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# The Parafoil Technology Demonstration (PTD) Project: Lessons Learned and Future Visions

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**Abstract**

In the last years some projects in the US and Europe examined the parafoil technology with respect to precise and soft land-landing of future manned/unmanned space vehicles and scientific payloads after balloon or sounding rocket tests.
This paper summarizes the lessons learned, achieved progress and potential prospects of the PTD project (ref.1) with respect to the intermediate results already presented in the 14th AIAA conference (San Francisco).
Meanwhile in the PTD program a parafoil/payload system for payloads up to 3200 kg with wing loading up to 21 $kg/m^2$ and dynamic opening pressures up to 1500 $N/m^2$ with a manual remote control and autonomous guidance system has been designed, fabricated and respective test campaigns have been performed in Europe for the first time.
Based on this experience the basic layout and flight data of a 5to parafoil/payload system for 3 different scenarios will be presented under variation of wind penetration, landing accuracy and cross range.

**Introduction/Objectives**

One of the results of the previous ESA sponsored Crew Return Vehicle (CRV) studies - concerning the reentry and recovery of those systems - is the recommendation to use parafoil technology as the potential recovery system for a precise and soft land-landing of reentry payload systems.
The feasibility of soft and precision landing with the required accuracy of large scaled return systems has not yet been demonstrated in Europe. In the US a limited number of controlled flights of large scaled parafoil/payload systems has been conducted in the programs GPADS (ref.2) and X-38/CRV (ref.3).
The feasibility and achievable landing precision of large scaled parafoil/payload systems will decide about the above mentioned land-landing capability in Europe. ESA initiated the PTD-Program to increase the knowledge and confidence in the parafoil technology as a potential land-landing technology in Europe for recovery of space vehicles.

The main objectives of the PTD-project are the following:

- parafoil/payload test-equipment for payloads up to 3.2to
- Performance of Wind Tunnel Tests with a downscaled canopy (71$m^2$) to study aerodynamics coefficients, angles of attack and rigging angle effects, control line loads and flow velocity effects of the canopy
- Performance of flights with large scaled parafoil/payload systems
- Demonstration of sequenced parafoil deployment and inflation, stable flight performance under remote and autonomous control
- Flight performance under different environmental conditions
- Precise and soft landing at preselected areas of approximately 300m diameter and afterwards stable upright conditions for the payload.
- Detailed analysis of the tests performed and comparison with the test predictions.

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The basic features and the logical flow of the PTD program are summarized in fig.1.

Under the prime contractorship of DASA, Space Infrastructure an industrial team was established, consisting as major participants of Aerazur, APCO, DASSAULT Aviation, DLR and FOKKER Space. Aerazur was mainly responsible for the deceleration subsystem, APCO for the mechanical architecture, FOKKER Space for the electrical architecture, DASSAULT for the aerodynamics including the wind tunnel tests and together with DASA for the development of the GNC subsystem and DLR for the mathematical modelization and the 3 D imaging. DASA - besides the o.m. items- was responsible for the general engineering, the AIT, the flight test performance and the study synthesis.

**Test Vehicle and Equipment**

The major items of the test equipment are the following:

- Parafoil System D160: canopy of 160m$^2$ with a CLARK Y airfoil section including programmer chutes, back-up chute and extraction devices
- GNC assembly with computer, sensors and actuators
- Communication function as TM-,TC-systems, data recording and video link
- Device to measure wind components during flight tests
- Mechanical system with structure, mass ballast, impact dampers
- Parafoil system D80: canopy of 71m2 (dimensions reduced by 2/3 of the D160), CLARK Y airfoil to perform Wind Tunnel Tests at ONERA S1 Modane wind tunnel test facility
- Simulation and Training facility: a PC simulation tool to predict flight trajectories and perform operator/pilot training for the remote control of parafoil/payload systems.

The developed GNC concept allows remote and autonomously controlled flights for large scale parafoil systems. The main role of the GNC is to make the best possible use of parafoil's intrinsic capabilities by optimizing the guidance and control strategy.

**Project Results**

In the course of 10 qualification tests the parafoil canopy (160 m$^2$) showed good characteristics during deployment, inflation and the gliding phase. The glide ratio of the parafoil/payload system was 2.5 at 50% brake deflection and close to 3.0 after brake release. Wind tunnel tests at ONERA Modane S1-facility with a downscaled canopy of 71 m$^2$ were performed to supply an aerodynamic data base with angle of attack and rigging angle effects, control lines efficiency and dynamic pressure effects on the canopy. The avionics system was firstly tested during helicopter flights where the on-board SW and in particular the integrity of all RF links under flight representative conditions were demonstrated.

In a series of remote controlled flights and one flight with autonomous guidance the parafoil/ payload system demonstrated its capability of good steerability, landing accuracy within a circle of 150m radius and reduction of impact shocks during landing by performing adequate flare maneuvers to less than 3.5g.

Pictures of the autonomous guided flight with a payload of 2.000 kg are depicted in fig.2.

**Lessons Learned in the PTD Project**

The GNC concept showed robustness with respect to initial positions and wind prediction errors. The onboard and ground station software are adequate for GNC development and supervisory vehicle control. The TM/TC equipment is appropriate for all investigations during nominal and non nominal flight situations. The accident during flight T2 was due to a software problem in an essential control device which caused a TC link failure. This failure has been identified and for the further tests runs - which, due to a tight test schedule, had to be performed shortly after, - a by-pass solution for functions of the control device has been designed and implemented with a deliberate operational risk. The developed GNC concept allows remote and autonomously controlled flights for large scale parafoil systems. The main role of the GNC is to make the best possible use of parafoil's intrinsic capabilities by optimizing the guidance and control strategy.

The electrical architecture was designed by using an instrumentation system based upon off-the-shelf equipment for flight testing in order to minimize the development and financial risk by an acceptable solution concerning weight and volume.

For the next test series the electrical architecture of the control device will be modified. The onboard video link has to be improved and strain gauges for measurement of the forces in steering and control lines will be installed in order to improve the system identification, operational performance and efficiency.

The D 160 canopy with a Clark Y airfoil section and 160 m$^2$ surface area showed good deployment behavior and regularity in opening sequence. Some discrepancies related to setup conditions of the opening procedure will be improved. A split of the canopy during qualification tests revealed the necessity of a leading and trailing edge reinforcement in order to enable the system to withstand also opening conditions with unintended high dynamic pressures. In remote and autonomous controlled flights the parafoil demonstrated excellent steerability with high turn rates and good flare behavior. The dynamics of the flare performance have to be further analyzed and tested in order to establish the complete autonomous final approach and touch down to ground.

The mechanical architecture with a steel and aluminum core box demonstrated its robustness during the total test campaign. For the envisaged next tests the actuator/winch assembly with respect to mass/volume and the control line arrangement, which caused a strong nonlinearity of the stroke efficiency, will be improved.

**Application of Parafoil Technology for Reentry Vehicles**

The PTD program results confirmed the capability of the parafoil technology to be applied in the X-38 and the future CRV/CTV programs. In addition, guided parafoil landing systems offer a versatile tool for recovery of scientific payloads within sounding rocket and balloon tests and further for recovery of large components of space transportation systems, e.g. boosters, tanks, structures, engines etc. or for various military applications.
Variation of wing loading enables parafoil/payload systems to cover a wide range of flight velocities (typically from 10 m/s @ 5 kg/m2 to 27 m/s @ 25 kg/m2). The use of sophisticated de-reefing systems allows for changing the wing surface also during guided flight, i.e. at high altitudes where strong winds are encountered a reefed and therefore fast flying canopy can be used to provide enough speed for wind penetration. Of course, operating the system in reefed conditions automatically decreases system performance in terms of lift-to-drag ratio, but application of adequately shaped (tapered) wing area can be used to reduce performance losses. Prior to landing a final de-reefing step can be carried out to achieve suitable landing velocities, especially w.r.t sink rate and flare capability.
Today's large systems - i.e. payload mass in the range of 1 to 10 tons (and even more) - make use of very robust but old-fashioned canopy designs (rectangular area, Clark Y airfoil section, etc.) and are therefore flying at lift-to-drag ratios in the range of 2.0 to 3.0. Looking at small scale - 100 kg (man carrying) up to 500 kg payload - applications of ram-air gliding parachutes a significant performance gain can be achieved by updating canopy design (advanced airfoil sections, modified air inlets, V-ribs) and suspension line arrangements (cascading). Improving overall flight performance will also help to further increase the landing accuracy, which already is rather good in low wind conditions, of autonomous guided systems.

**Basic Layout of a Parafoil Recovery System for a 5 to Reentry Vehicle**

In the following basic layouts of parafoil/payload system (L/D~ 3.0; payload 5 to) for different scenarios - concerning initial altitude and sequencing of the parafoil chain - are described to show the possibilities and limits of application of this technology.
As the vehicle is assumed to be aerodynamically unstable in higher altitude at lower Mach number a stabilized free fall phase is introduced followed by a drogue chute phase to reduce the dynamic pressure respectively the flight velocity in order to allow the opening of the parafoil at about v = 55m/s to 70m/s at a dynamic pressure of up to 1500 N/m2.
In case 1 the opening of the parafoil begins at an altitude of 8000m followed by a long descent and respective cross range of ~20km. In case 2 the sequence starts at 8000m with a rapid descent flight under drogue chute followed by a low altitude opening parafoil sequence at 2000m. Case 3 is a mixture of both a.m. scenarios: the opening of the parafoil starts at high altitude followed by a quick descent flight under reefed conditions, a complete dereefing at 2000m and a final approach to the landing site under parafoil.

The initial conditions for the parafoil sequence are the following:

| | |
|---|---|
| Altitude of initiation: | high: 8000m |
| | low: 2000m |
| Flight velocity: | 55m/s to 75 m/s |
| Dynamic pressure: | up to 1500 N/m2 |

In all 3 cases the layout parameters of the parafoil system are as follows:

| | |
|---|---|
| Surface area | 250m2 |
| Wing loading: | 20 kg/m2 |
| AR | 3.0 |
| L/D | 3.0 (canopy) |
| | 2.7 (total system) |

The descent sequences of the 3 cases are summarized in figure 3 and 4. The conditions and requirements to apply those scenarios w.r.t. environmental wind conditions, reentry accuracy and cross range are summarized in table 1. The opening and descent sequences in all 3 cases were designed and triggered to yield acceleration loads less than 5g. The current approach foresees a ram air canopy which is opened in 3 stages. The finally full open parafoil now achieves an aerodynamic performance of L/D = 2.7 at a final speed of v = 22m/s. In the case of higher altitude and zero wind conditions a maximum off-set of about 20km can be covered and in the case of low altitude opening a distance of about 2.5km can be reached. In case 2 the system has between 8000m and 2000m a high wind penetration due to its high velocity of 45 to 60 m/s. The landing accuracy - taking into account the excellent maneuverability of parafoil/payload system of the 5to class - is about 300m in diameter. The final velocity will be reduced by the dynamic flare maneuver below 3m/s for both components depending on wind conditions. As realistic conditions 5m/s in both components are envisaged. The major problem for such a maneuver is the determination of the exact altitude to introduce the dynamic flare.

The developed GNC concept allows remote and autonomously controlled flights for large scale parafoil systems. The main role of the GNC is to make the best possible use of parafoil's intrinsic capabilities by optimizing the guidance and control strategy.

| Condition/ Require-ments | Case 1 (8000m) | Case 2 (2000m) | Case 3 (mix) |
|---|---|---|---|
| Wind | low (overall | high | realistic profile |
| Reentry Accuracy | low | very high | moderate |
| Cross-Range | high | very low | medium |

Table 1: Scenarios for Application of a Parafoil Recovery System

**Sub-scale Testing with a powered Parafoil**

Drop tests of the full scale parafoil from an airplane as in the PTD project are always expensive and consequently the number of tests is limited. The guidance and control software can be tested with a sub-scale parafoil as well. It is possible to parameterize the GNC algorithm in such a way that only minor software modifications are needed when transferring to the full-scale hardware.

A special way of sub-scale test approach is chosen by the X38 project at NASA's Johnson Space Center in Houston for the parafoil GNC (ref.4), a further development of the PTD parafoil GNC algorithm. A commercially available powered parafoil from Buckeye Industries is modified so that it can be flown remotely from ground. Figure 5 illustrates the original use of the Buckeye. Figure 6 shows the control unit which replaces the seat for the pilot. It contains a GPS receiver, two winches, a computer and even telemetry and telecommands for a small ground station.

With the help of the ground station the vehicle is manually flown to a selected waypoint at which the motor is switched idle. Then the vehicle is controlled by the parafoil GNC software which shall guide the parafoil back to the landing zone.

The goals of the Buckeye tests are:

- To verify the GNC software. Since the core of the software, i.e. the guidance and control algorithm, is nearly unchanged the Buckeye serves as a very realistic 'hardware in the loop' test. The fact that the hardware, especially the GPS receiver, is of lower quality than the target hardware is of no disadvantage for this test purpose. The software must prove to be robust against temporary sensor failures, short outage of voltage and other unforeseen events.
- To show that it is possible to scale the guidance and control algorithm in such a way that only a couple of numeric parameters, which characterize the particular parafoil performance, must be adapted.
- To test the wind estimation and prediction feature of the GNC under various weather conditions and to prove the robustness.

Especially the last feature is of much interest since the atmospheric models are not very reliable near the surface. Lots of tests will be performed under various wind conditions. Again, it is of no disadvantage that the small vehicle is more susceptible to the wind. If the GNC algorithm proves stable under these conditions a larger parafoil will have no problem due to its smoother dynamics.

Tests will begin end of April and first flight results will be presented at the conference.

**Conclusions**

In the PTD project a parafoil canopy with a Clark Y airfoil section and a size of 160m$^2$ has been designed, fabricated and qualified for dynamic pressure up to 1500N/m$^2$ and mass-to-area ratios up to 20 kg/m$^2$ - i.e. 3200kg payloads. A GPS based avionics assembly has been designed and fabricated in order to perform autonomous flight tests including accurate and soft landing. In a series of wind tunnel tests with a downscaled canopy an aerodynamic data base of large sized parafoils has been studied and the results introduced into the GNC development and the aerodynamic simulation tools.

The GNC concept showed in simulations on the test bench and during the flight tests robustness with respect to vehicle control during nominal and non nominal flight situations. The D160 canopy showed good deployment behavior, regularity in opening sequences and excellent steerability with high turn rates and good flare behavior.

The basic layout of a parafoil descent system for re-entry vehicles of the 5 to class is depicted for three different scenarios: an opening of the parafoil system at an altitude of 8000m to reach a maximum cross range at low wind conditions, an opening at 2000m with a reduced cross range at higher wind conditions and finally a mixture of both scenarios with a rapid descent to encounter the jet stream in higher altitudes and a moderate cross range.

An outlook to the subscaled testing of the parafoil GNC algorithm in the X-38 project will be presented.

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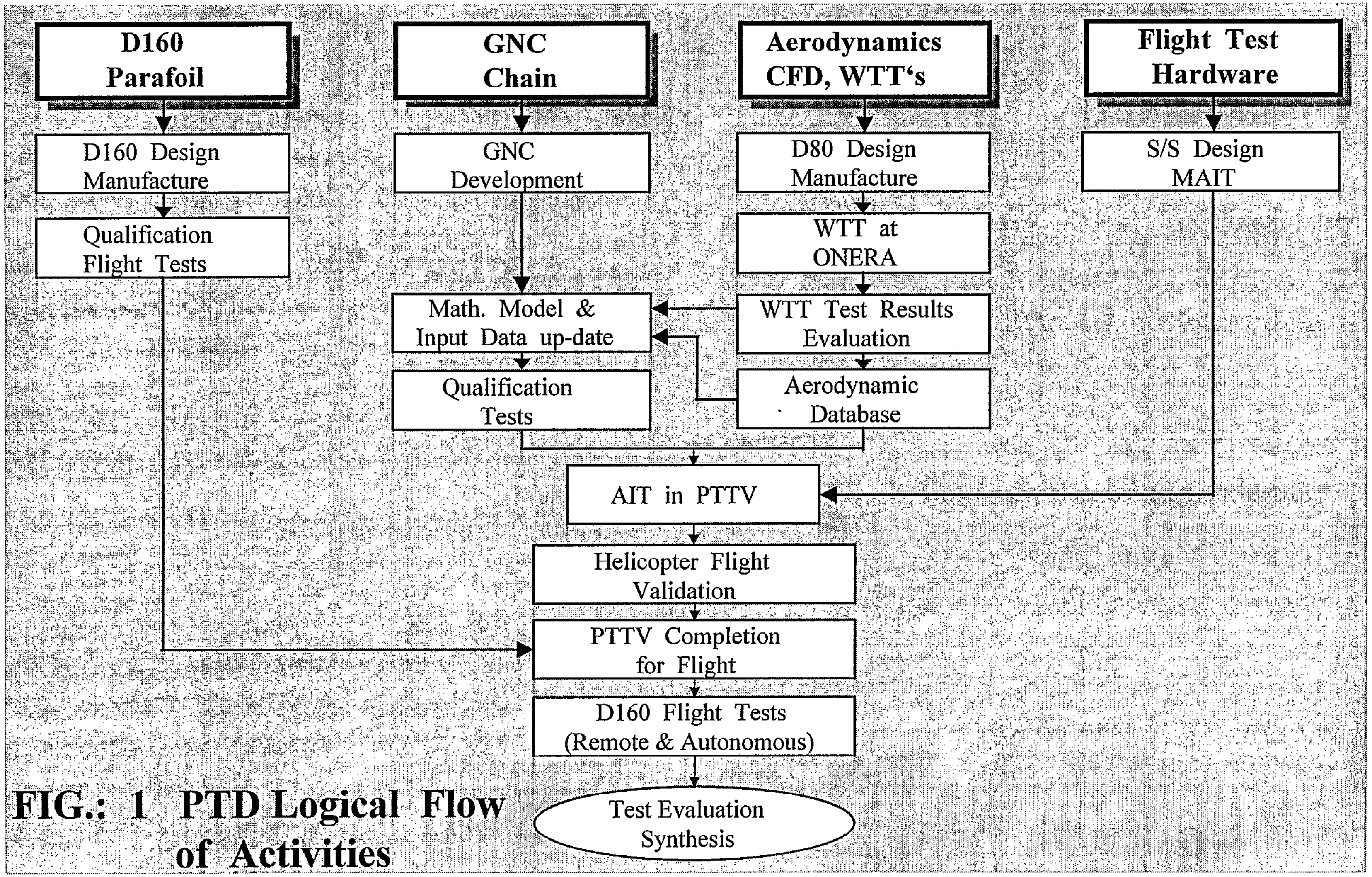


**FIG.: 1 PTD Logical Flow of Activities**

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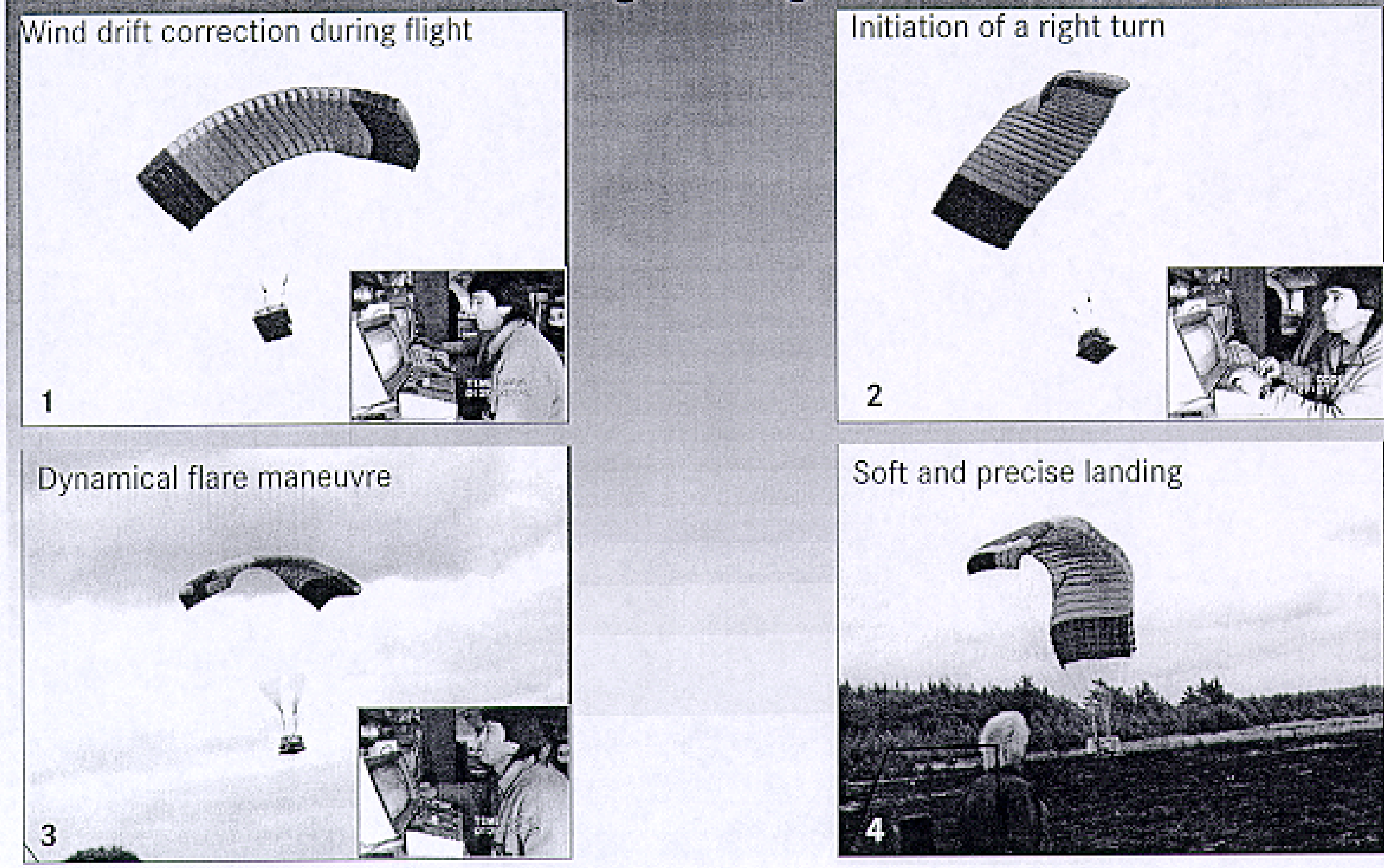
FIG.: 2 Autonomous guided flight with a 2 ton payload

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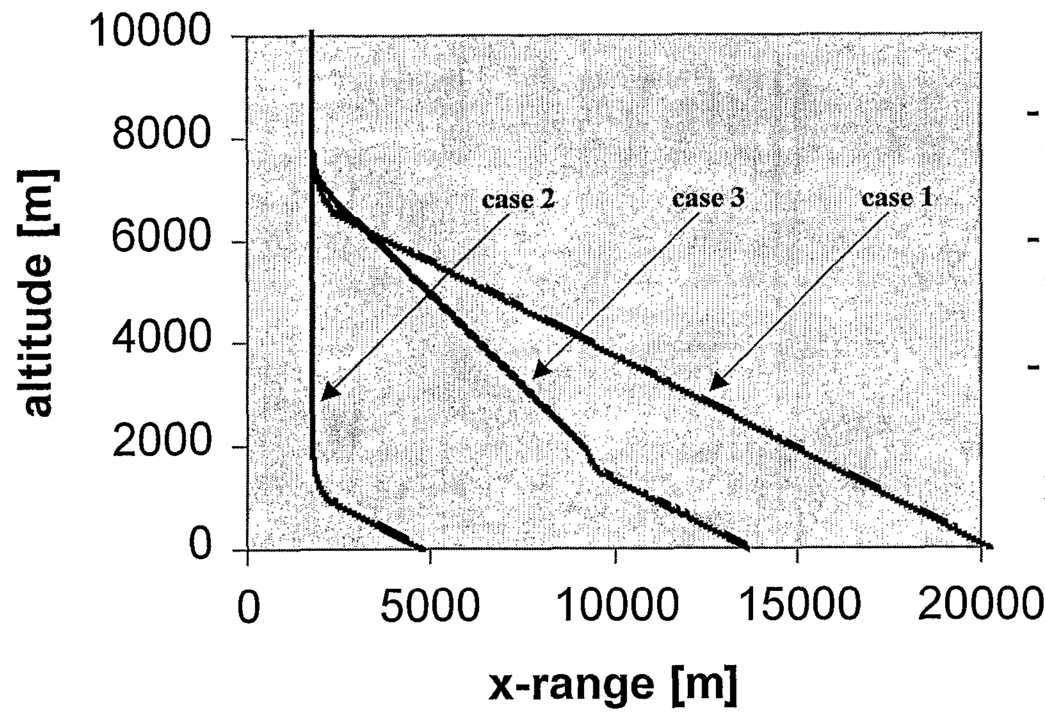
# FIG.: 3 Altitude vs. Distance Range

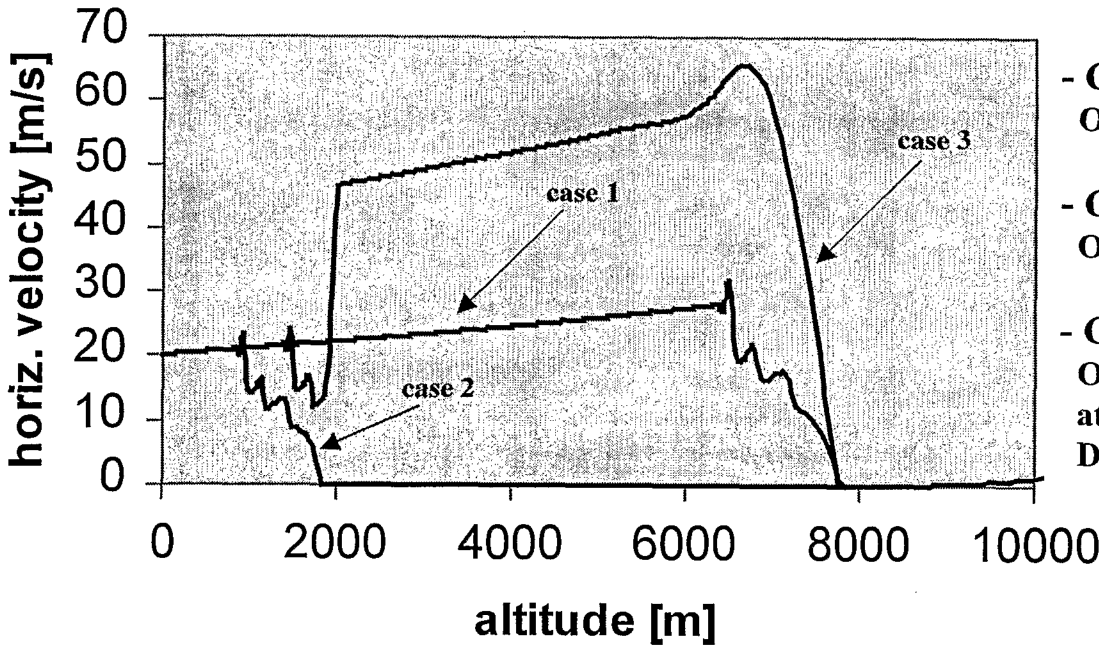



- Case 1:
  Opening at 8 000 m

- Case 2:
  Opening at 2 000 m

- Case 3:
  Opening 1st stage
  at 8 000 m
  Dereefing at 2 000 m

# FIG.: 4 Horizontal Velocity vs. Altitude




- Case 1:
  Opening at 8 000 m
- Case 2:
  Opening at 2 000 m
- Case 3:
  Opening 1st stage at 8 000 m
  Dereefing at 2 000 m

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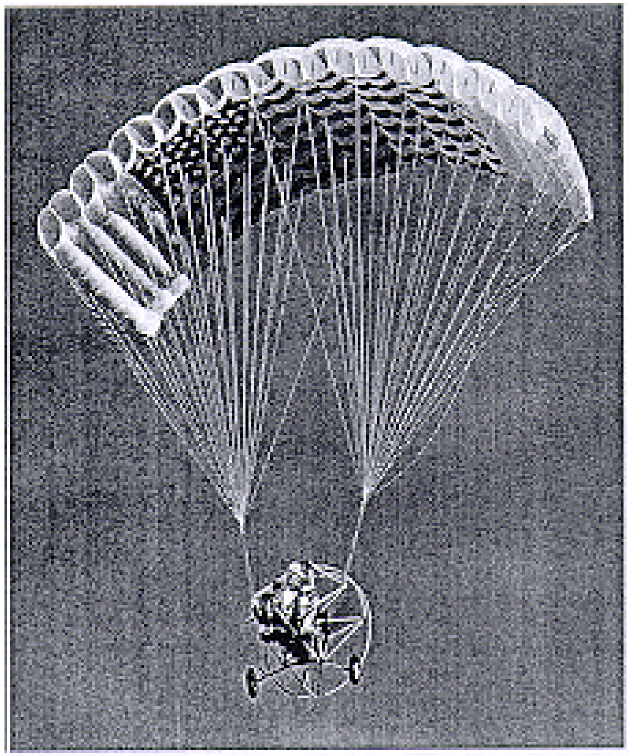

FIG.: 5 Powered Buckeye during Flight Test

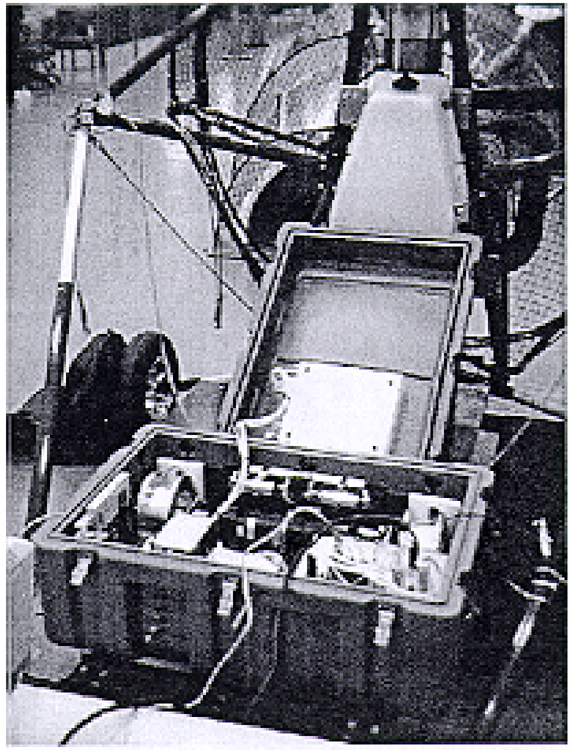

FIG.: 6 Control Unit for remote and autonomous controlled Buckeye Tests

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