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Stratospheric Towed Vehicle Concept

Wubbo J. Ockels,* Joris A. Melkert,† and Alfred L. C. Roelen†
Delft University of Technology, Delft, The Netherlands

The Stratospheric Towing Project (STRATOW) is a project started at Delft University of Technology to develop an alternative method for in situ study of the stratosphere. The STRATOW concept is to obtain a large altitude difference between a glider and its towing aircraft using a very long and thin tether, in which the glider is used as a kite. The STRATOW concept becomes feasible due to the development of high-performance fibers. This article describes the three major factors that limit the performance of STRATOW, 1) the tether strength, 2) glider wing area, and 3) the towplane power. A numerical model and an analytical model of the STRATOW performance is developed to identify the key parameters. Model calculations show possible altitude differences over 10 km. An initial test is reported with a tether of 3000 m length.

Nomenclature

C_L = lift coefficient of glider
c_d = pressure drag coefficient of tether
c_f = friction drag coefficient of tether
d = tether diameter
F = force
g = acceleration of gravity
H_p = pressure scale height
h = altitude
L = lift
l = tether length
M = Mach number
P = power
q = dynamic pressure at towing aircraft, $\frac{1}{2}\rho_1 V_1^2$
r = density ratio, ρ_2/ρ_1
S = wing area of glider
V = true airspeed
W = weight of glider
β = angle of tether with respect to horizontal plane
γ = fit factor
γ_{12} = $\ln \tan(\frac{1}{2}\beta_2) - \ln \tan(\frac{1}{2}\beta_1)$
Δh = altitude difference
ρ = density
σ_{max} = ultimate tensile stress of tether

Subscripts
d = drag
f = friction
g = gravity
IAS = indicated airspeed
t = tether
0 = at 0 m ICAO Standard Atmosphere (ISA)
1 = at towplane
2 = at glider

Introduction

PRESENTLY the access to the stratosphere is given either by high-altitude balloons or by fast airplanes such as the Concorde, U-2, etc. Balloons have the disadvantage of moving with the air mass at a predetermined altitude. The high-flying airplanes have high operating costs and are flying too fast for many experiments. Because of the increasing interest in environmental research, and particularly of in situ measurements in the stratosphere, a strong interest has been developed recently for high- and slow-flying aircraft.

Several projects have been initiated to realize such airplanes, i.e., Condor of Boeing,[1–3] Perseus of NASA/Aurora Flight Sciences,[4,5] and Strato 2C of Grob.[6,7] These aircraft are gliderlike from design, powered by specially developed engines. The main difficulty is to design an engine that gives sufficient power at the very low density of air corresponding to the high altitude.

The STRATOW concept uses a towing line (tether) to replace the engine at high altitude by the engine of a towing aircraft at low altitude where power is readily available because of the higher air density. The STRATOW concept, i.e., towing a glider as a kite, becomes feasible due to the new development of fibers of extreme strength, like Dyneema® (Dyneema is a trademark of DSM), such that very thin tethers can be used with little air drag.

Future development allows stronger and thus thinner tethers leading to even higher altitudes to be reached by STRATOW.

A numerical model is developed by Melkert[8] describing the forces on the tether and the resulting shape, taking into account the flight characteristics of the glider.[8] A simplified model can be derived by using approximations that then allow analytical integration. From the resulting analytical model the dependence on parameters such as tether diameter and flight speed can be shown. The analytic form is compared to the numerical results, indicating the validity of this simplified model.

The calculated performances of STRATOW do not take into account possible different flight speeds at different altitudes due to wind.

Numerical Model

The aerodynamic forces on a small part of the tether are shown in Fig. 1:

$$dF_{\parallel} = \tfrac{1}{2}\rho c_f \pi (V \cos \beta)^2 d \, dl \tag{1}$$

$$dF_{\perp} = \tfrac{1}{2}\rho c_d (V \sin \beta)^2 d \, dl \tag{2}$$

and due to gravity

$$dF_g = g\rho_t \pi \tfrac{1}{4} d^2 \, dl \tag{3}$$

Assuming c_f and c_d are constant and known, the numerical model integrates Eqs. (1–3), resulting in the tether tension F_t and tether shape.[8]

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*Professor, Faculty of Aerospace Engineering, P.O. Box 5058, 2600 GB; currently Science Astronaut, European Space Agency, ESTEC, Noordwijk, The Netherlands.
†Graduate Student, Faculty of Aerospace Engineering, P.O. Box 5058, 2600 GB.

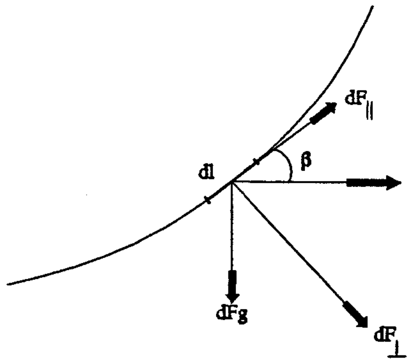

Fig. 1 Forces on the tether.

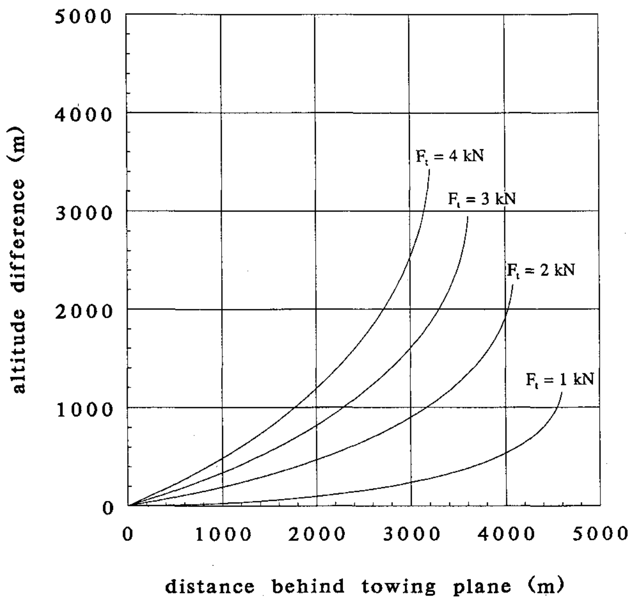

Fig. 2 Tether shape for various tether tensions (l = 5000 m, VIAS = 40 m/s, d = 2.5 mm). Towing aircraft flies at 0 m.

In the numerical model, first the equilibrium of the glider is considered. For a given glider, altitude, speed, and lift coefficient, the magnitude and the orientation of the tether tension at the upper end of the tether is determined, after which the calculation of the tether shape starts. For this purpose the tether is divided into a number of elements. The orientation of each element is set to be the same as the orientation of the force at its upper end. This orientation combined with the altitude, speed, length, and diameter of the element gives the aerodynamic and gravity forces on the element. With these forces known, the tether tension and its orientation at the lower end can be calculated through the equilibrium of the forces. This procedure is repeated until a boundary condition for length, force, or orientation is met. The complete shape of the tether is then known. This method of calculation converges rapidly when the length of the elements is decreased.

Figure 2 gives a few examples of calculated tether shapes for the case of l = 5000 m, d = 2.5 mm, and V = 40 m/s.

Analytical Model

Aerodynamic Forces

For the interpretation of the various relationships between parameters such as tether diameter and obtainable altitude, etc., an analytical model is developed. For this purpose it is assumed that the effects of the mass and the friction drag are low. Equations (1) and (3) can thus be neglected, and only the aerodynamic force (2) remains. The validity of this assumption is discussed later.

Using

$$\mathrm{d}h = \mathrm{d}l \sin \beta \tag{4}$$

$$\mathrm{d}\beta = \frac{\mathrm{d}F_\perp}{F_t} \tag{5}$$

Eq. (2) can be written as

$$\frac{\mathrm{d}\beta}{\sin \beta} = \frac{\frac{1}{2}\rho(h)c_d d V^2 \,\mathrm{d}h}{F_t} \tag{6}$$

A simplified atmospheric model is used:

$$\rho(h) = \rho_0 \exp(-h/H_p) \tag{7}$$

where h is 0 to 20 km, and the approximation is best for H_p = 9000 m.

Furthermore, the ratio of ρ_2/ρ_1 is used for convenience:

$$r = (\rho_2/\rho_1) = \exp[(h_1 - h_2)/H_p] \tag{8}$$

The analytical integration of Eq. (6) yields

$$\gamma_{12} = [\tfrac{1}{2}c_d V^2(\rho_1 - \rho_2)H_p/F_t] \tag{9}$$

where

$$\gamma_{12} = \ln \tan(\tfrac{1}{2}\beta_2) - \ln \tan(\tfrac{1}{2}\beta_1) \tag{10}$$

Typical values of β_2 will be close to 90 deg, and β_1 will be small (Fig. 2). γ_{12} will therefore not vary much, so that it is useful to write Eq. (9) as

$$F_t = [qc_d d(1 - r)H_p/\gamma] \tag{11}$$

where

$$q = \tfrac{1}{2}\rho_0 V_{\mathrm{IAS}}^2 \quad \text{(dynamic pressure at the towplane)} \tag{12}$$

$$V_{\mathrm{IAS}}^2 = (\rho_1/\rho_0)V^2 \tag{13}$$

Equation (11) shows that the dynamic force on the tether is proportional to q and d, and, for small altitude differences compared to H_p, proportional to $(h_2 - h_1)$.

Limitations Due to Tether Strength

The strength of the tether can be written as

$$F_{\max} = \tfrac{1}{4}\pi\sigma_{\max}d^2 \tag{14}$$

This strength must be larger than the tether tension F_t

$$F_{\max} \geq F_t \tag{15}$$

which, using Eqs. (11) and (14), gives the minimum diameter of the tether to withstand the aerodynamic forces:

$$d_{\min} = (4/\pi\sigma_{\max})q(c_d H_p/\gamma)(1 - r) \tag{16}$$

For constant tether diameter, Eq. (16) forms a curve in the altitude difference $h_2 - h_1$ vs the V_{IAS} plane, above and right of which the tether will break due to a too high aerodynamic force.

Limitations Due to the Lift of the Glider

Since the tether is almost vertical close to the glider (Fig. 2) the tension in the tether has to be lifted by the glider:

$$L \geq W + F_t \tag{17}$$

The lift is given by

$$L = \tfrac{1}{2}\rho_2 V_2^2 C_L S \tag{18}$$

or

$$L = qrC_L S \tag{19}$$

Substitution of F_t and L gives

$$qC_L Sr - W \geq dq(c_d H_p/\gamma)(1 - r) \tag{20}$$

or

$$d_{\max} = \frac{\gamma}{c_d H_p} \frac{C_L Sr - (W/q)}{1 - r} \tag{21}$$

Equation (21) gives the maximum diameter of the tether beyond which the aerodynamic force F_t becomes too high to be carried by the lift of the glider. For a specific glider, Eq. (21) gives lines in the $h_2 - h_1$ vs V_{IAS} plane, below and right of which the glider has sufficient lift.

Combination of Limitations

The highest altitude of the glider will be obtained when Eqs. (16) and (21) are satisfied simultaneously ($d_{\min} = d_{\max}$). This yields

$$\frac{4}{\pi\sigma_{\max}} q \left(\frac{c_d H_p}{\gamma}\right)^2 (1 - r)^2 - C_L Sr + \frac{W}{q} = 0 \tag{22}$$

This gives a relation between q and r.

The maximum obtainable altitude difference will be found when the derivative of Eq. (22) with respect to q is zero

$$\frac{4}{\pi\sigma_{\max}} \left(\frac{c_d H_p}{\gamma}\right)^2 (1 - r)^2 - \frac{W}{q^2} = 0 \tag{23}$$

Substitution gives

$$C_L Sr = (2W/q) \tag{24}$$

which says in fact

$$L = 2W \tag{25}$$

Apparently, the maximum obtainable altitude is reached when the lift of the glider is equally balanced over the aerodynamic force on the tether and the weight of the glider. Substitution of Eqs. (23) and (24) into Eq. (21) gives

$$d_{\mathrm{opt}} = \sqrt{(4W/\pi\sigma_{\max})} \tag{26}$$

Thus, the surprisingly simple result is obtained that the tether diameter for maximum altitude difference only depends on the weight of the glider and the ultimate tensile stress of the tether material.

With this result the minimum obtainable density ratio is

$$\frac{1}{r_{\mathrm{opt}}} = 1 + \frac{C_L S\gamma\sqrt{\pi\sigma_{\max}}}{4c_d H_p \sqrt{W}} \tag{27}$$

and the corresponding airspeed is

$$q_{\mathrm{opt}} = \frac{2W}{C_L S} \frac{1}{r_{\mathrm{opt}}} \tag{28}$$

Equation (27) shows that the largest altitude difference will be obtained with an aircraft with large $S/\sqrt{W}$, i.e., an aircraft with large wing area and low weight.

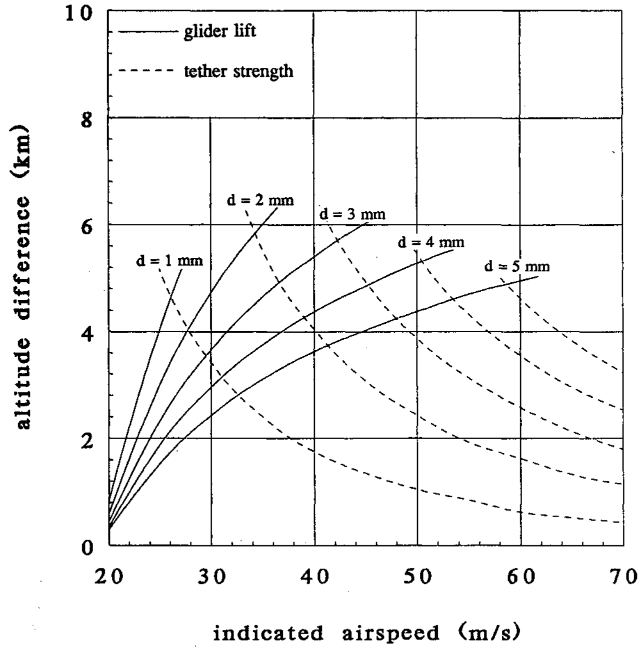

Fig. 3 Glider lift and tether strength limitations for ASW 19 glider. Tether material is Dyneema SK-60. Towing aircraft flies at 0 m.

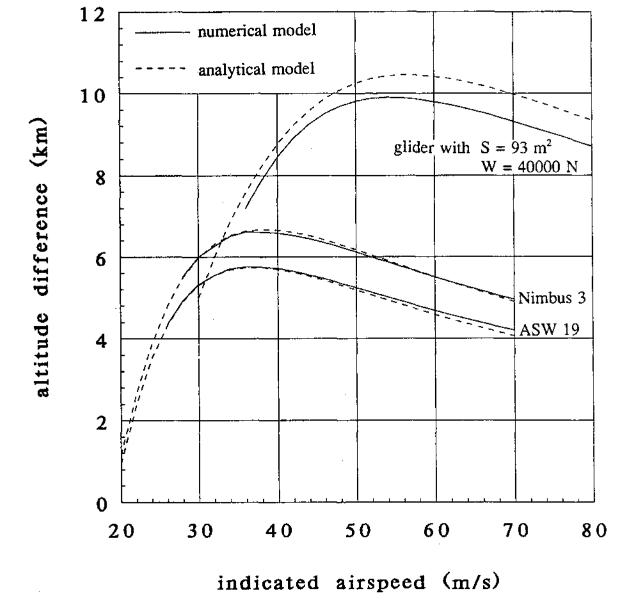

Fig. 4 Maximum altitude difference as a function of airspeed for different gliders. Tether material is Dyneema SK-60. Towing aircraft flies at 0 m.

Comparison of Numerical Model with Analytical Model

Using the numerical model, the aerodynamic force on the tether was calculated for different V_{IAS} and different values of d. For each V_{IAS}, the altitude difference was increased until either of two limitations was reached; the limitation of the glider lift (low-speed boundary) or the limitation of the tether strength (high-speed boundary). The results for a Schleicher ASW 19 glider are shown in Fig. 3.

From Fig. 3 one can see that for this particular example the maximum obtainable glider altitude is 6 km, using a tether diameter of 2 mm. This means that with the towing aircraft flying at 5 km it is possible for a standard glider to reach the lower stratosphere. The corresponding tether length is 20 km.

The obtainable altitude differences as a function of airspeed resulting from the numerical model can now be compared with the analytical model, i.e., Eq. (22). The unknown γ is used as a fit factor. Figure 4 shows the comparison for three different glider types (two standard gliders and an imaginary glider design). γ was chosen 2.6 for all three cases. The curves reveal a good agreement between the numerical and analytical models. The choice of $\gamma = 2.6$ is good for the region of interest. The ASW 19 glider limits the altitude difference to 6 km. A larger glider, such as the Nimbus 3, increases the performance to 7 km. For larger altitude differences a new glider design is needed, such as the imaginary glider used for the calculations.

Figure 4 shows a good fit between the numerical model and the simple analytical relation of Eq. (22). Therefore, one can apply the parameter dependence of the obtainable altitudes as indicated in Eqs. (22–28).

Power of the Towing Aircraft

In addition to the limitations given by the tether strength and the lift of the glider, a third limitation is given by the performance of the towing aircraft.

Since the tether is more or less horizontal at the towing aircraft (Fig. 2), the extra towing aircraft power required is

$$P = F_t V \tag{29}$$

and with Eq. (11) this gives

$$P = \frac{1}{2}\rho_0 \sqrt{\frac{\rho_0}{\rho_1}} \frac{c_d H_p}{\gamma} d(1 - r)V_{\mathrm{IAS}}^3 \tag{30}$$

For minimum power $d_{\min}$ is substituted into Eq. (30):

$$P = \rho_0^2 \sqrt{\frac{\rho_0}{\rho_1}} \left(\frac{c_d H_p}{\gamma}\right)^2 \frac{1}{\pi \sigma_{\max}} (1 - r)^2 V_{\mathrm{IAS}}^5 \tag{31}$$

Thus, it is shown that the power needed to tow the glider at the maximum altitude difference depends on the fifth power of the indicated airspeed. In practice this means that to reach the highest possible altitude of the glider, the towing aircraft has to fly as slow as possible. Normally, the power available is reduced at higher altitudes, whereas the minimum flight speed is increased. Since the excess power of the towplane is a function of the altitude one can, using Eqs. (31) and (22), determine a towing aircraft altitude for which the altitude of the glider is a maximum.

Proof of Concept Tests

Recently, the first flight tests of the STRATOW configuration have been conducted, for which special safety and operational requirements were defined.[10] The towing plane was a modified agricultural plane type Ayres S2R-T34 Turbo Trush with a P&W PT6-AG 800 shp turboprop engine. In the 2000-l fluid tank, a special winch system was placed. The glider (ASW 19) was a normal glider equipped with additional navigation systems and avionics. A special navigation system has been developed using "differential GPS" (telemetry between towing aircraft and glider comparing each other's position). A "rails in the sky" is projected on a display for the glider pilot, who cannot see the towing aircraft at large tether lengths.[11] The tether was a specially developed, 2.4-mm-thick line of Dyneema SK 60, made by Eurocord, a Dutch rope manufacturer, and DSM, a Dutch chemical corporation. The strength of the tether was over 5000 N. The tether was reeled out to 3200 m and an altitude difference of 800 m was obtained (the towing aircraft flew at 900 m). The main objectives of these first flights were to assess the configuration controllability and maneuverability. A 180-deg turn with a 5-deg bank angle was successfully performed. The longitudinal and pitch stability were shown to be good for tether lengths above 1000 m. Further tests are planned for spring 1994 when larger altitude differences will be obtained.

Potential

STRATOW gives an alternative and economic capability to reach the stratosphere. STRATOW mission costs will allow use within the scope of national programs and universities. Discussions with Dutch atmospheric experts[12] lead to the conclusion that STRATOW provides unique capabilities for low-speed flying around 11 km to study exhaust gas trails of commercial and military airplanes. The glider can make a scanning track through the exhaust trails, without interference of a propulsion system.

With the STRATOW concept also high-altitude (>16 km) flights are possible, to study, in particular, ozone levels in the middle of the ozone layer. For this capability a towing airplane has to be used that can fly up to 10-km altitude at low speed. The almost vertical part of the tether close to the glider gives the unique opportunity to attach small sensors at different altitudes (e.g., each 500 m) as to allow a combined horizontal and vertical scan. The high-altitude capability of STRATOW also provides a low-cost test bed for advanced wing section development for use at relatively high Mach ($M = 0.5$) and low Reynolds numbers.

Conclusions

The STRATOW concept provides a new and unique low-cost capability to reach the lower and middle stratosphere altitudes using a combination of a glider, a towing aircraft, and a very long and thin tether. The simple analytical model of the STRATOW performance that has been developed gives a good agreement with the numerical model, and can therefore be used to identify the key parameters. The analytical model shows that to reach a large altitude difference between the glider and the towing aircraft one needs a glider with a large $S/\sqrt{W}$. At the maximum altitude difference the glider flies with a lift that equals twice the weight of the aircraft. The optimal diameter of the tether depends on the weight of the glider and the ultimate tensile stress of the tether material.

For a standard glider the maximum obtainable altitude difference between towing aircraft and glider will be about 7 km. Altitude differences of over 10 km can be reached with a special glider design. The STRATOW concept will develop increased altitude capability in the future, following the development of high-performance fibers.

Actual flight testing of the STRATOW configuration has just begun, and is starting to show operational feasibility. Further tests, reaching 11 km, already provide interesting measurement capabilities of ozone boundaries and aircraft exhaust gas effects. The results of those tests will be published in a following paper.

References

[1]Johnstone, R., "CONDOR-High Altitude Long Endurance (HALE) Automatically Piloted Vehicle (APV)," AIAA Paper 90-3279, Sept. 1990.

[2]Goo, A. M. S., Arntz, N., and Murphy, R. D., "CONDOR for High Altitudes," *Aerospace America*, Vol. 27, No. 2, 1989, pp. 36, 37.

[3]Henderson, B. W., "Boeing Condor Raises UAV Performance Levels," *Aviation Week & Space Technology*, April 23, 1990, pp. 36–38.

[4]Dornheim, M. A., "Perseus High Altitude Drone to Probe Stratosphere for SST Feasibility Studies," *Aviation Week & Space Technology*, Dec. 9, 1991, pp. 36, 37.

[5]Taubes, G., "NASA Launches a 5-Year Plan to Clone Drones," *Science*, Vol. 260, April 16, 1993, p. 286.

[6]Anon., STRATO 2C Bringt Europas Klimaforschung Weiter Voran, *BundesMinisterium für Forschung und Technologie (BMFT) Journal*,

Nr. 5, Oct. 1992, p. 11.

[7]Künkler, H., "Antrieb der STRATO 2C—Integraler Bestandtteil Einer Systemlösung," *Zeitschrift für Flugwissenschaften und Weltraumforschung*, No. 17, 1993, pp. 239–244.

[8]Melkert, J. A., "STRATOW First Model Calculations and Tests," (in Dutch), Delft Univ. of Technology Thesis, Delft, The Netherlands, July 1992.

[9]Hoerner, S. F., *Fluid Dynamic Drag, Practical Information on Aerodynamic Drag and Hydrodynamic Resistance*, Hoerner Fluid Dynamics, Vancouver, WA, 1958.

[10]Roelen, A. L. C., "STRATOW Project: Operational Limits, Safety Analysis and Flight Procedures," (in Dutch), Delft Univ. of Technology Memorandum M-670, Delft, The Netherlands, April 1993.

[11]Boon, F. J. G., "Design, Implementation and Testing of a Real-Time Navigation System for the STRATOW Project Based on Relative GPS," Delft Univ. of Technology Thesis, Delft, The Netherlands, Dec. 1993.

[12]Kelder, H., private communication, Royal Dutch Meteorological Inst., De Bilt, The Netherlands, June 1993.