PEGASUS: DESIGN OF A STRATOSPHERIC LONG ENDURANCE UAV SYSTEM FOR REMOTE SENSING

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ABSTRACT:

The PEGASUS (Policy support for European Governments by Acquisition of information from Satellite and UAV borne Sensors) project's aim is to provide an economic way to gather high resolution data (visual, IR and thermal imagery, LIDAR, SAR, atmospheric measurements) from a high altitude platform. Because the platform will not be manned, it will be able to operate continuously for weeks or months.
The paper describes the various aspects involved in the design of both platform and instruments. These include optical design, weight considerations, power consumption, data transmission, processing and archiving. The design is driven by the requirements of many remote sensing applications.

RÉSUMÉ:

Le projet PEGASUS (Policy support for European Governments by Acquisition of information from Satellite and UAV borne Sensors) a pour but de fournir des images à très haute résolution spatiale au moyen de capteurs aéroportés (visible, infrarouge, thermique, LIDAR, SAR et mesures atmosphériques) placés sur une plateforme opérant à très haute altitude. De par le caractère inhabité de la plateforme, celle-ci pourra acquérir les données requises de façon continue durant des semaines, voir des mois.
Ce document décrit les différents aspects concernant les concepts tant de la plateforme porteuse que des instruments se trouvant à son bord. Sont décrit ci-dessous l'optique nécessaire, les considérations liées au poids et à la puissance électrique des divers instruments, les besoins en matière de transmission des données, de leur traitement ainsi que de leur archivage. Toutes ces considérations sont fondées sur les besoins réels rencontrés par de nombreuses applications de télédétection.

1. INTRODUCTION

Remote sensing is traditionally performed by either airborne or spaceborne systems, each having distinct advantages and disadvantages.

Spaceborne systems offer a very stable platform and allow global coverage (e.g. SPOT Végétation produces a global coverage every day, at 1km ground pixel size). Although the resolution of the satellites has improved significantly (IKONOS,…), it still is about one order of magnitude worse than that of airborne systems. Moreover, due to orbital mechanics, the satellite always passes over a certain spot on earth at the same local time. In case of frequent cloud cover, it may take a long time before an area is completely imaged.

Airborne systems offer great flexibility, short response times and are able to generate very high resolution data. They are expensive to operate, though, and their operation is usually limited by air traffic constraints. Operating in an unstable part of the atmosphere, the instruments are subjected to severe vibrations, and it is not easy to navigate the aircraft along the planned lines.

As an alternative to these traditional platforms, it is proposed to use an unmanned aerial vehicle (UAV), capable of operating in the stratosphere (12 – 20 km altitude) and powered by solar energy and batteries or fuel cells, so that it can remain aloft for several months. The instruments that will be installed have been selected to optimally satisfy the user community requirements (Fransaer et al., 2004). The first flight of the system is scheduled for the late summer of 2005, when it will perform demonstration flights over Flanders (Belgium).

The system will deliver data and information that is directly usable for GMES (Global Monitoring for Environment and Security) applications as well as for medium and small scale mapping applications (map scales 1:2 500 – 1: 20 000). The combination of its sensors gives it an all weather, 24 hour observing capability, which is critical in emergency situations, such as flooding, forest fires, earthquakes, etc., …

2. LONG ENDURANCE STRATOSPHERIC UAV

2.1 Unmanned Aerial Vehicle

Unmanned aerial vehicles are widely used in military applications (Butterworth-Hayes, 2003; Aldrige et al., 2002). They are often used for tasks that are described as "dull, dirty and dangerous". Some are less than 10 cm tall, others, such as the Helios prototype and the Global Hawk, have wingspans up to 75 m. The Helios prototype, powered by solar cells, holds the world altitude record for non-rocket powered aircraft by flying to 96,863 ft in August 2001 (Hindle, 2001).

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Since any amount of fuel that is carried will severely limit the aircraft's endurance to a few days at most, the only source of energy available to very long endurance platforms is solar energy.

Nuclear power is also technologically possible (Graham-Rowe, 2003) but it is not an acceptable technology due to the risks involved in case of a mishap. Due to its solar character, the platform will not contribute to atmospheric pollution at all.

Most high-altitude UAV systems are aerodynamic, generating lift by moving. The total lift force is determined by the craft's speed, its wing area, and the density of the surrounding air. As the air density is not varying and because the optimum air speed for a lightweight aircraft at stratospheric heights is about 20 m/s, to carry a substantial payload, the wing area needs to be increased. The total weight of the platform will thereby also increase. An extreme example of this is the Helios prototype which weighs about 930 kg (including a total payload of about 300 kg) and has a wing span of 75 meters, i.e. exceeding that of a Boeing 747. Apart from practical problems of finding suitable runways and hangars, these large UAVs are very expensive. Therefore, we favour using small UAVs (wingspans of 15 – 20 m) that carry small payloads (2 – 5 kg), batteries and electronics excluded.

Aerostatic systems (blimps) for high-altitude flight have been proposed, but are not operational yet. They rely on very large volumes (200 000 m^3 or more) of helium gas to provide lift. In principle, this allows very large payload mass to be carried (up to a ton or more). On the other hand, controlling such large volumes and steering them requires a large amount of power, to be provided by solar cells draped over the envelope of the blimp after inflation. These systems are likely to be an order of magnitude more expensive than aerodynamic systems (Küke, 2000)

2.2 Stratospheric environment

The stratosphere is characterized by an almost complete lack of water vapour, relatively low wind speeds (10 m/s on average), only limited turbulence and low temperatures (-50 to -70° C).

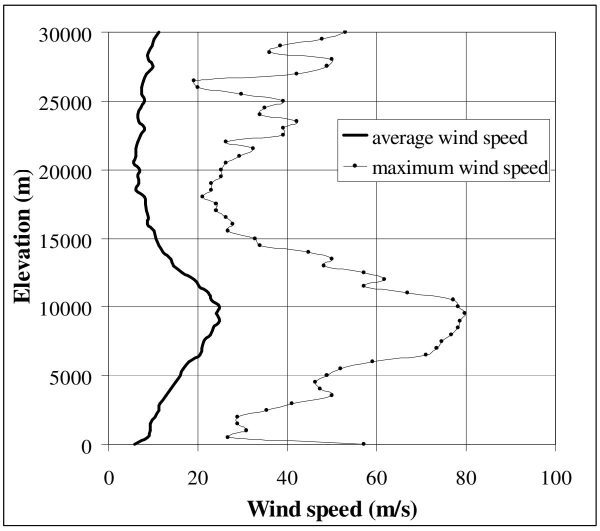

Figure 1. Average and maximum wind speeds for the years 2002-2003 for elevations up to 30 km (data for Den Helder, Netherlands, March-September)

Figure 1 shows that an aircraft moving at 20 m/s (airspeed) is able to overcome the average wind speeds. In extreme cases, the platform will have to change flying height to avoid being "blown away".

Air traffic is controlled up to 14 km altitude; above that height, an aircraft is not limited in its movements air traffic control, and there is virtually no air traffic. This allows for efficient mission planning.

2.3 Solar energy

At the top of the atmosphere, about 1 368 W/m^2 of energy is provided by solar radiation (BGC, 1994). Due to atmospheric absorption and depending on the time of year and the geographic latitude, this amount is reduced at lower altitudes.

Figure 2 shows the typical solar irradiance (in Wh/m^2/day) as a function of the month in the year for a horizontal surface at 55° latitude. In order to fly continuously, the UAV needs at least 2500 Wh/m^2/day, which is available for 7 months (March – September) at latitudes up to 55°.

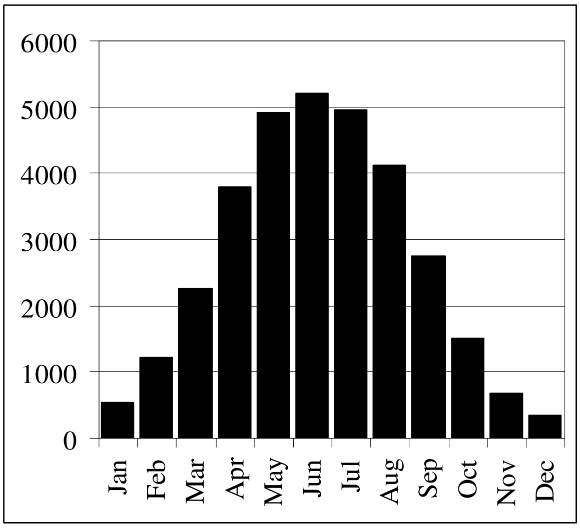

Figure 2. Typical solar irradiance (Wh/m^2/day) as a function of the month of the year for a location at 55° N latitude

During the day, batteries or reversible fuel cells are charged with the excess power, to provide sufficient energy during night time. The UAV can also glide downwards, using some of its potential energy. In emergency situations during winter time, the craft can be launched with non-regenerative fuel cells and a limited amount of fuel, so allowing short (several days) dedicated missions.

Whenever it is flying, the UAV platform is always available for earth observation, efficiently covering large areas (100 000 km2 in one flying season of 7 months, taking cloud cover into account). Unlike manned aircraft, it can take advantage of even very small windows in the cloud cover. Indeed, at a modest speed of 20 m/s, the platform can be transferred over large distances (over 1700 km) in 24 hours, even if there are no favourable winds.

3. INSTRUMENTS

3.1 Design philosophy

The constraints that are imposed onto the design of the remote sensing instruments and the auxiliary systems are weight, power consumption and volume. At this stage of the project, the UAV cannot carry payloads heavier than 2 kg, unless it is scaled up. The power available for the payload is of the order of 1 kW, the remaining electrical power generated by the solar cells being used for the flight systems itself. The volume constraint is probably the most difficult one to deal with : the instruments should be designed to fit within the limited volume and irregular shape of the aircraft's fuselage.

Using proven technology and designing the instruments so that they conform to but not exceed the applications' requirements allows the development to be time and cost effective. Also, this implies that the instruments will deliver data that are "just good enough", reducing significantly the cost of data processing.
The instruments will be defined and developed in sequence, allowing a possible response to changes in the market. In a few years from now, the UAV platform will evolve, being able to carry heavier payloads and provide more power.

3.2 Auxiliary payload

The auxiliary payload is shared between all instruments: a GPS/INS system for position and attitude determination and a data transmission system (S- or X-band, 75 Mbps).

For navigation, C/A based GPS positioning is sufficient. Attitude determination in real time is only required to support the image acquisition : it is used to control the line acquisition rate (so that sufficient forward overlap is guaranteed).

3.3 Implementation time line

As previously mentioned, the instruments to be carried by the UAV will be developed sequentially. Table 3 shows the projected time schedule. The first two instruments are currently under development, the latter two will be developed from mid-2005 onwards. Up to that time, changes in the specifications are possible, according to the market requirements.

	2004		2005		2006		2007	
Multispectral digital camera								
LIDAR								
Thermal digital camera								
SAR								

Table 3. Sequential development of the instruments.

3.4 Multispectral Digital Camera

The Multispectral Digital Camera is the first instrument to be implemented. It will provide images in up to 10 narrow spectral bands in the visual and near-infrared spectrum (400 – 1000 nm, 10 nm individual band width), at 15 to 20 cm ground pixel size. Due to the multispectral character of the instrument, it is implemented as a push broom system, using 12000 pixel wide line CCD arrays (see Reulke 2003 for an overview of available sensor technology). This results in a swath width of 1800 to 2400 m. Because of the small field of view of the system (6°), the images are not suited for stereoplotting, but they are much less affected by atmospheric refraction than commercial aerial survey systems; furthermore, the effects of the central perspective are very limited, making the images well suited for orthophoto production.

Using as high-grade position and orientation system, forward oversampling and the use of ground control, a position accuracy of 15 cm can be guaranteed. Oversampling is possible because of the low air speed of the system.

The design is based on the worst case situation : 8 hours usable for acquisition at equinox at 55° latitude, so that more than 8 hours can be used for data acquisition during the summer months. It is expected to obtain a system signal-to-noise ratio of 200 (worst case), which is comparable to scanned aerial film (in optimum circumstances). The signal will be digitized at 10 bits. The system MTF shall be better than 15%, where 10 % is deemed to be acceptable.
Using 7.5µm square pixels in the sensor line array (pitch), these requirements translate into a focal length of 0.75 m and a lens aperture of 0.13 m. This can be realized by a refractive system. The expected data-volume produced by the camera is : 12 000 pixels @ 10 bits per pixel @ 200 Hz = 22.9 Mbit/s per line sensor. When 10 spectral bands are recorded, this results in 229 Mbit/s. It is clear, however, that these spectral bands are correlated, allowing significant data compression prior to transmission.

An 8 hour survey day will yield a total of 0.8 Tbyte of raw data.

3.5 LIDAR

The LIDAR instrument will provide elevation information, that can be used for orthophoto production of the multispectral digital camera and also as information in its own right.

Covering the same swath as the digicam, it will produce a point density between 1 point per 2-4 m^2. Even higher point densities can be obtained by multiplying overpasses over the same area. This could be useful for detailed city mapping (e.g. Noble et al., 2003). Another application of the high point density is the statistical improvement of a DSM/DTM, e.g. for coastal zone or flood plane mapping.

The main challenges in the design of the LIDAR instrument are the power that is required for an active instrument and the limited mass (5 kg maximum) in which this power has to be dissipated. Recently, it has been shown that a LIDAR system designed for slant ranges up to 6 km was capable of successfully measuring ranges up to 15 km (Haarbrink, 2003).

To limit the power used by the scan mechanism, a nutating mirror setup will be used, so the scan angle (or swath width as a function of flying altitude) is fixed. The mirror rotation frequency will be constant, too. Together, this will generate a quasi-random point distribution.

The pulse repetition frequency is set to 15 kHz, which will produce a point density of 1 point per 2.5 m^2in the best case. The instrument will record the first and last reflected pulse, and the intensity of the reflected pulses.

3.6 Thermal Digital Camera

Information from the thermal spectrum can be used for example for heat-loss detection, for observations during night time, but also to detect moisture in the ground.

The thermal digital camera will operate in two thermal infrared bands (SWIR : 3-5 µm and LWIR : 8-12 µm), with spatial resolution between 1.1 and 2.2 m (depending on the wavelength).

Regarding the existing type of sensors, three alternatives are available : ternary semiconductors such as $Hg_xCd_{1-x}Te$ (also referred to as MCT, Mercury Cadmium Telluride), where the spectral sensitivity is determined by the value of x, multilayer structures or QWIP (Quantum Well Infrared Photodetector) sensors, where the spectral sensitivity is determined by the thickness of the successive layers, and microbolometers that work by heating from absorption of IR radiation. The former two require cooling (to 77K), the latter can work uncooled. However, large optics (f/1) are required for microbolometers, so they cannot be considered further in this project. Typical sensor pixel sizes are 25 µm for SWIR and 50 µm for LWIR. For a refractive instrument, ZnSe can be used as optical material, covering the 3–12 µm spectral range.

From a design point of view, it is important to be able to exchange different systems (sensors). For that reason, the aperture of the thermal camera is chosen to be the same as for the multispectral camera : 0.13 m. Using a 0.44 m focal length, this will have a 1.13 m resolution in SWIR and 2.25 m in LWIR. To cover the same swath as the mutispectral camera, the SWIR sensor will be a line array of 1 600 pixels, and the LWIR sensor will have an 800 pixels wide line.

3.7 SAR

The Synthetic Aperture Radar adds an all weather, day-and-night capability to the sensors suite. Aimed at environmental and security applications (oil spills, flooding, …), it will operate at short wavelength (X-band).

A preliminary study has shown that a 2.5 m ground resolution over a 4.5 km swath is achievable, with a 3 kHz pulse repetition frequency. Before development on the SAR instrument start, an evaluation of the available power for the instruments during night time will be performed.

3.8 Atmospheric measurements

Although not directly related to remote sensing activities, a small part of the UAV payload will be occupied by instruments that can provide *in situ* measurements of the stratospheric environment, such as temperature (required for atmospheric corrections) and the detection of chemical compounds such as water vapour, ozone, carbon monoxide, carbon dioxide, methane or nitrogen oxides, many of which are linked to global warming issues.

4. GROUND SEGMENT

4.1 Mission planning & execution

Mission planning and execution are critical parts of the data acquisition process. Both will be implemented with significant internal intelligence, so that it will not be required to interactively define flight strips, except when there is a requirement to do so (e.g. imaging a coastal zone should be done so that it takes tidal information into account).

Mission execution will be determined by the autonomous flight control system, taking priority issues and weather circumstances into account, so that the UAV does not have to loiter over a cloud-covered area. The most basic requirement for all instruments, at lowest priority, will be to produce a complete coverage of the project area.

Although the UAV will fly autonomously, it will always be possible to take over the aircraft's control from the ground reception station.

4.2 Data reception & archiving

On board data storage will be very limited, so all data will be downlinked to a ground reception station. Using X-band line-of-sight communication, an area of about 200 km in radius can be covered by a single UAV. Since this coincides with the annual coverage capability of the system, the ground reception station does not have to move to follow the UAV. Also, there is no need for satellite or UAV uplink.

If one of more UAV should be controlled from one ground reception station located at a distance higher than 200 km, an additional layer of data-relay UAV crafts, flying at higher altitude (e.g. 30 km) could be used.

After an instantaneous inspection of data integrity, the data will be archived as they are received. If any anomaly is detected, the mission planning will be adapted to re-image the concerned area.

4.3 Data processing

To deliver suitable images and information products to the public, all raw data have to be corrected. This includes applying the (spectral and geometric) calibration information, and correcting for atmospheric influences. This will be implemented as a processing chain, comparable to the methodology of satellite data processing.

During the demonstration flights in the summer of 2005, differential GPS correction will be possible by using the Flepos GPS network of 39 receivers distributed over the Flemish region in Belgium (Flepos, 2004) and the Walcors GPS network of 23 receivers in the Walloon region of Belgium (Walcors, 2004). Other countries that offer similar services in Europe include The Netherlands, Denmark and Switzerland.

Quality control and assurance will be formally documented and made available to the users. The data shall comply to the requirements of most mapping agencies and private users.

Standard products will be made available to the public, up to level 3 (information products), via established internet portals. These products include : aerial imagery (visual or thermal), ortho-images, elevation models, but also information derived from these, such as crop forecasts, mapping products, etc., …

5. CONCLUSIONS

The PEGASUS project will offer remotely sensed data and information with high spatial, spectral and temporal resolution.

The unique platform, which is unmanned and flying at stratospheric heights (between 12 and 20 km altitude) offers the advantages associated with both airborne and spaceborne systems, without their disadvantages, but with some limitation with respect to the weight of the payload.

The system is set to fly its first demonstration tests in the late summer of 2005, in Belgium.

REFERENCES

Aldridge, E.C., Stenbit, J.P., *2002. Unmanned Aerial Vehicles Roadmap 2002 – 2027*, Office of the Secretary of Defense, Washington DC, U.S.A.

BGC, 1994. *Solar influences on Global Change*, Board on Global Change, Commission on Geosciences, Environment, and Resources, National Research council, The National Academies Press, *ISBN 0-309-05148-7*, Washington DC, U.S.A, p.164.

Butterworth-Hayes, P. (ed.), *2003. UAVs, a Vision of the Future*, Newsdesk Communications Ltd., London, United Kingdom.

Flepos, 2004. http://www.gisvlaanderen.be/flepos/nl/, in Dutch (accessed 19 Apr. 2004)

Fransaer, D., Vanderhaeghen, F., Everaerts, J., 2004. PEGASUS: Business Plan for a Stratospheric Long Endurance UAV System for Remote Sensing. Accepted for *The International Archives of the Photogrammetry, Remote Sensing and Spatial Information Sciences, Istanbul, Turkey,* GITC, Lemmer, The Netherlands.

Graham-Rowe, D. 2003. Nuclear-powered drone aircraft on drawing board , *New Scientist*, 22 February 2003.

Haarbrink, R.B., 2003. High Altitude LIDAR to Enhance GeoSAR System Performance. In Maas, Vosselman, Streilein (eds.), Proceedings of the ISPRS working group III/3 workshop `3-D reconstruction from airborne laserscanner and InSAR data' Dresden, Germany 8-10 October 2003, GITC, Lemmer, The Netherlands.

Hindle, S., 2001. Helios Sets New World Record! Press release, http://www.aerovironment.com/new/news-archive/813flight.html (accessed 19 Apr. 2004)

Küke, R., 2000. HALE Aerostatic Platforms, ESA Study Contract Report, contract 13243/98/NL/JG

Noble, P., Nix, M., 2003. 3D North Sydney – Precise 3D database for Retrieval and Visualization. In Fritsch (ed.) *Photogrammetric Week 2003*, Wichmann Verlag, Heidelberg, Germany

Reulke, R., 2003. Film-based and Digital Sensors – Augmentation or Change in Paradigm? In Fritsch (ed.) *Photogrammetric Week 2003*, Wichmann Verlag, Heidelberg, Germany

Walcors, 2004. http://gps.wallonie.be, in French (accessed 19 Apr. 2004)

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