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Zeppelin NT, a new Platform for Atmospheric Studies in the Planetary Boundary Layer

Exploration of the chemistry and physics of the planetary boundary layer

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Abstract

The goal of the proposal is to investigate the oxidation of anthropogenic and biogenic emissions, as well as the formation of ozone and secondary aerosols, including the chemical aging of the aerosol phase, in an innovative setup. It will be comprised of a regional pseudo-Lagrangian field experiment using a Zeppelin as a novel platform for *in-situ* sensing measurements in the planetary boundary layer. Fast detection of free radicals, volatile organic compounds and aerosols will be combined with a comprehensive chemical and meteorological characterisation in the plume downwind of a large city. The experiment will improve our understanding of the chemical processing and the transport of pollutants from their source regions into the atmosphere. The experiment will also strengthen the European lead role in tropospheric research by establishing the Zeppelin NT as a new, unique platform to explore the planetary boundary layer and its role in atmospheric chemistry and physics. Other possible future missions comprise, for example, the investigations of convective transport and cloud formation in the lower atmosphere, or the quantification of local and regional fluxes of climatically relevant water vapour and carbon compounds above land ecosystems.

1. Introduction

Chemical and meteorological processes in the planetary boundary layer (PBL, the lowest 1-2 km of the atmosphere) have an important influence on air quality and climate (e.g., Brasseur et al., 2003). Most emissions of natural and anthropogenic pollutants are released at the earth's surface and are distributed by wind and convection over the PBL. Due to its high loading with pollutants, the PBL is chemically the most active and complex part of the atmosphere. Through air mass exchange the PBL has a major influence on the chemical composition of the free troposphere and the overlying stratosphere, and it has a major impact on the health of men and natural ecosystems through production and deposition of oxidants and particulates.

In order to understand the influential role of natural and anthropogenic emissions on air quality, climate and ecosystems, formation and transformation processes in the PBL have to be known. The following types of relevant processes are of particular interest:

- gas-phase oxidation processes involving free radicals that directly affect the abundances of reactive gases in the atmosphere and convert part of them into condensable vapours,
- processes that form aerosols either directly or indirectly from gaseous precursors,
- heterogeneous chemical processes that establish a direct feed back of aerosols to the atmospheric gas-phase composition, and result in significant modification of aerosol properties,
- transport processes that distribute primary emissions and secondary oxidation products by advection and turbulent diffusion within the PBL, ventilate trace substances into the free troposphere, or remove material by wet and dry deposition.

The investigation of the complex interactions of gases and aerosols requires a large set of instrumentation for the simultaneous measurement of free radicals, trace gases, aerosol size and composition, solar radiation and meteorological parameters. In the past, field studies with such comprehensive equipment were mostly performed at ground or in the free troposphere on large aircraft. Only very few missions including radical measurements were carried out in-flight in the planetary boundary layer. The main reason is the difficulty to find an appropriate carrier for the complete instrumentation needed to quantify the oxidation chemistry of trace gases and the physico-chemical processing of aerosols. Large airplanes capable of carrying the necessary equipment are not permitted to fly for extended time periods at low altitudes in the PBL, at least not over densely populated regions in Europe. Moreover they are generally moving too fast to allow a reasonable resolution of small-scale spatial patterns as encountered in the PBL within the instrumental response times. Helicopters are not suitable for instruments requiring contamination free air-sampling due to the turbulent airflow around the cabin caused by the rotors. Blimps have no internal rigid structure. For that reason they are not well manoeuvrable and suffer from vibrations since the propellers are directly connected to the cabin. As a novel approach, we propose to use a large rigid-frame Zeppelin as the ideal platform for chemical and physical observations in the planetary boundary layer.

2. Zeppelin NT

Based on long-existing experience and employing state-of-the-art technology, Zeppelin Luftschifftechnik GmbH & Co. KG (ZLT) in Friedrichshafen, Germany, has recently developed a safe and economical airship, the Zeppelin NT (Zeppelin New Technology). It has a length of 75 m and a diameter of about 14 m. The maximum payload is about 1.8 tons, of

Figure 1: Zeppelin-NT airship hovering above its landing site in Friedrichshafen, Germany.

which around 1 ton could be used as scientific payload (see Appendix B + C for technical details).

The first Zeppelin NT was launched in 1997 and has received type-certification by the German Luftfahrt-Bundesamt in 2001. Since then three NT airships have been put into operation on a regular basis for multi-missions (passenger transport, advertisement, surveillance, scientific data gathering etc.).

One exciting possibility, which has not been exploited so far, is the use of the Zeppelin NT as an airborne platform for atmospheric research. For field experiments in the lower troposphere the airship offers a unique combination of capabilities, which is not available when employing other aircraft. Important features of the Zeppelin NT are:

- a high scientific payload (instruments + operators): ~ 1 ton
- high manoeuvrability in all directions due to a vectored thrust propulsion system
- flight speed: 0 - 115 km per hour
- horizontal reach: 1111 km
- operating altitude: 20 - 3000 m
- maximum flight endurance: 20 hours

Beside the possibility to install measurement instruments in the gondola beneath the Zeppelin, the rigid framework of the Zeppelin can support additional measuring platforms mountable on the airship. Unlike on airplanes, specially designed aerodynamic sampling inlets for reactive gases and aerosols are not necessary, due to the relative low travelling speed of the Zeppelin. Accordingly, measurement instruments can be operated under similar conditions like at ground.

Based on these features the airship is especially suited to the following applications:

- *Measurements of locally limited phenomena with high spatial resolution:* the capability of the airship to permanently stay at a fixed position allows for the observation of the time development of events like biomass burning or industrial emission, as well as of the biogenically relevant CO_2 and H_2O fluxes. Furthermore, flying at low speed allows to resolve small scale patterns over highly structured landscapes and source regions, inside air plumes or between clouds.
- *Fast measurements of vertical profiles:* since the Zeppelin has a maximum climb and sink rate of 5 - 6 m/s, it will be possible to probe the vertical development of the planetary boundary layer and its transition into the free troposphere with a high time resolution. The possibility to operate at low altitudes allows to measure vertical profiles of trace compounds even in the lowest hundred meters above ground, where the largest gradients are expected. For example, a platform equipped with instruments can be lowered from the cabin, while the Zeppelin is drifting in a stable position (e.g. near ground or above a cloud) to allow for measurements without any disturbance from the body of the airship.
- *Measurements along Lagrange trajectories:* the airship is able to drift with the surrounding air mass to monitor *in-situ* the formation and transformation of gases and aerosols. The long operation time allows to determine complete day/night cycles of chemistry and meteorology in these air mass packages above ocean or land regions.
- *Long-time measurements:* field experiments of about 20 hours endurance are possible at reduced speed and correspondingly low fuel consumption. This enables the repetition of flight patterns with combined vertical and horizontal measurements.

3. Science Contributions

Following first contacts with Zeppelin Luftschifftechnik GmbH in Friedrichshafen, some of the leading research groups in the field of atmospheric science in Europe met within the frame of ACCENT, the European Network of Excellence on Atmospheric Composition Change, in summer 2004 at the research centre in Jülich. The aim of the workshop was to discuss the possibility of Zeppelin NT as a novel airborne platform for atmospheric research. The main outcome is documented in this proposal. It was decided to start an initiative for deployment of the Zeppelin in a first explorative field campaign and lay grounds for its long-run application in various kinds of scientific missions.

The following scientific topics, for which a Zeppelin offers totally new ways of investigation, were identified by the participants (Appendix A):

- Photochemistry
- Aerosol processes
- Cloud processes
- Meteorology
- Soil-Vegetation-Atmosphere interactions

These topics will be outlined briefly in the following.

3.1 Photochemistry (FZJ, IUP, MPI-C, ULEI, RIU)

The troposphere can be conceived as a photochemical reactor which processes enormous amounts of trace substances (e.g., Ehhalt, 1999). Their concentration levels, spatial distribution and temporal evolution depend on a sensitive balance between emissions, atmospheric transport, and atmospheric self-cleaning by chemical processing and wet and dry deposition. The driving force of the atmospheric self-cleaning processes is the solar ultraviolet radiation which generates highly reactive, free radicals by photolysis of trace gases. The most important radical is the hydroxyl (OH) which is primarily formed by photolysis of ozone in the presence of water vapour. OH is an oxidant which reacts with most trace gases, in many cases as the first and rate limiting step in sequences of processes that ultimately remove the trace gases from the atmosphere. Thus, the OH concentration controls the atmospheric lifetimes of these components and is considered to be a measure for the self-cleaning efficiency of the atmosphere.

An important secondary effect of the chemical degradation of atmospheric trace compounds is the formation of partially oxidised intermediate products. In air which is heavily loaded with volatile organic compounds (VOCs) and nitrogen oxides (NO_x), as is the case in the PBL over industrialised and densely populated areas, photooxidants like ozone and secondary particles are formed and may accumulate to harmful levels that adversely affect human health and the biosphere (e.g. Brasseur et al., 2003). The secondary gaseous and particulate pollutants can significantly feed back to the OH chemistry, either directly by chemical reactions or indirectly by altering the solar actinic UV flux as a result of light absorption and scattering. When exported, primary and secondary pollutants can significantly modify the composition of the remote and free upper troposphere, thus altering the state of the troposphere and the climate on earth.

The development of a thorough understanding of tropospheric photochemistry requires the simultaneous field measurement of a suite of radicals (OH, HO_2, RO_2), trace gases, aerosols, solar radiation and metorological parameters. Over the past ten years comprehensive instrument packages have been developed for the measurement of most of these quantities. They were deployed mostly in field campaigns at ground (see e.g. review by Heard and Pilling, 2003), or on large carrier platforms like the NASA DC-8 aircraft in the upper troposphere (e.g., Jaegle et al., 2000). Considerable progress has been achieved in the understanding of fundamental photochemical relationships, for example the relative dependence of OH on the solar UV radiation and the NO_x abundance. There is however still considerable uncertainty in the quantification of all relevant radical sources and sinks needed for the reliable prediction of absolute OH concentrations and of the production rate of secondary pollutants (e.g., DiCarlo et al., 2004; Kleffmann et al., 2005). This is particularly the case in the PBL at heights between ~20 m and 1500 m, where observational data for radicals are almost entirely missing due to the lack of a suitable airborne measurement platform. Thus not surprisingly, relatively little is known about the spatial distribution of free radicals in the planetary boundary layer, where the radicals are influenced by horizontal and vertical gradients of longer lived trace gases, aerosols and clouds, solar UV radiation and the diurnal variation of the PBL thickness.

Ground-based field experiments have allowed local studies of tropospheric photochemistry by measuring radicals in air masses with varying chemical composition that passed the measurement site (e.g., Holland et al., 2003; Volz-Thomas et al., 2003). While this concept allows the investigation of the radical chemistry over a range of chemical conditions, it is not possible to follow the chemical evolution of a specific airmass. A Lagrangian type experiment, which enables the *in-situ* study of the degradation pathways of trace gases and the build-up of new gaseous and particulate pollutants in real time under natural field conditions, will require a slowly flying platform like the Zeppelin NT following an airmass along the wind trajectory.

The deployment of the Zeppelin NT as a carrier for a comprehensive payload of instruments which measure free radicals and other photochemically relevant parameters offers totally new ways to explore the complex chemistry of the lower troposphere. The recent technological development of compact measurement instruments with fast time resolution facilitates the set-up of an instrument package for the most important atmospheric parameters. This would allow for the vertical and horizontal profiling, and for pseudo-Lagrangian studies of air plumes originating from different sources, e.g. large cities, industrialised regions, or forests. Zeppelin based experiments would ideally bridge the existing gap between the well established ground-based field observations and free-troposphere investigations.

3.2 Aerosol processes (UMIST, PSI)

The processes by which primary particulate material emitted by anthropogenic sources is modified and its properties altered in the atmosphere on city wide to regional scales is extremely poorly understood. Model descriptions of secondary aerosol processes and transformations remain poor and as a result do not capture the distributions or loadings of material on a European scale effectively. It is imperative that we are able to predict the regional burden of aerosol across Europe to make assessments of loading to the biosphere, model air quality and understand regional climate forcings so that the impacts of the current emission profile of the region can be understood and future modifications predicted with considerably more reliability than is presently possible. To do this, the key processes must be clearly identified and described, only then can reliable process understanding be gained and used to effectively parameterise the main transformations in regional models.

Large urban conurbations dominate emissions of oxides of nitrogen and organic material in north western Europe. Many fine mode particles are emitted from motor vehicles and other combustion sources, these subsequently mix with the regional accumulation mode aerosol population at the city canopy scale. The large numbers of aerosol efficiently coagulate when numbers are high, as is often the case before significant dilution can occur. Once in the atmosphere the emitted NO_x and volatile organic compounds (VOCs) oxidise over timescales of a few hours to a day or so, a fraction of which forms highly condensable products that partition to the aerosol. Nitrate partitioning to aerosol is highly dependent on the availability of ammonia, which is often in excess in north western Europe and ammonium nitrate can become a substantial contributor to the secondary aerosol population. This phenomenon is highly seasonal due to the volatility of the salt and the local to regional repartitioning back to the gas phase as the ambient ammonia field changes. It is now widely recognised that organic material contributes significantly to secondary aerosol and is often the major component. Field and laboratory studies have identified that whilst the secondary organic is condensed onto the aerosol from the gas phase it most likely continues to be processed once in the particle phase and becomes less volatile. This macromolecular organic material may account for a significant fraction of the organic secondary material. However, the conversion processes, rates and impacts are only beginning to be recognised. A substantial amount of work is required in this area to properly understand the cycle of organic material in the aerosol phase. Much of the primary aerosol contains black carbon and metallic material, the former is an efficient absorber of visible radiation and so can locally warm the air mass, the latter also can be highly toxic in the biosphere. The transport of these aerosol components will be dictated by the rates at which they become internally mixed with other aerosol components by either coagulation or condensation.

Many of these processes: coagulation, condensation and further aerosol oxidation take place close to the source of the emitted particles and are competitive with each other. In combination, they dictate the source contribution to the regional background as the air advects from the city. It has until now been extremely difficult to perform high quality measurements of aerosol physical and chemical properties and the phenomenological variables such as hygroscopicity, scattering and absorption at the city-scape to regional scales that are necessary to properly test our understanding of the above transformations. Furthermore, only now are detailed process models with the necessary level of complexity available for testing.

Two main problems have beset the community until recently. Firstly, the measurement capability has not existed. In the past sampling technology required long integration times to obtain sufficient sample for analysis, reducing temporal resolution and prohibiting the measurement of many of the dynamic phenomena that take place. Furthermore, a lack of analytical probes limited the variables in the aerosol that could be measured. In the last few years this has changed dramatically. Online instruments that are capable of measuring aerosol composition in a quantitative way, either as single particles or as bulk collections have now been developed. Detailed measurements of aerosol properties are now possible in situ and highly specialised analytical tools can now analyse collected aerosol in much more detail.

The second problem has been the lack of suitable airborne platform to follow the development of secondary aerosols in city plumes and wider polluted regions. The recently developed Zeppelin NT can solve this problem and provides the ideal platform for such experiments. It is highly manoeuvrable, can carry a significant payload, is capable of following air parcels in a pseudo Lagrangian fashion and can remain stationary. By fitting the Zeppelin NT with a comprehensive suite of aerosol instrumentation sampling from well characterised inlets and supported with a wide range of state variables the platform will be able to probe the regional continental boundary layer and investigate processes that have been virtually impossible to probe until now. The measurements should include: particle counters; scanning mobility particles sizers; optical particle counters; online aerosol mass spectrometers for composition mass loadings and size distributions of sulphate, ammonium, nitrate and organics; bulk online measurements such as the steam jet impactor; drum impactors for metals and single particle microscopy analysis; black carbon measurements; nephelometers; and measurements of supporting trace gas species such as NO_x, O_3, CO, VOCs and NH_3 and HNO_3.

3.3 Cloud processes (IFT)

The interaction between turbulence and aerosol (particles or cloud drops) is still not well understood. Such processes include turbulent mixing in clouds or at cloud edges (cloud-top and lateral entrainment) and the resulting cloud processing (e.g., drop spectra broadening) or turbulent fluxes of cloud drops in general. Turbulence is also important for drop clustering and inhomogeneities of drop concentration and, therefore, for coalescence and coagulation (e.g., drop growth, onset of precipitation). An overview about these processes can be found in Shaw (2003). On the other hand, turbulence affects also aerosol particles outside of clouds. In recent literature the influence of turbulent mixing processes on new particle formation in the planetary boundary layer (PBL) is widely discussed (e.g., Bigg, 1997 and Nilsson et al., 2001). For example, an increased concentration of ultrafine particles was found around the inversion layer of the PBL where turbulent mixing can be very effective (Siebert et al., 2004). Finally, turbulent fluxes of particles are very important for vertical and horizontal aerosol transport. All processes mentioned above take place on a wide range of temporal and spatial scales down to the Kolmogorov microscale of a few millimetres.

To investigate this kind of processes, a measurement system with low true air speed (TAS) is required yielding a maximum spatial resolution with a given sampling rate of the sensors. As a consequence, at the Institute for Tropospheric Research (IfT) the Airborne Cloud Turbulence Observation System ACTOS has been developed. ACTOS is a stand-alone payload, which can be suspended from carrier platforms providing low TAS such as large tethered balloons, airships or helicopters. ACTOS includes a complete set of state-of-the-art turbulence and standard meteorological probes including an ultrasonic anemometer, fine-wire sensors for temperature, a fast Lyman-alpha hygrometer and a high resolution pressure sensor. To determine attitude angles and velocity components of ACTOS, the payload is equipped with a fast navigation unit based on inertial sensors and a Differential Global Positioning System (DGPS). The payload has its own power supply, real time data acquisition and telemetry link for online monitoring. Therefore, ACTOS is completely independent from the used carrier platform.

In previous field campaigns ACTOS was lifted up to about 1.5 km with help of a large tethered balloon provided by the German Bundeswehr. Depending on the specific goal of the missions several sensors packages are available and can be added to the base system. For the investigation of the influence of turbulence on cloud processing a particle volume monitor (PVM) was integrated to perform fast measurements of the liquid water content (LWC). A modified version of the Fast-FSSP (Forward Scattering Spectrometer Probe) counts individual cloud drops yielding their size distribution.

For the investigation of new particle formation in the PBL during the SATURN experiment, two condensation particle counters (CPCs) with different lower size cut-offs were integrated on ACTOS (Stratmann et al., 2003 and Siebert et al., 2004). The difference of both measured concentrations is used as an indication for newly formed particles in the size range between 5 and 10 nm. Additional aerosol units including a fast CPC for turbulent particle fluxes and a small size-resolving system are planned for the near future.

For experiments with the new Zeppelin NT ACTOS is well suited for all measurements concerning the influence of turbulence on physical and chemical processes. A suspended payload such as ACTOS is the only way to overcome the influence of self-induced flow distortions by the Zeppelin NT. The payload is a proven system, which has demonstrated its capabilities in several field campaigns with different scientific goals. Further devices can easily be included within the limits of weight, size and power consumption.

3.4 Meteorology (FZK, RIU)

One of the most challenging tasks in the near future in meteorology is the improvement of numerical models for local scale, short-range weather forecasts with emphasis on prediction of precipitation. There exist shortcomings in operational weather prediction models with respect to onset, duration and amount of rainfall. This is particularly the case for precipitation caused by convection, especially triggered over low mountain ranges. A better understanding of such processes is important for risk assessment and forecast, as convective rainfall is often accompanied by thunderstorms and flash-floods with high risks of damage and loss of lives.

Beside large scale forcing in the upper troposphere, there are important triggering processes for convection and subsequent rainfall in the boundary layer and at the earth’s surface. These are the development of secondary circulations in mountainous terrain, transporting humid air from the valleys to the mountains and inevitably forcing the formation of convergence zones over the ridges (Fiedler et al., 2000). In the frame of the “Quantitative Precipitation Forecast” program “PQP”, initiated by Hense et al. (2003) and funded by DFG, and the HGF “Convective Storms Virtual-Institute (VI) COSITRACKS”, initiated by FZK together with DLR and the universities of Mainz and Hohenheim, considerable efforts will be made to investigate the processes triggering convection and precipitation over low mountain ranges.

The international PQP field campaign COPS (Convective and Orographically-induced Precipitation Study) in 2007 in Germany and France will require highly accurate, high resolution and long time (daily cycle) meteorological measurements above complex terrain and near to the ground for process investigations and data assimilation studies. The VI COSITRACKS is doing research work on convective processes, risk assessment and forecast. It is envisaged to analyse atmospheric processes by field data leading to local and regional scale severe weather. One scope of the VI is the investigation of “Transport and Chemical Conversion in Convective Systems” (Kottmeier and Höller, 2001). A Zeppelin based platform measuring meteorological and chemical data would be able to deliver reliable data about chemical transport under and around convective systems, covering the cycle from the preconvective environment over the full convective development to the post-convective situation. This allows estimates about cleaning of the boundary layer by convection.

Another field of research the Zeppelin can be used for is the investigation of precipitation intensification of large scale rainfall triggered by mountains. A combination of dynamic, thermodynamic and precipitation data gathered windward of the mountains and at the top of the ridges are used to calculate the precipitation intensification forced by the mountains (Kunz and Kottmeier, 2005a/b). The model has to be evaluated by data of vertical and horizontal profiles of wind speed and stability above and upstream the mountains during precipitation.

The Zeppelin equipped with state of the art instrumentation for meteorological measurements will be an ideal platform to investigate the local and regional scale circulation pattern over low mountain ranges during COPS, COSITRACKS and other projects with high resolution in complex terrain which is not easily accessible to aircraft measurements. Equipment necessary for such investigations are fast response sensors for temperature, humidity, pressure and the three dimensional wind, operated with high resolution and valid for turbulence detection. The sensors should be mounted at the tip of the Zeppelin, stored in an easy to install autonomous nose boom and in an instrument pod, mounted in a lowering device under the Zeppelin's cabin. This enables Zeppelin to perform simultaneously 2-dimensional measurements, e.g. detecting secondary circulations and boundary layer heights in and over narrow valleys. This is a unique feature of Zeppelin, which allows the detection of the structure of moisture convergence above mountain ridges. A future perspective of the Zeppelin is the integration of a Wind-LIDAR system below the cabin to measure horizontal wind profiles up to 8 km radius around the Zeppelin and vertical profiles from the flight level to the ground. This technique enables measurements in the cloud's surrounding without approaching too close to the cloud. The data are valuable for the analysis of transport under the base of convective clouds and for the evaluation of the quality of cloud parameterisation schemes within forecast models.

There has been done preparatory work to realise the meteorological measurements on board the Zeppelin. Nose booms are available for research aircraft with integrated sensors for wind, temperature, humidity and pressure, which could be adapted for use with the Zeppelin. With the exception of hard points to mount a nose boom, and data and power supply lines, no modifications will be necessary at the air ship. Data acquisition and avionic data recording will be done in the cabin. Accessory there are plans for the development of an autonomous pod with meteorological instruments, with trace gas monitors and with instruments for the detection of size distributions of particulate matter. The pod will be equipped with power supply, data acquisition, GPS and inertial platform. It will be operated as lowering device below the cabin. Horizontal and vertical profiles can be measured in complex terrain, not easy accessible to aircraft. The installation of a Wind-LIDAR on board the Zeppelin is a challenging approach. But the value of the available data for cloud physics, cloud modelling, model evaluation and investigation of convection are definitely incomparable high.

Remote sensing of large-scale variability of soil moisture

Determining the spatial and temporal variability of soil moisture for use in meteorological and hydrological models is one of the challenges in climate and natural hazards research. Up to now there exists neither an operational soil moisture measurement network on larger scales nor validated data on the actual soil moisture variability on a scale of 1-10 km, which is important for interpolation of point measurements onto a smaller-scale numerical model grid. Spatially integrating soil moisture data can be obtained from satellite on an either coarse temporal or coarse spatial grid or by using ground-based geophysical techniques on a scale up to 1 km. For the intermediate and in the context of natural hazards most important scale of 1 to 10 km no measurement system exists.

To overcome this problem, a project between the Forschungszentrum Karlsruhe and the University of Karlsruhe is currently developing a soil moisture sensor based on reflected GPS signals. The system shall determine the integrated soil moisture of the surface over a spatial footprint, which is dependent on the height of the antenna over ground. After a test phase, the system shall be used on airborne platforms to enlarge the spatial footprint. A Zeppelin-based platform would be ideal, as height and speed could be varied, enabling both temporally high resolution monitoring as well as the determination of the large-scale variability of soil moisture. Furthermore, repeatability of the measurements could be ensured due to the quasi-stationary flight modus of the Zeppelin. The data would be used in meteorological and hydrological process studies as well as for initialisation and validation of diagnostic and prognostic weather and flood prediction models.

3.5 Soil-Vegetation-Atmosphere interactions (FZJ)

The vegetation canopy represents the interface between the earth's terrestrial biomass and the atmosphere and has great influence on the exchange of climatically relevant carbon dioxide (CO_2) and water vapour (H_2O) between the biosphere and atmosphere. The terrestrial photosynthetic productivity is probably the most fundamental measure of global change, but is difficult to quantify on a regional scale. The reason is that CO_2 and H_2O fluxes are highly variable in time and space, and strategies to assess long-term regional and global carbon and water balances must address the inherent spatial variability of ecosystem photosynthesis. The understanding of biogenic CO_2 and H_2O fluxes is furthermore complicated by simultaneous anthropogenic contributions to the overall budgets of these gases.

The global atmospheric-carbon budget is rather well constrained (IPCC, 2001). Likewise, eddy-covariance flux measurements provide reasonably accurate measurements of local ecosystem carbon balances on spatial scales of a few hundreds of meters (e.g. Baldocchi et al., 1996). However, very little experimental information exists on the carbon budget at regional scales, ranging from a few hundred to several thousands of square kilometers. These budgets are estimated either by downscaling from the global scale or by upscaling from local flux measurements using biophysical models and remotely sensed information about vegetation activity. Most airborne experiments have been made under comparatively simple boundary conditions with approximately stationary meteorological conditions over smooth horizontal surfaces, where the influence of freshly polluted air was negligible (e.g. Denmead et al., 1996, Schmitgen et al., 2004). But in more populated areas like in large parts of Central Europe, the overall CO_2 flux within the region of interest is formed by the superposition of the biogenic CO_2 surface flux and CO_2 emissions from fossil-fuel combustion sources.

The influence of local structures on the regional fluxes of energy and momentum has been investigated in several studies (e.g. Isaac et al., 2004), but there was little attempt to clearly and quantitatively attribute single atmospheric structures to local surface elements. In the past there was definitely no attempt to use cross correlations between simultaneously measured meteorological parameters, biogenic and anthropogenic emissions, and surface signatures to attack the problem, although those correlations may give important additional informations for the budgets. A method to monitor and estimate the photosynthetic activity of ecosystems, correlating the uptake of CO_2 and the transpiration of H_2O, are airborne hyperspectral reflectance measurements. The photochemical reflectance index (PRI), which can be easily derived from such measurements, was developed to serve as an estimate of photosynthetic-light use efficiency (Gamon et al., 1997). PRI positively correlates with photosynthetic efficiency, is negatively correlated with non-photochemical energy dissipation (NPQ) and has been successfully used to detect changes in photosynthesis on the leaf level, small canopy level and recently at the ecosystem level (Nichol et al., 2002).

We expect that the analysis of correlations of airborne CO_2 and H_2O patterns and structures of the near-ground planetary-boundary layer with hyperspectral-reflectance measurements, together with measured signatures of anthropogenically produced carbon monoxide and nitrogen compounds, will provide new and more profound insights into the co-action of meteorological conditions, land surface structures, and the physiological state of the plants with respect to respiration and evapo-transpiration. The required measurement data can be obtained over heterogeneous land surfaces in much more detail than in the past by airborne measurements on a slowly-flying Zeppelin, equipped with state-of-the-art instrumentation for meteorological measurements and chemical species (O_3, CO, CO_2, NO, NO_2), in combination with simultaneous aircraft measurements observing lateral and top PBL boundary conditions. It will then be possible to close the budgets of CO_2 and H_2O as well as those of solely anthropogenically emitted trace gases with a much higher degree of reliability than currently achieved. The meteorological equipment necessary for such investigations is identical with that described in section 3.4. The required instruments for the airborne measurement of trace gases have already been developed and operated successfully for several years in a large number of national and European research projects, e.g. POLLUMET, TRACT, BERLIOZ, ESQUIF, Vertikator, COCA, ECHO, AEROCARB, CarboEurope. Furthermore, it would be useful to adopt the concept of a lowering device, like ACTOS (Section 3.3), for additional measurements of meteorological parameters, CO_2, H_2O and nitrogen compounds on a suspended payload below the Zeppelin.

4. Proposal for a Pseudo-Lagrangian Field Experiment

4.1 Scientific goal

As a first Zeppelin project, a field campaign is proposed which is designed as a regional, pseudo-Lagrangian experiment. The scientific aim is to study the emissions from a complex source area (a large city with mostly biogenic emissions in the surroundings) and the evolution of the plume in conjunction with transport and diffusion processes and changing stability conditions within the diurnal cycle, in order to quantify the various ageing processes that remove primary emissions over different scales: locally within the source area and regionally down-wind in the planetary boundary layer. As an innovative approach, the study of gas phase and aerosol processes will be linked in the project. The second aim which is more technical in nature is to demonstrate the capabilities of the Zeppelin NT as an airborne resarch platform.

4.2 Experimental concept

Following an airmass with well-constrained field measurements of the development of radicals, photooxidants and secondary aerosols in city plumes and wider polluted regions is a challenging problem. In the past, ground based sites were widely used, but they are fixed and so cannot follow the air mass as it is advected from the source region. Whilst multiple site experiments have been realised, they are at the surface, provide no vertical structure and are expensive as duplication of instrumentation is required. Mobile laboratories can help but again are surface based. Remote sensing offers vertical resolution, but is either fixed at one location if ground based, or offers limited vertical resolution when viewing from space. Furthermore remote sensing cannot as yet deliver the detailed physical and chemical information required. Aircraft provide mobile platforms that can probe the lower atmosphere in three dimensions, but light aircraft are limited by payload and larger research aircraft fly too quickly to resolve smaller scale features. Larger aircraft also cannot easily follow air masses on the scales of advection and are often not allowed in airspace above and around larger conurbations limiting their usefulness for these applications. In fact the ideal way to follow the development of trace compounds in an air plume is to perform a Lagrangian experiment in which a measurement platform is drifting with the air mass of interest. Execution as a pseudo-Lagrangian experiment, i.e. a zigzag course traversing the air trajectory multiple times, prevents sampling of contaminations emitted from the aircraft and provides horizontal coverage of the air plume. The Zeppelin NT promises to be the ideal platform to achieve such an experiment.

4.3 Field campaign

The field campaign will be carried out in a critical source area in Europe. Cities like Bordeaux, Marseille, Paris, Warsaw, London, Berlin, Augsburg would be options, where results of previous campaigns focussed on gas phase chemistry and would be a good basis to build on. Another option would be to follow the outflow of pollutants from a location in the Netherlands onto the North Sea. Preferred options are:

- Berlin; this place has been well characterised in previous campaigns, e.g. BERLIOZ 1998 (Becker et al., 1999; Volz-Thomas et al., 2003); it has a well established network of ground monitoring stations and a cooperative air surveillance.
- Augsburg; the emission of gaseous pollutants was well characterised in a previous field campaign, EVA 1998 (Slemr et al., 2002); Augsburg would have the additional advantage to lie close to the base of the Zeppelin NT in Friedrichshafen, offering low costs for transfer flights.
- Netherland towards to sea; several starting positions like Cabauw, Petten or Kollumerwaard are of interest where ground-based stations can provide data on aerosol and photooxidant compounds.

The experiment will focus on airborne measurements on board the Zeppelin NT. The flight will be guided by constant level balloons so that the pollutant transformations including all aspects of gas phase and aerosol chemistry can be quantified in detail, starting from the urban area moving with the average air trajectories. A case study of a pseudo-Lagrangian experiment in the city plume of Berlin is described in Appendix C. A typical experiment would have a total endurance of about 10 hours, of which 5 hrs would be needed for the experiment itself and 4.4 hrs for the transfer flights between the base at Berlin-Schönefeld airport and the start and destination points of the flight track. The air plume would be monitored over a distance of 180 km, while the Zeppelin would follow on a zigzag pattern of 40 km width. The scientific payload would be about 1200 kg and 850 kg at cruising altitudes of 500 m and 1000 m, respectively, allowing to carry a large number of state-of-the-art measurement instruments (see Appendix D). The measurements may be complemented by small research aircraft and by ground-based measurements including both *in-situ* and remote sensing techniques (LIDAR, MAX-DOAS). Modelling activities will support the planning and analysis stage. Additional 3-dimensional mappings of trace gases and aerosol parameters will be provided by remote measurements by MAX-DOAS instruments at ground and on board the Zeppelin. Meteorological measurements performed by aircraft, radio- and/or dropsondes and surface stations will deliver all relevant information for the estimation of diurnal boundary layer development and structure.

4.4 Modelling activities

Modelling activities comprise

- the planning (air quality forecasting) of the Lagrangian experiment,
- chemical weather and air trajectory predictions during the field campaign,
- and the analysis of the field experiment.

The field measurements will be used to test and improve mathematical modules that describe the gas-phase chemistry, aerosol physics and chemistry, and the interactions between the pollutants and the earth's surface. The modules will be used depending on the application in zero-dimensional box models, one-dimensional Lagrangian and three-dimensional Eulerian models. These activities will be supported by model based space-time chemical data assimilation methods that will help to provide a consistent picture of the field campaign. Pivoting around the Zeppelin drift experiment, the model hierarchy will include a grid configuration, which enables:

- the reconstruction of the longer term background air mass origin and its precampaign ageing,
- highly resolved modelling of chemical processes in the sampled air mass, primarily aiming to simulate the chemical and dynamical processes associated with urban air and background air interaction, including emissions, and
- simulation the fate of the sampled air mass, again on a longer time scale.

These demands enforce the use of a hemispheric chemistry transport model, as well as local scale chemistry transport models down to 1 km resolution, in a nested way. Supporting simulations will also be carried out from the Lagrangian viewpoint, employed as pointers to the origin of air masses encountered.

4.5 Deliverables

- A set of high-quality, consistent field data (physical and chemical properties of aerosols, chemical compounds, and radicals)
- Improved source apportionment and sinks of ambient aerosols (especially quantification of primary vs. secondary aerosol)
- Improved understanding and quantification of the chemical transformation of complex volatile organic compounds into products that affect the atmospheric oxidation efficiency and climate. Quantification of the effect these transformations have on the physical nature of the formed particulate, in particular its hygroscopicity and cloud nucleating and optical properties
- Improved understanding of the radical budget of OH and the day- and night-time oxidation efficiency of the tropospheric boundary layer
- Improved understanding of the importance of local surface dependent CO_2 and H_2O fluxes for the regional and global budgets.
- Evaluation of complex atmospheric chemistry models as well as soil-vegetation-atmosphere (SVAT) models with field data.

5. Funding

The realisation of the first Zeppelin experiment requires financial resources for

- the modifications of the Zeppelin-NT (e.g. additional platforms, gas inlets, etc.)
- the adaptation of the measurement instruments to the Zeppelin platforms
- the costs for the field campaign and flight hours.

It is planned to share the costs among the participating groups, relying on a mixed funding from institutional resources as well as national and EU funded projects.

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Appendix B: Technical Description of the Zeppelin NT

The following technical information has been kindly supplied by Zeppelin Luftschifftechnik GmbH (ZLT) in Friedrichshafen, or has been taken from the brochures and data sheets listed in the References (Appendix E). Technical modifications for airborne measurements, concerning the gondola and additional platforms, were discussed with ZLT on meetings in Friedrichshafen and checked for feasibility by the flight physics and engineering division of ZLT.

B1. Fundamentals

The airship is build around a framework of triangular carbon-fibre frames hold in place by three aluminium longerons. The cabin, empennage, and engines are mounted on this rigid structure. The pressurised envelope of the Zeppelin, which is made of a multi-layer laminate fabric, encloses a volume of 8450 m^3. The dimensions of the Zeppelin are 75.0 m x 19.5 m x 17.4 m (length x width x height).

The airship body consists of a carrier gas cell which is filled with non-flammable helium and

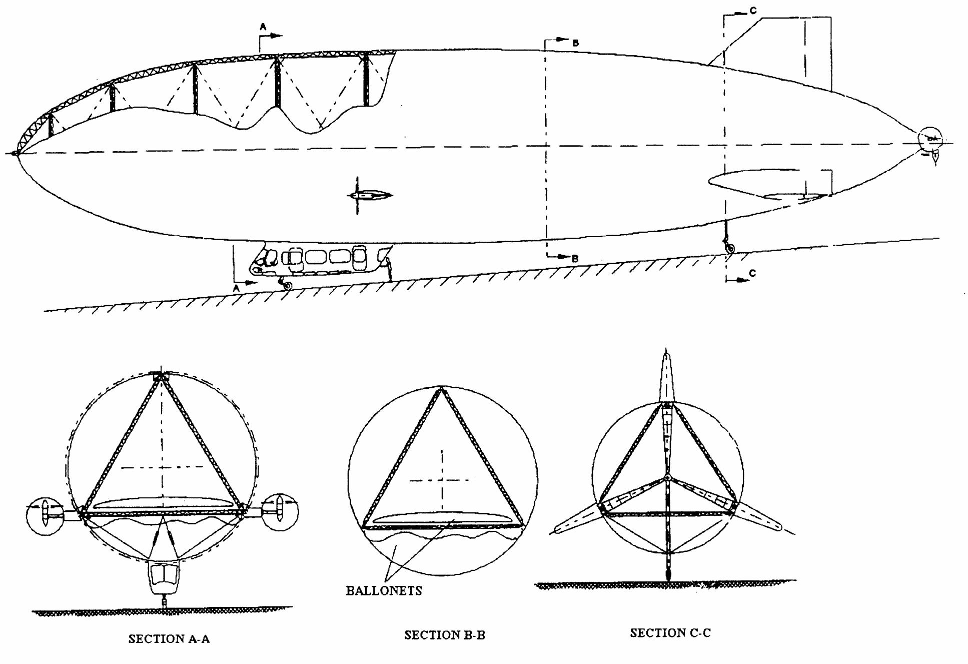

Figure 2: Schematic structure and cross-sectional views of the Zeppelin NT (from Zeppelin Luftschifftechnik GmbH).

two internal air cells (ballonets). For transport of a certain payload a corresponding amount of helium has to be filled in to generate the required lift. During the ascent of the airship the helium expands and the volume of the carrier gas cell increases. To compensate for this expansion air is expelled from the ballonets. When the carrier gas cell is completely filled by the expansion of the helium the airship has reached the so called ballonet ceiling and no further climb is possible. When the airship reduces its altitude the helium is compressed by the increasing air pressure and ambient air is blown into the ballonets to account for the reduced helium volume. When the air ballonets are filled completely the airship has reached its minimum flight altitude. For a given altitude profile of a flight mission the maximum amount of helium and thus the weight of the payload can be determined. At lower payloads the helium content can be reduced so that the upper and lower levels of the pressure altitude can be increased in the same way. Note that the flight altitude and the payload of the Zeppelin also depend on air temperature (see Tables below).

The Zeppelin is equipped with three 147 kW engines which drive two side and two rear swivelling propellers which allow for very precise manoeuvres even at very low airspeed, i.e. during take-off, landing or hovering. Due to the large distance from the side engines the cabin is nearly free of vibrations and noise. Each engine carries its own fuel tank adding up to a maximum amount of about 825 kg. Taking into account 50 kg for takeoff and landing and 70 kg as a reserve the maximum available amount of fuel for a scientific mission is about 705 kg. The cruising speed of about 70 km/h can be reached with a fuel consumption of about 50 kg/h. The fuel consumption with all three engines running is about 100 kg/h resulting in a cruising speed of 110 km/h with respect to the surrounding air. It is possible to run the engines in an idle mode to produce full electrical power but less thrust.

The avionic system of the airship is comparable to that of a normal commuter aircraft. The instrument flight systems allows for flights during night or in clouds. The exact position of the airship is determined from a GPS system and a radar altimeter allowing for a precise positioning of the Zeppelin above ground. Operation of the Zeppelin far away from an airbase is possible. Due to its high manoeuvrability only a flat airfield with a minimum diameter of 300 m is necessary for takeoff and landing even under gust conditions. A mast truck is needed to secure the airship on the ground. Depending on the length of the flight missions one or two pilots are needed. The ground crew can be reduced to a minimum of three people.

B.2 Gondola

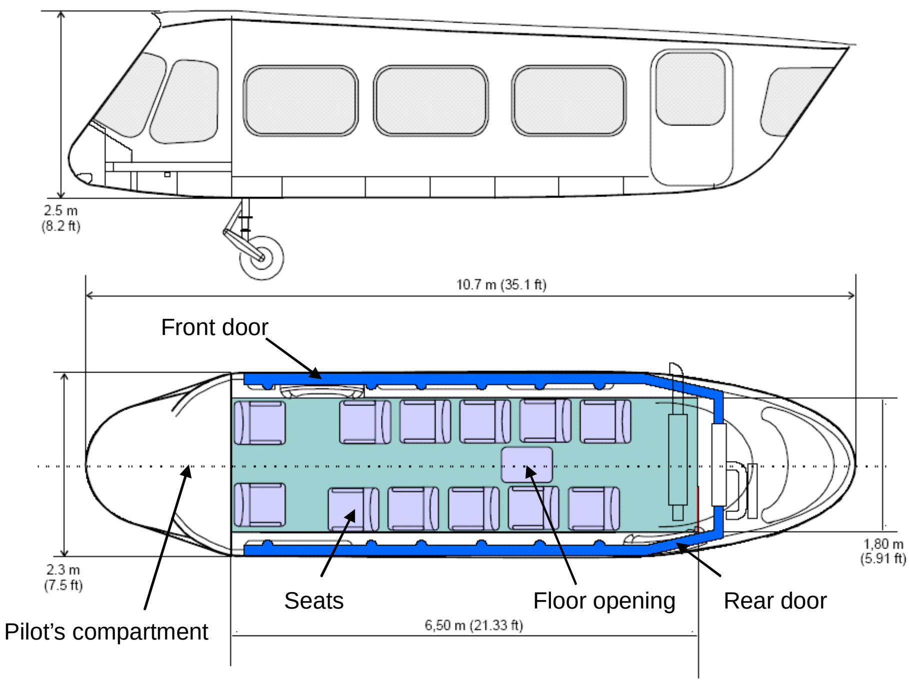

Figure 3: Schematic of the gondola (adapted from Zeppelin Luftschifftechnik GmbH).

The gondola of the Zeppelin will carry most of the scientific instruments. Its interior dimensions are 6.5 m long, 1.8 m wide and 1.9 m high, and can be loaded with up to 1400 kg. For touristy flights the gondola houses 12 seats mounted on the same type of rails like in an airplane. The seats can be removed to provide space for 19” standard flight racks. The floor provides an opening (65 cm x 45 cm) which allows for the release of dropsondes, lifting of a platform, operating a downward looking remote sensing instrument, or mounting an ambient air or aerosol inlet system. Other possible ports for an inlet system are the gondola front door or the nose of the cabin. In principle it is possible to extend inlet lines from the gondola to the nose or top of the Zeppelin. A meteorological boom (5.5 m long) can be mounted below the gondola. The thickness of the boundary layer around the cabin was calculated to increase from a couple of centimetres at its nose to 10—20 cm at its rear end.

B.3 Additional measurement platforms

A movable platform equipped with an instrument can be installed, which can be lifted up and down from the gondola using a winch to make measurements completely undisturbed from the airship itself, or to obtain vertical profiles of chemical or physical quantities. The platform will carry a load of approx. 100 kg over a vertical range of up to 500 m with a maximum velocity of 5 m/s.

Additional measurement instruments can be mounted on top of the Zeppelin in order to have unobscured view into the upper hemisphere (radiation measurements, remote sensing) or to sample air whose composition has not been altered by the shadow of the Zeppelin itself (radical concentration measurements). It is possible to mount a stable platform (approx. 6.5 m x 1 m, 500 kg load) on two top-nodes of the triangular grid elements. A third platform (approx. 1 m x 1 m, 200 kg load) mounted at the nose of the airship can provide an undisturbed airflow for in-situ measurements and an unobscured view horizontally, in azimuth and in nadir for remote sensing instruments. For both platforms a cable channel (4 cm diam.) will provide a connection to the gondola.

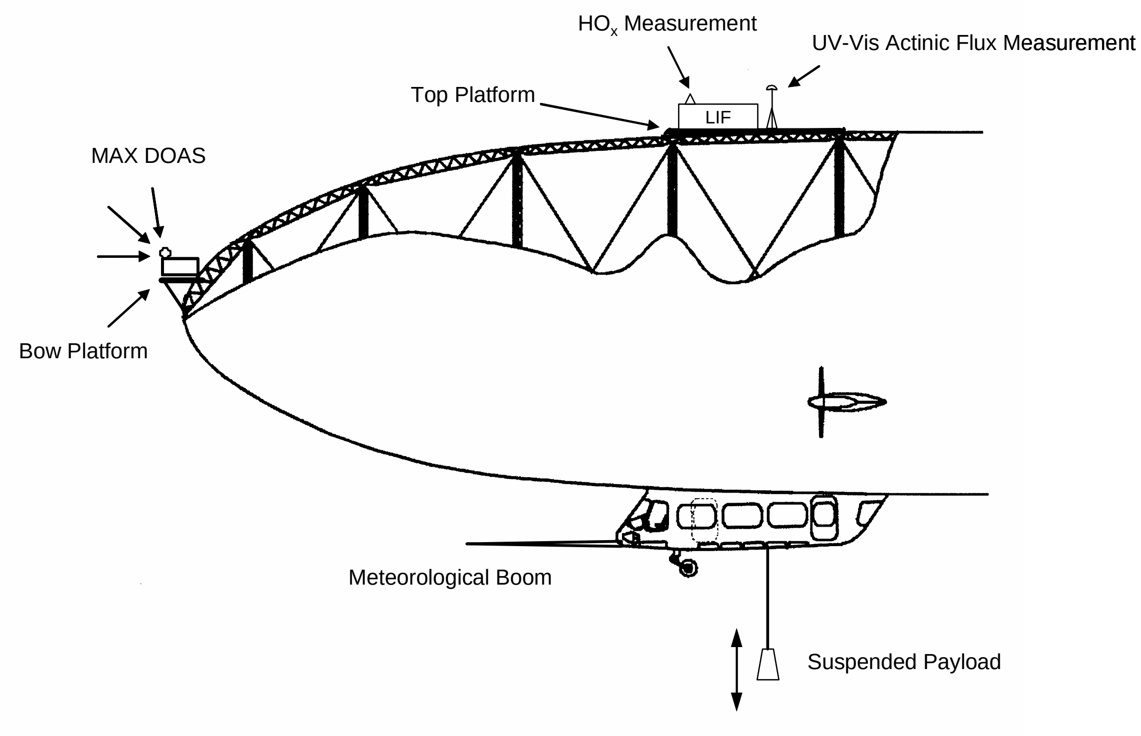

Figure 4: Possible additional platforms for atmospheric measurements.

B.4 Electrical power supply

The electrical power supply of the airship consists of 28 VDC produced by three generators coupled to the propulsion engines. The generators of the side engines produce 130 A each while the third generator produces 10 kW three-phase 100-200 VAC (no access) which is transformed into 300 A of 28 VDC. In total 560 A at 28 VDC are available if all three engines are running. Operation of the airship requires 340 A at maximum (during fast descent when blowers are running at full speed to fill the ballonets with air) leaving 220 A (approx. 6 kW) for the scientific mission. Scientific instruments need not to be turned off after landing and can remain on power, however the supply must be switched from on-board to external power supply. The on-board power supply will be shut down completely after landing.

Figure 5: Rear swivelling propulsion engines including electrical power generation units.

B.5 Technical Tables

Table B.5.1: Maximum zero-ballast heaviness.

Air temperature at take-off site [°C]	*Elevation of take-off site above MSL [m]*	*Maximum zero-ballast heaviness [kg]*
10	0	386
20		368
30		352
20	300	350
	600	334
	1000	318

The static weight at take-off is called *maximum zero-ballast heaviness*. It depends on the air temperature and elevation of the take-off site. The take-off heaviness of the airship must be less or equal to the maximum zero-ballast heaviness. If hovering is required, the maximum zero-ballast heaviness must be reduced depending on hover altitude and temperature. The table then applies with the following changes: 1. the temperature column denotes the air temperature at hover altitude; 2. the elevation column denotes the hover altitude. Note: the zero-ballast heaviness is limited by the certification requirements for safe take-off, landing and hovering in case of critical engine failure.

Table B.5.2: Useful load

Pressure height above main sea level [m]	*Air temperature at take-off site [°C]*	*Elevation of take-off site above MSL [m]*	*Useful load [kg]* †
500	20	0	1660
1000			1290
2000			600
1000	10	0	1520
	15		1400
	30		1070
1000	20	300	1260
		600	1200
2000		1000	490

† In addition to the airship plus gondola with interior panelling and 1 pilot.

The *useful load* of the Zeppelin is defined as the weight which the airship can carry in equilibrium (0 kg static weight at take-off) in addition to its own weight, including the gondola with interior panelling and one pilot. The useful load depends directly on the flight altitude (pressure height) and air temperature and elevation of the take-off site. It is directly related to the available buoyancy and thus to the amount of helium filled into the airship.

The *maximum useful load* is the sum of the useful load and the zero-ballast heaviness. It represents the upper limit of the total weight of equipment, on-board scientists, modifications to the Zeppelin (additional platforms etc.) and fuel.

The maximum available amount of *fuel* and the *fuel consumption* for different modes of operation and flight speeds are given in the following tables.

Table B.5.3: Maximum available fuel

Maximum usable amount of fuel	825 kg
fuel for take-off and landing	-50 kg
security reserve	-70 kg
Maximum amount of fuel available for mission	705 kg

Table B.5.4: Number of engines running

Number of engines running	Flight speed relative to wind [km/h]	Engine power setting [%]	Fuel consumption§ [kg/h]	Electrical power (as 28 VDC) available for experiments [kW]
1†	55		36	
2‡	55		36	
2‡	80		60	
3	55		36	6.16
3	80		60	
3	110		115	

§If an engine is used as an electrical generator only its fuel consumption is about 10 kg/h.

†Only the rear engine is running

‡Only the two side engines are running

Table B.5.5: Specific range (all engines running)

Specific range [km/kg Fuel]		*Headwind [m/s]*		
		0	*5*	*10*
Flight speed relative to head wind [km/h]	*37*	1.07	0.54	-
	55	1.59	1.06	0.53
	74	1.41	1.06	0.70
	93	1.18	0.95	0.70

Additional tables and diagrams are available from the airship flight handbook.

Appendix C: Scenario of a Pseudo-Lagrangian Experiment at Berlin

As a case study a pseudo-Lagrangian experiment in the city plume of Berlin was chosen with the following assumptions:

- the chemical development of an air parcel will be followed from 70 km upwind to the centre and for further 110 km downwind of Berlin (for about 5 hours);
- the wind direction is from SE to NW with a mean wind velocity of 10 m/s;
- in order to discriminate the city plume against the background atmosphere the airship will follow a zigzag route in a corridor of about 40 km width crossing the central trajectory of the air parcel every 20 km (approx. every ½ hour);
- the Zeppelin NT is stationed at the airport Berlin Schönefeld.

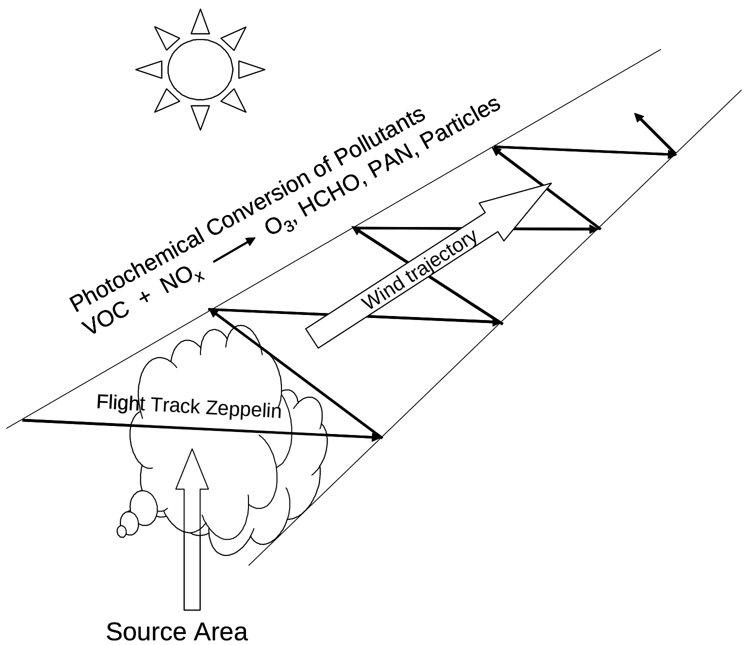

Figure 6: Schematic of the flight track during the pseudo-Lagrangian experiment.

In order to encounter the same air mass every time when the Zeppelin crosses the central trajectory, an average flight speed of about 72 km/h is required, resulting in a fuel consumption of approx. 50 kg/h. The total amount of fuel which has to be carried by the Zeppelin during take-off can be calculated as follows:

Section	*Distance [km]*	*Time [h]*	*Fuel [kg]*
Schönefeld → X0	60	0.83	42‡
X0 → X8	360	5.0	250
X8 → Schönefeld	130	3.6†	180
Take-off and landing			50
Reserve			70
Total	**550**	**9.43**	**592‡**

X0, X8: Start and destination of the Lagrangian experiment.

‡Add 6 kg (3 kg) to reach mission flight altitude of 1000 m (500 m).

†With head wind of 36 km/h.

The scientific payload, i.e. the weight of all instruments (incl. racks) and accompanying scientific staff which can be carried by the Zeppelin can be calculated as the sum of the maximum zero-ballast heaviness and the useful load of the airship, minus the required weight for fuel and additional platforms (see Appendix B.5). The useful load depends on the flight altitude (pressure height) and the air temperature at that height. For the above scenario the airfield elevation is 47 m, the air temperature is assumed to be 20 °C. It is assumed that a top platform is mounted to carry equipment for radical measurements. The scientific payload is calculated for 500 m and 1000 m flight altitude.

Weights [kg]	*Flight altitude 1000 m*	*Flight altitude 500 m*
Maximum zero-ballast heaviness	365	365
Useful load	1290	1650
Fuel	-598	-595
Top platform and general gondola equipment	-200	-200
Scientific payload	**857**	**1220**

In summary, the flight would have a total endurance of ca. 10 hours (5 hrs for the Lagrangian experiment, 4.4 hrs for transfer flights). The air plume would be monitored over a distance of 180 km, while the Zeppelin would fly zigzag over a distance of 360 km. The scientific payload would be about 1200 kg and 850 kg at cruising altitudes of 500 m and 1000 m, respectively.

Appendix D: Scientific Payload

D.1 Core instrumentation

Parameter	*Technique*
Position	Global position system (GPS)
Altitude	Radar altimeter
Ground speed, pitch and roll	Inertial navigation system
Wind speeds, static pressure	Turbulence probe
Temperature	Temperature probe
Humidity	Infrared red (IR) photometer, capacitive humidity sensor
Vision	Video camera
Data exchange gondola - ground	Satellite communication
Data storage	Data logging system

D.2 Meteorology Instrumentation

Parameter	*Technique*
Fundamental parameters	see Core instrumentation D.1
Temperature, humidity, pressure, wind speed, wind direction	Integrated nose boom or lowering device (suspended payload)
Wind fields (remote sensing)	Light detection and ranging (LIDAR)
Soil moisture (remote sensing)	GPS antenna, data acquisition
Clouds, turbulence + meteorol. parameters (wind, temperature, pressure, humidity cloud droplets, aerosol)	ACTOS package (see section 3.3) suspended payload

D.3 Photochemistry instrumentation

Parameter	*Technique*
OH, HO_2, RO_2 radicals	Laser induced fluorescence (LIF)
RO_x	Peroxy radical amplifier (PERCA)
O_3	UV photometer
H_2O	IR photometer, capacitive humidity sensor
CO, CH_4	Gas chromatography (GC)
CO	Quantum cascade laser spectrometry (QCLS)
CO_2	IR photometer
NO, NO_x, NO_y	Chemiluminescence
HONO	Long-path absorption photometer
NH_3	Quantum cascade laser spectrometry
PAN	Gas chromatography
H_2O_2	Quantum cascade laser spectrometry
H_2O_2, ROOH	Enzyme fluorescence
HCHO	Hantzsch fluorometry
HCHO	Quantum cascade laser spectrometry
VOCs	Gas chromatograph mass spectrometry (GC-MS)
OVOCs	Proton-transfer mass spectrometry (PTR-MS)
O_3, NO_2, HCHO	Remote sensing by Multi-axis Differential Optical Absorption Spectroscopy (MAX-DOAS)
Actinic radiation	Spectroradiometry, filter radiometry

D.4 Aerosol instrumentation

Parameter	*Technique*
Aerosol number density	Optical particle counter (OPC)
Particle size distribution	Scanning mobility particle sizer (SMPS)
Aerosol size and composition	Aerosol mass spectrometer (AMS)
Aerosol black carbon	Aethalometer
Aerosol light scattering	Nephelometer

Appendix E: References

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