Prospects for Commercial Stratospheric Industrialization at the Threshold of Space

by using
large, reduced-cost, tethered stratospheric platforms
for
large-scale solar power plants
followed by
low-g km drop tower fabrication of ultra-lightweight solid foams
ultra-lightweight extended-spectrum large-optics systems
airports for ultra-lightweight stratosphere-only UAVs
microwave-beam orbital-booster power stations
top-of-atmosphere rocket launch pads
spectacular near-space tourism

(Last revised: 2010-10-16)

Contents

1. Preface

Editorial note: for {economy and explicitness} of expression, I sometimes use "{...}" to visually delimit {lists, compound phrases, long phrases, or other items} — especially when these occur {in mid-sentence, or in combinations}.

2. Introduction

For various historical reasons, the seeming great {technological and commercial} potential of large tethered stratospheric platforms has yet to be realized. Due to continuing improvements in {solar conversion technology and materials capabilities}, this seems like an auspicious time to try jump-starting this realm. Hence this brief introductory overview.

I'm very interested in encouraging further investigation of these realms. I'm also very interested in collaborating with others having related interests. So please feel free to share this write-up with others, and to suggest improvements.

3. The mid-stratosphere, at the threshold of space

While commercial aircraft routinely fly in the lower stratosphere (at about 35,000 feet altitude, or about 10 km), our main focus will be on (the lower half of) the mid-stratosphere, in the 22–30 km altitude range (roughly between 72,000 feet and 100,000 feet).

- This region is above more than 95–98% the earth's atmosphere, and has negligible weather in the conventional sense.
- This region is also above the ozone layer (which is approximately in the 13–20 km altitude range).

Please review the illustrations and tables in the "Appendix of background information" for more information.

3.1 Advantageous features of the mid-stratosphere

Large earth-based structures could often be {much lighter and much less expensive} if they didn't need to be:

- designed to withstand weather, including {heavy gusting winds, thunderstorms, icy conditions, and so on}, and
- designed to compressively support their own weight against gravity.

Being well above conventional weather (including above the {polar and subtropical} jet streams) is a huge engineering advantage that helps offset many other challenges of stratospheric structures. Of course practical all-weather aerodynamically-optimized tether systems are still needed, and geographic regions prone to {tornadoes and tropical mega-storms} must be avoided. But this tradeoff can still be very advantageous overall for very large mid-stratospheric platforms.

Large stratospheric structures (and the modules used to assemble them) may be regarded as being suspended on air bearings. Although this also makes mid-stratospheric structures subject to prevailing light mid-stratospheric winds, this can still be a net advantage.

At the mid-stratosphere, sunlight is substantially stronger than at ground level, and is not attenuated by weather. On the other hand, even in daytime, the darkness of outer space can be readily seen.

The lower-mid-stratospheric environment thus presents some intriguing large-scale engineering development possibilities for large tethered platforms.

3.2 Reducing the cost of mid-stratospheric platforms

The mid-stratosphere is well above the altitude where there is sufficient oxygen to support combustion, so hydrogen may be used as the buoyancy gas. Hydrogen is very much less expensive than helium, hydrogen is abundantly available, and hydrogen provides superior buoyancy.

High-altitude lighter-than-air craft (balloons, blimps, and dirigibles) have traditionally amounted to very large gas bags. However, rather than making even larger gas bags for large mid-stratospheric platforms, it makes better sense to use a lattice of gas bags within lightweight lattice truss structures. Such structures would in effect be comprised of many effectively neutrally-buoyant modules (at their nominal target pressure-altitude). This approach is advantageous for several reasons, including {easier fabrication, easier assembly, fault-tolerance, maintenance, and design flexibility}.

4. Mid-stratospheric solar power stations

The stratosphere has a number of advantages for intercepting solar radiation:

- An altitude of 22 km (a little over 72,000 feet) is above more than 95% of the earth's atmosphere.
  - This is well above obscuring weather.
  - This is well about the parts of the atmosphere that absorb a significant fraction of the higher-energy spectrum of sunlight. (This is also above the ozone layer, so much more of the higher energy UV spectrum is available.)
  - Sunlight energy at the earth's surface is substantially reduced by taking longer slant paths through the earth's atmosphere during early-to-mid morning and mid-to-late afternoon.
  - For ground solar stations located at middle-US latitudes, sunlight energy is reduced due to lower sun angles in winter months.
- As a result of the above factors, at least 2-to-3 times as much solar energy is available at mid-stratospheric sites over the course of a year. (Depending on weather and latitude, this relative advantage can be substantially larger.)
- Since the solar power station need not withstand storms (excepting the connecting tether and power line), very lightweight construction can be used, saving materials costs.
- Stratospheric solar power stations can be sited over {land and water} that is unsuitable for conventional solar power stations.

4.1 Mid-stratospheric solar energy conversion

The economic-engineering challenges for large stratospheric structures impose some fairly severe practical feasibility constraints on prospective stratospheric solar power stations.

- One intriguing candidate technology system for adapting to mid-stratospheric sites is the concentrating photovoltaic (CPV) system of (www.REhnu.com). This system makes use of {inexpensive shaped reflectors, a lightweight support lattice, and high-efficiency triple-junction solar cells}. (There are additional design advantages that we haven't described here.)
  - Given the very low air density of the stratosphere, some additions to this system would likely be needed for thermal management of triple junction cell temperatures. Fortunately, the heat sink challenge for this system is very widely distributed into lots of localized hot zones. Dissipating excess heat should be readily tractable by means of fairly modest space-engineering {thermal shielding and heat radiator} technology. (Recall that sizable portions of the cold dark sky are always accessible at mid-stratospheric altitudes, even at midday.)
    - Waste heat rejection will be less of a challenge if new generation thermophotovoltaic cells can be practically produced, since they are even more tolerant of (and operate better at) fairly high operating temperatures. Likewise if other prospective {thermovoltaic or thermotunneling} systems become sufficiently {efficient, affordable, and durable}.

    - The solar tracking and pointing system would need to be redone to accommodate changes from {a ground-sited-platform to a floating platform}.
- Additional equipment would be needed for handling electric power transmission to ground (which requires conversion to high voltage to minimize transmission line losses).

4.2 Ground-oriented mid-stratospheric heliostats

Large (km-diameter) stratospheric heliostats (either planar or concentrating) that redirect sunlight to ground-level might be used as follows:

- Such heliostats could substantially increase the net productivity of ground-based solar power stations at low-cloudiness sites during periods when the sun is at relatively low angles (such as during early morning hours, late afternoon hours, and fall-winter seasons).
- Such heliostats might be cost-effective means for boosting the average efficiency of large-scale desalinization plants at low-cloudiness sites.
- Such capabilities might also be useful for solar-chemical fuel production.

4.3 Related work of interest

Many of the items that originally got us interested in these ideas long predated the web, and are difficult to find online. We may eventually be able to locate some of them in cartons of unfiled copies of papers. Meanwhile, here are some more recent items of interest.

4.3.1 Tethered aerostats for solar power conversion

Items of interest:

- “High Altitude Electrical Power Generation”
    - WSEAS Transactions on Environment and Development
    - http://www.wseas.us/e-library/transactions/environment/2008/28-627.pdf
- “An Evaluation of a High Altitude Solar Radiation Platform”
    - J. Sol. Energy Eng., February 2010, Volume 132, Issue 1, page 011004 (8 pages).

4.3.2 Very large tethered stratospheric platforms for optical energy conversion

- “Foundations of Liquid Space Optics for Astronomy, Solar Power Satellites and Interplanetary Shuttles” by J. H. Bloomer.
    - Space Power, 1994, Volume 13, Numbers 3 & 4, p. 145–183.

4.3.3 StratoSolar — tethered stratospheric sunlight concentrators with big light guide to ground

This is a very cool project!

While we expect in situ conversion will win out for electric power generation, there are still many industrially-valuable thermal energy applications of such systems (especially in regions with year-round mild weather).

Items of interest:

- StratoSolar’s home page:
    - http://www.stratosolar.com/about-us.html

- “StratoSolar Overview”
    - http://www.slideshare.net/chris8649/stratosolar-overview
- CAD models for StratoSolar
    - http://www.zinzzu.com/stratosolar.html

5. Stratospheric low-g drop-tower materials processing

Ground-based materials processing of ultra-lightweight {metallic, glass, polymer, and hybrid material} {bubbles and foams} is severely constrained by the earth's gravity, due to weight-induced {flowing. sagging, or material segregation} during solidification.

- Stratospheric low-g drop-towers (or drop zones) are one intriguing possibility for practically overcoming such limitations in some cases.
- The year-round daytime availability of {uninterrupted sunlight at uniform power levels} facilitates the {design and operation} of:
    - high performance solar furnaces for pre-drop material preparation, and
    - intense solar-derived narrowly-tuned spectral bands of {UV and IR} fluxes for photochemically processing materials {during or just before} free fall. (This could involve selectively {activating, crosslinking, or decomposing} materials, among other possibilities.)
- The very low atmospheric pressure is also potentially advantageous.

The following table gives a rough idea of some of the key parameters involved.

Free fall time	Fall distance		Final velocity	
5 sec.	0.12 km	394 feet	176 km/hr	110 mi/hr
10 sec.	0.49 km	1,608 feet	353 km/hr	219 mi/hr
20 sec.	1.96 km	1.22 miles	706 km/hr	438 mi/hr
30 sec.	4.41 km	2.74 miles	1058 km/hr	658 mi/hr

The figures of the preceding table presume arrangements to keep the effects of tenuous air resistance at negligible levels. A brief period of 1/10-to-1/20 normal effective weight should be sufficient for a great many applications, when followed by a smoothly increasing effective weight back to normal levels as solidification-strengthening proceeds. (Of course this will be followed by greater than normal effective weight when the material is finally brought to rest.) Note that for continuous-stream (versus discrete stream) production processes, the acceleration due to falling will result in elongation-inducing tensile forces, which might be advantageous in special cases.

The requirement for fairly rapid {radiative cooling or UV-curing} (excluding cases of rapid intrinsic chemical curing) imposes fairly stringent restrictions on target material cross-sections (for at least 1 dimension). This suggests that {balls/clusters, rods, hollow cylinders, and slabs} of material will be the predominant geometric configurations of material products. However, much more substantial structures could be built up by {multi-pass processing or post-processing consolidation}.

Here are some possibilities to consider:

- Types of materials:
    - ultralight big bubbles that are {discrete or clumped, or optionally spun during solidification}
    - ultralight foams (blobs, rods, slabs), optionally {spun, molded, corrugated, dimpled, and so on}
- Post-processing:

  - sintering (into larger shapes, possibly with many internal low-pressure voids)
  - bagging (for use as ingredients of further ground-based processing)
- Applications:
  - advanced materials for the aerospace industry
  - structural elements for second-generation stratospheric technology
  - large ultra-light astronomical-quality mirrors
  - extremely {energy-efficient and long-duration} near-neutrally-buoyant UAVs
  - near-neutral-buoyancy {heliostats and concentrator mirror blanks}

Not all applications need to be especially high-tech. One mundane speculative possibility might be mass production (many kilotons per day) of large ultra-lightweight fiber-reinforced foam {basalt, silica, recycled plastic} slabs with about twice the density of balsa wood. These materials could be useful for moderately {low-cost, energy-efficient, pest-proof, waterproof, and more earthquake-safe} construction.

6. Further stratospheric industrialization prospects

6.1 Large stratospheric structures for in-situ fabrication bootstrapping

Consider a self-supporting spherical geodesic lattice-truss (with an interlaced lattice of interstitial hydrogen gas bags) comprised of 2 hinged half-spheres, with interior gas-tight surfaces. This provides a chamber that can be opened to {insert or remove} large structural {components or forms}, and that can be closed for processing purposes.

The interior can be pumped down for purposes of:

- vacuum-deposition fabrication of semi-monolithic ultralight structures
- attaining much higher altitudes
- supporting much larger payloads at the same altitude
- feeding material into top of second-generation evacuated drop-tower

Some potential applications:

- providing bigger cost-effective platforms for large astronomical instruments
- silvering large ultralight mirrors
- fabricating advanced stratospheric craft that couldn’t survive passage through the lower atmosphere

6.2 Ultra-lightweight extended-spectrum large-optics systems

To be written.

6.3 Airports for ultra-lightweight stratosphere-only UAVs

To be written.

6.4 Microwave-beam orbital-booster power stations

To be written.

6.5 Top-of-atmosphere rocket launch pads

A stratospheric crane for {raising and launching} rockets from the mid-stratosphere (30 km or about 100,000 feet, above 98% of the atmosphere) would reduce the substantial {fuel and structure} mass penalty that ground-launched rockets incur for overcoming aerodynamic {drag and buffeting}.

6.6 Spectacular near-space tourism and optional weightless descents

Both the {daytime and nighttime} views will be spectacular.

6.7 Longer-term prospects and speculations

6.7.1 Miscellaneous prospects

Here are some miscellaneous long-term prospects:

- Using intense mid-stratospheric UV for solar-pumped lasers for:

  - chemically reducing magnesium oxides for high-energy solid state fuel production
  - high energy density power beaming to orbital tugs
  - photo-thermally processing (such as melting, curing, or sintering) drop tower material streams (pre-injection or post-injection)
- Long-distance self-supporting stratospheric power lines.

6.7.2 Semi-isolated city-scale "Stratospheric Valley" industrialization zones

For a variety of {political, regulatory, insurance, economic, safety, and public relations} reasons, many very large scale stratospheric industrialization activities could be much more expediently carried out in a handful of {large, semi-isolated, specially-designated} regions. This would be advantageous for:

- reducing project {overhead costs, lead times, and approval cycles}, and thereby facilitating {funding and higher returns on investments}
- consolidating forests of stratospheric tether networks
- sharing {ground and airspace} security arrangements
- sharing airspace warn-away {beacons and backup systems}
- sharing long-distance ground-based electric power transmission lines to major markets
- sharing the outer 20-km buffer region around such industrial zones
- sharing {light and heavy} transportation facilities
- getting {first-mover, learning curve, and economies of scale} advantages in world markets

6.7.3 Speculative geo-engineering and geo-remediation

These possibilities are very speculative, but may suggest more practical alternatives:

- Dealing with volcanic ash: Consider grandiose-scale solar-powered self-propelled stratospheric-islands that could be positioned {well above and around} actively-erupting volcanoes. This might make possible the development of suspended sparse high-voltage-electrified nets to electrostatically precipitate aircraft-threatening ash out of the air.
- Dealing with massive forest fires: Consider grandiose-scale solar-powered self-propelled stratospheric-islands that could be positioned {well above and around} massive forest fires. This might make possible the development of suspended sparse high-voltage-electrified nets to electrostatically precipitate water out of the troposphere below.
- Thwarting the formation of hurricanes: Consider grandiose-scale solar-powered self-propelled stratospheric-islands augmented with 100 (1 km x 1 km)-sized heliostats that could intensely concentrate sunlight down into a few-km diameter zone. Is there some effective way to use this energy input to disrupt hurricane formation?
- Consider using very large stratospheric platforms as an extremely high voltage capacitive circuit node. Is there some way to exploit this capability, either for {DC or resonant-AC} excitation?

7. Deployment and maintenance strategies

Due to the harsh mid-stratospheric environment (near vacuum, intense UV in daytime, dangerous height), it is obviously very desirable to minimize on-site human activity.

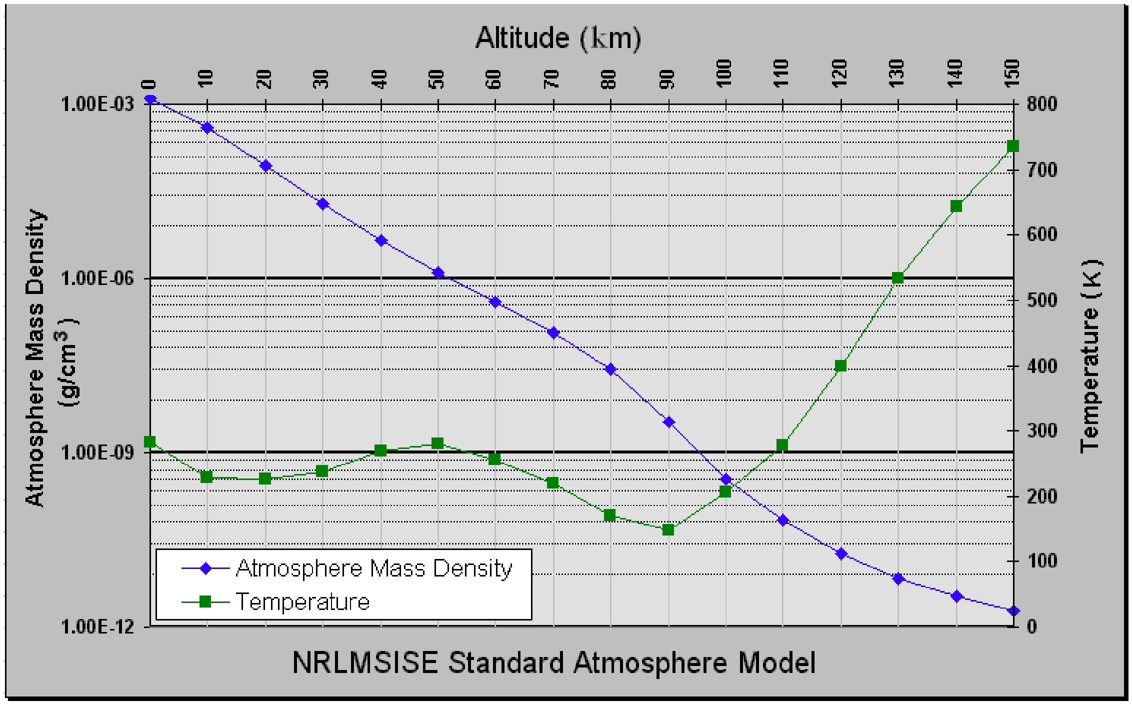
8. Safety and environmental concerns

These are some of the {safety and environmental} concerns that large-scale stratospheric industrialization will need to contend with:

- siting systems well away from commercial aviation corridors
- insuring that large systems stay where intended
- insuring that large systems aren’t prone to {cascading or catastrophic} failure modes
- insuring that stuff doesn’t fall out of the sky
- keeping the stratospheric environment (and the lower atmosphere) free of floating junk

9. Appendix of background information

9.1 Atmospheric information



This next table is an {abridged, extended, reformatted} version of:

http://www.engineeringtoolbox.com/air-altitude-pressure-d_462.html

Altitude Above Sea Level			Absolute Atmospheric Pressure		
feet	*mile*	*meter*	*psia*	kg/cm^2	*kPa*
0	0.00	0	14.696	1.0333	101.33
3,500	0.66	1,068	12.93	0.909	89.15
7,000	1.33	2,136	11.34	0.797	78.19
15,000	2.84	4,577	8.29	0.583	57.16
35,000	6.63	10,679	3.47	0.244	23.93
50,000	9.47	15,255	1.69	0.119	11.65
60,000	11.36	18,306	1.05	0.074	7.24
70,000	13.26	21,357	0.65	0.046	4.48
80,000	15.15	24,408	0.41	0.029	2.83
90,000	17.05	27,459	0.26	0.018	1.79
100,000	18.94	30,510	0.16	0.011	1.10

From http://en.wikipedia.org/wiki/Atmospheric_pressure

Although the pressure changes with the weather, NASA has averaged the conditions for all parts of the earth year-round. The following table shows air pressures (as a fraction of one atmosphere) with the corresponding average altitudes above sea level. The table gives a rough idea of air pressure at various altitudes.

fraction of 1 atm	**average altitude**	
	(m)	**(ft)**
1	0	0
3/4	2,750	7,902
1/2	5,486	18,000
1/3	8,376	27,480
1/10	16,132	52,926
1/100	30,901	101,381
1/1,000	48,467	159,013
1/10,000	69,464	227,899
1/100,000	86,282	283,076

From http://en.wikipedia.org/wiki/Atmosphere_of_Earth

The density of air at sea level is about 1.2 kg/m3 (1.2 g/L).

90% of the atmosphere by mass is below an altitude of 16 km (52,000 ft).

The stratosphere extends from the tropopause to about 51 km (32 mi; 170,000 ft). Temperature increases with height, which restricts turbulence and mixing.

The stratopause, which is the boundary between the stratosphere and mesosphere, typically is at 50 to 55 km (31 to 34 mi; 160,000 to 180,000 ft). The pressure here is 1/1000th sea level.

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http://en.wikipedia.org/wiki/Stratosphere

The border of the troposphere and stratosphere, the tropopause, is marked by where this inversion begins, which in terms of atmospheric thermodynamics is the equilibrium level. The stratosphere is situated between about 10 km (6 miles) and 50 km (31 miles) altitude above the surface at moderate latitudes, while at the poles it starts at about 8 km (5 miles) altitude.

From http://www.nsf.gov/news/news_summ.jsp?cntn_id=103063

The National Science Foundation (NSF), through its Office of Polar Programs, supports long-duration balloon (LDB) flights in Antarctica to conduct astrophysical experiments. Circling the continent on unique stratospheric winds at altitudes of roughly 37 kilometers (22.9 miles) for periods of up to 31 days, experiments operate in an area that is almost free of atmospheric interference. For some experiments, this provides scientists with conditions equivalent to flight aboard a satellite or the space shuttle, at much lower cost.

9.2 Solar energy

9.2.1 Relative solar energy available at the earth's surface compared to space

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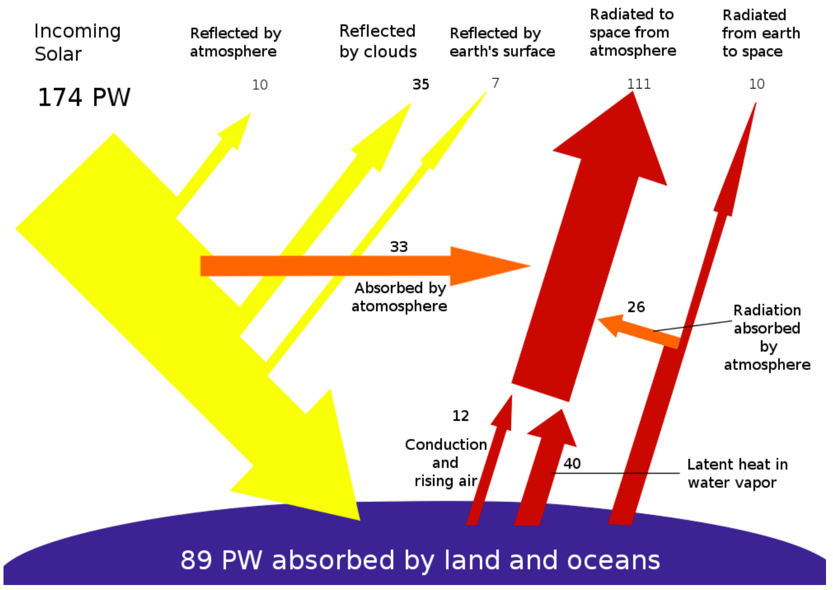

http://en.wikipedia.org/wiki/File:Breakdown_of_the_incoming_solar_energy.svg

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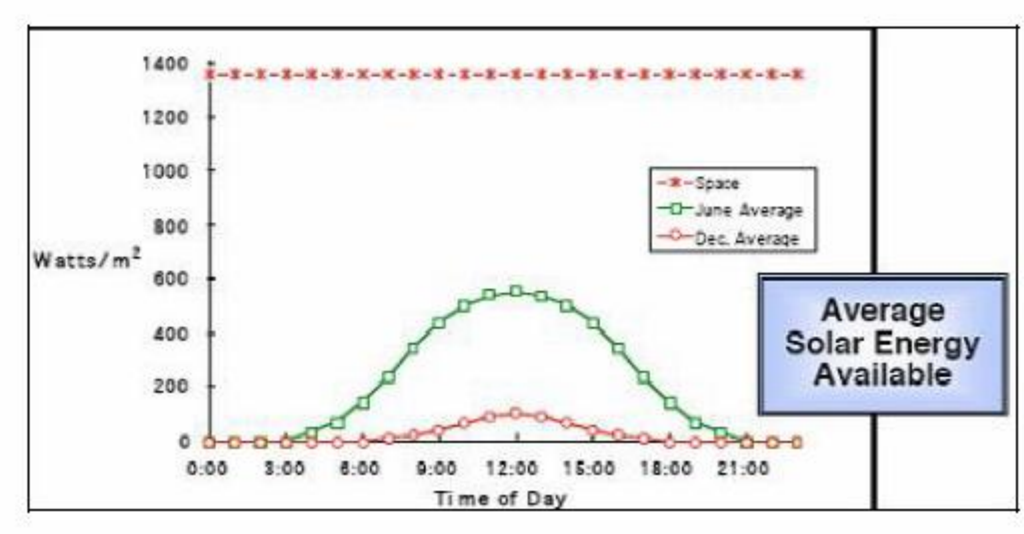
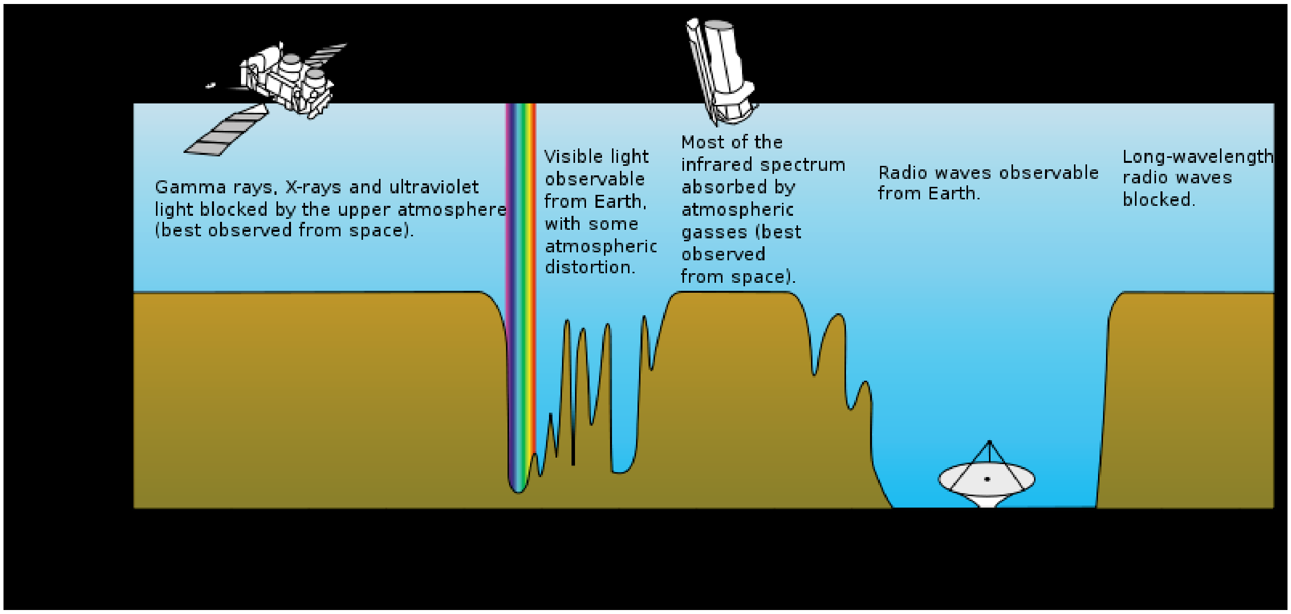
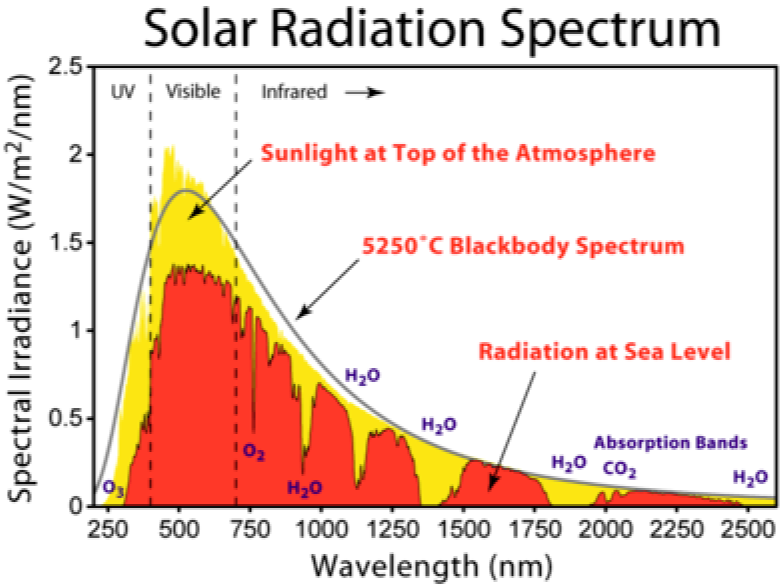


http://www.nss.org/settlement/ssp/library/final-sbsp-interim-assessment-release-01.pdf

9.2.2 Solar radiation and atmospheric absorption

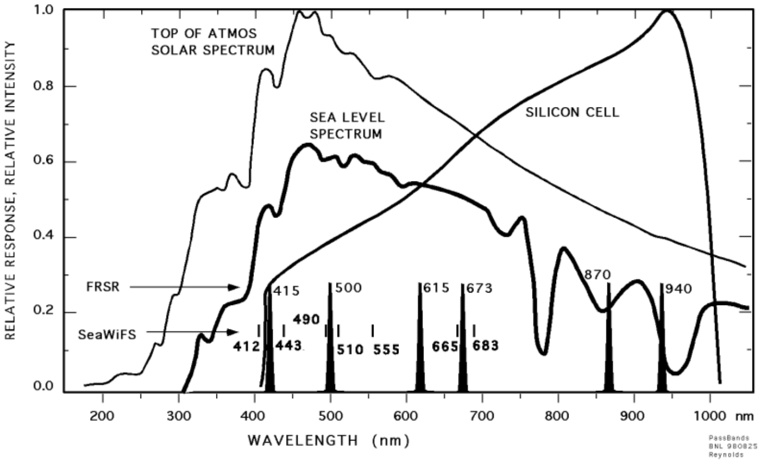


From: **https://inlportal.inl.gov/portal/server.pt?open=514&objID=1269&mode=2&featurestory=DA_524323**

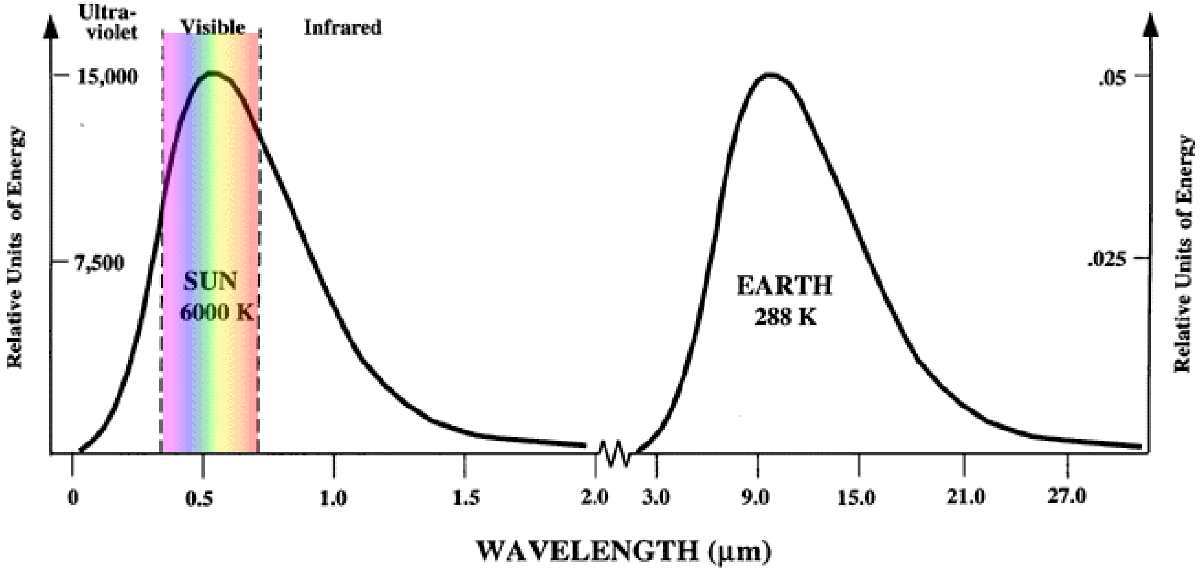


The top of red curve is the solar spectrum at sea level; the top of the yellow curve is spectrum at top of earth's atmosphere (above stratospheric ozone layer).

From: http://www.gim.bnl.gov/instruments/prp/PrpDetails.html



SiO2 protected aluminum reflectors will efficiently reflect UV down to about 250–300 nm.



Comparison of the emission spectra of the sun and the earth. Note the huge disparity in the amount of energy emitted by the sun (left-hand scale) and the earth (right-hand scale).

9.2.3 Ozone layer

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http://en.wikipedia.org/wiki/Ozone_layer

The ozone layer is a layer in Earth's atmosphere which contains relatively high concentrations of ozone (O3). This layer absorbs 97–99% of the sun's high frequency ultraviolet light, which is potentially damaging to life on earth.[1] Over 90% of the ozone in Earth's atmosphere is present here. It is mainly located in the lower portion of the stratosphere from approximately 13 km to 20 km above Earth, though the thickness varies seasonally and geographically.

9.3 Materials

9.3.1 Tether material self-supporting breaking heights for 1g (earth gravity)

From: http://en.wikipedia.org/wiki/Lunar_space_elevator

All of these materials have breaking lengths over one hundred kilometers under 1*g* (earth gravity) conditions.

Material	**Density** ρ **kg/m^3**	**Stress Limit** σ **GPa**	**Breaking height** **($h = \sigma/\rho g$)** **km**
Single-wall carbon nanotubes (laboratory measurements)	2266	50	2200
Toray Carbon fiber (T1000G)	1810	6.4	361
Aramid, Ltd. polybenzoxazole fiber (Zylon PBO)	1560	5.8	379

Honeywell extended chain polyethylene fiber (Spectra 2000)	970	3.0	316
Magellan honeycomb polymer M5 (with planned values)	1700	5.7(9.5)	342(570)
DuPont Aramid fiber (Kevlar 49)	1440	3.6	255
Glass fiber	2600	3.4	133

9.3.2 Miscellaneous

This site [NextBigFuture] has been writing recently about ETFE and its widespread use in new architecture and proposing its use for domes over cities and canopies over roads. Ethylene tetrafluoroethylene, ETFE, a kind of plastic, was designed to have high corrosion resistance and strength over a wide temperature range. Technically ETFE is a polymer, and its systematic name is poly(ethylene-co-tetrafluoroethylene). ETFE could be combined with carbon nanotubes or graphene to get 40% or more improvement in structural strength. Incorporating graphene into a polymer so that 0.1% of the weight of the composite material is graphene can make the material 31-53% stronger.

Zylon tethers (used in ocean applications).

9.4 World map

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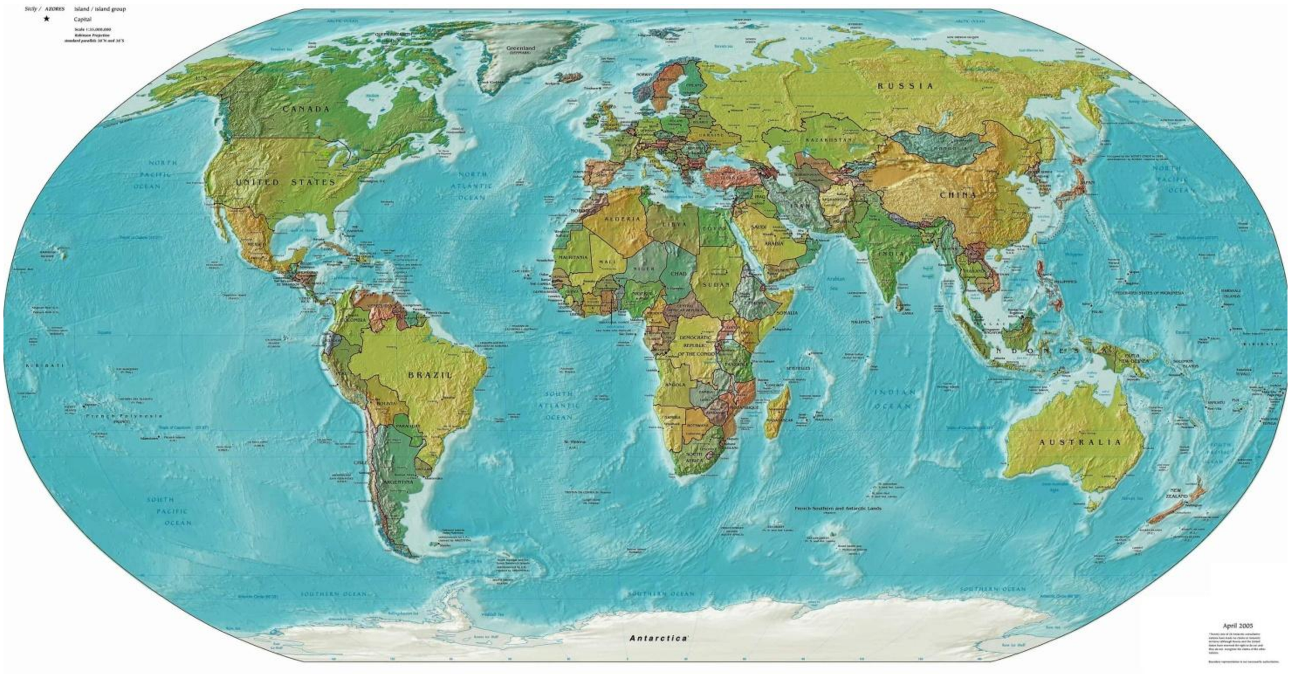
http://mapsof.net/the_world/static-maps/jpg/political-and-physical-world-map/xlarge-size



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10. Conclusion

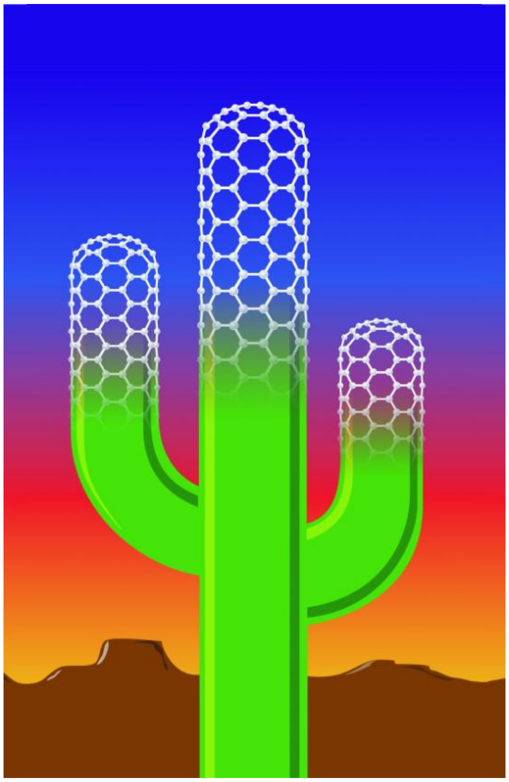
I hope you found this overview interesting and thought-provoking.

I'm especially in any technical feedback that could be used to improve future versions of this overview, which I hope to expand as {time and resources} permit.

Needless to say, I'm also very interested collaborating with anyone interested in developing this technology.

Any leads pertaining to {grant, contract, or business} opportunities would be greatly appreciated (please see contact information below the illustration).

Thanks.



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