# Starduster
## A Solar Powered High Altitude Airplane

A paper presented by
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at the

**AIAA/SAE/ASME**
**21St Joint Propulsion Conference**
**July 10, 1985 Monterey California**

## Abstract

This paper presents an analysis of a proposed solar powered high altitude airplane named called “Starduster”. Starduster is designed to reach extreme altitudes of 200,000 feet and although flight is limited to daylight hours long distance flights over thousands of miles are possible. Air vehicle configurations are examined and subsystem functional requirements are defined.

## Introduction

One decade ago in 1974 the Astro Flight Sunrise Solar Powered Aircraft demonstrated that airplanes could fly on solar power alone without the help of batteries and that flights of over 50,000 ft altitude were possible. Since that time carbon fiber composites have been developed thereby reducing airframe structural weight while at the same time permitting the construction of very large structures. Electric motor technology has improved. Our new motors are lighter more powerful and more efficient. The large scale integration of silicon micro chips has dramatically reduced the size, weight, and power requirement of the electronic payloads while at the same time increasing their data handling capability. Today in 1985 solar cell efficiency has not improved significantly over the past decade but the weight of the solar panels has been reduced four fold. See ref.1, 2,3,4,5 and6. An improved version of Sunrise II, to be named **Starduste**r is proposed. This paper will define and analyze the functional requirements of this solar powered airplane.

## Energy Requirements

Starduster is to be solar powered because solar power had more than enough energy to power the aircraft to very high altitudes. The electric motor does not need to breathe the rarefied air found at high altitudes, a definite advantage over air breathing combustion engines. Solar cells have lower power density than fossil fuels and are subject to the effects of diurnal, seasonal and climatic conditions but they are the clear winners in energy density. Table1 Shows the energy density of various energy sources available today and used in Model Airplanes and unmanned air vehicles (UAV). Energy density is expressed in units of feet (foot pounds of energy/ pounds of “fuel” source. In other words this metric represents the altitude to which each fuel source could attain if all its stored energy were converted to potential energy.

**Table 1**
**Energy Sources**

| | |
|---|---|
| **Pirelli Rubber** | **3000 feet** |
| **Nicad Battery** | **33,000 feet** |
| **Silver Zinc Battery** | **132,000 feet** |
| **Primary Lithium Battery** | **330, 000 feet** |
| **Sunrise II Solar Cell** | **1,500,000 feet** |
| **IC engine Gasoline** | **3,900,000 feet** |
| **Diesel engine Diesel** | **4,900,000 feet** |
| **Light weight Solar Cell** | **6,300,000 feet** |

The calculations for the energy density of the solar cells assumed the equivalent of a six hour day at noon solar intensity. This is about average for a summer day in southern California, 28 degrees north latitude. In some applications the day will be much longer. The calculations for the internal combustion engine are for fuel alone and do not include fuel tanks, fuel pumps or other ancillary equipment. The lightweight solar cell is the clear winner in the energy race.

## Fuel Fraction

The air vehicle cannot be all fuel. Some weight allocations must be made for airframe, propulsion, command and control and payload. Reasonable weight allocations can be derived by comparing those of Sunrise II and those of a FAI-F3E competition sailplane.

**Table 2**
**Air Vehicle Weight Allocation**

| Vehicle | Sunrise II | FAI-F3E | Starduster |
|---|---|---|---|
| Airframe | 48% | 40% | 40% |
| Propulsion | 9% | 16% | 20% |
| Control | 13% | 7% | 5% |
| Payload | 5% | none | 5% |
| Energy Source | 25% | 37% | 30% |
| Total Weight | 100% | 100% | 100% |

## Potential Energy Limit

Since the solar array weight allocation is 30% of the gross weight we might expect altitudes as high as 30% of those shown in table 1. But there are other losses. Cabling and internal resistance of the solar array can dissipate 5% of the available energy. Similarly the motor can be expected to waste another 10% and if gearing is used perhaps another 5%. A well designed propeller can be expected to yield 90 % efficiency. These losses total 26.8 percent and when combined with the 30% weight fraction of the solar array yields an upper limit on the potential altitude limit for Starduster. These limits are 22% of potential energy values shown in table 1 and are shown below in table 3.

**Table 3**
**Potential Energy Limits**

| | |
|---|---|
| Nicad Battery | 7,275 feet |
| Silver Zinc Battery | 28,500 feet |
| Primary Lithium Battery | 72,750 feet |
| Sunrise II Solar Cell | 348,000 feet |
| Improved Solar Cell | 1,392,000 feet |

Clearly the available energy is not the limiting factor for high altitude flight. Table 3 shows that even battery powered aircraft can reach high altitudes. For example by using a simple two stage jettisonable lithium battery flights of 100,000 feet should be possible but the very large energy advantage of solar power is obvious.

## Power Requirements

Not all the energy available from the solar array can be converted to altitude; some of the energy must be used to overcome aerodynamic losses. Furthermore the energy must be extracted at a high enough rate to guarantee that Starduster reaches its design altitude in the daylight hours while the sun still shines. This means that Starduster must have an average climb rate of 278 feet per minute to reach an altitude of 100,000 feet during six hours of sunlight or 556 feet per minute to reach 200,000 feet. The electrical power requirement based on an assumed conversion efficiency of 73.2% from electrical power to propeller thrust means that would require 8.85 watts per pound for a climb to 100,000 feet and 17.15 watts per pound for a climb to 200,000 feet.

My brother Roland Boucher proposed a simplified sink rate equation which has proven to be a very useful tool (ref. 7).

Sink rate = 5.5 x (square root of gross weight) / wing span

The author of this paper has evaluated the multiplier constant by substituting the weight, wing span and published glide polars of fifty winning A1 and A2 Nordic designs and fifty high performance competition sailplanes as well as powered aircraft including the Piper J-3 Cub, the Beachcraft Bonanza, the Gossamer Albatross, and the DuPont Solar Challenger. The following conclusions were reached.

1. The formula is very powerful. For any class of aircraft the constant is practically invariant regardless of large variations in wingspan, wing loading and airfoil.
2. A1 and A2 Nordic models operating at Reynolds numbers between 25,000 and 40,000 have figures of merit between 6.25 and 6.5.
3. R/C Sailplanes operating at Reynolds numbers between 100,000 and 200,000 have figures of merit between 5.25 and 5.5.
4. Competition Sailplanes such as the ASW-15 and ASW-17 operating at Reynolds numbers above 1,000,000 have figures of merit between 3.75 and 4.0
5. Sunrise II had a figure of merit of 5.5, Gossamer Albatross had a figure of merit of 6.5 and the DuPont Solar Challenger had a figure of merit of 5.5.

Based on these observations we can estimate that Starduster can reasonably be expected to have a figure of merit of 5.5 when operating at Reynolds numbers greater than 100.000 and a figure of merit of 6.5 when operating at a Reynolds number of 25,000.

Let us assume that:

1. S = 5.5 x (square root W) / B

W = gross weight of airplane in pounds
B = airplane wing span in feet
S = sink rate in feet per second

Since the power required to maintain level flight is equal to product of the sink rate times the gross weight we have:

2. P = 5.5 x W x (square root W) / B

P = Power in ft-lb. / sec
Converting power into Watts we obtain:

3. P = 7.5 W x (square root W) /B

For the purpose of example the author has reconfigured the basic Sunrise II design holding solar array weight constant and using the weight allocation of Table 2. Since the lightweight cells have about the same efficiency but one fourth the weight of Sunrise II cells, the solar array will occupy four times the surface area on the wings. The Starduster array will occupy 120 square feet of surface area vs. 30 square feet on Sunrise II. Assuming that 80% of the wing surface can be covered with solar panels, Starduster will have a minimum wing area of 150 square feet. The solar array will generate 2,300 watts of electrical power, four times that of Sunrise II. To handle this increased power the motor weight allocation is increased to two pounds. The airframe structural weight allocation is reduced from 50% to 40%. This seems reasonable since Starduster will employ the latest composite structural materials in lieu of the balsa wood and spruce used in Sunrise II.

**Table 4**
**Starduster Configuration**

| | |
|---|---|
| **Wing Span** | **32 feet** |
| **Wing Area** | **160 square feet** |
| **Wing Loading** | **0.116 pounds per sq. ft.** |
| **Solar Array Weight** | **5.5 pounds** |
| **Solar Array Power** | **2,300 Watts** |
| **Gross Weight** | **18.5 pounds** |
| **Motor Power** | **2,000 Watts** |
| **Thrust Power** | **1,800 Watts** |

4. S = 5.5 x (square root 18.5) / 32 = 0.75 feet per second
The calculated sink rate at sea level is 0.75 feet per second or 45 feet / minute.

5. P = 45 x 18.5 = 832 ft pounds/min = 0.025hp = 19 Watts

The power required for level flight at sea level is only 19 watts but we have 1800 watts available. Starduster has more than 90 times the power required for level flight!!! If all the excess power were used for climbing Starduster would have a climb rate of 4250 feet per minute. If this climb rate could be maintained Starduster could climb in excess of 200,000 feet in less than one hour. But at high altitudes the air is thin and much more

Power is required to fly. Three effects of high altitude need to be considered. First, the flight speed, sink rate and power required to maintain level flight increase as the inverse square root of air density. Secondly, operating Reynolds number decreases with altitude and therefore drag increases which places a minimum size constraint on the aircraft. Thirdly, both propeller and wing must operate at sub-sonic speeds so this places a constraint on maxim wing loading. Table 5 below depicts these effects.

**Table 5**
**Atmospheric effects at Altitude**

| Altitude | Speed | Reynolds Number | Mach 1 |
|---|---|---|---|
| **Sea Level** | **1.000** | **1.000** | **1117 fps** |
| **10,000 feet** | **1.164** | **0.812** | **1078 fps** |
| **20,000 feet** | **1.370** | **0.648** | **1037 fps** |
| **30,000 feet** | **1.635** | **0.506** | **995 fps** |
| **40,000 feet** | **2.006** | **0.394** | **968 fps** |
| **50,000 feet** | **2.563** | **0.308** | **968 fps** |
| **60,000 feet** | **3.259** | **0.243** | **968 fps** |
| **70,000 feet** | **4.139** | **0.191** | **971 fps** |
| **80,000 feet** | **5.255** | **0.150** | **971 fps** |
| **90,000 feet** | **6.836** | **0.116** | **971 fps** |
| **100,000 feet** | **8.476** | **0.093** | **971 fps** |
| **110,000 feet** | **10.998** | **0.075** | **995 fps** |
| **120,000 feet** | **14.311** | **0.062** | **1043 fps** |
| **130,000 feet** | **18.206** | **0.052** | **1089 fps** |
| **140,000 feet** | **22.733** | **0.045** | **1132 fps** |
| **150,000 feet** | **27.918** | **0.039** | **1174 fps** |
| **160,000 feet** | **33.822** | **0.034** | **1215 fps** |
| **170,000 feet** | **39.797** | **0.029** | **1231 fps** |
| **180,000 feet** | **46.181** | **0.025** | **1231 fps** |
| **190,000 feet** | **53.590** | **0.022** | **1231 fps** |
| **200,000 feet** | **61.686** | **0.019** | **1220 fps** |

Since Starduster has 1800 watts available but needs only 19 watts it has 95 times the power needed to fly at sea level. Starduster should be able to reach altitudes well in excess of 200,000 feet. But detailed performance calculations indicate that a ceiling of 200,000 feet is all that can be expected. Profile drag increased with decreasing Reynolds number and Reynolds number decreases with altitude. Table6 Below shows how the section profile drag coefficient varies with altitude. At 200,000 feet Starduster will be operating at very low Reynolds numbers of between 5,000 and 10,000. In this range profile drag increases more slowly than the reciprocal square root of Reynolds number as in viscous flow and more rapidly than the reciprocal fifth root as is usually assumed at higher Reynolds numbers. The author has devised the following approximation which seems to fit the published data on Eppler airfoils. It is

Cd ( R ) = 0.5 x Cd0 {square root ( Rn0/Rn) + fifth root (Rn0/Rn) }

## Table 6

## The Effect of altitude on Profile Drag

| Altitude | Reynolds Number | Cd |
|---|---|---|
| Sea Level | 1.000 | 1.00 |
| 10,000 feet | 0.812 | 1.08 |
| 20,000 feet | 0.648 | 1.17 |
| 40,000 feet | 0.394 | 1.40 |
| 60,000 feet | 0.243 | 1.68 |
| 70,000 feet | 0.191 | 1.84 |
| 80,000 feet | 0.150 | 2.02 |
| 90,000 feet | 0.116 | 2.24 |
| 100,000 feet | 0.093 | 2.44 |
| 110,000 feet | 0.075 | 2.66 |
| 120,000 feet | 0.062 | 2.87 |
| 130,000 feet | 0.052 | 3.08 |
| 140,000 feet | 0.045 | 3.29 |
| 150,000 feet | 0.039 | 3.51 |
| 160,000 feet | 0.034 | 3.72 |
| 170,000 feet | 0.029 | 3.95 |
| 180,000 feet | 0.025 | 4.20 |
| 190,000 feet | 0.022 | 4.48 |
| 200,000 feet | 0.19 | 4.79 |

The drag sources on Starduster can be divided into three categories, section profile drag tabulated above, induced drag and all other parasite drag. The increased power required to fly the complete air vehicle at altitude is only about one half that shown in table 6. None the less it is still a sizable increase. A third restriction is the necessity of keeping the air speed subsonic to avoid the very high drag associated with trans-sonic flight. Assuming a reasonably high advance ratio of 3.1416 for the propeller and assuming a critical Mach number of 0.9 for the propeller tips, we calculate that the maximum allowable Mach number for Starduster is Mach 0.64. Table7. Below lists the maximum allowable wing loading above 100,000 feet at Mach 0.64.

## Table 7

## Critical Mach number limitation on wing loading CL = 0.8

| Altitude | Mach 0.64 | Maximum Wing Loading |
|---|---|---|
| 100,000 feet | 621 feet per second | 5.12 pounds per square foot |
| 110,000 feet | 637 feet per second | 3.19 pounds per square foot |
| 120,000 feet | 667 feet per second | 2.07 pounds per square foot |
| 130,000 feet | 697 feet per second | 1.39 pounds per square foot |
| 140,000 feet | 724 feet per second | 0.95 pounds per square foot |
| 150,000 feet | 751 feet per second | 0.69 pounds per square foot |
| 160,000 feet | 777 feet per second | 0.50 pounds per square foot |
| 170,000 feet | 788 feet per second | 0.35 pounds per square foot |
| 180,000 feet | 788 feet per second | 0.30 pounds per square foot |
| 190,000 feet | 788 feet per second | 0.24 pounds per square foot |
| 0,000 feet | 781 feet per second | 0.17 pounds per square foot |

Starduster is limited by the power available to an altitude of 200,000 feet and with wing loading of 0.117 pounds per square foot is within the limits on table 7.

Still another restriction needs to be addressed. The author could find no airfoil data on operation at Reynolds numbers below 25,000. This is not to say that suitable profiles cannot be found but simply that the author could not find any. Suitable scale models should be tested a Reynolds numbers between 5,000 and 25,000. Limiting the minimum Reynolds number to 25,000 dictates a minimum wing chord of 22 feet and propeller chord of 15 feet for flight at an altitude of 200,000 feet. Table 8 shows minimum wing and prop chord for operation at 200,000 feet.

**Table 8**
**Minimum Chord at 200,000 feet, wing Mach 0.64, prop tip Mach 0.9**

| Reynolds Number | Wing Chord | Prop Chord |
|---|---|---|
| 5,000 | 4.4 feet | 3.1 feet |
| 10,000 | 8.8 feet | 6.2 feet |
| 15,000 | 13.1 feet | 9.4 feet |
| 20,000 | 17.5 feet | 12.5 feet |
| 25,000 | 21.9 feet | 15.6 feet |
| 30,000 | 26.3 feet | 18,7 feet |
| 40,000 | 35.1 feet | 24.9 feet |
| 50,000 | 43.8 feet | 31.2 feet |

Our 32 foot span Starduster has the power to climb to 200,000 feet. At this altitude both wing and prop are operating at Reynolds numbers of 5,000. The author has increased the profile drag to account for these low Reynolds numbers in his performance calculations but has no actual measured data on the behavior of airfoils in this region.

## Starduster Performance

A detailed analysis of the flight envelope of Starduster is summarized in table 9. The aircraft is capable of level flight speeds of Mach 0.5 at 200,000 feet. But at this altitude Starduster has a very slim climb margin of 17 feet per minute. At 190,000 feet the climb rate is a respectable 600 feet per minute and at sea level over 3,000 feet per minute with a climb angle of 74 degrees. Sea level climb rate is maintained up to 120,000 feet.

## Sensitivity Analysis

Since the climb margin at design altitude is a marginal 17 feet per minute, the author has examined the effect of increasing wing span and wing chord and of scaling Starduster to a larger size. Increasing wing span or wing chord by 1 foot increased climb rate to 60 feet per minute. By increasing both wing span and chord by 1 foot the climb rate increased to 150 feet per minute. Doubling the size of Starduster to a wing span of 64 feet and thereby quadrupling the weight to 74 pounds increased the climb rate to 495 feet per minute. Doubling again to 128 feet and 296 pounds increased the climb rate to 849 feet per second. These improvements are not the result of reduced span loading which is unchanged but solely the result of increased Reynolds number.

## The Propeller

Mach number limitations place severe design constraints on the propeller. Tip speed must be kept below Mach 0.9 The author has analyzed dozens of propeller configurations with diameters ranging from 8 feet to 16 feet ( ¼ to ½ wing span) while holding tip speed constant at Mach 0.9. The best results seem to come at designs with blade lift coefficient of 0.7 and prop diameters between 10.5 and 11.5 feet. The best design found was 11 feet in diameter with a pitch of 30 feet and a maximum chord of 3.6 feet. Its calculated efficiency was 84.9%, this is the kind of propeller normally found on a boat not an airplane. The Reynolds number along the blade remains relatively constant at between 5,000 and 6,000. This large propeller is impossible to match to the motor speed of 1,400 Rpm at lower altitudes. At lower altitudes both propeller Rpm and propeller pitch must be reduced. At sea level the efficiency of this propeller is a little less than 60%.

**Table 9**
**Starduster Performance Envelope**

| Altitude | Speed | Climb Rate | Climb Angle | Sink Rate | Reynolds No. |
|---|---|---|---|---|---|
| sea level | 18 mph | 3050 fpm | 74 deg. | 40 fpm | 498,000 |
| 10,000 | 26 mph | 3050 fpm | 69 deg | 47 fpm | 432,000 |
| 20,000 | 31 mph | 3500 fpm | 67 deg | 57 fpm | 372,000 |
| 30,000 | 38 mph | 3550 fpm | 63 deg | 69 fpm | 291,000 |
| 40,000 | 46 mph | 3600 fpm | 57 deg | 87 fpm | 225,000 |
| 50,000 | 55 mph | 3650 fpm | 55 deg | 113 fpm | 164,000 |
| 60,000 | 65 mph | 3625 fpm | 48 deg | 143 fpm | 132,000 |
| 70,000 | 79 mph | 3575 fpm | 42 deg | 192 fpm | 95,000 |
| 80,000 | 93 mph | 3550 fpm | 38 deg | 250 fpm | 80,000 |
| 90,000 | 111 mph | 3475 fpm | 34 deg | 327 fpm | 48,000 |
| 100,000 | 139 mph | 3350fpm | 28 deg | 428 fpm | 38,000 |
| 110,000 | 160 mph | 3250 fpm | 23 deg | 571 fpm | 28,000 |
| 120,000 | 205 mph | 3050 fpm | 17 deg | 763 fpm | 22,000 |
| 130,000 | 226 mph | 2875 fpm | 13 deg | 996 fpm | 18,000 |
| 140,000 | 275 mph | 2600 fpm | 10 deg | 1274 fpm | 16,000 |
| 150,000 | 338 mph | 2225 fpm | 7 deg | 1603 fpm | 14,000 |
| 160,000 | 380 mph | 1925 fpm | 5 deg | 1989 fpm | 12,000 |
| 170,000 | 405 mph | 1550 fpm | 3 deg | 2399 fpm | 10,000 |
| 180,000 | 425 mph | 1106 fpm | 2 deg | 2861 fpm | 8,000 |
| 190,000 | 441 mph | 600 fpm | 1 deg | 3415 fpm | 7,000 |
| 200,000 | 416 mph | 17 fpm | zero | 4051 fpm | 6,000 |

## Starduster Mission Analysis

Mission 1. Climb to maximum altitude, stay as long as possible then glide home in the evening. Assume that the flight begins at 8 AM on a summer day with the sun about 30 degrees above the horizon. Starduster is launched in a north westerly heading with the sun to its back. This tactic puts the maximum amount of sun on the solar array.

## Table 10
## Maximum Climb

| Time of day | Altitude | Climb Rate |
|---|---|---|
| 8:00 | sea level launch | 3,050 ft/ min |
| 8:06 | 20,000 feet | 3,500 ft/min |
| 8:12 | 40,000 feet | 3,600 ft/min |
| 8:18 | 60,000 feet | 3,626 ft/min |
| 8:24 | 80,000 feet | 3,550 ft /min |
| 8:29 | 100,000 feet | 3,350 ft/min |
| 8:35 | 120,000 feet | 3050 ft/min |
| 8:38 | 130,000 feet | 2,875 ft/min |
| 8:42 | 140,000 feet | 2,600 ft/min |
| 8:46 | 150,000 feet | 2,225 ft/min |
| 8:50 | 160,000 feet | 1,925 ft/min |
| 8:55 | 170,000 feet | 1,550 ft/min |
| 9:01 | 180,000 feet | 1,106 ft/min |
| 9:11 | 190,000 feet | 606 ft/min |
| 10:00 | 200,000 feet | 17 ft/min |

Once maximum altitude is reached Starduster will circle until 18:00 by which time it will have descended to 180,000 feet at the sun sets in the west. Starduster will then begin a long gliding flight back to earth.

## Table 11
## Descent to Earth

| time of day | Altitude | sink rate |
|---|---|---|
| 18:00 | 180.000 feet | 2,861 ft/min |
| 18:03 | 170,000 feet | 2,399 ft/min |
| 18:07 | 160,000 feet | 1,989 ft/min |
| 18:12 | 150,000 feet | 1,603 ft/min |
| 18:18 | 140,000 feet | 1,274 ft/min |
| 18:26 | 130,000 feet | 996 ft/min |
| 18:36 | 120,000 feet | 763 ft/min |
| 18:49 | 110,000 feet | 571 ft/min |
| 19:07 | 100.000 feet | 428 ft/min |
| 19:30 | 90,000 feet | 327 ft/min |
| 20:01 | 80,000 feet | 250 ft/min |
| 20:41 | 70,000 feet | 192 ft/min |
| 21:33 | 60,000 feet | 142 ft/min |
| 22:43 | 50,000 feet | 113 ft/min |
| 00:12 | 40,000 feet | 87 ft/min |
| 02:07 | 30,000 feet | 69 ft/min |
| 04:32 | 20,000 feet | 57 ft/min |
| 07:28 | 10,000 feet | 47 ft/min |
| 10:59 | touch down | 40 ft/min |

Total flight time is 26 hours and 59 minutes. Since dawn returns while Starduster is still above 12,000 feet Starduster could resume its climb, and weather permitting, and continue flying throughout the summer months.

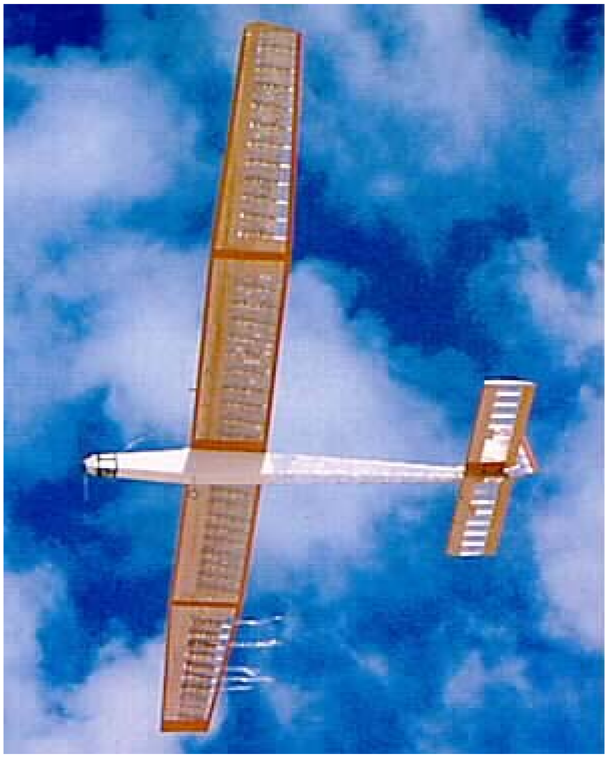
Mission 2  Cross Country Distance. At altitudes above 150,000 feet Starduster is traveling at about Mach 0.5. This speed is a sizable fraction of the velocity of the sun line which circles the globe every 24 hours. The velocity of the sun line is approximately 950 mph at the equator. At 30 deg north latitude (California) the sun line velocity is about 825 mph. If Starduster were to travel on a westerly heading at Mach 0.5 the 6 hour day would be extended to 13 hours and so Starduster could travel about 6,000 miles in one day. This assumes no head wind, but even with 100 mph head wind range is still over 4,000 miles. Starduster has more than enough range to fly non stop across the USA. At 59 degrees north latitude (Northern Canada) on a westerly heading Starduster would be in sun synchronous orbit and would circle the globe every 24 hours forever basking in the noon day sun.

## Conclusions

Solar powered airplanes can be built today using available technology that can reach extreme altitudes even exceeding 200,000 feet. Under certain conditions they can travel very long distances. In 1974 Sunrise I showed the world that an airplane could fly on solar power alone without the help of batteries. In 1975 Sunrise II was flown to over 20,000 feet and had a calculated service ceiling of over 50,000 feet. In 1981 the DuPont Solar Challenger crossed the English Channel. Perhaps in this second decade of solar flight we will see solar airplanes circle the globe nonstop!

## References

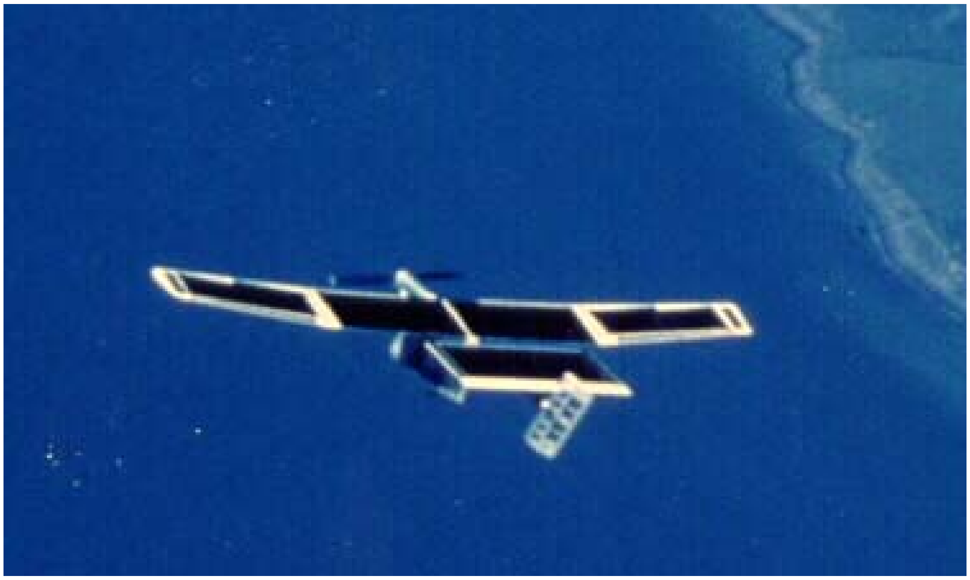
1. Boucher R. J. “ Project Sunrise” AIAA paper 79-1264  June 1979
2. Boucher R. J. “ History of Solar Flight” AIAA paper 84-1429  June 1984
3. Boucher R. J. “ The Quiet Revolution” book published by Astro Flight Inc. 1979
4. Boucher R. A. and Boucher R.J. “ Remotely Controlled Electric Airplane” U.S. Patent 3957230
5. Boucher R. J. “The Gossamer Penguin makes historic solar flight” RCM magazine July 1980
6. MacCready P.B., Lissaman P.B.S., Morgan W.R and Burke J.D. “Sun Powered Aircraft Designs” AIAA paper May 1981.
7. Boucher R.A. “ Look Ma No Noise” Model Builder Magazine July 1973
8. Eppler Profil MTB-1  Published by Verlag fur Technik und Handwerk GMBH 1983
9. Hoerner S.F.  “ Fluid Dynamic Drag” Published by S.F. Hoerner 1965



**Sunrise I flying at 4,000 feet over Camp Irwin California
November 1974**

**Sunrise II ready for launch on a dry lake in Mercury Nevada September1975**

**The Gossamer Penguin with Pilot Marshal MacCready on board making Its historic manned solar flight on May 18, 1980 at Shafter California**



**The DuPont Solar Challenger with Pilot Steve Patacek aboard crossing the English Channel July 8, 1981**