3. The upper bound on cost is derived by mass-based estimation, compared to that of the US Space Shuttle Transportation system. This gives an upper bound of $450B with existing sheet materials, with the possibility that the limit can be brought to $45B with ultra light solar sail material in future.
4. Three types of concepts are presented: A fixed-wing aerodynamically supported reflector sheet (flying carpet), a

rotary-wing quadrotor, and an aerostatically supported sheet with hydrogen-filled aerostats providing the lift.

5. The flying carpet concept is considered in more detail. Several design variations are considered. Self-excited flag flutter is the major issue limiting use of simple trailed sheets. A tethered hang-glider mode of operation appears to be practical.
6. In-flight rendezvous is proposed to increase the effective aspect ratio of the flying carpet while permitting takeoff from existing fields. Formation flying further improves efficiency.
7. The ability to stay above FL60 is demonstrated in concept estimation for the Flying Carpet, while using only the gravitational potential for energy storage.
8. A bottom-up cost estimation reveals that manufacturing dominates the cost. Similarities to automobile assembly line manufacturing are evident. The total cost for the Flying Carpet architecture, even at the flight test-ready technology available today, is bounded at $1.73Trillion.
9. With expected improvements, the total cost to completely reverse global warming appears to be well within our grasp.

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