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An Aerospace Approach To Counter Climate Change

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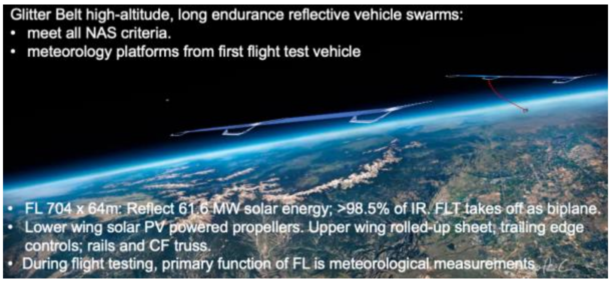
Abstract—Combating Climate Change requires temporally and spatially-resolved atmospheric and solar data planetwide. The Glitter Belt HALE architecture of reflective vehicles serves both as meteorology platforms and as a scalable, reversible option to reduce insolation. The 30.5km altitude and 12-hour night glide requirements, rendezvous and swarm operation for high-precision distributed antenna applications all pose unique challenges, but are shown feasible with the present approach. Conceptual design, small scale design-build-fly tests, and dynamic flight simulation are used to remove uncertainties and derive system properties. Scale-up to reduce atmospheric heat retention is viable in concert with GHG reduction and efficiency improvement measures. Given international will, Global Warming can be controlled in verified, safe and reversible manner that uniquely satisfies all guidance from the National Academies.

Keywords—Glitter Belt; Flying Leaf; Flying Leaflet; Solar Reflection; UAV swarm

I. INTRODUCTION

There are 4 obvious contributors to atmospheric heat retention. The first is solar input. The second is heat input from the surface and atmosphere from (a) natural and (b) anthropogenic sources. The third is the presence of Greenhouse Gases that absorb and retain energy in the infrared spectrum. A possible fourth is heating of the Near Solar System by the Solar System bow shock. The fourth has been ruled out for the present, since Deep Space probes have not detected any appreciable shock strength, suggesting very low density of the local Galactic gas cloud. Part 2(a) comprises geo-thermal heat as from volcanic eruptions, increased radiation due to decreased albedo (icecaps melting). Part 2b) includes increased reflection into a more absorptive atmosphere, due to deforestation and urbanization. However, the vast majority of 2b) is the emission of waste heat from heat engines of human progress. The third contributor (GHG) receives the overwhelming majority of attention from the scientific and political community among the industrialized nations, with developing nations following suit due to pressure and lack of indigenous scientific capability. The list of topics for this conference exemplifies this.

Incentives to reduce fossil fuel use, GHG emissions and increasing thermodynamic efficiency since the Kyoto Protocol of 1992, have produced significant results, but not enough to even reduce the rate of increase of Warming [1,2]. Rising urgency has been repeatedly derailed by other major events such as economic downturns, COVID-19 pandemic, conflicts and political instability. This has brought back sharp divisions between industrial nations who emphasize drastic emissions in carbon reduction [3-5] and less developed nations who must find ways for their populations to adjust.


Glitter Belt high-altitude, long endurance reflective vehicle swarms:
- meet all NAS criteria.
- meteorology platforms from first flight test vehicle

- FL 704 x 64m: Reflect 61.6 MW solar energy; >98.5% of IR. FLT takes off as biplane.
- Lower wing solar PV powered propellers. Upper wing rolled-up sheet; trailing edge controls; rails and CF truss.
- During flight testing, primary function of FL is meteorological measurements.

Fig. 1 Glitter Belt Concept. From prior work of the authors by permission.

Thermodynamics dictates the efficiency of heat engines. Alarmingly, Smil [6] shows that overall heat engine efficiency of the US economy rose from about 14% circa 1900 to over 50% by 1950, only to come down to about 33% with a vastly increased magnitude. Some of this is attributed to conversion from mechanical to electrical energy, and the prevalence of air conditioning as standards of living rose.

Under this reality, it is hard to see how the less developed nations can place much credence on the demands from the developed nations to accept sharp changes in lifestyle and earnings.

While the above debates dominate the news, it is becoming clearer that direct reduction of solar input or other direct intervention (also called Geo-Engineering) will be essential [7-12] to buy time to adjust to Climate Change. The US National Academy of Science, for instance, came out with a rather hurried report [13] in January 2021, whose primary aim appeared to be to discourage and deter efforts to reflect sunlight - other than one approach involving injecting atmospheric aerosols from aircraft over the Tropical Zone in order to mitigate Climate Change over the Temperate Zone. More recent work has pointed to some questions and concerns, as expected from any such intervention technique [14-22].

The above suggests that the present exclusive focus on GHG reduction faces poor prospects to actually slow down, much less reduce, Global Warming (best represented by the rate of atmospheric heat retention rate, AHRR). A return to a more objective view of the entire problem – and assessment of global will to implement real solutions – appears to be essential.

The approach described in this short paper comes under Mitigation Technologies, in fact the much-reviled "Geo-Engineering", and specifically its most despised form, Reflecting Sunlight. This paper shows why it is (a) technically feasible, (b) economically viable, indeed economically viable, (c) transparent, (d) politically viable and (e) scientifically responsible. Indeed it goes beyond, with clear benefits to meteorological prediction, climate modeling, disaster warning and response. The first 5 aspects are considered using the wisdom set out by the US National Academies of Science in early 2021 [13].

The resulting architecture weaves the crucial step of meteorology and climate monitoring for simulation, right into the project. The Consortium structure goes beyond mere scientific collaboration and transparency, to give all nations actual partner status. It presents a proposal for Nature Credits for all nations to do what makes sense for their own national priorities. Welcome to the Glitter Belt.

II. THE GLITTER BELT

A. *Basics*

Basic optics and thermodynamics prove that if a part of solar radiation is reflected back into Space before it heats the atmosphere, the amount of heat retained in the atmosphere will decrease. How can this be accomplished with reasonable parameters? The first observation is that putting up reflectors in Space is hugely impractical. A minimum delta-V of 7500 m/s (delta-v being defined as the square root of twice the total energy input) must be imparted to get to any stable orbit, meaning over 28 MegaJoules per kilogram placed in orbit. Given that orbital payload is well below 10% of the launch mass of any present launcher, the actual number is over 0.3 GW per kilogram of payload. Dumping the exhaust from this much energy, typically from combustion at extremely high temperatures, into the atmosphere, would greatly aggravate the problem that is to be solved. Given that the cheapest large-rocket launchers today use several solid fuel or acidic liquid fuel modules, the atmospheric pollution would also be prohibitive, at least in public opinion.

However, reflectors do not have to be in orbit. The Glitter Belt concept (see Fig. 1) is to place a large number of ultralight reflectors at 30.5 km (roughly 100,000 feet) altitude. Absorption above that level is negligible, so the full AM0 solar intensity is reflected into Space. The most obvious reflectors are thin Mylar sheets aluminized on one side, with an IR-absorbing layer on the ground-facing (lower) side to catch night-time radiation from below. Nominal thickness of mass-market sheets is 25 micrometers (microns), but far thinner sheets can be made, as for Solar Sails. The power source to lift and keep these at 30km is solar photovoltaic, so the net energy input for launch and altitude-keeping is zero, compared to the 0.3GW/kg of Space-based solutions. There is no pollution at all, no perceptible noise beyond those of small propellers and electric motors at startup, and no visual pollution. Being above the "blue sky", the reflectors will not be visible to the unaided eye from the ground, day or night.

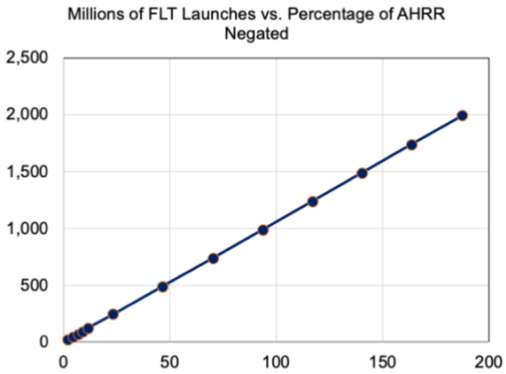


Fig. 2: Millions of Glitter Belt Flying Leaflet launches needed to achieve given levels of reduction in Atmospheric Heat Retention Rate

There are 3 basic approaches to holding such sheets steady, smooth and stiff at altitude. The first is linear aerodynamic: pull them along so that they act as lifting surfaces. The second is also aerodynamic but as rotating wings: centrifugal stretching like a spinning parasol. The third is aerostatic: slung between several lighter-than-air (hydrogen-filled) balloons. We discuss only the first here, with passing refence to the second for scaled-up designs.

The linear aerodynamic reflector is called the "Flying Leaf" (FL). The vehicles used to form FL reflectors that are too large for runways, are called Flying Leaflets (FLT). Fig. 3 shows the FLT and FL. As conceived, the FLT is a solar-powered biplane where the upper reflector "wing" is extensible in chord as the vehicle climbs into the smoother stratosphere. Approaching 30 km, FLTs rendezvous with each other. Once an FL is formed from 11 FLTs, 8 of the 11 lower wings with propulsion systems detach and return to base, to transport the next FL to altitude. The formed 11-sheet FL starts its night-long glide until it picks up sunlight and climbs at dawn. This process is illustrated in Fig.4.

The rest of the paper is organized as follows: An initial "sanity check" is presented on system size and cost, for interventions for different levels of reduction in atmospheric heat retention rate. Next, generalized conceptual design results are given for the linear aerodynamic vehicles.

Initial uncertainty reduction used ground and small-scale unpowered tests and then powered tests. These provided structural and stability guidance, feeding into flight simulation. Dynamic flight simulation has been used extensively to prove different parts of the mission profiles, and to design the first 16m-span FLT prototype to be built at a university for coastal flight testing. A table presents how this solution more than satisfies all valid concerns posted in the NAS 2021 report, which also drives some of the initial plans. An argument is presented on the viability of the project, along with a proposed Consortium structure. The brevity demanded by length constrains is addressed by referring to publications already in the open literature.

III. INITIAL CHECKS

A. *Project Scope*

For simplicity we use conservative numbers. Many details and complications help or detract, but not by large amounts. The United Nations Inter Governmental Panel on Climate

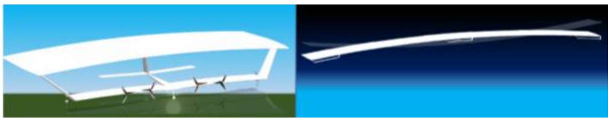


Fig. 3: The Flying Leaflet (FLT) and the Flying Leaf (FL) formed from 11 FLTs with 8 carriers released.

Change (IPCC) estimates that Earth's atmosphere is retaining 2.92 Watts per square meter of Earth's total surface area. Thus the objective of the present calculation is to see what reflector area might be needed to reduce this Atmospheric Heat Retention Rate (AHRR) by specified percentages – and what that implies in mass, energy, cost and other impacts. Reflectors will be roughly parallel to Earth's surface, and only those on the daytime side will be effective. Heat retention may depend on the slant angle of the Sun's rays, spectral content and cloud cover. Mylar reflectors are experimentally proven to reflect up to 98 percent of the solar InfraRed (IR) spectrum even at a shallow 30 degrees solar azimuth (60 degrees specular incidence angle). Solar input of 1367 W/m^2 (Air Mass 0 or AM0, at Earth's orbit around the Sun) falls on the projected disc of Earth's area, and the Earth's spin changes the effectiveness of each reflector with time. With all these caveats, Fig. 2 shows that roughly 2 million square kilometers of reflector area at 30km altitude would cancel out the present AHRR, and 4 million square kilometers would start cooling the planet at the same rate (-2.92 W/m^2 AHRR). This is assuming that all other national and international efforts to control Global Warming achieve nothing more than keeping AHRR at the present rate. An optimistic view is that a 50% reduction will be achieved by reforestation and other GHG reduction. With the basic Flying Leaflet modules that we propose to launch, each resulting in a 32m x 64m reflector being added, reducing 100% of AHRR would require roughly 2 billion launches, meaning that it has to be a widely distributed global effort, spanning 10 years given the urgency of the need. Launches can only be done on clear calm summer mornings, as explained later. The total mass delivered, at the weight target of 1 N/m^2, is nearly 0.5 billion Metric Tons. Launch energy is entirely from the Sun. Unlike fossil-fueled tankers to carry sun-scattering aerosol liquid to the stratosphere, or space launchers, there is no launcher exhaust to pollute or heat the atmosphere. Importantly, our launches will only need a clearing with firm ground, not airport runways. In fact, few airports would want them in the vicinity, given how long it might take them to clear the airport's airspace at their very slow speeds.

B. *Initial Cost Estimation*

The simplest cost estimation rule for aerospace projects is that cost scales linearly with mass launched. The number of launches and the mass launched, are both topics of interest here. Let us compare the ambitious-sounding numbers above with present operations. The Boeing 787 airliner is one of many types that are in present service. Roughly 1000 of this model are in operation, and we conservatively estimate that each takes off twice a day, 300 days per year. Each weighs roughly 228 MT. In other words, just this one type of airliner would account for over 0.5 Billion MT of launches inside 3 years.

The cost per square meter of GB vehicles may be comparable to that of an equivalent weight of jet fuel at today's prices. Roughly 30 percent of the 787's takeoff weight is hydrocarbon fuel that is expended in each flight, burned in the atmosphere. Thus the cost of the Glitter Belt is quite modest, assuming that there is a global will to stop and reverse Global Warming beyond holding conferences to which experts fly across continents on said airliners. At this stage, more detailed cost analysis is not warranted. The initial expenditure is on prototype development and testing, in concert with installation and operation of monitoring facilities all over the world. These are justified by the unique meteorological and climate simulation validation data benefits of the project. Beyond that, the scale up is mostly achievable with automated facilities and a widely distributed launch program. A self-sustaining source of revenue is discussed later.

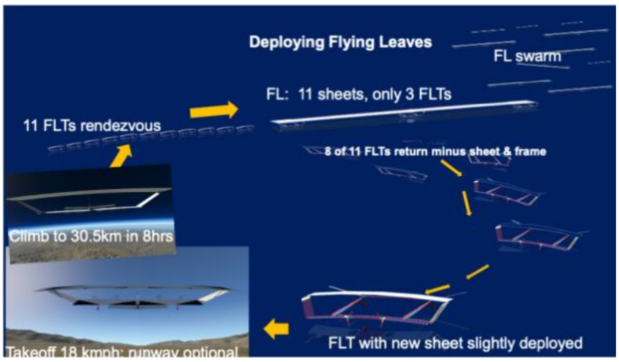


Fig. 4: Typical launch and rendezvous mission profile

IV. GENERALIZED CONCEPTUAL DESIGN

In prior work we have discussed the Glitter Belt architecture [23-24]. It proposes a steadily growing number of solar-powered ultralight reflector surfaces, floated at about 30.5 km above mean sea-level and staying aloft continuously for periods of months if not years. The design altitude ensures AM0 sunlight intensity, and negligible absorption of reflected light back into Space. Yet, air density is adequate for aerodynamic lift. The Sun is visible over the horizon several degrees below the horizontal, so that durations of reflection and power generation both exceed the day length as seen at the ground below.

A. *Staying Above Controlled Airspace*

The primary design challenge is to ensure that the solar-powered platforms do not descend further during the night, than they can climb during the day. The rough troposphere can kill ultralights. The stratosphere is criss-crossed by human-carrying airliners at transonic speeds. Thus the requirement that we imposed is that the platforms had to stay above Controlled (Class A) Airspace, which is 60,000 feet or 18.3km MSL. The maximum length of night, during which no solar power could be generated, was set at 12 hours. This is because it is much better to reflect sunlight at the height of summer. Hence, reflector swarms will "follow the summer sun", drifting northwards or southwards at a steady 1m/s. Equator-crossing twice a year poses the 12-hour night – but as noted before, the sun can be seen about 10 to 15 degrees below the horizontal plane, adding a few minutes. Elementary aerodynamic performance calculations translate this requirement into a simple result. The Wing Loading (W/S or vehicle weight divided by lifting area) must not exceed 1.25 N/m^2, nor must the profile drag coefficient exceed 0.025. Desirable values are 1N/m^2 and 0.02. No doubt this challenges both aerodynamic and structural design, but both are feasible, as we have proved.

B. *Distributed Global Ownership and Operation*

Initial work [25,26] showed basic features of the architecture, and its overall feasibility. Given the large reflector area needed to make a significant impact, and the large number of vehicles to be built and launched to build such an area, the initial architecture considered ways to reduce manufacturing cost through standardization and simplification. Such a project, which will benefit or otherwise impact most of Humanity, must also include participation by most nations. Hence manufacturing, launch, monitoring and retrieval/maintenance facilities will be spread all over the planet. These considerations have first-order influence on design decisions, in contrast to most High Altitude Long Endurance (HALE) vehicle projects which focus on ownership by a single nation with possible exports to a few others. This is a global endeavor.

C. *Basic vehicle types*

Initial architecture is comprised of only two kinds of vehicles. The Flying Leaflet (FLT), shown on the left side of Fig. 3 is a biplane with the upper wing being the ultralight sheet. Initially the sheet is rolled up, and then partially unrolled as altitude increases, to reduce wing loading. The lower wing which is offset to the front of the upper wing, is covered with solar panels, powering electric motor-driven propellers. FLTs cannot stay aloft through a night without power: their mission is to deliver the sheet and sheet frame with control surfaces to rendezvous at 30.5km. The vehicle formed by linking 11 sheets is the Flying Leaf, the basic unit of the reflective Glitter Belt swarms.

Minimum descent rate in unpowered flight is a function of wing loading, profile drag coefficient and aspect ratio. We examined the process of night-time glide, to stay above Class A airspace. Starting at 30.48 km, descent was traced to 18800 m (60,000 ft). At W/S of 1.25 N/m^2, achievable with larger-scale FL vehicles, the upper limit for C_{D0} is 0.02. Reducing W/S allows C_{D0} of 0.025, whereas C_{D0} of 0.015 permits W/S to exceed 2 N/m^2. Typical Mission Profile

The present choice of 32m FLT span facilitates transport and launch from anywhere in the world. Low wing loading enables low takeoff speed but restricts takeoffs in windy conditions. Fig. 4 shows FLTs taking off. Morning takeoff is needed to climb to 30.5km in time to complete rendezvous before sunset to start their nighttime glide at the highest potential energy, and return 8 out of 11 FLTs to landing by fast glide. Solar intensity rises from about 1.0 kW/m^2 at sea level to to 1.367 kW/m^2 at 30.5 km, with much of the loss being in the lower troposphere. Temperature at 30.5km varies from 85 deg. C in direct sunshine, to below -57 deg. C at night in the Stratosphere during glide. Winds are strongest in the lower stratosphere during initial climb, while dynamic pressure is highest at sea level. Motor cooling in solar-heated near-vacuum, rendezvous and swarm operation for high-precision distributed antenna applications pose some challenges. The sheets are fully deployed to 64m chord once formed, so that Aspect Ratio remains moderate. FLs form swarms. Many functions such as station-keeping, health monitoring and damage reporting are done autonomously within the swarm, while navigation and communication are handled by the swarm leaders.

D. *Benchmarking*

The GB vehicles were compared to 3 successful High Altitude Long Endurance (HALE) concepts: NASA Pathfinder, Helios-1 and Helios-2. FLT and FL aspire to far lower wing loading (W/S) than prior concepts. This is because much of the lift is carried by the large area of ultrathin reflective sheets, supported by a carbon fiber truss and grid. Quinlan [28] has described a scheme to join wingtips in flight; there are other options for this as well.

V. APPLICATIONS

The ability to stay airborne through the night without consumable fuel, enables very long endurance and global range. Beyond initial flight tests for small periods, the first long-range missions will follow the Summer Sun: a continuous north-south drift speed of about 1 m/s keeps up with the latitude of Peak Summer, traversing at least between the Tropics of Cancer and Capricorn. A separate system could stay over the Antarctic coastline throughout summer. Initial focus is expected to be on meteorological data collection, starting with FLTs [29], in the Indian and Pacific Ocean Regions as seen in Fig.6. Since control is presumed adequate to perform wingtip rendezvous at 30.5km altitude, it is also possible to form swarms of sufficient precision to act as synthetic aperture antennae. Such antennae can be very large, exceeding the size, though not the spatial precision of terrestrial distributed-antenna astronomical observatories. These open up wavetop imaging, as well as looking upwards for millimeter wave astronomy and health monitoring of spacecraft.

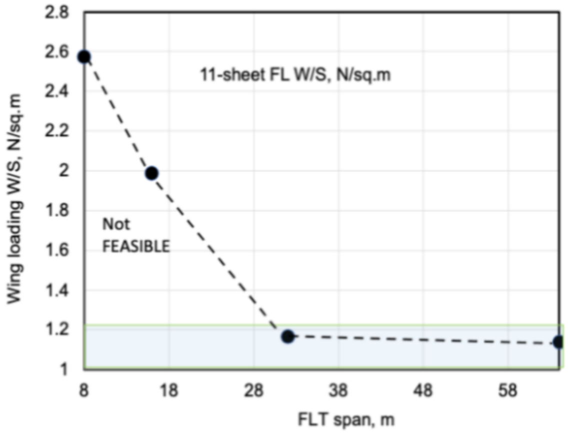


Fig. 5: Bounds on span to achieve desired wing loading.

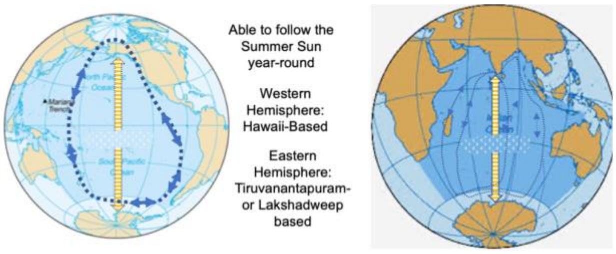


Fig. 6: Initial planning for annual summer-follower trajectories in the Pacific and Indian Oceans. From

TABLE 1: HOW GLITTER BELT ADDRESSES NAS CONCERNS

Item	**Response to NAS Concerns.**		
	Expressed Concerns	***NAS recommendation***	***Glitter Belt Approach***
1	Unauthorized/ unilateral actions; Uncontrolled in case of unknown response	Authorization, consultation, notification; Transparency & Trust across nations & generations; Ethical accountability; Research in public interest; Legitimacy and accountability. Fairness & inclusion; Maximized benefits; minimized harm.	Informed collaboration with national & international agencies. Completely monitored test & deployment
2	Impractical or poorly understood	Timely technical availability, respecting ethical and ecological norms; Predictability	Flight tests integrated with measurement & simulation
3	Public awareness & policy-relevant knowledge, inclusion, stakeholder participation	Disciplinary balance, stakeholder engagement; self-organized coalition of state & non-state actors; Coordinate across international entities; Peer Review & transparency. Participation and engagement independent of whether a proposed experiment has any known environmental risks	Seeking tech./ policy collaboration, global interests. Continuous data; International NGO & Consortium. Publication. International Participation
4	Removes urgency; reduce other climate funding;	Funding for geoengineering must be limited to be small relative to expenditures for emission reduction and other proactive measures	Broaden from CEU for global buy-in. Micro credits. No zero-sum approach.
5	Emissions	Inert & non-toxic Test materials. No experiment to release over 1,000 kg, global less than 10,000 kg/yr.	Zero emissions except electromagnetic signals for data, control and navigation.
6	Temperature Change in Experiment Stage	Induced change in global mean surface temperature under 100 nK (100x10-9 C) for a 100-yr horizon (or 10μK normalized to a 1-yr horizon) for individual experiment, 1μK (1x10-6 C) for 100-yrs/ 100μK normalized to 1-yr horizon.	Detectable changes only with massive scaleup when agreed. No concentration: swarms move w/ Summer Sun.

VI. FLIGHT SIMULATION OF FLT AND FL

Solar panel long-term efficiency is taken as 20% [30,31] covering 40 to 85% of FLT wings including leading edge capture of low-horizon sunlight, and bottom surface capture of diffused cloud reflections. A 100Wh battery operates instruments and communications at night. A generator charges batteries during the day, augmented by propeller windmilling at night, also enabling a burst flare maneuver for landing at night. Lift and drag coefficient data for a thin cambered flat plate were used to model the lifting sheet (Gilbert, Lester 2020). Maximum lift coefficient is 1.2. We restrict operations to CL of 1.0. Structural weight was modelled assuming the technology of the benchmark vehicles to estimate total weight of the FLTs, and known strength/weight profile of carbon fibre beams supporting 0.05kg/m^2 Aluminized Mylar sheets.

VII. SATISFYING NAS CONCERNS

The Glitter Belt architecture, by its very nature, more than satisfies all concerns and guidelines in the NAS report, as seen in Table 1. FL swarms will carry out much of the day-to-day health monitoring and positioning of individual FLs, while each swarm itself will be monitored and controlled as a unit from the ground and via satellites. Climate data acquisition is integrated from the beginning, and the effects of reflectors themselves will be measured locally and globally. The data are also crucial as calibration/validation resources for computational meteorology, and to refine the resolution and confidence of climate predictions. Finally, the data are also essential throughout the deployment and operation of the Glitter Belt project to sense the positive effects and gain early warnings about any possibility of negative impacts. As we discussed in [29] high-altitude ultralight vehicles fill a major gap in data acquisition capability, complementing Space satellites that fly above 400km in altitude, and 25,000 kmph speeds, subsonic aircraft that are confined to about 14km altitude, radiosondes and other instruments, with special missions using expendable drop-sondes for vertical profile data of the atmosphere. The FLs offer unprecedented coverage, persistence and resolution. over remote areas.

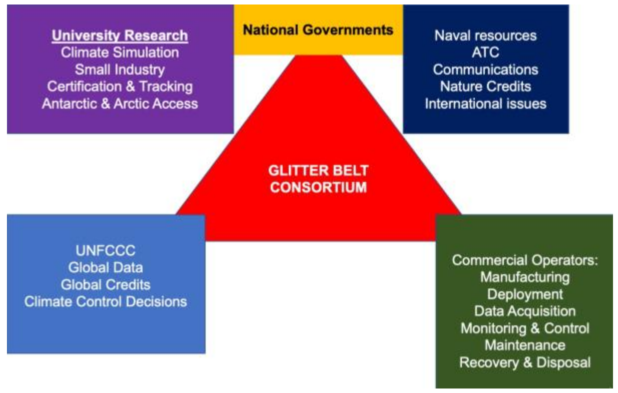


Fig. 7: Consortium Structure

VIII. CONSORTIUM CONCEPT

A Consortium concept is used to organize initial testing and simulation activities, and tie in with work at other organizations. This is sketched in Fig. 7. We have several organizations informed and collaborating, each pursuing their own specialization while staying informed of the overall project progress. International collaboration requires incorporating national interests of other nations. The Kyoto Protocol's Carbon Credit system is a start, but as mentioned before, this does not address the priorities of many nations, particularly when this is seen as being used to support the low-thermodynamic efficiency people in Advanced Nations who are loudest about GHG reduction, from breaking a sweat in summer, using airconditioning. Most nations do buy into the United Nations Sustainable Development Goals where GHG is one of 17 priorities. Several of those goals can be supported by expanding the "CEU" metric into a broader "Nature Credit" for reforestation, and cleaning up the land, water and air. We [24] suggested a range of equivalences for Nature Credits, including one between sunlight reflection and CEUs as a starting point.

IX. CONCLUSIONS

It is possible to reduce, stop and reverse Atmospheric Heat Retention, in a safe, controlled, monitored and reversible manner using the Glitter Belt architecture. In 6 years of development, all cited objections have been met and addressed. The architecture proactively satisfies the concerns expressed by the NAS about sunlight-reflection projects, with an open, peer-reviewed, internationally collaborative approach that addresses the interests of stakeholders not only across generations in the advanced nations, but the aspirations and concerns of people the world over. Conceptual design aspects of Flying Leaflet (FLT) and Flying Leaf (FL) vehicles that comprise the initial Glitter Belt system are summarized. The 30.5km altitude and slow glide requirements provide unique challenges. Rendezvous and swarm operation for high-precision distributed antenna applications pose unique challenges and opportunities. Conceptual design, small scale design-build-fly tests, and dynamic flight simulation are used to remove uncertainties and derive properties of this system.

This project seeks and welcomes participation from all over the world. There is more than enough work and thinking to keep us all busy. In the end, it is our world and up to us to be proactive to reduce atmospheric heat retention. It can be done.

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